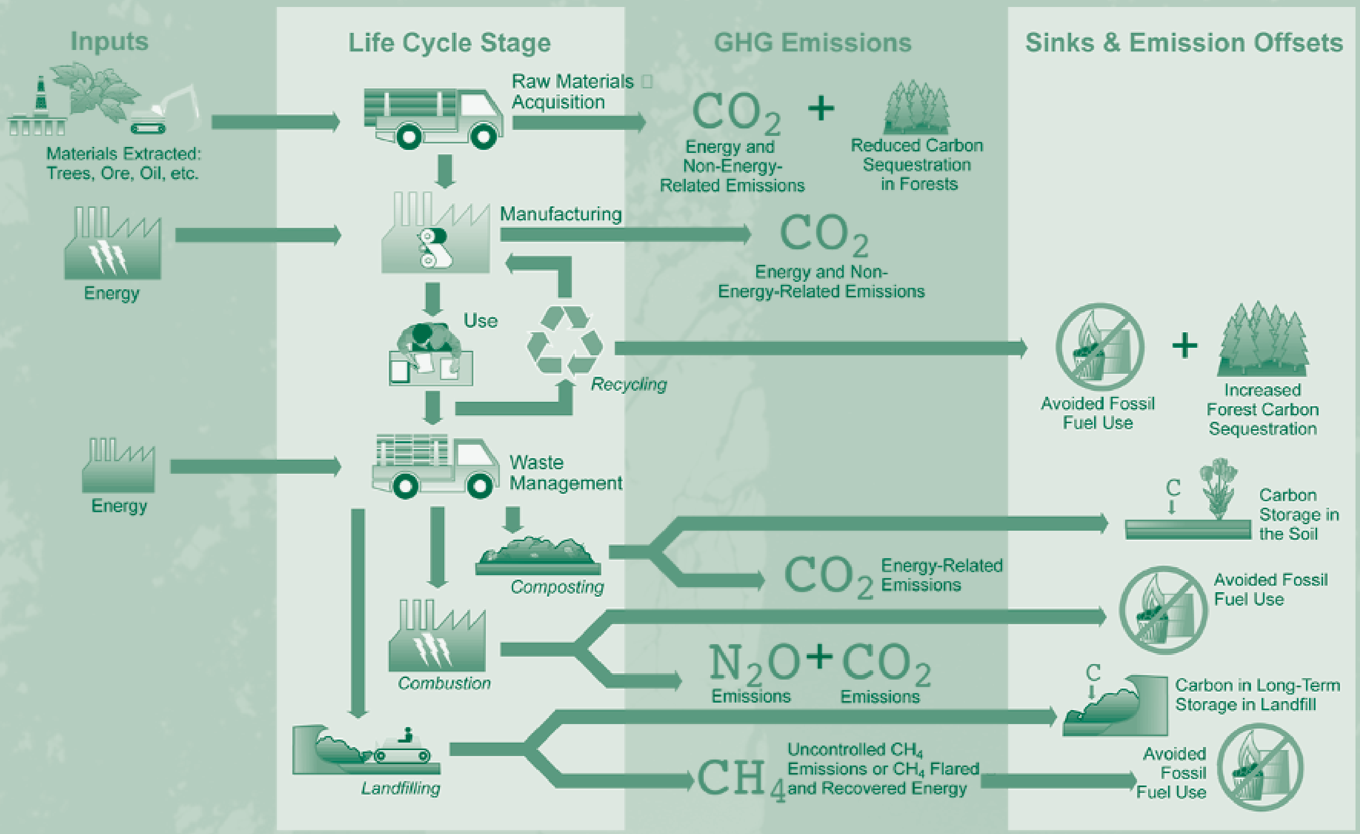
UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Solid Waste Management And Greenhouse Gases

A Life-Cycle Assessment of Emissions and Sinks



SOLID WASTE MANAGEMENT AND GREENHOUSE GASES
A Life-Cycle Assessment of Emissions and Sinks

2nd EDITION

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EXECUTIVE SUMMARY: BACKGROUND AND FINDINGS

In the 21st century, management of municipal solid waste (MSW) continues to be an important environmental challenge facing the United States. In 2000, the United States generated 232 million tons of MSW, an increase of 13 percent over 1990 generation levels and 53 percent over 1980 levels.[1] Climate change is also a serious issue, and the United States is embarking on a number of voluntary actions to reduce the emissions of greenhouse gases (GHGs) that can intensify climate change. By presenting material-specific GHG emission factors for various waste management options, this report examines how the two issues—MSW management and climate change—are related.

Among the efforts to slow the potential for climate change are measures to reduce emissions of carbon dioxide (CO_2) from energy use, decrease emissions of methane (CH_4) and other non-carbon dioxide GHGs, and promote long-term storage of carbon in forests and soil. Management options for MSW provide many opportunities to affect these processes, directly or indirectly. This report integrates information on the GHG implications of various management options for some of the most common materials in MSW. To our knowledge, this work represents the most complete national study on climate change emissions and sinks from solid waste management practices. The report's findings may be used to support a variety of programs and activities, including voluntary reporting of emission reductions from waste management practices.

ES.1 GREENHOUSE GASES AND CLIMATE CHANGE

Climate change is a serious international environmental concern and the subject of much research and debate. Many, if not most, of the readers of this report will have a general understanding of the greenhouse effect and climate change. However, for those who are not familiar with the topic, a brief explanation follows.[2]

A naturally occurring shield of "greenhouse gases" (primarily water vapor, carbon dioxide, methane, and, nitrous oxide), comprising 1 to 2 percent of the Earth's atmosphere, absorbs some of the solar radiation that would otherwise be radiated to space and helps warm the planet to a comfortable, livable temperature range. Without this natural "greenhouse effect," the average temperature on Earth would be approximately -2 degrees Fahrenheit, rather than the current 57 degrees Fahrenheit.[3]

Many scientists are alarmed by a significant increase in the concentration of CO_2 and other GHGs in the atmosphere. Since the pre-industrial era, atmospheric concentrations of CO_2 have increased by nearly 30 percent and CH_4 concentrations have more than doubled. There is a growing international scientific consensus that this increase has been caused, at least in part, by

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[1] U.S. EPA Office of Solid Waste, *Municipal Solid Waste in the United States: 2000 Facts and Figures*, EPA (2002), p. 2.

[2] For more detailed information on climate change, please see *The 2001 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*, (http://www.epa.gov/globalwarming/publications/emissions/us2001/index.html) (April 2001); and *Climate Change 2001: The Scientific Basis* (J.T. Houghton, et al., eds. Intergovernmental Panel on Climate Change [IPCC]; published by Cambridge University Press, 2001). To obtain a list of additional documents addressing climate change, access EPA's global warming Web site at www.epa.gov/globalwarming.

[3] *Climate Change 2001: The Scientific Basis*, op. cit., pp. 89-90.

human activity, primarily the burning of fossil fuels (coal, oil, and natural gas) for such activities as generating electricity and driving cars.[4]

Moreover, in international scientific circles a consensus is growing that the buildup of CO_2 and other GHGs in the atmosphere will lead to major environmental changes such as (1) rising sea levels that may flood coastal and river delta communities; (2) shrinking mountain glaciers and reduced snow cover that may diminish fresh water resources; (3) the spread of infectious diseases and increased heat-related mortality; (4) possible loss in biological diversity and other impacts on ecosystems; and (5) agricultural shifts such as impacts on crop yields and productivity.[5] Although reliably detecting the trends in climate due to natural variability is difficult, the most accepted current projections suggest that the rate of climate change attributable to GHGs will far exceed any natural climate changes that have occurred during the last 1,000 years.[6]

Many of these changes appear to be occurring already. Global mean surface temperatures already have increased by about 1 degree Fahrenheit over the past century. A reduction in the northern hemisphere's snow cover, a decrease in Arctic sea ice, a rise in sea level, and an increase in the frequency of extreme rainfall events all have been documented.[7]

Such important environmental changes pose potentially significant risks to humans, social systems, and the natural world. Many uncertainties remain regarding the precise timing, magnitude, and regional patterns of climate change and the extent to which mankind and nature can adapt to any changes. It is clear, however, that changes will not be easily reversed for many decades or even centuries because of the long atmospheric lifetimes of GHGs and the inertia of the climate system.

ES.2 WHAT IS THE UNITED STATES DOING ABOUT CLIMATE CHANGE?

In 1992, world leaders and citizens from some 200 countries met in Rio de Janeiro, Brazil, to confront global ecological concerns. At this "Earth Summit," 154 nations, including the United States, signed the Framework Convention on Climate Change, an international agreement to address the danger of global climate change. The objective of the Convention was to stabilize GHG concentrations in the atmosphere over time at a level at which man-made climate disruptions would be minimized.

By signing the Convention, countries made a voluntary commitment to reduce GHGs or take other actions to stabilize emissions of GHGs. All Parties to the Convention were required to develop and periodically update national inventories of their GHG emissions. The United States ratified the Convention in October 1992. One year later, the United States issued its *Climate Change Action Plan* (CCAP), which calls for cost-effective domestic actions and voluntary cooperation with states, local governments, industry, and citizens to reduce GHG emissions.

In order to achieve the goals outlined in the Climate Change Action Plan, EPA initiated several new voluntary programs to realize the most cost-effective opportunities for reducing emissions. For example, in 1994 EPA created the Landfill Methane Outreach Program, which aims to reduce landfill CH_4 emissions by facilitating the development of projects that use landfill

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[4] *Ibid.,* p. 7.

[5] J.J. McCarthy, et al., eds. 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. IPCC. Cambridge University Press. pp. 9-13.

[6] *Climate Change 2001: The Scientific Basis* , op. cit., p. 2.

[7] *Ibid.,* p. 4.

gas to produce energy.[8] In that same year, EPA introduced the Climate and Waste Program, with its focus on a broader set of waste management practices and climate protection.

To date, EPA's voluntary partnership programs for climate protection have achieved substantial environmental results. In 2000 alone, these programs reduced GHG emissions by 35 million metric tons of carbon equivalent (MMTCE)—the equivalent of eliminating the emissions from approximately 25 million cars. In addition, substantial CH_4 emission reductions—estimated at more than 1 MMTCE for the period from 1999-2000—are being obtained as an ancillary benefit of Clean Air Act (CAA) regulatory requirements that were promulgated in 1996. These reductions are expected to rise to nearly 47 MMTCE by 2004.

Meanwhile, an increasing number of states have been instituting their own voluntary actions to reduce emissions. Thirty-nine states and Puerto Rico have created GHG Inventories for their own emissions. Twenty-five states and Puerto Rico have completed or initiated state action plans, which list steps to reduce emissions. At least six of these states—Delaware, Iowa, Minnesota, Montana, New Jersey, and Oregon—have incorporated the reduction of waste into their GHG mitigation strategies. Finally, a few states—including California, Maine, New Hampshire, and Wisconsin—are in the process of establishing GHG registries, which enable companies and other entities to report voluntary emission reductions.

ES.3 WHAT IS THE RELATIONSHIP OF MUNICIPAL SOLID WASTE TO GREENHOUSE GAS EMISSIONS?

What does MSW have to do with rising sea levels, higher temperatures, and GHG emissions? For many wastes, the materials in MSW represent what is left over after a long series of steps: (1) extraction and processing of raw materials; (2) manufacture of products; (3) transportation of materials and products to markets; (4) use by consumers; and (5) waste management.

Virtually every step along this "life cycle" impacts GHG emissions. Waste management decisions can reduce GHGs by affecting one or more of the following:

(1) Energy consumption (specifically, combustion of fossil fuels) associated with making, transporting, using, and disposing the product or material that becomes a waste.

(2) Non-energy-related manufacturing emissions, such as the CO_2 released when limestone is converted to lime (which is needed for use in aluminum and steel manufacturing).

(3) CH_4 emissions from landfills where the waste is disposed.

(4) Carbon sequestration, which refers to natural or man-made processes that remove carbon from the atmosphere and store it for long periods or permanently.

The first three mechanisms *add* GHGs to the atmosphere and contribute to global warming. The fourth—carbon sequestration—*reduces* GHG concentrations by removing CO_2 from the atmosphere. Forest growth is one mechanism for sequestering carbon; if more biomass is grown than is removed (through harvest or decay), the amount of carbon stored in trees increases, and thus carbon is sequestered.

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[8] The Landfill Methane Outreach Program (LMOP) is a voluntary assistance and partnership program that helps facilitate and promote the use of landfill gas as a renewable energy source. By controlling landfill gas instead of allowing it to migrate into the air, the LMOP helps businesses, states, and communities protect the environment and build a sustainable future. The program has an Internet home page (http://www.epa.gov/landfill.html) and can be reached via a toll-free hotline number (800-782-7937).

Different wastes and waste management options have different implications for energy consumption, CH_4 emissions, and carbon sequestration. Source reduction and recycling of paper products, for example, reduce energy consumption, decrease combustion and landfill emissions, and increase forest carbon sequestration.

ES.4 WHY EPA PREPARED THIS REPORT AND HOW IT HAS BEEN USED

Recognizing the potential for source reduction and recycling of municipal solid waste to reduce GHG emissions, EPA included a source reduction and recycling initiative in the original 1994 Climate Change Action Plan and set an emission reduction goal based on a preliminary analysis of the potential benefits of these activities. It was clear that a rigorous analysis would be needed to gauge more accurately the total GHG emission reductions achievable through source reduction and recycling. That *all* of the options for managing MSW should be considered also became clear. By addressing a broader set of MSW management options, a more comprehensive picture of the GHG benefits of voluntary actions in the waste sector could be determined and the relative GHG impacts of various waste management approaches could be assessed. To this end, EPA launched a major research effort, the results of which were published in the first edition of this report in September 1998. This edition of the report includes additional materials and incorporates updated data affecting many of the material-specific results. The emission factors presented will continue to be updated and improved as more data become available. The latest emission factors, reflecting these ongoing revisions, can be found on the EPA Global Warming Web site <http://www.epa.gov/globalwarming/actions/waste/w-online.htm>.

The primary application of the GHG emission factors in this report is to support mitigation accounting for waste management practices that mitigate climate change. In recent years, the emission factors have been applied for this purpose in a number of ways. In conjunction with the U.S. Department of Energy, EPA has used these estimates to develop guidance for voluntary reporting of GHG reductions, as authorized by Congress in Section 1605(b) of the Energy Policy Act of 1992.

Other applications have included quantifying the GHG reductions from voluntary programs aimed at source reduction and recycling, such as EPA's WasteWise and Pay-As-You-Throw programs. EPA also has worked with the Climate Neutral Network to develop company-specific GHG "footprints" for the network's member companies, who have pledged to become GHG "neutral" through emission reductions or offset activities.

The international community has shown considerable interest in using the emission factors—or adapted versions—to develop GHG emissions estimates for non-U.S. solid waste streams.[9] For example, Environment Canada recently employed our life-cycle methodology and components of our analysis to develop a set of Canada-specific GHG emission factors to support analysis of waste-related mitigation opportunities.[10]

Additionally, EPA worked with the International Council for Local Environmental Initiatives (ICLEI) to incorporate GHG emission factors into its municipal GHG accounting software. Currently, 350 communities participate in ICLEI's Cities for Climate Protection Campaign, which helps them establish a GHG emission reduction target and implement a

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[9] Note that waste composition and product life cycles vary significantly among countries. This report may assist other countries by providing a methodologic framework and benchmark data for developing GHG emission estimates for their solid waste streams.

[10] Environment Canada. 2001. *Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions*. Prepared by ICF Consulting, Torrie-Smith Associates, and Enviros-RIS.

comprehensive local action plan designed to achieve that target. Currently, we are exploring other options for broadening the use of our research internationally.

To make it easier for organizations to use these emission factors, EPA created the Waste Reduction Model (WARM) spreadsheet tool.[11] WARM enables waste managers and other users to calculate changes in total GHG emissions quickly by entering in information on baseline and alternative waste management practices. By applying the appropriate material-specific emission factors for each practice, the tool generates an estimate of the net GHG impact from implementing the alternative waste management practice as compared to the baseline practice.

ES.5 HOW WE ANALYZED THE IMPACT OF MUNICIPAL SOLID WASTE ON GREENHOUSE GAS EMISSIONS

To measure the GHG impacts of MSW, one must first decide which wastes to analyze. We surveyed the universe of materials and products found in MSW and determined those that are most likely to have the greatest impact on GHGs. These determinations were based on (1) the quantity generated; (2) the differences in energy use for manufacturing a product from virgin versus recycled inputs; and (3) the potential contribution of materials to CH_4 generation in landfills. By this process, we limited the analysis to the following 16 items:

- Aluminum Cans;
- Steel Cans;
- Glass;
- HDPE (high-density polyethylene) Plastic;
- LDPE (low-density polyethylene) Plastic;
- PET (polyethylene terephthalate) Plastic;
- Corrugated Cardboard;
- Magazines/Third-class Mail;
- Newspaper;
- Office Paper;
- Phonebooks;
- Textbooks;
- Dimensional Lumber;
- Medium-density Fiberboard;
- Food Discards; and
- Yard Trimmings.

The foregoing materials constitute 64.4 percent, by weight, of MSW, as shown in Exhibit ES-1.[12]

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[11] WARM is available on the EPA Web site: http://www.epa.gov/globalwarming/actions/waste/warm.htm.

[12] Note that these data are based on national averages. The composition of solid waste varies locally and regionally; local or state-level data should be used when available.

We also examined the GHG implications of managing mixed paper, mixed plastics, mixed organics, mixed recyclables, and mixed MSW.

- *Mixed paper* is recycled in large quantities and is an important class of scrap material in many recycling programs. Presenting a single definition of mixed paper is difficult, however, because recovered paper varies considerably, depending on the source. For purposes of this report, we identified three categories of mixed paper according to the dominant source—broad (general sources), office, and residential.

- *Mixed plastics* is comprised of HDPE, LDPE, and PET, and is estimated by taking a weighted average of the 2000 recovery rates for these three plastic types.

- *Mixed organics* is a weighted average of food discards and yard trimmings, using generation rates for 2000.

- *Mixed recyclables* are materials that are typically recycled. As used in this report, the term includes the items listed in Exhibit ES-1, except food discards and yard trimmings. The emission factors reported for mixed recyclables represent the average GHG emissions for these materials, weighted by the tonnages at which they were recycled in 2000.

- *Mixed MSW* is comprised of the waste material typically discarded by households and collected by curbside collection vehicles; it does not include white goods (e.g., refrigerators, toasters) or industrial waste. This report analyzes mixed MSW on an "as-disposed" (rather than "as-generated") basis.

Exhibit ES-1
Percentage of 2000 U.S. Generation of MSW for Materials in This Report

Material	**Percentage of MSW Generation (by Weight)**
Aluminum Cans	0.7%
Steel Cans	1.1%
Glass	5.5%
HDPE	1.6%
LDPE	1.3%
PET	0.8%
Corrugated Cardboard	13.0%
Magazines/Third-class Mail	3.3%
Newspaper	6.5%
Office Paper	3.2%
Phonebooks	0.3%
Textbooks	0.5%
Dimensional Lumber (listed as "Wood – Containers and Packaging)	3.4%
Medium-density Fiberboard	NA
Food Discards	11.2%
Yard Trimmings	12.0%
TOTAL	64.4%

Source: U.S. EPA. 2002. *Municipal Solid Waste in the United States: 2000 Facts and Figures,* EPA 530-R-02-001.

We developed a streamlined life-cycle inventory for each of the selected materials. Our analysis is streamlined in the sense that it examines GHG emissions only and is not a more comprehensive environmental analysis of all emissions from municipal solid waste management options.[13]

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[13] EPA's Office of Research and Development (ORD) performed a more extensive application of life-cycle assessment for various waste management options for MSW. A decision support tool (DST) and life-cycle inventory (LCI) database for North America have been developed with funding by ORD through a cooperative agreement with the Research Triangle Institute (RTI) (CR823052). This methodology is based on a multi-media, multi-pollutant approach and includes analysis of GHG emissions as well as a broader set of emissions (air, water, and waste) associated with MSW operations. At the time of publication of this report, the MSW-DST is available for site-specific applications. For further information, contact Keith Weitz at rti.org or (919) 541-6973. The LCI database is expected to be released in 2002. The Web site address for further information is: <http://www.rti.org/units/ese/p2/lca.cfm#life>.

We focused on those aspects of the life cycle that have the potential to emit GHGs as materials change from their raw states to products and then to waste. Exhibit ES-2 shows the steps in the life cycle at which GHGs are emitted, carbon sequestration is affected, and utility energy is displaced. As shown, we examined the potential for these effects at the following points in a product's life cycle:

- Raw material acquisition (fossil fuel energy and other emissions, and changes in forest carbon sequestration);
- Manufacturing (fossil fuel energy emissions); and
- Waste management (CO_2 emissions associated with composting, non-biogenic CO_2 and nitrous oxide (N_2O) emissions from combustion, and CH_4 emissions from landfills); these emissions are offset to some degree by carbon storage in soil and landfills, as well as avoided utility emissions from energy recovery at combustors and landfills.

At each of these points, we also considered transportation-related energy emissions. Estimates of GHG emissions associated with electricity used in the raw materials acquisition and manufacturing steps are based on the nation's current mix of energy sources,[14] including fossil fuels, hydropower, and nuclear power. Estimates of GHG emission reductions attributable to utility emissions avoided from waste management practices, however, are based solely on the reduction of fossil fuel use.[15]

We did not analyze the GHG emissions associated with consumer use of products because energy use for the selected materials is small (or zero) at this point in the life cycle. In addition, the energy consumed during use would be approximately the same whether the product was made from virgin or recycled inputs.

To apply the GHG estimates developed in this report, one must compare a baseline scenario with an alternative scenario, on a life-cycle basis. For example, we could compare a baseline scenario, where 10 tons of office paper are manufactured, used, and landfilled, to an alternative scenario, where 10 tons are manufactured, used, and recycled.

Improvements to the First Edition

This report is the second edition of *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*. This edition includes the following improvements:

- Incorporates new data on energy and recycling loss rates from EPA's Office of Research and Development;
- Expands the analysis of the GHG benefits of composting, including results of CENTURY model runs;
- Develops emission factors for five new material types: magazines/third-class mail, phonebooks, textbooks, dimensional lumber, and medium-density fiberboard;
- Develops emission factors for two new categories of mixed materials: mixed plastics and mixed organics;
- Incorporates new energy data into calculations of utility offsets;
- Revises carbon coefficients and fuel use for national average electricity generation;
- Updates information on landfill gas recovery rates;
- Adds a discussion of emerging issues in the area of climate change and waste management; and
- Provides a list of suggested proxy values for voluntary reporting of GHG emission reductions.

These changes and/or revisions are described in more detail throughout the report.

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[14] The emissions are based on the current national grid mix, as opposed to regional grids.

[15] We adopted this approach based on suggestions from several reviewers who argued that fossil fuels should be regarded as the marginal fuel displaced by waste-to-energy and landfill gas recovery systems.

Exhibit ES-2 Greenhouse Gas Sources and Sinks Associated with the Material Life Cycle

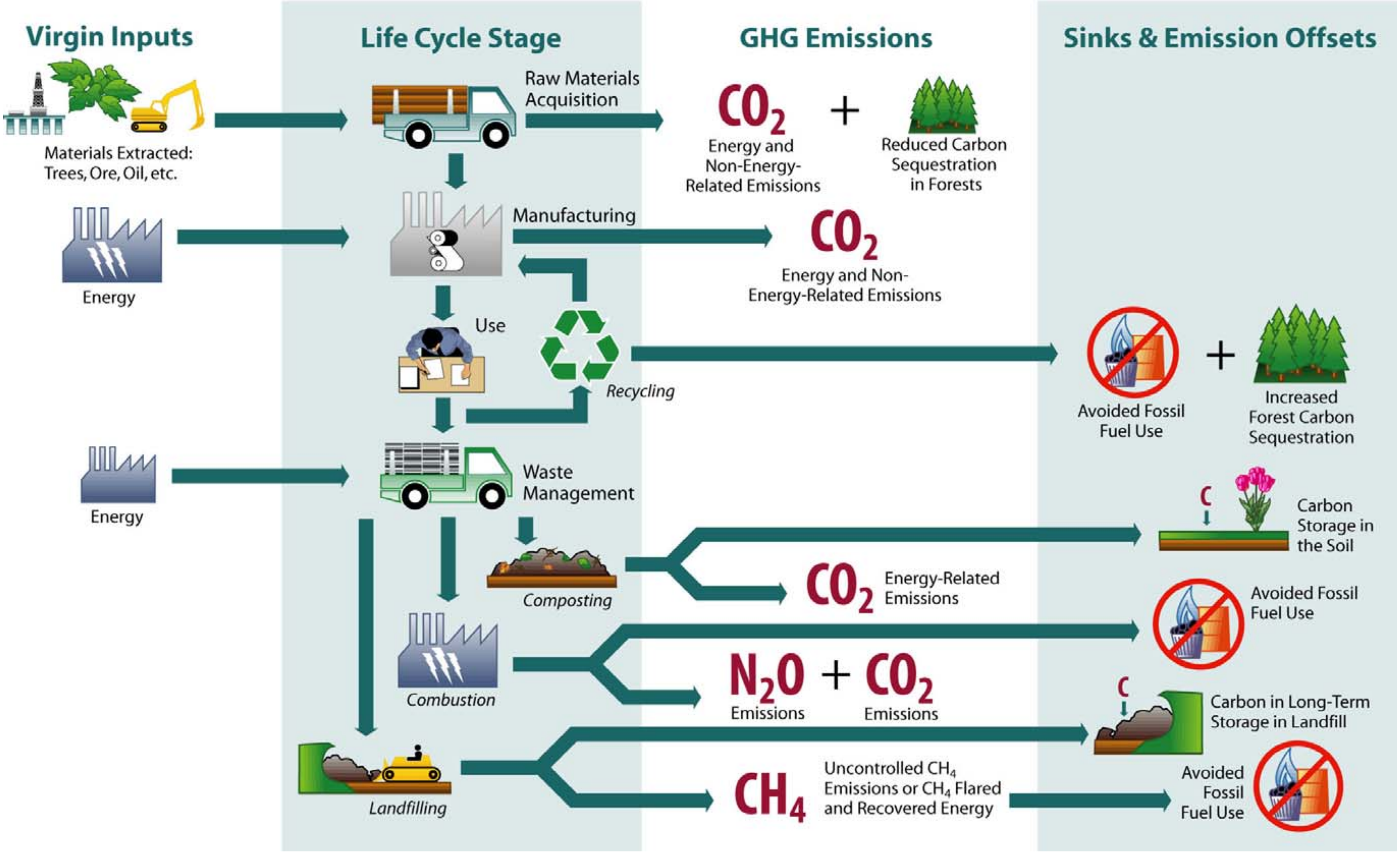

Exhibit ES-3 shows how GHG sources and sinks are affected by each waste management strategy. For example, the top row of the exhibit shows that source reduction[16] (1) reduces GHG emissions from raw materials acquisition and manufacturing; (2) results in an increase in forest carbon sequestration; and (3) does not result in GHG emissions from waste management. The sum of emissions (and sinks) across all steps in the life cycle represents net emissions.

Exhibit ES-3 Components of Net Emissions for Various MSW Management Strategies

MSW Management Strategy	**GHG Sources and Sinks**		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**Waste Management**
Source Reduction	Decrease in GHG emissions, relative to the baseline of manufacturing	Increase in forest carbon sequestration (for organic materials)	No emissions/sinks
Recycling	Decrease in GHG emissions due to lower energy requirements (compared to manufacture from virgin inputs) and avoided process non-energy GHGs	Increase in forest carbon sequestration (for organic materials)	Process and transportation emissions associated with recycling are counted in the manufacturing stage
Composting (food discards, yard trimmings)	No emissions/sinks	Increase in soil carbon storage	Compost machinery emissions and transportation emissions
Combustion	No change	No change	Non-biogenic CO_2, N_2O emissions, avoided utility emissions, and transportation emissions
Landfilling	No change	No change	CH_4 emissions, long-term carbon storage, avoided utility emissions, and transportation emissions

ES.6 RESULTS OF THE ANALYSIS

Management of municipal solid waste presents many opportunities for GHG emission reductions. Source reduction and recycling can reduce GHG emissions at the manufacturing stage, increase forest carbon sequestration, and avoid landfill CH_4 emissions. When waste is combusted, energy recovery displaces electricity generated by utilities by burning fossil fuels (thus reducing GHG emissions from the utility sector), and landfill CH_4 emissions are avoided. Landfill CH_4 emissions can be reduced by using gas recovery systems and by diverting organic materials from landfills. Landfill CH_4 can be flared or utilized for its energy potential. When used for its energy potential, landfill CH_4 displaces fossil fuels, as with MSW combustion.

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[16] In this analysis, the source reduction techniques we analyze involve using less of a given product without using more of some other product—e.g., making aluminum cans with less aluminum (“lightweighting”); double-sided rather than single-sided photocopying; or reuse of a product. We did not consider source reduction of one product that would be associated with substitution by another product—e.g., substituting plastic boxes for corrugated paper boxes. Nor did we estimate the potential for source reduction of chemical fertilizers and pesticides with increased production and use of compost. For a discussion of source reduction with material substitution, see Section 4.3.

In order to support a broad portfolio of climate change mitigation activities covering a range of GHGs, many different methodologies for estimating emissions will be needed. The primary result of this research is the development of material-specific GHG emission factors that can be used to account for the climate change benefits of waste management practices.

Exhibits ES-4 and ES-5 present the GHG impacts of source reduction, recycling, composting, combustion, and landfilling. The impacts are presented on a per-ton managed basis for the individual and mixed materials, using the waste generation reference point. Exhibit ES-4 presents these values in MTCE/ton, and Exhibit ES-5 presents the values in metric tons of carbon dioxide equivalent/ton ($MTCO_2E$/ton). For comparison, Exhibits ES-6 and ES-7 show the same results (in MTCE/ton and $MTCO_2E$/ton, respectively) using the raw material extraction reference point. In these tables, emissions for 1 ton of a given material are presented across different management options.[17] The life-cycle GHG emissions for each of the first four waste management strategies—source reduction, recycling, composting, and combustion—are compared to the GHG emissions from landfilling in Exhibits ES-8 and ES-9. These exhibits show the GHG values for each of the first four management strategies, minus the GHG values for landfilling. With these exhibits, one may compare the GHG emissions of changing management of 1 ton of each material from landfilling (often viewed as the baseline waste management strategy) to one of the other waste management options.

All values shown in Exhibits ES-4 through ES-9 are for national average conditions (e.g., average fuel mix for raw material acquisition and manufacturing using recycled inputs; typical efficiency of a mass burn combustion unit; national average landfill gas collection rates). GHG emissions are sensitive to some factors that vary on a local basis, and thus site-specific emissions will differ from those summarized here.

Following is a discussion of the principal GHG emissions and sinks for each waste management practice and the effect that they have on the emission factors:

- Source reduction, in general, represents an opportunity to reduce GHG emissions in a significant way.[18] For many materials, the reduction in energy-related CO_2 emissions from the raw material acquisition and manufacturing process, and the absence of emissions from waste management, combine to reduce GHG emissions more than other options.
- For most materials, recycling has the second lowest GHG emissions. For these materials, recycling reduces energy-related CO_2 emissions in the manufacturing process (although not as dramatically as source reduction) and avoids emissions from waste management. Paper recycling increases the sequestration of forest carbon.
- Composting is a management option for food discards and yard trimmings. The net GHG emissions from composting are lower than landfilling for food discards (composting avoids CH_4 emissions), and higher than landfilling for yard trimmings (landfilling is credited with the carbon storage that results from incomplete decomposition of yard trimmings). Overall, given the uncertainty in the analysis, the emission factors for composting or combusting these materials are similar.

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[17] Note that the difference between any two values for a given material in Exhibit ES-4 (i.e., emissions for the same material in two waste management options) is the same as the difference between the two corresponding values in Exhibit ES-5.

[18] As noted above, the only source reduction strategy analyzed in this study is lightweighting. Consequently, the results shown here do not directly apply to material substitution.

Exhibit ES-4

Net GHG Emissions from Source Reduction and MSW Management Options - Emissions Counted from a Waste Generation Reference Point (MTCE/Ton)[1]

Material	Source Reduction[2]	Recycling	Composting[3]	Combustion[4]	Landfilling[5]
Aluminum Cans	-2.49	-4.11	NA	0.02	0.01
Steel Cans	-0.79	-0.49	NA	-0.42	0.01
Glass	-0.14	-0.08	NA	0.01	0.01
HDPE	-0.49	-0.38	NA	0.23	0.01
LDPE	-0.61	-0.47	NA	0.23	0.01
PET	-0.49	-0.42	NA	0.28	0.01
Corrugated Cardboard	-0.51	-0.71	NA	-0.19	0.08
Magazines/Third-class Mail	-1.04	-0.74	NA	-0.13	-0.12
Newspaper	-0.81	-0.95	NA	-0.21	-0.21
Office Paper	-0.80	-0.68	NA	-0.18	0.62
Phonebooks	-1.28	-0.91	NA	-0.21	-0.21
Textbooks	-1.23	-0.75	NA	-0.18	0.62
Dimensional Lumber	-0.55	-0.67	NA	-0.22	-0.10
Medium-density Fiberboard	-0.60	-0.67	NA	-0.22	-0.10
Food Discards	NA	NA	-0.05	-0.05	0.17
Yard Trimmings	NA	NA	-0.05	-0.06	-0.09
Mixed Paper					
Broad Definition	NA	-0.67	NA	-0.19	0.10
Residential Definition	NA	-0.67	NA	-0.18	0.07
Office Paper Definition	NA	-0.83	NA	-0.17	0.15
Mixed Plastics	NA	-0.41	NA	0.25	0.01
Mixed Recyclables	NA	-0.76	NA	-0.17	0.05
Mixed Organics	NA	NA	-0.05	-0.06	0.03
Mixed MSW as Disposed	NA	NA	NA	-0.04	0.07

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] MTCE/ton: Metric tons of carbon equivalent per short ton of material. Material tonnages are on an as-managed (wet weight) basis.

[2] Source reduction assumes initial production using the current mix of virgin and recycled inputs.

[3] There is considerable uncertainty in our estimate of net GHG emissions from composting; the values of zero are plausible values based on assumptions and a bounding analysis.

[4] Values are for mass burn facilities with national average rate of ferrous recovery.

[5] Values reflect estimated national average methane recovery in year 2000.

Exhibit ES-5

Net GHG Emissions from Source Reduction and MSW Management Options - Emissions Counted from a Waste Generation Reference Point ($MTCO_2E$/Ton)[1]

Material	Source Reduction[2]	Recycling	Composting[3]	Combustion[4]	Landfilling[5]
Aluminum Cans	-9.15	-15.07	NA	0.06	0.04
Steel Cans	-2.89	-1.79	NA	-1.53	0.04
Glass	-0.50	-0.28	NA	0.05	0.04
HDPE	-1.79	-1.40	NA	0.85	0.04
LDPE	-2.25	-1.71	NA	0.85	0.04
PET	-1.78	-1.55	NA	1.04	0.04
Corrugated Cardboard	-1.89	-2.60	NA	-0.68	0.28
Magazines/Third-class Mail	-3.80	-2.70	NA	-0.49	-0.44
Newspaper	-2.97	-3.48	NA	-0.77	-0.76
Office Paper	-2.95	-2.48	NA	-0.65	2.28
Phonebooks	-4.70	-3.34	NA	-0.77	-0.76
Textbooks	-4.49	-2.74	NA	-0.65	2.28
Dimensional Lumber	-2.01	-2.45	NA	-0.81	-0.38
Medium-density Fiberboard	-2.20	-2.47	NA	-0.81	-0.38
Food Discards	NA	NA	-0.20	-0.19	0.62
Yard Trimmings	NA	NA	-0.20	-0.23	-0.34
Mixed Paper					
Broad Definition	NA	-2.47	NA	-0.68	0.37
Residential Definition	NA	-2.47	NA	-0.68	0.25
Office Paper Definition	NA	-3.05	NA	-0.62	0.56
Mixed Plastics	NA	-1.51	NA	0.93	0.04
Mixed Recyclables	NA	-2.80	NA	-0.61	0.19
Mixed Organics	NA	NA	-0.20	-0.21	0.12
Mixed MSW as Disposed	NA	NA	NA	-0.13	0.24

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] $MTCO_2E$/ton: Metric tons of carbon dioxide equivalent per short ton of material. Material tonnages are on an as-managed (wet weight) basis.

[2] Source reduction assumes initial production using the current mix of virgin and recycled inputs.

[3] There is considerable uncertainty in our estimate of net GHG emissions from composting; the values of zero are plausible values based on assumptions and a bounding analysis.

[4] Values are for mass burn facilities with national average rate of ferrous recovery.

[5] Values reflect estimated national average methane recovery in year 2000.

Exhibit ES-6

Net GHG Emissions from Source Reduction and MSW Management Options - Emissions Counted from a Raw Materials Extraction Reference Point (MTCE/Ton)

Material	Source Reduction[1]	Recycling[2]	Composting[2]	Combustion[2]	Landfilling[2]
Aluminum Cans	0.00	-1.61	NA	2.51	2.50
Steel Cans	0.00	0.30	NA	0.37	0.80
Glass	0.00	0.06	NA	0.15	0.15
HDPE	0.00	0.10	NA	0.72	0.50
LDPE	0.00	0.15	NA	0.85	0.63
PET	0.00	0.06	NA	0.77	0.50
Corrugated Cardboard	-0.28	-0.47	NA	0.05	0.32
Magazines/Third-class Mail	-0.58	-0.28	NA	0.33	0.34
Newspaper	-0.35	-0.49	NA	0.25	0.25
Office Paper	-0.50	-0.37	NA	0.13	0.93
Phonebooks	-0.65	-0.27	NA	0.42	0.43
Textbooks	-0.64	-0.16	NA	0.41	1.21
Dimensional Lumber	-0.50	-0.62	NA	-0.17	-0.06
Medium-density Fiberboard	-0.50	-0.58	NA	-0.12	-0.01
Food Discards	NA	NA	-0.05	-0.05	0.17
Yard Trimmings	NA	NA	-0.05	-0.06	-0.09
Mixed Paper					
Broad Definition	NA	-0.30	NA	0.19	0.48
Residential Definition	NA	-0.30	NA	0.19	0.45
Office Paper Definition	NA	0.02	NA	0.68	1.01
Mixed Plastics	NA	0.09	NA	0.76	0.52
Mixed Recyclables	NA	-0.40	NA	0.19	0.41
Mixed Organics	NA	NA	-0.05	-0.06	0.03
Mixed MSW as Disposed	NA	NA	NA	-0.04	0.07

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Source reduction assumes initial production using the current mix of virgin and recycled inputs.

[2] Includes emissions from the initial production of the material being managed, except for foodwaste, yard waste, and mixed MSW.

Exhibit ES-7

Net GHG Emissions from Source Reduction and MSW Management Options - Emissions Counted from a Raw Materials Extraction Reference Point (MTCO$_2$E/Ton)

Material	Source Reduction[1]	Recycling[2]	Composting[2]	Combustion[2]	Landfilling[2]
Aluminum Cans	0.00	-5.92	NA	9.21	9.18
Steel Cans	0.00	1.09	NA	1.35	2.92
Glass	0.00	0.22	NA	0.55	0.54
HDPE	0.00	0.38	NA	2.64	1.82
LDPE	0.00	0.54	NA	3.11	2.29
PET	0.00	0.23	NA	2.82	1.82
Corrugated Cardboard	-1.01	-1.72	NA	0.20	1.16
Magazines/Third-class Mail	-2.11	-1.02	NA	1.20	1.25
Newspaper	-1.29	-1.79	NA	0.91	0.92
Office Paper	-1.82	-1.36	NA	0.47	3.41
Phonebooks	-2.37	-1.01	NA	1.56	1.57
Textbooks	-2.35	-0.60	NA	1.49	4.43
Dimensional Lumber	-1.84	-2.28	NA	-0.64	-0.21
Medium-density Fiberboard	-1.84	-2.11	NA	-0.45	-0.03
Food Discards	NA	NA	-0.20	-0.19	0.62
Yard Trimmings	NA	NA	-0.20	-0.23	-0.34
Mixed Paper					
Broad Definition	NA	-1.09	NA	0.70	1.76
Residential Definition	NA	-1.08	NA	0.71	1.64
Office Paper Definition	NA	0.07	NA	2.50	3.69
Mixed Plastics	NA	0.34	NA	2.79	1.89
Mixed Recyclables	NA	-1.48	NA	0.71	1.51
Mixed Organics	NA	NA	-0.20	-0.21	0.12
Mixed MSW as Disposed	NA	NA	NA	-0.13	0.24

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Source reduction assumes initial production using the current mix of virgin and recycled inputs.

[2] Includes emissions from the initial production of the material being managed, except for foodwaste, yard waste, and mixed MSW.

Exhibit ES-8

GHG Emissions of MSW Management Options Compared to Landfilling[1] (MTCE/Ton)

Material	Source Reduction[2] Net Emissions Minus Landfilling Net Emissions (Current Mix)	Source Reduction Net Emissions Minus Landfilling Net Emissions (100% Virgin Inputs)	Recycling Net Emissions Minus Landfilling Net Emissions	Composting[3] Net Emissions Minus Landfilling Net Emissions	Combustion[4] Net Emissions Minus Landfilling Net Emissions
Aluminum Cans	-2.50	-4.68	-4.12	NA	0.01
Steel Cans	-0.80	-1.02	-0.50	NA	-0.43
Glass	-0.15	-0.17	-0.09	NA	0.00
HDPE	-0.50	-0.54	-0.39	NA	0.22
LDPE	-0.63	-0.65	-0.48	NA	0.22
PET	-0.50	-0.59	-0.43	NA	0.27
Corrugated Cardboard	-0.59	-1.03	-0.79	NA	-0.26
Magazines/Third-class Mail	-0.92	-1.07	-0.62	NA	-0.01
Newspaper	-0.60	-1.11	-0.74	NA	0.00
Office Paper	-1.43	-1.63	-1.30	NA	-0.80
Phonebooks	-1.07	-1.19	-0.70	NA	0.00
Textbooks	-1.85	-1.94	-1.37	NA	-0.80
Dimensional Lumber	-0.44	NA	-0.56	NA	-0.12
Medium-density Fiberboard	-0.50	NA	-0.57	NA	-0.12
Food Discards	NA	NA	NA	-0.22	-0.22
Yard Trimmings	NA	NA	NA	0.04	0.03
Mixed Paper					
Broad Definition	NA	NA	-0.78	NA	-0.29
Residential Definition	NA	NA	-0.74	NA	-0.25
Office Paper Definition	NA	NA	-0.99	NA	-0.32
Mixed Plastics	NA	NA	-0.42	NA	0.24
Mixed Recyclables	NA	NA	-0.82	NA	-0.22
Mixed Organics	NA	NA	NA	-0.09	-0.09
Mixed MSW as Disposed	NA	NA	NA	NA	-0.10

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Values for landfilling reflect projected national average methane recovery in year 2000.

[2] Source reduction assumes initial production using the current mix of virgin and recycled inputs.

[3] Calculation is based on assuming zero net emissions for composting.

[4] Values are for mass burn facilities with national average rate of ferrous recovery.

Exhibit ES-9

GHG Emissions of MSW Management Options Compared to Landfilling[1] ($MTCO_2E$/Ton)

Material	Source Reduction[2] Net Emissions Minus Landfilling Net Emissions (Current Mix)	Source Reduction Net Emissions Minus Landfilling Net Emissions (100% Virgin Inputs)	Recycling Net Emissions Minus Landfilling Net Emissions	Composting[3] Net Emissions Minus Landfilling Net Emissions	Combustion[4] Net Emissions Minus Landfilling Net Emissions
Aluminum Cans	-9.18	-17.15	-15.11	NA	0.02
Steel Cans	-2.92	-3.72	-1.83	NA	-1.57
Glass	-0.54	-0.61	-0.32	NA	0.01
HDPE	-1.82	-1.99	-1.44	NA	0.81
LDPE	-2.29	-2.38	-1.75	NA	0.81
PET	-1.82	-2.18	-1.59	NA	1.00
Corrugated Cardboard	-2.17	-3.79	-2.88	NA	-0.96
Magazines/Third-class Mail	-3.36	-3.94	-2.26	NA	-0.05
Newspaper	-2.21	-4.07	-2.72	NA	-0.01
Office Paper	-5.23	-5.99	-4.77	NA	-2.94
Phonebooks	-3.94	-4.37	-2.57	NA	-0.01
Textbooks	-6.78	-7.13	-5.03	NA	-2.94
Dimensional Lumber	-1.63	NA	-2.07	NA	-0.43
Medium-density Fiberboard	-1.82	NA	-2.09	NA	-0.43
Food Discards	NA	NA	NA	-0.82	-0.81
Yard Trimmings	NA	NA	NA	0.15	0.11
Mixed Paper					
Broad Definition	NA	NA	-2.84	NA	-1.06
Residential Definition	NA	NA	-2.72	NA	-0.93
Office Paper Definition	NA	NA	-3.62	NA	-1.18
Mixed Plastics	NA	NA	-1.55	NA	0.90
Mixed Recyclables	NA	NA	-2.99	NA	-0.80
Mixed Organics	NA	NA	NA	-0.32	-0.33
Mixed MSW as Disposed	NA	NA	NA	NA	-0.38

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Values for landfilling reflect projected national average methane recovery in year 2000.

[2] Source reduction assumes initial production using the current mix of virgin and recycled inputs.

[3] Calculation is based on assuming zero net emissions for composting.

[4] Values are for mass burn facilities with national average rate of ferrous recovery.

- The net GHG emissions from combustion of mixed MSW are lower than landfilling mixed MSW (under national average conditions for landfill gas recovery). Because, in practice, combustors and landfills manage a mixed waste stream, net emissions are determined more by technology factors (e.g., the efficiency of landfill gas collection systems and combustion energy conversion) than by material specificity. Material-specific emissions for landfills and combustors provide a basis for comparing these options with source reduction, recycling, and composting.

The ordering of combustion, landfilling, and composting is affected by (1) the GHG inventory accounting methods, which do not count CO_2 emissions from sustainable biogenic sources,[19] but do count emissions from sources such as plastics; and (2) a series of assumptions on sequestration, future use of CH_4 recovery systems, system efficiency for landfill gas recovery, ferrous metals recovery, and avoided utility fossil fuels. On a site-specific basis, the ordering of results between a combustor and a landfill could be different from the ordering provided here, which is based on national average conditions.

We conducted sensitivity analyses to examine the GHG emissions from landfilling under varying assumptions about (1) the percentage of landfilled waste sent to landfills with gas recovery, and (2) CH_4 oxidation rate and gas collection system efficiency. The sensitivity analyses demonstrate that the results for landfills are very sensitive to these factors, which are site-specific.[20] Thus, using a national average value when making generalizations about emissions from landfills masks some of the variability that exists from site to site.

The scope of this report is limited to developing emission factors that can be used to evaluate GHG implications of solid waste decisions. We do not analyze policy options in this report. Nevertheless, the differences in emission factors across various waste management options are sufficiently large as to imply that GHG mitigation policies in the waste sector can make a significant contribution to U.S. emission reductions. A number of examples, using the emission factors in this report, bear this out.

- At the firm level, targeted recycling programs can reduce GHGs. For example, a commercial facility that shifts from (a) a baseline practice of landfilling (in a landfill with no gas collection system) 50 tons office paper and 4 tons of aluminum cans to (b) recycling the same materials can reduce GHG emissions by more than 100 MTCE.
- At the community level, a city of 100,000 with average waste generation (4.5 lbs/day per capita), recycling (30 percent), and baseline disposal in a landfill with no gas collection system could increase its recycling rate to 40 percent—for example, by implementing a pay-as-you-throw program—and reduce emissions by about 10,000 MTCE per year. (Note that further growth in recycling would be possible; some communities already are exceeding recycling rates of 50 percent).
- A city of 1 million, disposing of 650,000 tons per year in a landfill without gas collection, could reduce its GHG emissions by nearly 138,000 MTCE per year by managing waste in a mass burn combustor unit.

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[19] Sustainable biogenic sources include paper and wood products from sustainably managed forests. When these materials are burned or aerobically decomposed to CO_2, the CO_2 emissions are not counted. Our approach to measuring GHG emissions from biogenic sources is described in detail in Chapter 1.

[20] For details on the sensitivity analyses, see section 7.5 and Exhibits 7-7 and 7-8.

- A town of 50,000 landfilling 30,000 tons per year could install a landfill gas recovery system and reduce emissions by about 6,000 MTCE per year.
- At the national level, if the United States attains the goal of a 35 percent recycling rate by 2005, emissions will be reduced by nearly 10 million MTCE per year compared to a baseline where we maintain the current 30 percent recycling rate and use the "national average" landfill for disposal.

ES.7 OTHER LIFE-CYCLE GHG ANALYSES AND TOOLS

Life-cycle analysis is being used increasingly to quantify the GHG impacts of private and public sector decisions. In addition to the life-cycle analyses that underpin the emission factors in this report, Environmental Defense,[21] ICLEI, Ecobilan, and others have analyzed the life-cycle environmental impacts of various industry processes (e.g., manufacturing) and private and public sector practices (e.g., waste management). In many cases, the results of life-cycle analyses are packaged into software tools that distill the information according to a specific user's needs.

As mentioned earlier, the WARM model was designed as a tool for waste managers to weigh the GHG impacts of their waste management practices. As a result, the model focuses exclusively on waste sector GHG emissions, and the methodology used to estimate emissions is consistent with international and domestic GHG accounting guidelines. Life-cycle tools designed for broader audiences necessarily include other sectors and/or other environmental impacts, and are not necessarily tied to the Intergovernmental Panel on Climate Change (IPCC) guidelines for GHG accounting or the methods used in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.

- WARM, developed by ICF Consulting for EPA, allows users to input several key variables (e.g., landfill gas collection system information, electric utility fuel mix, transportation distances).[22] The model covers 21 types of materials and 5 waste management options: source reduction, recycling, combustion, composting, and landfilling. WARM accounts for upstream energy and non-energy emissions, transportation distances to disposal and recycling facilities, carbon sequestration, and utility offsets that result from landfill gas collection and combustion. The tool provides participants in the U.S. Department of Energy's 1605b program with the option to report results by year, by gas, and by year and gas. WARM software is available free of charge in both a Web-based calculator format and a Microsoft Excel© spreadsheet. The tool is ideal for waste planners interested in tracking and reporting voluntary GHG emission reductions from waste management practices and for comparing the climate change impacts of different approaches. To access the tool, visit: <http://www.epa.gov/globalwarming/actions/waste/warm.htm>.
- ICLEI Cities for Climate Protection (CCP) Campaign Greenhouse Gas Emission Software was developed by Torrie Smith Associates for ICLEI. This Windows-based tool, targeted for use by local governments, can analyze emissions and emission reductions on a community-wide basis and for municipal operations alone. The

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[21] Blum, L., Denison, R.A., and Ruston, V.F. 1997. A Life-Cycle Approach to Purchasing and Using Environmentally Preferable Paper: A Summary of the Paper Task Force Report," *Journal of Industrial Ecology*. I:3:15-46. Denison, R.A. 1996. "Environmental Life-Cycle Comparison of Recycling, Landfilling, and Incineration: A Review of Recent Studies;" Annual Review of Energy and the Environment 21:6:191-237.

[22] Microsoft Excel and Web-based versions of this tool are available online at the following Web site: http://www.epa.gov/globalwarming/actions/waste/tools.html.

community-wide module looks at residential, commercial, and industrial buildings, transportation activity, and community-generated waste. The municipal operations module looks at municipal buildings, municipal fleets, and waste from municipal in-house operations. In addition to computing GHG emissions, the CCP software estimates reductions in criteria air pollutants, changes in energy consumption, and financial costs and savings associated with energy use and other emission reduction initiatives. A version of the software program was made available for use by private businesses and institutions during the summer of 2001. CCP software subscriptions, including technical support, are available to governments participating in ICLEI for a subsidized price of $240. The full retail price of the software in the United States is $2,000. For more information, visit: <http://www.iclei.org/us/ccpsoftware.html> or contact the U.S. ICLEI office at (510)-540-8843, iclei_usa@iclei.org.

- The MSW Decision Support Tool (DST) and life-cycle inventory database for North America have been developed through funding by ORD through a cooperative agreement with the Research Triangle Institute (CR823052). The methodology is based on a multi-media, multi-pollutant approach and includes analysis of GHG emissions as well as a broader set of emissions (air, water, and waste) associated with MSW operations. The MSW-DST is available for site-specific applications and has been used to conduct analyses in several states and 15 communities including use by the U.S. Navy in the Pacific Northwest. The tool is intended for use by solid waste planners at state and local levels to analyze and compare alternative MSW management strategies with respect to cost, energy consumption, and environmental releases to the air, land, and water. The costs are based on full cost accounting principles and account for capital and operating costs using an engineering economics analysis. The MSW-DST calculates not only projected emissions of GHGs and criteria air pollutants, but also emissions of more than 30 air- and water-borne pollutants. The DST models emissions associated with all MSW management activities, including waste collection and transportation, transfer stations, materials recovery facilities, compost facilities, landfills, combustion and refuse-derived fuel facilities, utility offsets, material offsets, and source reduction. The differences in residential, multi-family, and commercial sectors can be evaluated individually. The software has optimization capabilities that enable one to identify options that evaluate minimum costs as well as solutions that can maximize environmental benefits, including energy conservation and GHG reductions.

  At the time of the publication of this report, the life-cycle inventory (LCI) database for North America was to be released in 2002. Plans to develop a Web-based version are being considered. The MSW-DST provides extensive default data for the full range of MSW process models and requires minimum input data. However, these defaults can be tailored to the specific communities using site-specific information. The MSW-DST also includes a calculator for source reduction and carbon sequestration using a methodology that is consistent with the IPCC in terms of the treatment of biogenic CO_2 emissions. For more information, refer to the project Web site: <http://www.rti.org/units/ese/p2/lca.cfm#life> or contact Susan Thornloe, U.S. EPA, (919)-541-2709, thornloe.susan@epamail.epa.gov, or Keith Weitz, Research Triangle Institute, (919)-541-6973, kaw@rti.org.

- The Tool for Environmental Analysis and Management (TEAM), developed by Ecobilan, simulates operations associated with product design, processes, and activities associated with several industrial sectors. The model considers energy consumption, material consumption, transportation, waste management, and other factors in its evaluation of environmental impacts. Many private firms and some government agencies have used the model. Users pay a licensing fee of $3,000 and an annual maintenance contract of $3,000.

This model is intended for use in Europe and was not developed for use in North America. For more information, visit: <http://www.ecobalance.com/software/gb_software.html>.

ES.8 LIMITATIONS OF THE ANALYSIS

When conducting this analysis, we used a number of analytical approaches and numerous data sources, each with its own limitations. In addition, we made and applied assumptions throughout the analysis. Although these limitations would be troublesome if used in the context of a regulatory framework, we believe that the results are sufficiently accurate to support their use in voluntary programs. Some of the major limitations include the following:

- The manufacturing GHG analysis is based on estimated industry averages for energy usage, and in some cases the estimates are based on limited data. In addition, we used values for the average GHG emissions per ton of material produced, not the marginal emission rates per incremental ton produced. In some cases, the marginal emission rates may be significantly different.
- The forest carbon sequestration analysis deals with a very complicated set of interrelated ecological and economic processes. Although the models used represent the state-of-the-art in forest resource planning, their geographic scope is limited. Because of the global market for forest products, the actual effects of paper recycling would occur not only in the United States but in Canada and other countries. Other important limitations include: (1) the estimate does not include changes in carbon storage in forest soils and forest floors; (2) the model assumes that no forested lands will be converted to non-forest uses as a result of increased paper recycling; and (3) we use a point estimate for forest carbon sequestration, whereas the system of models predicts changing net sequestration over time.
- The composting analysis considers a small sampling of feedstocks and a single compost application (i.e., agricultural soil). The analysis did not consider the full range of soil conservation and management practices that could be used in combination with compost and their impacts on carbon storage.
- The combustion analysis uses national average values for several parameters; variability from site to site is not reflected in our estimate.
- The landfill analysis (1) incorporates considerable uncertainty on CH_4 generation and carbon sequestration, due to limited data availability; and (2) uses landfill estimated CH_4 recovery levels for the year 2000 as a baseline.

Finally, throughout most of the report, we express analytical inputs and outputs as point estimates. We recognize that a rigorous treatment of uncertainty and variability would be useful, but in most cases the information needed to treat these in statistical terms is not available. The report includes some sensitivity analyses to illustrate the importance of selected parameters and expresses ranges for a few other factors such as GHG emissions from manufacturing. We encourage readers to provide more accurate information where it is available; perhaps with additional information, future versions of this report will be able to shed more light on uncertainty and variability. Meanwhile, we caution that the emission factors reported here should be evaluated and applied with an appreciation for the limitations in the data and methods, as described at the end of each chapter.

1. METHODOLOGY

This report is the second edition of *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*. We made the following improvements to the first edition of the report:

- Incorporated new energy data and information on recycling loss rates from EPA's Office of Research and Development (ORD);
- Expanded analysis of the GHG benefits of composting, including results of CENTURY model runs;
- Developed emission factors for five new material types: magazines/third-class mail, phonebooks, textbooks, dimensional lumber, and medium-density fiberboard;
- Developed emission factors for two new categories of mixed materials: mixed plastics and mixed organics;
- Updated national recovery and generation rates to include 2000 data;
- Incorporated new energy data into calculations of utility offsets;
- Revised carbon coefficients and fuel use for national average electricity generation;
- Updated information on landfill gas recovery rates;
- Added a discussion of emerging issues in the area of climate change and waste management; and
- Provided a list of suggested proxy values for voluntary reporting of GHG emission reductions.

All of these changes and/or revisions are described in more detail throughout the body of the report.

Because this is the second edition, we have moved some of the background information from the body of the report to background documents, which are available in the docket in the Resource Conservation and Recovery Act (RCRA) Information Center. Background Document A provides data on life-cycle energy intensity and fuel mix, provided by Franklin Associates, Ltd. (FAL) (All other background documents, and this report, were written by ICF Consulting.) Background Document B provides a discussion of the review cycles leading up to the first and second editions of the report. Background Document C includes a discussion of how we screened materials for the first edition of the report.

The remainder of this chapter provides an overview of the methodology used to calculate the GHG emissions associated with various management strategies for MSW. The first section briefly describes the life-cycle framework used for the analysis. Next is a discussion of the materials included in the analysis. The final three sections present a description of key inputs and baselines, a summary of the life-cycle stages, and an explanation of how to estimate and compare net GHG emissions and sinks.

1.1 THE OVERALL FRAMEWORK: A STREAMLINED LIFE-CYCLE INVENTORY

Early in this analysis of the GHG benefits of specific waste management practices, it became clear that all waste management options provide opportunities for reducing GHG emissions, depending on individual circumstances. Although source reduction and recycling are often the most advantageous waste management practices from a GHG perspective, a material-specific comparison of all available waste management options would clarify where the greatest GHG benefits can be obtained for particular materials in MSW. A material-specific comparison can help policymakers identify the best options for GHG reductions.

This study determined that the best way to conduct such a comparative analysis is a streamlined application of a life-cycle assessment (LCA). A full LCA is an analytical framework for understanding the material inputs, energy inputs, and environmental releases associated with manufacturing, using, and disposing of a given material. A full LCA generally consists of four parts: (1) goal definition and scoping; (2) an inventory of the materials and energy used during all stages in the life of a product or process, and an inventory of environmental releases throughout the product life cycle; (3) an impact assessment that examines potential and actual human health effects related to the use of resources and environmental releases; and (4) an assessment of the change that is needed to bring about environmental improvements in the product or processes.

A full LCA is beyond the scope of this analysis. Rather, the streamlined LCA described in this report is limited to an inventory of the emissions and other environmental impacts related to global warming. This study did not assess human health impacts, necessary environmental improvements, and air, water, or environmental impacts that do not have a direct bearing on climate change.

1.2 MSW MATERIALS CONSIDERED IN THE STREAMLINED LIFE-CYCLE INVENTORY

Each material in MSW has different GHG impacts depending on how it is manufactured and disposed of. We began our research by performing a screening analysis of 37 of the most common materials and products found in MSW.[1] The materials included in screening analysis then were ranked by their potential for GHG reductions.[2] The first edition of the report included 12 materials: aluminum cans, steel cans,[3] glass, high-density polyethylene (HDPE) plastic blow-molded containers, low-density polyethylene (LDPE) plastic blow-molded containers, polyethylene terephthalate (PET) plastic blow-molded containers, corrugated cardboard, newspaper, office paper,[4] and three grades of mixed paper (broad, residential, and office). In addition to these materials, we examined the GHG implications of various management strategies for food discards, yard trimmings, mixed MSW, and mixed recyclables.

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[1] In addition to the materials and products covered in the first edition of the report, the screening analysis included the following materials and products: other paper materials (bags and sacks, other paper packaging, books, other paperboard packaging, wrapping papers, paper plates and cups, folding cartons, other nonpackaging paper, and tissue paper and towels), other plastic materials (plastic wraps, plastic bags and sacks, other plastic containers, and other plastic packing), other metal materials (aluminum foil/closures, other steel packaging), and other miscellaneous materials (miscellaneous durable goods, wood packaging, furniture and furnishings, carpet and rugs, and other miscellaneous packaging).

[2] For more information on the screening analysis used to identify materials for the first edition of the report, see Background Document C.

[3] Other steel materials also may be recycled, but this analysis was limited to steel cans from households.

[4] Office paper refers to the type of paper used in computer printers and photocopiers.

Comparison of EPA/ORD and EPA/OSW Emission Factors

Efforts to harmonize our previous life-cycle emission factors with the results of recent work by EPA's Office of Research and Development (ORD) began in October 2000. Noticing significant differences in our bottom line emission factors, we compared a range of assumptions, including energy consumption, fuel mix, loss rates, landfill oxidation rate, timing of landfill methane emissions, fraction of landfill gas collected, electricity mix, transportation distances, and carbon storage. Our comparison of energy intensities and fuel mixes included process and transportation energy for virgin and recycled production of each material type. Because the previous Office of Solid Waste (OSW) energy values were based on an average of Franklin Associates, Ltd. (FAL) and Tellus data, we compared the ORD values to the FAL data, Tellus data, and average of FAL and Tellus data.

This comparison revealed that the differences between the OSW and ORD emission factors are mostly attributable to the different assumptions about energy consumption (i.e., the sum of precombustion, process, and transportation energy), fuel mix, and loss rates. In general, we found that ORD's total energy values are lower than OSW's energy values for both virgin and recycled materials. Comparing fuel mix, we found the most significant differences occurring for electricity, coal, natural gas, and "other" fuel types comprising process energy. The fractions of diesel fuel, residual fuel, and natural gas exhibited the greatest disparities for transportation energy. Our comparison of loss rates, which are used to develop the recycling emission factors, showed significant variation for office paper, steel cans, and, to a lesser extent, newspaper.

In an effort to reconcile the remaining differences between ORD and OSW estimates of GHG emissions from the acquisition of raw materials and their manufacture into products, we identified additional methodological differences that could be affecting the recycling numbers. In particular, we found that ORD simulates closed-loop recycling for all materials, while OSW assumes open-loop recycling for office paper and corrugated cardboard. We also found that ORD's estimates do not include non-energy process emissions from perfluorocarbons (PFCs). To isolate any remaining differences between the two analyses, we substituted ORD energy intensities, fuel mixes, and loss rates into the OSW model.

Once we had identified and resolved all methodological differences between ORD and OSW estimates for raw materials acquisition and manufacturing, we selected the material types for which we could substitute ORD data for the existing OSW data: aluminum, glass, HDPE, LDPE, PET, corrugated cardboard, magazines/third-class mail, newspaper, office paper, phonebooks, and textbooks. For wood products, ORD did not develop emission factors, while for steel its data was not sufficiently disaggregated to replace the existing OSW data.

Most of the changes from the first edition of this report reflect additions of new or updated data. This second edition features an expanded list of material types, including magazines and third-class mail, phonebooks, textbooks, dimensional lumber, medium-density fiberboard, and several additional categories of mixed recycled materials (e.g. mixed plastics, mixed organics). This edition also incorporates updated data developed by ORD through its work on life-cycle management of MSW. ORD's data set on energy, fuel mix, and loss rates has been thoroughly reviewed by industry and other stakeholders, and is likely to be more up-to-date than some of the information in the first edition of this report. Thus, where a complete set of energy intensity and fuel mix data was available from ORD, that information was incorporated in this report. For other materials—steel cans and mixed paper (broad, residential, and office definitions)—we retained the original data set developed by FAL. This edition includes new data (also developed by FAL) on dimensional lumber and medium-density fiberboard. Exhibit 1-1 lists the materials that were analyzed for this report and the energy-related data sources underlying the estimates. All of the material types listed in Exhibit 1-1 are discussed in subsequent chapters and included in exhibits throughout the report, with the exception of three mixed waste categories. Mixed plastics, mixed recyclables, and mixed organics are included only in Chapter 8 because emission factors for these materials simply reflect the weighted average emissions of other material types.

Exhibit 1-1 Materials Analyzed and Energy-related Data Sources

Material	Energy Data Source	Material	Energy Data Source
Aluminum Cans	ORD	Medium-Density Fiberboard	FAL
Steel Cans	FAL	Food Discards	NA
Glass	ORD	Yard Trimmings	NA
Corrugated Cardboard	ORD	Mixed Paper – Broad Definition	FAL
Magazines/Third-class Mail	ORD	Mixed Paper – Residential Definition	FAL
Newspaper	ORD	Mixed Paper – Office Paper Definition	FAL
Office Paper	ORD	Mixed Plastics	Weighted Average
Phonebooks	ORD	Mixed Recyclables	Weighted Average
Textbooks	ORD	Mixed Organics	NA
Dimensional Lumber	FAL	Mixed MSW	NA

NA = Not applicable (data not energy-related)

1.3 KEY INPUTS AND BASELINES FOR THE STREAMLINED LIFE-CYCLE INVENTORY

Evaluating the GHG emissions of waste management requires analysis of three factors: (1) GHG emissions throughout the life cycle of the material (including the chosen disposal option); (2) the extent to which carbon sinks are affected by manufacturing and disposing of the material; and (3) the extent to which the management option recovers energy that can be used to replace electric utility energy, thus reducing utility GHG emissions. In addition, to provide a consistent basis for comparison, we made several choices in our GHG accounting framework in terms of timing and levels of production. Each of these factors warrants further discussion.

Comparing GHGs

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are very different gases in terms of their heat-trapping potential. An international protocol has established CO_2 as the reference gas for measurement of heat-trapping potential (also known as global warming potential or GWP). By definition, the GWP of 1kilogram (kg) of CO_2 is 1.

CH_4 has a GWP of 21, which means that 1 kg of methane has the same heat-trapping potential as 21 kg of CO_2.

N_2O has a GWP of 310.

PFCs are the most potent GHG included in this analysis; GWPs are 6,500 for CF_4 and 9,200 for C_2F_6.

In this report, emissions of CO_2, CH_4, N_2O, and PFCs have been converted to their "carbon equivalents." Because CO_2 is 12/44 carbon by weight, 1 metric ton of CO_2 is equal to 12/44 or 0.27 metric tons of carbon equivalent (MTCE). The MTCE value for 1 metric ton of each of the other gases is determined by multiplying its GWP by a factor of 12/44. (All data provided here are from The Intergovernmental Panel on Climate Change (IPCC), *Climate Change 1995: The Science of Climate Change*, 1996, p. 121.)

GHG Emissions Relevant to Waste: The most important GHGs for purposes of analyzing MSW management options are CO_2, CH_4, N_2O, and perfluorocarbons (PFCs). Of these, CO_2 is by far the most common GHG emitted in the United States. Most CO_2 emissions result from energy use, particularly fossil fuel combustion. A great deal of energy is consumed when a product is manufactured and then discarded. This energy is used in the following stages: (1) extracting and processing raw materials; (2) manufacturing products; (3) managing products at the end of their useful lives; and (4) transporting materials and products between each stage of their life cycles. This study estimated energy-related GHG emissions during all of these stages, except for transportation of products to consumers (because GHG emissions resulting from transportation to consumers will vary little among the options considered). Much of this report is devoted to explaining the methodology point in the life cycle. In addition, the energy consumed during use would be about the same whether the product is made from virgin or recycled inputs.

CH_4, a more potent GHG, is produced when organic waste decomposes in an oxygen-free (anaerobic) environment, such as a landfill. CH_4 from landfills is the largest source of CH_4 in the United States;[5] these emissions are addressed in Chapter 7. CH_4 is also emitted when natural gas is released to the atmosphere during production of coal or oil, production or use of natural gas, and agricultural activities.

N_2O results from the use of commercial and organic fertilizers and fossil fuel combustion, as well as other sources. This analysis estimated N_2O emissions from waste combustion.

Perfluorocarbons (CF_4 and C_2F_6) are emitted during the reduction of alumina to aluminum in the primary smelting process. The source of fluorine for CF_4 and C_2F_6 is the molten cryolite (Na_3AlF_6) where the reduction of alumina occurs. Perfluorocarbons are formed when the fluorine in cryolite reacts with the carbon in the anode (a carbon mass of paste, coke briquettes, or prebaked carbon blocks) and in the carbon lining that serves as the cathode. Although the quantities of perfluorocarbons emitted are small, these gases are significant because of their high global warming potential.

Carbon Stocks, Carbon Storage, and Carbon Sequestration: This analysis includes carbon storage to the extent that it is due to waste management practices. For example, landfilled organic materials result in landfill carbon storage, as carbon is moved from a product pool (e.g., furniture) to the landfill pool. The same is true for composted organics that lead to carbon storage in soil.

Carbon sequestration differs from carbon storage because it represents a transfer of carbon from the atmosphere to a carbon pool. For example, trees in a forest undergo photosynthesis, converting CO_2 in the atmosphere to carbon in biomass. In this analysis, we consider the impact of waste management on forest carbon sequestration.

The baseline against which changes in carbon stocks are measured is a projection by the U.S. Forest Service of forest growth, mortality, harvests, and other removals under anticipated market conditions for forest products. One of the assumptions for the projections is that U.S. forests will be harvested on a sustainable basis (i.e., trees will be grown at a rate at least equal to the rate at which they are cut).[6] Thus, the baseline assumes that harvesting trees at current levels results in no diminution of the forest carbon stock and no additional CO_2 in the atmosphere. On the other hand, forest carbon sequestration *increases* as a result of source reduction or recycling of paper products because both source reduction and recycling cause annual tree harvests to drop below otherwise anticipated levels (resulting in additional accumulation of carbon in forests). Consequently, source reduction and recycling “get credit” for increasing the forest carbon stock, whereas other waste management options (combustion and landfilling) do not.

Although source reduction and recycling are associated with forest carbon sequestration, composting—in particular, application of compost to degraded soils—enhances soil carbon storage. Four mechanisms of increased carbon storage are hypothesized in Chapter 5; a modeling approach is used to estimate the magnitude of carbon storage associated with three of these mechanisms.

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[5] U.S. EPA. 2001.*Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*. U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC. EPA-236-R-01-001.

[6] Assuming a sustainable harvest in the United States is reasonable because from 1952 to 1997 U.S. forest carbon stocks steadily increased. In the early part of this period, the increases were mostly due to reversion of agricultural land to forest land. More recently, improved forest management practices and the regeneration of previously cleared forest areas have resulted in a net annual uptake (sequestration) of carbon. The steady increase in forest carbon stocks implies sustainable harvests, and it is reasonable to assume that the trend of sustainable harvests will continue.

Finally, landfills are another means by which carbon is removed from the atmosphere. Landfill carbon stocks increase over time because much of the organic matter placed in landfills does not decompose, especially if the landfill is located in an arid area. However, not all carbon in landfills is counted in determining the extent to which landfills are carbon stocks. For example, the analysis does not count plastic in landfills toward carbon storage. Plastic in a landfill represents simply a transfer from one carbon stock (the oil field containing the petroleum or natural gas from which the plastic was made) to another carbon stock (the landfill); thus, no change has occurred in the overall amount of carbon stored. On the other hand, the portion of organic matter (such as yard trimmings) that does not decompose in a landfill represents an addition to a carbon stock, because it would have largely decomposed into CO_2 if left to deteriorate on the ground.

Although changes in fossil fuel carbon stocks (i.e., reductions in oil field stores that result from the extraction and burning of oil resources) are not measured *directly* in this analysis, the reduction in fossil fuel carbon stocks is indirectly captured by counting the CO_2 emissions from fossil fuel combustion in calculating GHG emissions.

Avoided Electric Utility GHG Emissions Related to Waste: Waste that is used to generate electricity (either through waste combustion or recovery of CH_4 from landfills) displaces fossil fuels that utilities would otherwise use to produce electricity. Fossil fuel combustion is the single largest source of GHG emissions in the United States. When waste is substituted for fossil fuel to generate electricity, the GHG emissions from burning the waste are offset by the avoided electric utility GHG emissions.

Baseline Year: The baseline year selected for most parts of the analysis is the most recent year for which data are available. However, for the system efficiency and ferrous recovery rate at waste combustors, this study uses values previously projected for the year 2000. For paper recycling, annual projections through 2010 were used to develop an average forest carbon storage value for the period from 1996 through 2010.[7] The compost analysis relied on model simulations of compost application, beginning in 1996 and ending in 2005. The carbon storage estimates resulting from these model runs correspond to model outputs in 2010 in order to maintain consistency with forest carbon storage estimates. We developed "future"[8] scenarios for paper recycling, composting, and carbon storage analyses because some of the underlying factors that affect GHG emissions are changing rapidly, and this study seeks to define relationships (e.g., between tonnage of waste landfilled and CH_4 emissions) that represent an average over the next several years.

- Although the existing U.S. municipal waste combustors include a few small facilities that do not recover energy, the study assumes that those facilities will be closed in the near future. Thus, the report assumes that all combustors recover energy. The study used an estimate provided by the combustion industry for anticipated levels of ferrous recovery.
- For paper recycling, earlier analyses indicated that the marginal impact of increased paper recycling on forest carbon sequestration changes over time. The impact also differs depending on the initial paper recycling rate and how that rate changes over time. To estimate the impact of increased paper recycling on forest carbon sequestration, the study needed to account for these influences. First, we used the American Forest and Paper Association's baseline projection that paper recycling rates will continue to increase from about 35 percent

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[7] The models we used simulated carbon sequestration through 2040, but we selected a value based on average conditions through 2010.

[8] In the case of system efficiency and ferrous recovery at waste combustors, the year 2000 represented a future value when the first edition of this report was published. This edition of the report does not reflect these updated values because more recent data are not available.

in 1994 to 50 percent by 2000.[9] The trajectory for a baseline scenario for paper recycling passes through 50 percent in 2000, with continued modest increases in the following years. Because of the need to estimate the effect of efforts (e.g., by EPA) to enhance recycling beyond the baseline projected rate, we developed a plausible scenario for enhanced paper recycling rates and then compared the projected forest carbon sequestration under the baseline and increased recycling scenarios.[10] (This approach is fully described in Chapter 3.)

- The baseline for our landfill recovery scenario is based on estimated recovery rates and percentages of waste disposed in landfills with no recovery, landfills with flaring, and landfills with landfill-gas-to-energy projects for the year 2000. According to our estimates, 49 percent of all landfill CH_4 was generated at landfills with recovery systems, and the remaining 51 percent was generated at landfills without landfill gas (LFG) recovery.[11] Of the 49 percent of all CH_4 generated at landfills with LFG recovery, 49 percent (or 24 percent of all CH_4) was generated at landfills that use LFG to generate electricity, and 51 percent (or 25 percent of all CH_4) at landfills that flare LFG.[12,13]

1.4 SUMMARY OF THE LIFE-CYCLE STAGES

Exhibit 1-2 shows the GHG sources and carbon sinks associated with the manufacture of various materials and the post-consumer management of these materials as wastes. As shown in the exhibit, GHGs are emitted from (1) the pre-consumer stages of raw materials acquisition and manufacturing, and (2) the post-consumer stage of waste management. No GHG emissions are attributed to the consumer's use of any product.

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[9] Actual paper recovery in 2000 (taken from EPA's *Municipal Solid Waste in the United States: 2000 Facts and Figures*) averaged about 53%, confirming that 50 percent is a reasonable estimate for 2000.

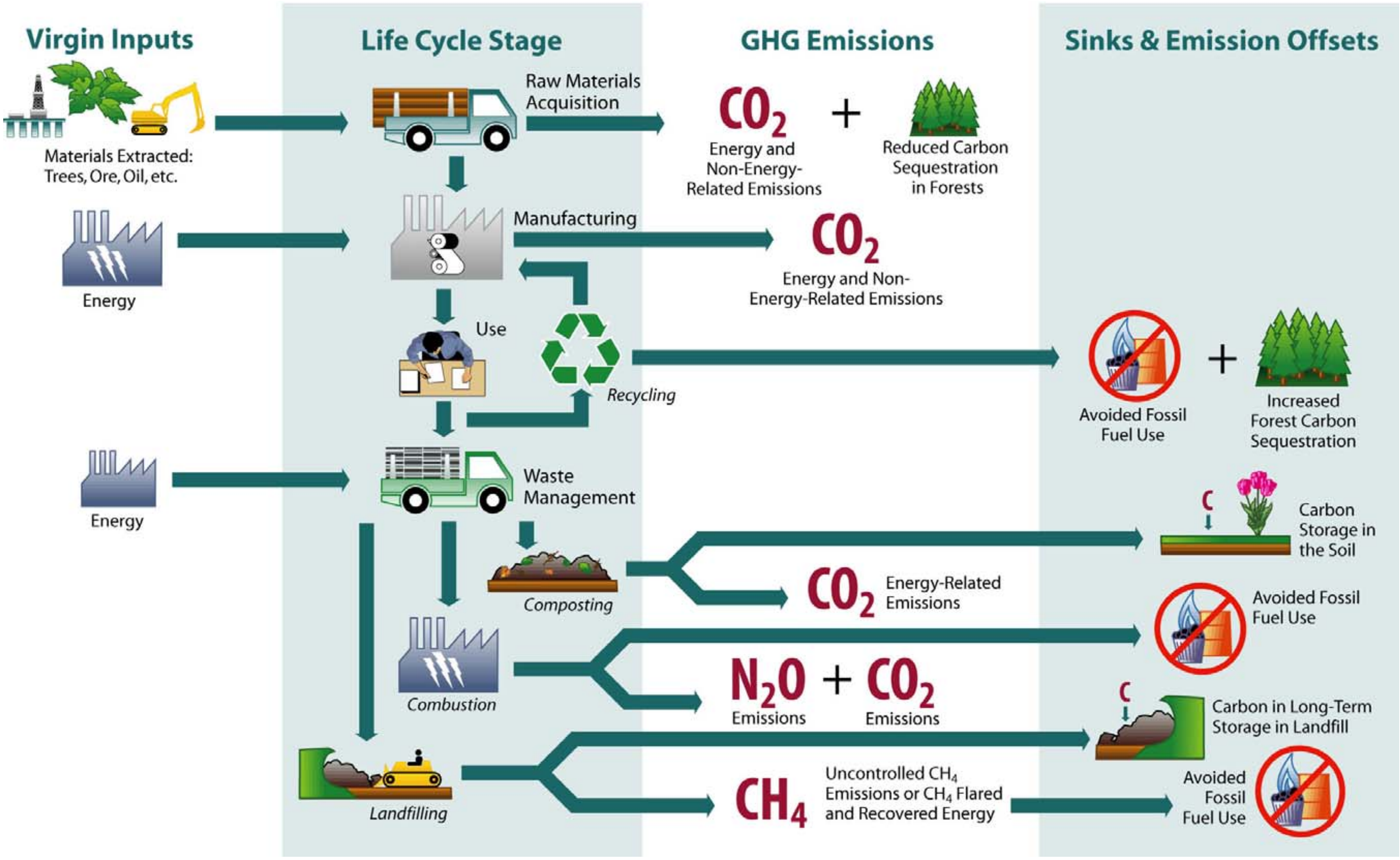
[10] Note that this estimate is necessary for analyzing the scenarios; however, it does not represent a plan of action by EPA.

[11] Based on data on (1) year 2000 MSW landfill methane generation of 72.7 million MTCE (from draft *U.S. Climate Action Report – 2001*), (2) year 2000 landfill methane recovery of 26.7 million MTCE (also from draft *U.S. Climate Action Report – 2001*), and (3) estimated landfill methane recovery efficiency of 75 percent (from *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*).

[12] Draft *U.S. Climate Action Report – 2001.*

[13] The assumption that 49 percent of landfills recovering methane will use it to generate electricity is subject to change over time based upon changes in the cost of recovery, and the potential payback. Additionally, new technologies may arise that use recovered methane for purposes other than generating electricity.

Exhibit 1-2 Greenhouse Gas Sources and Sinks Associated with the Material Life Cycle



The remainder of this chapter describes how this study analyzed each of the upstream (raw materials acquisition, manufacturing, and forest carbon sequestration) and downstream (source reduction, recycling, composting, combustion, and landfilling) stages in the life cycle. The following sections explain stages of the life cycle and the corresponding emission factor components presented in Exhibit 1-3, and outline the GHG emissions and carbon sinks at each stage of the product life cycle. These GHG emissions and carbon sinks are described in detail and quantified for each material in Chapters 2 through 7.

Exhibit 1-3 Components of Net Emissions for Various MSW Management Strategies

MSW Management Strategy	**GHG Sources and Sinks**		
	Process and Transportation GHGs from Raw Materials Acquisition and Manufacturing	**Forest Carbon Sequestration or Soil Carbon Storage**	**Waste Management GHGs**
Source Reduction	Decrease in GHG emissions, relative to the baseline of manufacturing	Increase in forest carbon sequestration	No emissions/sinks
Recycling	Decrease in GHG emissions due to lower energy requirements (compared to manufacture from virgin inputs) and avoided process non-energy GHGs	Increase in forest carbon sequestration	Process and transportation emissions are counted in the manufacturing stage
Composting	No emissions/sinks*	Increase in soil carbon storage	Compost machinery emissions and transportation emissions
Combustion	Baseline process and transportation emissions due to manufacture from the current mix of virgin and recycled inputs	No change	Nonbiogenic CO_2, N_2O emissions, avoided utility emissions, and transportation emissions
Landfilling	Baseline process and transportation emissions due to manufacture from the current mix of virgin and recycled inputs	No change	CH_4 emissions, long-term carbon storage, avoided utility emissions, and transportation emissions

* No manufacturing transportation GHG emissions are considered for composting of food discards and yard trimmings because these materials are not considered to be manufactured.

1.4.1 GHG Emissions and Carbon Sinks Associated with Raw Materials Acquisition and Manufacturing

The top left of Exhibit 1-2 shows inputs for *raw materials acquisition*. These virgin inputs are used to make various materials, including ore for manufacturing metal products, trees for making paper products, and petroleum or natural gas for producing plastic products. Fuel energy also is used to obtain or extract these material inputs.

The inputs used in *manufacturing* are (1) energy and (2) either virgin raw materials or recycled materials. In the exhibit these inputs are identified with arrows that point to the icon labeled “Manufacturing.”

For source reduction, the "baseline" GHG emissions from raw materials acquisition and manufacturing are avoided. This analysis thus estimates, for source reduction, the GHG *reductions* (relative to a baseline of initial manufacture) at the raw materials acquisition and manufacturing stages. Source reduction is assumed to entail more efficient use of a given material. Examples are lightweighting (reducing the quantity of raw material in a product), double-sided photocopying, and extension of a product's useful life. No other material substitutions are assumed for source reduction; therefore, this report does not analyze any corresponding increases in production and disposal of other materials (which could result in GHG emissions).[14]

The GHG emissions associated with raw materials acquisition and manufacturing are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport materials,[15] and (3) non-energy GHG emissions resulting from manufacturing processes (for aluminum, steel, plastics, office paper, and medium-density fiberboard). Each type of emission is described below. Changes in carbon sequestration in forests also are associated with raw materials acquisition for paper products.

Process Energy GHG Emissions: Process energy GHG emissions consist primarily of CO_2 emissions from the combustion of fuels used in raw materials acquisition and manufacturing. CO_2 emissions from combustion of biomass are not counted as GHG emissions. (See "CO_2 Emissions from Biogenic Sources" on page 12.)

The majority of process energy CO_2 emissions are from combustion of fuels used directly, e.g., to operate ore mining equipment or to fuel a blast furnace. Fuel also is needed to extract the oil or mine the coal that is ultimately used to produce energy and transport these fuels to the place where they are used. Thus CO_2 emissions from this "pre-combustion energy" are counted in this category as well. When electricity generated by combustion of fossil fuels is used in manufacturing, the CO_2 emissions from the fossil fuels also are counted.

To estimate process energy GHG emissions, the study first obtained estimates of both the total amount of process energy used per ton of product (measured in British thermal units or Btu's), and the fuel mix (e.g., diesel oil, natural gas, fuel oil, etc.). Next, emissions factors for each type of fuel were used to convert the amount of each type of fuel used to GHG emissions. As noted earlier, making a material from recycled inputs generally requires less process energy (and uses a different fuel mix) than making the material from virgin inputs.

Details of the methodology for estimating process energy GHG emissions are provided in Chapter 2.

Transportation Energy GHG Emissions: Transportation energy GHG emissions consist of CO_2 emissions from the combustion of fuels used to transport raw materials and intermediate products to the final manufacturing or fabrication facility. The estimates of transportation energy emissions are based on: (1) the amounts of raw material inputs and intermediate products used in manufacturing 1 ton of each material; (2) the average distance that each raw material input or intermediate product is transported; and (3) the transportation modes and fuels used. For the amounts of fuel used, the study used data on the average fuel consumption per ton-mile for each mode of transportation.[16] Then an emission factor for

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[14] Although material substitution is not quantitatively addressed in the report, it is discussed from a methodological standpoint in Chapter 2 and also is discussed briefly in Chapter 4, Section 4.3.

[15] For some materials (plastics, magazines/third-class mail, office paper, phonebooks, and textbooks), the transportation data we received were included in the process energy data. For these materials, we report *total* GHG emissions associated with process and transportation in the "process energy" estimate.

[16] These data are found in Background Document A.

each type of fuel was used to convert the amount of each type of fuel consumed to the GHG emissions produced.

More detail on the methodology to estimate transportation energy GHG emissions is provided in Chapter 2.

Process Non-Energy GHG Emissions: Some GHG emissions occur directly in the manufacture of certain materials and are not associated with energy consumption. In this analysis, these emissions are referred to as *process non-energy emissions*. For example, the production of steel or aluminum requires lime (calcium oxide, or CaO), which is produced from limestone (calcium carbonate, or $CaCO_3$), and the manufacture of lime results in CO_2 emissions. Other process non-energy GHG emissions are associated with the manufacture of plastics, office paper, and medium-density fiberboard. In some cases, process non-energy GHG emissions are associated only with production using virgin inputs; in other cases, these emissions result when either virgin or recycled inputs are used. These emissions are described in Chapter 2.

Carbon Sinks: The only carbon sink during the stages of raw materials acquisition and manufacturing is the additional carbon sequestration in trees associated with source reduction or recycling of paper products. The methodology for estimating forest carbon sequestration is described in Chapter 3.

1.4.2 GHG Emissions and Carbon Sinks Associated with Waste Management

As shown in Exhibit 1-3, there are up to five post-consumer waste management options, depending on the material: recycling, composting, combustion, and landfilling. This section describes the GHG emissions and carbon sinks associated with these five options.

Source Reduction: In this analysis, source reduction is measured by the amount of material that would otherwise be produced but is not generated due to a program promoting source reduction. Thus, with source reduction there are no emissions from MSW management.

Recycling: When a material is recycled, it is used in place of virgin inputs in the manufacturing process. The avoided GHG emissions from remanufacture using recycled inputs is calculated as 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 (including the process of collecting and transporting the recyclables). No GHG emissions occur at the MSW management stage because the recycled material is diverted from waste management facilities.[17] (If the product made from the recycled material is later composted, combusted, or landfilled, the GHG emissions at that point would be attributed to the product that was made from the recycled material.) Chapter 4 details GHG emissions from recycling.

All 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 variety of paper types are recycled under the general heading of “mixed paper.” Mixed paper can be remanufactured, via an open loop, into boxboard or paper towels. Other materials are recycled in open-loop processes, but due to limited resources, this study could not analyze all open-loop processes.[18]

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[17] We do not include GHG emissions from managing residues (e.g., wastewater treatment sludges) from the manufacturing process for either virgin or recycled inputs.

[18] For example, not all steel cans are recycled into more steel cans; not all aluminum cans are recycled into more aluminum cans.

CO_2 Emissions from Biogenic Sources

The United States and all other parties to the U.N. Framework Convention on Climate Change (UNFCCC) agreed to develop inventories of GHGs for purposes of (1) developing mitigation strategies and (2) monitoring the progress of those strategies. The Intergovernmental Panel on Climate Change (IPCC) developed a set of inventory methods to be used as the international standard. (IPCC 1997. *IPCC Guidelines for National Greenhouse Gas Inventories*, three volumes.) The methodologies used in this report to evaluate emissions and sinks of GHGs are consistent with the IPCC guidance.

One of the elements of the IPCC guidance that deserves special mention is the approach used to address CO_2 emissions from biogenic sources. For many countries, the treatment of CO_2 releases from biogenic sources is most important when addressing releases from energy derived from biomass (e.g., burning wood), but this element is also important when evaluating waste management emissions (for example, the decomposition or combustion of grass clippings or paper). The carbon in paper and grass trimmings was originally removed from the atmosphere by photosynthesis, and under natural conditions, it would cycle back to the atmosphere eventually as CO_2 due to degradation processes. The quantity of carbon that these natural processes cycle through the Earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic GHG sources. But the focus of the UNFCCC is on anthropogenic emissions—those resulting from human activities and subject to human control. Those emissions have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle and altering the atmosphere's heat-trapping ability. For processes with CO_2 emissions, if the emissions are from biogenic materials and the materials are grown on a sustainable basis, then those emissions are considered simply to close the loop in the natural carbon cycle. They return to the atmosphere CO_2 that was originally removed by photosynthesis. In this case, the CO_2 emissions are *not* counted. (For purposes of this analysis, biogenic materials are paper, yard trimmings, and food discards.) On the other hand, CO_2 emissions from burning fossil fuels *are* counted because these emissions would not enter the cycle were it not for human activity. Likewise, CH_4 emissions from landfills *are* counted. Even though the source of carbon is primarily biogenic, CH_4 would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH_4 formation. Note that this approach does not distinguish between the timing of CO_2 emissions, provided that they occur in a reasonably short time scale relative to the speed of the processes that affect global climate change. In other words, as long as the biogenic carbon would eventually be released as CO_2, it does not matter whether it is released virtually instantaneously (e.g., from combustion) or over a period of a few decades (e.g., decomposition on the forest floor)

Composting: When organic materials are composted, the anaerobic decomposition of materials produces CH_4. Similarly, the collection and transportation of organics produces non-biogenic emissions. During the composting process and after the compost is added to the soil, the decomposition of plants produces biogenic CO_2 emissions. Carbon compounds that do not decompose, however, result in long-term carbon storage. All of the materials that may be composted (e.g., leaves, brush, grass, food waste, newspaper) originally are produced by trees or other plants. As described in the above in "CO_2 Emissions from Biogenic Sources," the biogenic CO_2 emitted from these materials during composting is not counted in GHG emissions. However, composting does result in increased soil carbon storage due to increased production of humic material (natural organic polymers, which degrade at a slow rate) and several other factors, which are described in Chapter 5.

Although composting may result in some production of CH_4 (due to anaerobic decomposition in the center of the compost pile), compost researchers believe that the CH_4 is almost always oxidized to CO_2 before it escapes from the compost pile.

Because the CO_2 emissions from composting are biogenic—generally producing no CH_4 emissions—the only GHG emissions from composting result from transportation of compostable materials to composting facilities and mechanical turning of the compost piles. GHG emissions associated with compost application are discussed in Chapter 5.

Combustion: When waste is combusted, two GHGs are emitted: CO_2 and N_2O. Non-biogenic CO_2 emitted during combustion (i.e., CO_2 from plastics) is counted toward the GHG emissions associated with combustion, but biogenic CO_2 is not. Because most waste combustors produce electricity that substitutes for utility-generated electricity, the net GHG emissions are calculated by subtracting the utility GHG emissions avoided from the gross GHG emissions. GHG emissions from combustion are described in Chapter 6.

Landfilling: When organic matter is landfilled, some of this matter decomposes anaerobically and releases CH_4, a GHG. Some of the organic matter never decomposes at all; instead, it becomes stored carbon. (Landfilling of metals and plastics does not result in either CH_4 emissions or carbon storage.)

At some landfills, virtually all of the CH_4 produced is released to the atmosphere. At others, CH_4 is captured for flaring or combustion with energy recovery (i.e., electricity production). Most of the captured CH_4 is converted to CO_2, but that CO_2 is not counted in this study as a GHG because it is biogenic. With combustion of CH_4 for energy recovery, credit is given for the electric utility GHG emissions avoided. Regardless of the fate of the CH_4, credit is given for the landfill carbon storage associated with landfilling of some organic materials. GHG emissions and carbon sinks from landfilling are described in Chapter 7.

1.5 ESTIMATING AND COMPARING NET GHG EMISSIONS

To calculate the net GHG implications of a waste management strategy for a given material, a baseline and alternative scenarios must be established. For example, a baseline scenario in which 10 tons of office paper are manufactured, used, and landfilled could be compared with an alternative scenario in which 10 tons are manufactured, used, and recycled. For each scenario, net GHG emissions are estimated based on (1) the GHG emissions associated with that material, and (2) any increases in carbon stocks and/or displaced fossil fuel combustion that offset those emissions. The formula for net GHG emissions is as follows:

Net GHG emissions = Gross GHG emissions - (Increase in carbon stocks + Avoided utility GHG emissions)

Comparing net GHG emissions for the two scenarios enables the lowest net GHG emissions to be identified. For example, when a material is source reduced (i.e., some or all of it is not produced), GHG emissions throughout the life cycle are avoided. In addition, when paper products are source reduced, additional carbon may be sequestered in forests.

Similarly, when a material is recycled, the GHG emissions from making an equivalent amount of material from virgin inputs are reduced. In most cases, recycling reduces GHG emissions because manufacturing a product from recycled inputs requires less fossil energy than making the product from virgin inputs and thus reduces energy-related GHG emissions.

If a waste is not source reduced or recycled, it may be either composted (if it is organic matter), combusted, or landfilled. In any of these cases, GHG emissions are produced during acquisition and manufacture. These GHG emissions may be augmented by CH_4 emissions from landfills (which themselves may be offset to some degree by energy recovery at landfills or landfill carbon storage). If the wastes are combusted, there may be an offset for avoided utility emissions.

In calculating emissions for the life-cycle scenarios, we can use the following two reference points:

- In a “raw material extraction” approach (i.e., cradle-to-grave perspective), raw material acquisition can be used as the “zero point” for emissions, with all emissions being added (and sinks deducted) from that point on through the life cycle.

- In a “waste-generation” approach (solid waste manager’s perspective), accounting for GHG emissions can start at the point of waste generation. All subsequent emissions and sinks from waste management practices then are accounted for. Changes in emissions and sinks from raw material acquisition and manufacturing processes are captured to the extent that certain waste management practices (i.e., source reduction and recycling) affect these processes.

Because it is the difference in emissions between the baseline and alternate scenarios that is meaningful, using either of these reference points yields the same results. The March 1997 draft working paper used the cradle-to-grave method to display GHG emissions because it is most consistent with standard accounting techniques for life-cycle inventories. Several reviewers pointed out that solid waste decision-makers tend to view raw materials acquisition and manufacturing as beyond their control and suggested that a waste generation GHG accounting approach would provide increased clarity for evaluating waste management options. Thus, both editions of this report use the waste generation approach and define the “standard” raw material acquisition and manufacturing step for each material as consisting of average GHG emissions based on the current mix of virgin and recycled inputs.[19]

Exhibit 1-3 indicates how GHG sources and sinks have been counted for each MSW management strategy in order to estimate net GHG emissions using the post-consumer reference point. For example, the top row of the exhibit shows that source reduction (1) reduces GHG emissions from raw materials acquisition and manufacturing, (2) results in an increase in forest carbon sequestration, and (3) does not result in GHG emissions from waste management. The sum of emissions (and sinks) across all steps in the life cycle represents net emissions. Section 8.2, “Applying Emission Factors,” describes how waste managers and companies have used these emission factors to estimate GHG emissions and potential GHG emission reductions associated with integrated waste management. In addition, EPA used these emission factors to develop the Waste Reduction Model (WARM). WARM enables users to analyze the GHG savings associated with changing their waste management practices. WARM is available on EPA’s Web site at <http://www.epa.gov/globalwarming/actions/waste/warm.htm>.

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[19] Changes in the mix of production (i.e., higher proportions of either virgin or recycled inputs) result in incremental emissions (or reductions) with respect to this reference point.

2. RAW MATERIALS ACQUISITION AND MANUFACTURING

The GHG emissions associated with raw materials acquisition and manufacturing are a key element of a life-cycle GHG analysis. This chapter describes how we estimated these emissions for 15 materials: aluminum cans, steel cans, glass, three types of plastic (HDPE, LDPE, and PET), corrugated cardboard, magazines/third-class mail, newspaper, office paper, phonebooks, textbooks, dimensional lumber, medium-density fiberboard, and mixed paper.

In manufacturing, substantial amounts of energy are used both in the acquisition of raw materials and in the manufacturing process itself. In general, the majority of energy used for these activities is derived from fossil fuels. Combustion of fossil fuels results in emissions of CO_2, a GHG. In addition, manufacturing of some materials also results in GHG emissions that are not associated with energy consumption. Section 2.1 addresses energy-related CO_2 emissions, and Section 2.2 covers non-energy GHG emissions. Sections 2.3 and 2.4 discuss results and limitations of the analysis, respectively.

2.1 GHG EMISSIONS FROM ENERGY USE IN RAW MATERIALS ACQUISITION AND MANUFACTURING

To begin our analysis, we estimated the GHG emissions from fossil fuel combustion for both (1) raw materials acquisition and manufacturing (referred to here as “process energy”), and (2) transportation (referred to as “transportation energy”).

In this analysis, process energy GHG emissions consist primarily of CO_2.[1] The majority of CO_2 emissions are from combustion of fuels used directly, e.g., to operate mining equipment or fuel a blast furnace. CO_2 emissions from fuels used to generate electricity during the manufacturing stage also are included in process energy emissions. In addition, process energy GHG emissions include indirect emissions from “pre-combustion” activities, such as oil exploration and extraction, coal mining and beneficiation, and natural gas production.

Transportation energy GHG emissions consist of CO_2 emissions from combustion of fuels used to transport raw materials and intermediate products to the final manufacturing or fabrication facility. For transportation of recycled inputs, this analysis considers transportation (1) from the curbside to the materials recovery facility (MRF), (2) from the MRF to a broker, and (3) from a broker to the plant or mill where the recycled inputs are used. The transportation values for recycled inputs generally include the energy used to process the inputs at an MRF. Transportation of finished manufactured goods to consumers is not included in the analysis. We did not estimate transportation emissions of CH_4 or N_2O; these emissions are considerably less significant than CO_2 emissions.[2] This omission would tend to understate the GHG impacts from transportation slightly.

Emissions from raw materials acquisition and manufacturing also include CH_4 associated with producing, processing, and transporting coal, oil, and natural gas. CH_4 is emitted during the various stages of fossil fuel production because CH_4 is trapped within coal and oil deposits, and is released when they are mined. Natural gas, of course, consists largely of CH_4.

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[1] Note, however, that CO_2 emissions from combustion of biomass (e.g., in paper manufacturing) are not counted as GHG emissions (as described in Chapter 1).

[2] The *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999* estimates 1999 emissions from transportation to be 468.1 MMTCE for CO_2 and 18.5 MMTCE for CH_4 and N_2O combined.

We developed separate estimates for GHG emissions from process and transportation energy for virgin inputs and recycled inputs, generating a total of four separate GHG emissions estimates for each material: (1) process energy with virgin inputs, (2) process energy with recycled inputs, (3) transportation energy with virgin inputs, and (4) transportation energy with recycled inputs.

2.1.1 Methodology

We developed GHG emission estimates for each material based on two sets of data: (1) the amount of each type of fuel used to make 1 ton of the material, and (2) the “carbon coefficient” for each fuel (a factor that translates the energy value of fuel combusted into the mass of GHGs emitted).

Our methodology in using these two sets of data to estimate process and transportation energy GHG emissions is best illustrated by an example: To estimate process energy GHG emissions from the production of 1 ton of newspaper from virgin inputs, we multiplied the amount of each type of fuel consumed (as measured in million Btu) by the carbon coefficient for that type of fuel (as measured in metric tons of carbon equivalent, or MTCE, per million Btu). The result was an estimate of the GHG emissions (in MTCE) from the combustion of each type of fuel required to make 1 ton of newspaper. Total process energy GHG emissions from making 1 ton of newspaper are simply the sum of the GHG emissions across all of the fuel types. To estimate the GHG emissions when electricity is used, we used the national average mix of fuels used to generate electricity.

We estimated GHGs from the energy used to transport raw materials for making 1 ton of a given product (e.g., newspaper) in the same way. The amount of each fuel used was multiplied by its carbon coefficient, and the resulting values for each of the fuels were summed to yield total transportation energy GHG emissions.

In this way, GHG estimates for raw materials acquisition and manufacturing were developed for each of the manufactured materials considered. As noted in Chapter 1, much of the energy information in this edition of the report is drawn from an effort conducted by EPA’s Office of Research and Development (ORD) to construct a Decision Support Tool for solid waste managers. The remaining energy data was developed by Franklin Associates, Ltd. (FAL) as part of the original effort or subsequent updates.

Most of the materials included in this analysis are assumed to undergo closed-loop recycling (i.e., materials are remanufactured into a similar product). However, mixed paper is recycled in an open loop into boxboard and paper towels.[3] Thus, the exhibits in this chapter show data not only for the 15 materials of interest, but also for boxboard and paper towels. Because recycling processes data are similar for HDPE, LDPE, and PET, we adopted the approach used by ORD of using a single energy profile (fuel mix and energy intensity) for all recycled plastics. For steel cans, we developed GHG estimates for virgin production using the basic oxygen furnace process,[4] and for recycled production, we used the electric arc furnace process.[5]

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[3] FAL provided virgin and recycled manufacturing and transportation data for boxboard and paper towels. For virgin boxboard, only one type of product is manufactured, as shown in Exhibits 2-3 and 2-4. For recycled boxboard, there are two types of products, and we obtained two different sets of manufacturing and transportation data as shown in Exhibits 2-5 and 2-6. We have labeled the two types of boxboard as boxboard “A” and boxboard “B.” These two products differ only with respect to their recycled material inputs (i.e., the proportion of newspaper, corrugated cardboard, office paper, and coated paper used to manufacture either boxboard “A” or boxboard “B”); both products share the same manufacturing and transportation values for virgin inputs.

[4] Note that the basic oxygen furnace process can utilize approximately 25 percent recycled inputs.

[5] Note that when recovered steel cans are used as inputs to an electric arc furnace, the resulting steel is not suited for milling to the thinness of steel sheet needed for use in making new steel cans. Thus, a more precise approach would have been to model recovery of steel cans as an open-loop process, in which recovered steel cans

We used carbon coefficients from the U.S. Department of Energy's Energy Information Administration for all fuels except electricity.[6] The carbon coefficient for electricity was based on the weighted average carbon coefficients for all fuels used to generate electricity in the United States.[7]

Because the carbon coefficients from these sources accounted for only the CO_2 emissions from combustion of each type of fuel, we added to these carbon coefficients (1) the average amount of CH_4 emitted during the production, processing, and transportation of fossil fuels, and (2) the average CO_2 emissions from oil production, due to the flaring of natural gas. We calculated the average fugitive GHG emissions associated with U.S. production of coal, oil, and natural gas. The resulting average estimates for fugitive GHG emissions from fossil fuel production were 0.92 kilograms of carbon equivalent per million Btu (kg CE/million Btu) for coal, 0.10 kg CE/million Btu for oil, and 0.70 kg CE/million Btu for natural gas.[8]

The carbon coefficients that reflect both CO_2 and CH_4 emissions are supplied in Exhibit 2-1. (All exhibits are provided at the end of this chapter.)

The process and transportation GHG values are shown in summary form in Exhibit 2-2. For each product and each type of input (virgin or recycled), we summed the estimates for process and transportation GHG emissions, as shown in columns "b" (for virgin inputs) and "c" (for recycled inputs) of Exhibit 2-2. We also estimated the energy-related GHG emissions from manufacturing each material from the current mix of virgin and recycled inputs. These values are shown in column "e." (The remaining two columns of Exhibit 2-2 are discussed later in this chapter.)

The energy intensity and fuel mix data are provided in Exhibits 2-3 through 2-6. For most materials, the data in the exhibits are for manufacturing processes that either use (1) 100 percent virgin inputs or (2) 100 percent recycled inputs.[9]

To estimate the types and amounts of fuels used for process and transportation energy, ORD and FAL relied on published data (such as engineering handbooks and published production data), contacts with industry experts, and review by stakeholders and trade organizations. ORD and FAL counted all energy, no matter where it was used. For example, much aluminum produced in the United States is made

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are made into some other steel product. By modeling recovery of steel cans as a closed-loop process, we implicitly assumed that 1 ton of steel produced from recovered steel cans in an electric arc furnace displaces 1 ton of steel produced from virgin inputs in a basic oxygen furnace. We believe this is a reasonable assumption. (For the fabrication energy required to make steel cans from steel, we used the values for fabrication of steel cans from steel produced in a basic oxygen furnace.)

[6] U.S. Department of Energy, Energy Information Administration. 2000. *Annual Energy Review: 1999.*

[7] FAL reported the Btu value for electricity in terms of the Btu of fuel combusted to generate the electricity used at the factory, rather than the (much lower) Btu value of the electricity that is delivered to the manufacturer. Thus, FAL had already accounted for the efficiency of converting fuels to electricity, and the losses in transmission and distribution of electricity. We therefore did not need to account for these factors in the carbon coefficient for electricity.

[8] ICF Consulting. 1995. Memorandum, "Fugitive Methane Emissions from Production of Coal, Natural Gas, and Oil," August 8, updated to use global warming potential for CH_4 of 21.

[9] In the FAL data set, the one exception is the data for steel cans made from virgin inputs, for which FAL provided data for manufacture from 80 percent virgin inputs and 20 percent recycled inputs. We extrapolated from this data (and the corresponding values for production using 100 percent recycled inputs) to obtain estimates of the energy inputs for manufacturing these materials from 100 percent virgin inputs. Similarly, for corrugated cardboard, ORD assumed that a virgin corrugated box contains a minimum of 14.7 percent total recycled content.

from bauxite that is mined and processed into alumina in other countries. The energy required for overseas bauxite mining and processing is counted in the analysis.

Neither the ORD nor the FAL transportation data reflect transportation of the finished manufactured product to the retailer and consumer. This omission is only important in estimating the GHG reductions associated with source reduction (i.e., source reduction reduces transportation energy). It is not relevant in analyzing GHG implications of recycling compared to other post-consumer management options, because the amount of transportation energy from the factory to the consumer is about the same whether the product is manufactured from virgin inputs or recycled inputs. Even for the source reduction analysis, we expect that the transportation energy from factory to consumer would represent a very small fraction of the total process and transportation energy.

Finally, it should be noted that during our extensive review of ORD and FAL data, we examined the most critical assumptions and data elements that each model used to ensure that they accurately reflect the energy requirements of the raw materials acquisition and manufacturing for the material types considered. Nevertheless, we recognize that different manufacturers making the same product use somewhat different processes with different energy requirements and fuel mixes, and that there are limited data on the extent to which various processes are used. Thus, although our goal was to estimate as accurately as possible the national average GHG emissions for the manufacture of each material from virgin and recycled inputs, it is quite likely that individual companies will have GHG emissions that vary significantly from those estimated here.

2.2 NON-ENERGY GHG EMISSIONS FROM MANUFACTURING AND RAW MATERIALS ACQUISITION

In addition to GHG emissions from energy use, we also accounted for three additional sources of GHGs in manufacturing processes:

- When limestone (calcium carbonate, or $CaCO_3$) is converted to lime (calcium oxide, or CaO), CO_2 is emitted. Significant quantities of lime are used in the production of steel, aluminum, and, to a much lesser extent, office paper.
- CH_4 emissions from natural gas pipelines and processing of natural gas are associated with the manufacture of plastic products.
- Perfluorocarbons (CF_4 and C_2F_6) are emitted during aluminum smelting.

For plastics and office paper, process non-energy GHG emissions are associated only with production using virgin inputs. In the case of steel, however, these emissions result when either virgin or recycled inputs are used (because lime is used in the production of steel from recycled as well as virgin inputs).

The process non-energy GHGs for each material are shown in the second-to-last column of Exhibits 2-3 and 2-5 (for manufacture from virgin inputs and recycled inputs, respectively), and are repeated in column “f” of Exhibit 2-2. ORD supplied the non-energy CO_2 emissions for aluminum, glass, corrugated cardboard, and newspaper. We based our calculation for PFC emissions from aluminum on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1998*.[10]

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[10] To estimate aluminum PFC emissions on a per-ton basis, we divided the inventory estimates for CF_4 and C_2F_6 emissions from aluminum by total primary aluminum production, yielding units in MTCE/ton.

Non-energy CO_2 emissions for the other materials, as well as CH_4 emissions, are based on the original analysis supporting the first edition of this report.[11]

2.3 RESULTS

Our estimates of the total GHG emissions from raw materials acquisition and manufacturing for each material are shown in Exhibit 2-2, column "g." In order to obtain these estimates, we summed the energy-related GHG emissions (column "e") and the non-energy GHG emissions (column "f").

The process energy and transportation GHG values that were developed as described earlier in this chapter are shown in the third-to-last columns of Exhibits 2-3 and 2-5, and in the last columns of Exhibits 2-4 and 2-6 (the last columns of Exhibits 2-3 and 2-5 show the total process energy GHG emissions).

Total GHG emissions associated with the raw materials acquisition and manufacturing stage of the product life cycle are shown in the three righthand columns of Exhibit 2-2. These three columns correspond to the type of inputs that occur during the recycling process: virgin inputs, recycled inputs, or the current mix of virgin and recycled inputs.

2.4 LIMITATIONS

There are several limitations to the analysis of the GHG emissions associated with raw materials acquisition and manufacturing, as described below.

The approach used in this analysis provides values for the average GHG emission rates per ton of material produced, not the marginal emission rates per incremental ton produced. In some cases, the marginal emission rates may be significantly different. For example, reducing production of plastic products from virgin inputs may not result in a proportional decrease in CH_4 emissions from natural gas pipelines and natural gas processing. The operating pressure in natural gas pipelines and the number and size of leaks in the pipeline determine CH_4 emissions from natural gas pipelines. Consequently, the amount of natural gas consumed at one end of the pipeline (e.g., to make plastic) does not affect the level of pipeline CH_4 emissions in a direct, linear way. As another example, long-term reductions in electricity demand could selectively reduce demand for specific fuels, rather than reducing demand for all fuels in proportion to their representation in the current average fuel mix. This analysis estimates average carbon conversion rates largely because the marginal rates are much more difficult to estimate. Nevertheless, we believe the average values provide a reasonable approximation of the GHG emissions.

In addition, the analysis assumes that the GHG emissions from manufacturing a given product change in a linear fashion as the percentage of recycled inputs moves from 0 to 100 percent. In other words, the analysis assumes that both the energy intensity and the fuel mix change in linear paths over this range. However, it could be that GHG emissions from manufacturing move in a non-linear path, (e.g., some form of step function) when the percentage of recycled inputs changes, due to capacity limits in manufacturing or due to the economics of manufacturing processes.

The transportation energy required for the final stage of transportation (to the consumer) was not considered. Consequently, some carbon emissions reductions for "lightweighted" products for these transportation stages were not considered; these savings are likely to be small.

The information used in this analysis represents the best available data from published and unpublished industry sources, some of it quite dated. Therefore, the data may not necessarily reflect recent trends in industrial energy efficiency or changes in the fuel mix.

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[11] ICF Consulting. 1994. Memorandum, "Detailed Analysis of Greenhouse Gas Emissions Reductions from Increased Recycling and Source Reduction of Municipal Solid Waste," July 29, p. 48 of the Appendix prepared by Franklin Associates, Ltd., dated July 14, 1994.

Finally, this static analysis does not consider potential future changes in energy usage per unit of output or alternative energy (e.g., non-fossil) sources. Reductions in energy inputs due to efficiency improvements could occur in either virgin input processes or recycled input processes. Efficiency improvements and switching to alternative energy sources will result directly in GHG emissions reductions and may change the reductions possible through increased recycling or source reduction.

Exhibit 2-1
Carbon Coefficients For Selected Fuels

Fuel Type	Metric Tons of CO_2 from Combustion Per Million Btu	kg Carbon Equivalent (CE) from Combustion Per Million Btu	Metric Tons of Fugitive CH_4 Emissions Per Million Btu	kg CE from Fugitive Methane Emissions Per Million Btu	kg CE Emitted Per Million Btu Consumed
Gasoline	0.07	19.25	0.00002	0.098	19.35
LPG	0.06	16.91	0.00002	0.10	17.01
Distillate Fuel	0.07	19.87	0.00002	0.10	19.97
Residual Fuel	0.08	21.41	0.00002	0.10	21.51
Diesel	0.07	19.87	0.00002	0.10	19.97
Oil/Lubricants	0.07	20.16	0.00002	0.10	20.26
Steam (non-paper products)	0.07	18.21	0.00011	0.61	18.81
Steam (paper products)	0.05	12.92	0.00004	0.25	13.17
National Average Fuel Mix for Electricity	0.06	15.79	0.00010	0.59	16.25
National Average Fossil Fuel Mix for Electricity	0.08	23.18	0.00015	0.86	24.04
Coal Used for Electricity	0.09	24.86	0.00016	0.92	25.78
Coal Used by Industry (Non-Coking Coal)	0.09	25.10	0.00016	0.92	26.02
Natural Gas	0.05	13.78	0.00012	0.70	14.48
Nuclear	0.00	0.84			0.84
Other (Petroleum Coke)	0.10	27.78	0.00002	0.10	27.87

Exhibit 2-2
GHG Emissions from the Manufacture of Selected Materials
(Metric Tons of Carbon Equivalent (MTCE) per Ton of Product)

(a)	(b) Virgin Input Combined Process and Transportation Energy Emissions	(c) Recycled Input Combined Process and Transportation Energy Emissions	(d)	(e) Current Mix Combined Process and Transportation Energy Emissions	(f) Process Non-Energy Emissions (MTCE per Ton of Product)			(g) Average Combined Process and Transportation Energy and Process Non-Energy Emissions (MTCE per Ton of Product)		
Type of Product	(MTCE per Ton of Product Made With Virgin Inputs)	(MTCE per Ton of Product Made With Virgin Inputs)	Percent Recycled Inputs in the Current Mix of Virgin and Recycled Inputs	(MTCE per Ton of Product Made With the Current Mix of Virgin and Recycled Inputs)	Virgin Inputs	Recycled Inputs	Current Mix	Virgin Inputs	Recycled Inputs	Current Mix
Aluminum Cans	3.52	0.25	49%	1.90	1.15	0.02	0.59	4.67	0.27	2.49
Steel Cans	0.77	0.27	44%	0.55	0.24	0.24	0.24	1.01	0.51	0.79
Glass Containers	0.11	0.07	23%	0.10	0.04	0.00	0.03	0.16	0.07	0.14
HDPE	0.48	0.04	9%	0.44	0.05	0.00	0.05	0.53	0.04	0.49
LDPE	0.59	0.04	4%	0.56	0.05	0.00	0.05	0.64	0.04	0.61
PET	0.55	0.04	18%	0.46	0.03	0.00	0.02	0.58	0.04	0.49
Corrugated Boxes	0.22	0.25	62%	0.24	0.00	0.00	0.00	0.22	0.25	0.24
Magazines/Third-class Mail	0.46	0.46	22%	0.46	0.00	0.00	0.00	0.46	0.46	0.46
Newspaper	0.59	0.34	52%	0.46	0.00	0.00	0.00	0.59	0.34	0.46
Office Paper	0.27	0.37	32%	0.30	0.01	0.00	0.00	0.28	0.37	0.31
Phonebooks	0.67	0.41	12%	0.64	0.00	0.00	0.00	0.67	0.41	0.64
Textbooks	0.59	0.57	13%	0.59	0.00	0.00	0.00	0.59	0.57	0.59
Dimensional Lumber	0.05	0.07	0%	0.05	0.00	0.00	0.00	0.05	0.07	0.05
Medium-density Fiberboard	0.10	0.12	0%	0.10	0.00	0.00	0.00	0.10	0.12	0.10
Mixed Paper										
Broad Def'n (= Boxboard "A")	0.32	0.43	51%	0.38	0.00	0.00	0.00	0.32	0.43	0.38
Residential Def'n (= Boxboard "B")	0.32	0.43	53%	0.38	0.00	0.00	0.00	0.32	0.43	0.38
Office Def'n (= Paper Towels)	0.91	0.75	38%	0.85	0.00	0.00	0.00	0.91	0.75	0.85

Explanatory notes: To estimate the GHG emissions from manufacturing, we first estimated the process and transportation GHG emissions when 100 percent virgin inputs, or 100 percent recycled inputs, are used. For each product and each type of input (virgin or recycled), we summed the estimates for process and transportation GHG emissions. Next we estimated the GHG emissions from manufacturing each material from the current mix of virgin and recycled inputs. We began with estimates of the percentage of recycled inputs currently used in the manufacture of each material, as shown in column “d.” We used these percentages to develop a weighted average value for the GHG emissions associated with the manufacture of each material from the current mix of virgin and recycled inputs. Specifically, we used the estimate of the percentage of recycled inputs in the current mix, together with the estimates for GHG emissions from manufacture using virgin or recycled inputs, to develop estimates of GHG emissions from manufacture using the current mix of virgin and recycled inputs (column “e”).

Explanatory notes for Exhibit 2-2 (continued):

Column “f” shows estimates of the process non-energy GHG emissions from manufacturing. First, this column shows the process non-energy GHG emissions when virgin inputs are used. Then it shows the emissions when recycled inputs are used (these values are simply copied from the final columns of Exhibits 2-3 and 2-5). Finally, column “f” shows the process non-energy GHG emissions from manufacturing each product from the current mix of virgin and recycled inputs. The values for the current mix are the weighted averages of the values for virgin and recycled inputs, based on the percentage of recycled inputs used in the current mix (as shown in column “d”).

The total GHG emissions from manufacturing are shown in column “g.” This column shows total GHG emissions when a product is manufactured from virgin or recycled inputs, or from the current mix of virgin and recycled inputs.

Exhibit 2-3

GHG Emissions Per Ton of Product Manufactured from Virgin Inputs

Process GHGs Only

Type of Product	Process Energy (Million Btu Per Ton of Product)	Average Fuel Mix (in Percent)												Process Energy GHG Emissions (MTCE/Ton of Product)	Process Non-Energy GHG Emissions (MTCE/Ton of Product)	Total Process GHG Emissions (MTCE/Ton of Product)
		Gasoline	LPG	Distillate Fuel	Residual Fuel	Biomass/Hydro	Diesel	Electricity	Coal	Natural Gas	Nuclear	Other	Total			
Aluminum Cans	205.80	0.16	0.01	0.82	4.06	0.03	0.50	80.36	0.83	13.04	0.17	0.02	100	3.36	1.15	4.51
Steel Cans	31.58	0.21	0.00	5.06	0.35	0.00	0.00	21.02	53.90	19.45	0.00	0.00	100	0.68	0.24	0.91
Glass	6.49	0.55	0.00	1.45	0.47	0.03	0.00	10.12	7.18	79.95	0.23	0.02	100	0.10	0.04	0.15
HDPE	28.69	0.00	0.00	0.00	33.14	1.16	0.00	5.64	4.59	51.35	4.00	0.13	100	0.48	0.05	0.53
LDPE	35.26	0.00	0.00	0.00	32.59	1.56	0.00	7.66	6.15	46.52	5.36	0.17	100	0.59	0.05	0.64
PET	32.82	0.00	0.00	0.00	36.67	1.62	0.00	7.10	6.42	42.41	5.59	0.18	100	0.55	0.03	0.58
Corrugated Cardboard	25.13	0.01	0.00	0.02	0.54	61.33	1.20	14.06	15.52	7.31	0.01	0.00	100	0.19	0.00	0.20
Magazines/Third-class Mail	32.99	0.15	0.01	0.32	8.30	24.27	0.00	25.40	17.11	24.33	0.11	0.01	100	0.46	0.00	0.46
Newspaper	39.92	0.25	0.00	0.52	0.75	9.09	0.68	54.21	1.75	32.43	0.27	0.04	100	0.58	0.00	0.58
Office Paper	37.01	0.08	0.00	0.17	4.33	60.53	0.00	13.24	8.92	12.68	0.06	0.01	100	0.27	0.01	0.28
Phonebooks	39.61	0.18	0.01	0.38	9.99	8.86	0.00	30.56	20.59	29.28	0.13	0.02	100	0.67	0.00	0.67
Textbooks	35.07	0.18	0.01	0.38	9.96	9.14	0.00	30.47	20.52	29.19	0.13	0.02	100	0.59	0.00	0.59
Dimensional Lumber	2.53	1.57	0.00	0.00	0.00	32.81	15.99	43.09	0.00	6.53	0.00	0.00	100	0.03	0.00	0.03
Medium-density Fiberboard	10.18	0.14	0.00	0.38	0.05	51.90	1.26	27.61	0.00	18.68	0.00	0.00	100	0.08	0.00	0.08
Boxboard	32.26	0.00	0.00	0.00	0.94	59.34	1.36	5.32	24.01	9.02	0.00	0.00	100	0.29	0.00	0.29
Paper Towels	73.44	0.00	0.00	0.01	1.80	24.89	0.45	28.15	2.93	41.78	0.00	0.00	100	0.87	0.00	0.87

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

Exhibit 2-4

GHG Emissions Per Ton of Product Manufactured from Virgin Inputs

Transportation GHGs Only

Type of Product	Transportation Energy (Million Btu Per Ton of Product)	Average Fuel Mix (in Percent) Gasoline	LPG	Distillate Fuel	Residual Oil	Biomass/Hydro	Diesel	Electricity	Coal	Natural Gas	Nuclear	Other	Total	Transportation Energy GHG Emissions (MTCE/Ton of Product)
Aluminum Cans	7.47	0.10	0.08	0.39	79.88	0.05	11.34	0.34	0.86	6.58	0.33	0.05	100	0.16
Steel Cans	4.60	0.00	0.00	0.00	1.76	0.00	98.24	0.00	0.00	0.00	0.00	0.00	100	0.09
Glass	0.58	0.10	0.08	0.40	2.64	0.04	88.95	0.00	0.89	6.51	0.36	0.03	100	0.01
HDPE	NA													NA
LDPE	NA													NA
PET	NA													NA
Corrugated Cardboard	1.31	0.05	0.00	0.05	0.27	0.01	98.51	0.00	0.00	1.07	0.04	0.01	100	0.03
Magazines/Third-class Mail	NA													NA
Newspaper	0.50	0.10	0.08	0.39	3.63	0.05	87.97	0.00	0.86	6.53	0.34	0.05	100	0.01
Office Paper	NA													NA
Phonebooks	NA													NA
Textbooks	NA													NA
Dimensional Lumber	0.88	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	100	0.02
Medium-density Fiberboard	1.01	0.00	0.00	0.00	0.06	0.00	98.10	0.00	0.00	1.84	0.00	0.00	100	0.02
Boxboard	1.79	0.00	0.00	0.00	0.05	0.00	99.93	0.00	0.00	0.01	0.00	0.00	100	0.04
Paper Towels	2.07	0.00	0.00	0.00	0.52	0.00	99.46	0.01	0.00	0.02	0.00	0.00	100	0.04

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

Note that for some materials, transportation data was included in the process energy estimates and not provided separately, denoted by "NA" in this table.

Exhibit 2-5
GHG Emissions Per Ton of Product Manufactured from Recycled Inputs
Process GHGs Only

Type of Product	Process Energy (Million Btu Per Ton of Product)	Average Fuel Mix (in Percent)												Process Energy GHG Emissions (MTCE/Ton of Product)	Process Non-Energy GHG Emissions (MTCE/Ton of Product)	Total Process GHG Emissions (MTCE/Ton of Product)
		Gasoline	LPG	Distillate Fuel	Residual Fuel	Biomass/Hydro	Diesel	Electricity	Coal	Natural Gas	Nuclear	Other	Total			
Aluminum Cans	14.85	0.27	0.01	5.12	0.44	0.05	0.52	63.74	0.75	28.78	0.29	0.04	100	0.24	0.02	0.26
Steel Cans	11.78	0.01	0.17	0.07	0.03	0.00	0.00	77.28	0.65	21.80	0.00	0.00	100	0.19	0.24	0.43
Glass	4.32	0.55	0.00	0.39	0.26	0.03	0.00	5.10	0.54	92.91	0.21	0.02	100	0.06	0.00	0.06
HDPE	4.17	0.03	0.03	1.05	1.24	12.48	0.05	33.21	0.02	20.34	0.09	31.44	100	0.04	0.00	0.04
LDPE	4.17	0.03	0.03	1.05	1.24	12.48	0.05	33.21	0.02	20.34	0.09	31.44	100	0.04	0.00	0.04
PET	4.17	0.03	0.03	1.05	1.24	12.48	0.05	33.21	0.02	20.34	0.09	31.44	100	0.04	0.00	0.04
Corrugated Cardboard	11.73	0.01	0.05	0.05	0.66	0.00	0.31	51.11	38.40	9.40	0.01	0.00	100	0.23	0.00	0.23
Magazines/Third-class Mail	31.97	0.16	0.01	0.32	8.45	22.85	0.00	25.87	17.43	24.79	0.11	0.01	100	0.46	0.00	0.46
Newspaper	21.98	0.30	0.00	0.58	0.30	0.05	0.00	57.75	1.09	39.59	0.30	0.04	100	0.34	0.00	0.34
Office Paper	20.12	0.20	0.01	0.42	10.96	0.02	0.00	33.53	22.58	32.12	0.14	0.02	100	0.37	0.00	0.37
Phonebooks	22.02	0.20	0.01	0.42	10.96	0.02	0.00	33.53	22.58	32.12	0.14	0.02	100	0.41	0.00	0.41
Textbooks	33.51	0.21	0.01	0.60	10.02	8.38	0.00	30.40	20.61	29.57	0.17	0.02	100	0.57	0.00	0.57
Dimensional Lumber	3.17	0.00	0.00	0.00	0.00	0.00	23.61	76.39	0.00	0.00	0.00	0.00	100	0.05	0.00	0.05
Medium-density Fiberboard Made from Reused Dimensional Lumber	10.99	0.13	0.00	0.35	0.04	48.05	8.56	25.56	0.00	17.29	0.00	0.00	100	0.09	0.00	0.09
Boxboard Made from Broad Definition of Mixed Paper	22.53	0.00	0.03	0.02	0.36	0.00	0.49	67.46	24.36	7.25	0.00	0.00	100	0.42	0.00	0.42
Boxboard Made from Residential Definition of Mixed Paper	22.53	0.00	0.03	0.02	0.36	0.00	0.49	67.46	24.36	7.25	0.00	0.00	100	0.42	0.00	0.42
Paper Towels Made from Recoverd File Stock	51.69	0.00	0.00	0.00	0.45	6.94	0.15	36.32	0.98	55.14	0.00	0.00	100	0.74	0.00	0.74

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

* Recycled boxboard using a "broad" definition of mixed paper comprised of 24 percent newsprint, 48 percent corrugated cardboard, 20 percent office paper, and 8 percent coated paper.

** Recycled boxboard using a "residential" definition of mixed paper comprised of 23 percent newsprint, 53 percent corrugated cardboard, 14 percent office paper, and 10 percent coated paper.

*** Recycled boxboard using an "office paper" definition of mixed paper comprised of 21 percent newsprint, 5 percent corrugated cardboard, 38 percent office paper, and 36 percent coated paper.

Exhibit 2-6
GHG Emissions Per Ton of Product Manufactured from Recycled Inputs
Transportation GHGs Only

	Transportation Energy	Average Fuel Mix (in Percent)												Transportation Energy GHG Emissions
Type of Product	(Million Btu Per Ton of Product)	Gasoline	LPG	Distillate Fuel	Residual Oil	Biomass/Hydro	Diesel	Electricity	Coal	Natural Gas	Nuclear	Other	Total	(MTCE/Ton of Product)
Aluminum Cans	0.40	0.08	0.06	0.32	3.07	0.04	90.11	0.00	0.68	5.32	0.27	0.04	100	0.01
Steel Cans	4.03	0.00	0.00	0.00	0.01	0.00	99.99	0.00	0.00	0.00	0.00	0.00	100	0.08
Glass	0.34	0.10	0.08	0.41	2.59	0.04	89.01	0.00	0.89	6.51	0.35	0.03	100	0.01
HDPE	0.08	0.00	0.00	0.00	56.50	0.00	5.96	2.53	0.00	35.01	0.00	0.00	100	0.00
LDPE	0.08	0.00	0.00	0.00	56.50	0.00	5.96	2.53	0.00	35.01	0.00	0.00	100	0.00
PET	0.08	0.00	0.00	0.00	56.50	0.00	5.96	2.53	0.00	35.01	0.00	0.00	100	0.00
Corrugated Cardboard	0.80	0.05	0.00	0.05	0.22	0.01	98.55	0.00	0.00	1.07	0.04	0.00	100	0.02
Magazines/Third-class Mail	NA													0.00
Newspaper	0.03	0.10	0.08	0.39	3.75	0.05	87.87	0.00	0.86	6.53	0.32	0.05	100	0.00
Office Paper	NA													0.00
Phonebooks	NA													0.00
Textbooks	NA													0.00
Recycled Lumber from	0.97	0.00	0.00	0.00	0.00	0.00	100.06	0.00	0.00	0.00	0.00	0.00	100	0.02
Medium-density Fiberboard Made from Reused Dimensional Lumber	1.27	0.00	0.00	0.00	0.05	0.00	98.46	0.00	0.00	1.47	0.00	0.00	100	0.03
Boxboard Using the "Broad Definition" for Mixed Paper	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00
Boxboard Using the "Single-Family Residential Definition" for Mixed Paper	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00
Paper Towels Using "Office Paper" for Mixed Paper	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

Note that for some materials, transportation data was included in the process energy estimates and not provided separately, denoted by "NA" in this table.

* Recycled boxboard using a "broad" definition of mixed paper comprised of 24 percent newsprint, 48 percent corrugated cardboard, 20 percent office paper, and 8 percent coated paper.

** Recycled boxboard using a "residential" definition of mixed paper comprised of 23 percent newsprint, 53 percent corrugated cardboard, 14 percent office paper, and 10 percent coated paper.

*** Recycled boxboard using an "office paper" definition of mixed paper comprised of 21 percent newsprint, 5 percent corrugated cardboard, 38 percent office paper, and 36 percent coated paper.

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3. FOREST CARBON SEQUESTRATION

This chapter presents estimates of the forest carbon sequestration that results from recycling or source reducing corrugated cardboard, magazines and third-class mail, newspaper, office paper, phonebooks, textbooks, dimensional lumber, and medium-density fiberboard.

One of the large-scale processes that influences the cycling of carbon is the uptake or release of carbon from forests. When trees are cleared for agriculture or other activities, carbon is released (generally in the form of CO_2). On the other hand, when forests are planted and allowed to continue growing, 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*.

In the United States, uptake by forests has exceeded release since about 1977, primarily due to forest management activities and the reforestation of previously cleared areas. This net sequestration of carbon in forests represents a large and important process. EPA estimates that the annual net CO_2 flux (i.e., the excess of uptake minus release) in U.S. forests was about 107 million metric tons of carbon equivalent (MMTCE) in 1999,[1] offsetting about 7 percent of U.S. energy-related CO_2 emissions. In addition, about 17 million metric tons of carbon was stored in wood products.

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 paper and wood product manufacture and use tends to release carbon.[2] In the long term, some of the short-term benefits disappear as market forces result in less planting of new managed forests than would otherwise occur, so that there is comparatively less forest acreage in trees that are growing rapidly (and thus sequestering carbon rapidly).

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. The complexity and long time frame of carbon sequestration in forests, coupled with the importance of market dynamics that determine land use, dictated the use of best available models. This chapter describes our method for applying models to estimate the effect of forest carbon sequestration associated with paper and wood product recycling and source reduction.

We 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 and wood reduced and recycled. We used the USDA-FS system of models because (1) they are the best models available in modeling the species composition, inventory, and growth of forests; and (2) these models had been used previously to analyze climate change mitigation options for the *Climate Change Action Plan*. Because the models did not enable us to estimate the forest carbon sequestration associated

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[1] U.S. EPA. 2001. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*. U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC. EPA-236-R-01-001. Note that the estimate cited (110 MMTCE) includes only carbon storage in trees and understory, which is consistent with the forest components included in this report. If forest floor and soils were included as well, the total would be 171 MMTCE.

[2] The forest carbon inventory in any year equals the carbon inventory the year before, plus net growth, less harvests, less 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.

with recycling of each type of paper separately, we obtained a single estimate of the sequestration from recycling *any* type of paper.

The methodology described in this chapter finds that increased recycling of paper or wood products results in incremental forest carbon sequestration of 0.73 MTCE/ton and 0.50 MTCE/ton, respectively.[3] The USDA-FS models do not directly estimate the effect of source reduction. To derive these estimates we 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 range from 0.30 MTCE/ton (for corrugated cardboard) to 0.66 MTCE/ton (for phone books).

Performance of the USDA-FS Forest Models

Researchers have never formally assessed the accuracy of the USDA-FS models of the forest sector. In analyses that compare the forest impacts of a policy scenario with those of a baseline scenario (such as the analysis described in this chapter), the USDA-FS model results are probably reasonable. Much of the uncertainty in the model results is due to assumptions that apply to both the baseline and policy scenarios—assumptions about population growth, economic growth, tree growth, and land use changes. Any error in these assumptions would tend to bias the results in the baseline and policy scenarios in the same direction. Thus, when the outcomes of the baseline and policy scenarios are compared, errors in the assumptions tend to cancel each other out.

The remainder of this chapter is divided into seven parts. Section 3.1 provides an overview of the linkages between the five models used in the paper and wood analysis. Sections 3.2 through 3.5 describe the models in greater detail and briefly discuss the inputs, assumptions, and outputs for each model, focussing on the paper analysis. Section 3.6 describes the approach used to analyze wood products. Section 3.7 presents the results of the analysis, and Section 3.8 discusses the limitations of the individual models and of the analysis as a whole.

3.1 MODELING FRAMEWORK

Working with the USDA-FS, we used six models to estimate the impacts of increased recovery and source reduction of paper and wood products on forest carbon sequestration.

For paper and wood products, we used five linked models to arrive at forest carbon sequestration estimates. The first model projects the decline in U.S. pulpwood harvests when paper recovery increases. The second and third models use the outputs of the first model, together with other inputs and assumptions, to estimate the extent to which reduced pulpwood harvests due to paper recovery result in lower U.S. timber harvests and increased timber inventories.[4] The fourth and fifth models use the outputs of the second and third models, and estimate how the increased timber inventories and decreased timber harvests due to paper recovery translate into (1) increased forest carbon sequestration and (2) changes in carbon sequestration in wood-in-use carbon sinks (e.g., wood used in home construction). Exhibit 3-1 shows how the models are linked.

The paper analysis proceeded as follows:

(1) We developed two recovery scenarios − an estimated baseline paper recovery rate for the year 2000 of 50 percent and a hypothetical year 2000 paper recovery rate of 55 percent as inputs to

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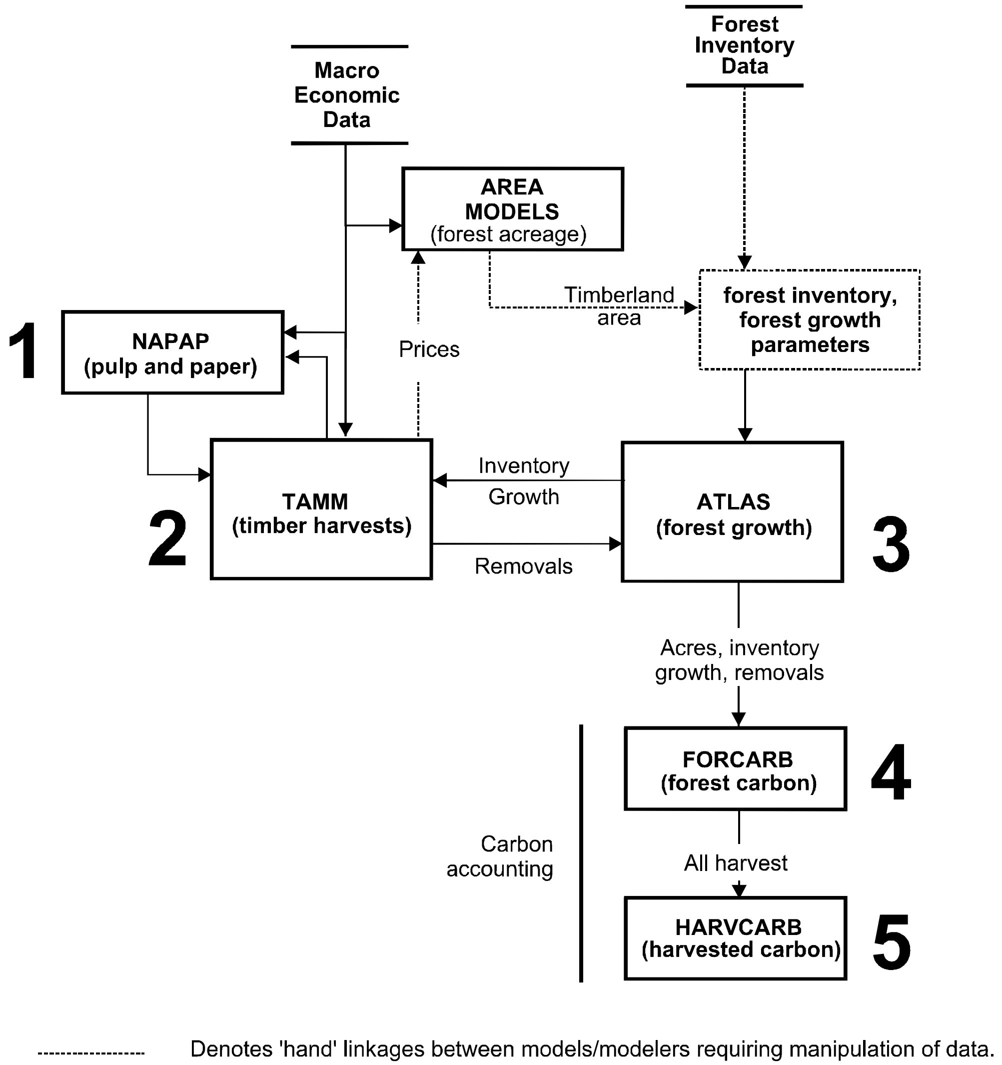
[3] Although a relationship exists, it is not directly measurable. Moreover, for the relationship to remain valid, there must be continued investment in tree planting and growth. We believe this continued investment will occur, because projections of forest product use consistently point to increases in demand.

[4] The USDA-FS projections of forest product demand account for continued high demand for all types of forest products.

Exhibit 3-1
USFS Models of the Forest Sector



the North American Pulp and Paper (NAPAP) model (the model is described in Section 3.2). The 50 percent recovery rate used for the baseline scenario was based on previous paper industry projections.[5] We used a 55 percent recovery rate for the high recovery scenario because (1) we considered this to be a plausible recovery rate with additional government programs to promote recycling, and (2) this recovery rate corresponded to EPA's goal of increasing recovery of MSW in the original (1993) Climate Change Action Plan. We then assumed that over the next 15 years, the recovery rates under both scenarios would continue to rise and would converge in the year 2016 at 57 percent. (We assumed convergence so that we

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[5] Actual paper recovery in 2000 (taken from EPA's *Municipal Solid Waste in the United States: 2000 Facts and Figures*) averaged about 53%, confirming that 50 percent is a reasonable estimate for 2000.

could isolate the long-term carbon sequestration effects that might result from increasing paper recovery in the near term.) The paper recovery rates for both scenarios then were projected to rise slowly from 57 percent in 2016 to 61 percent in 2040. This adjustment to the model incorporated our assumption that the current trend of increasing paper recovery rates would continue into the future. The NAPAP model then was run to model the pulpwood harvests from 1985 to 2040 that would be associated with (1) the baseline paper recovery rate and (2) the high paper recovery rate.

(2) The outputs from NAPAP for projected pulpwood harvests in the two scenarios were used as inputs to the Timber Assessment Market Model (TAMM), which projects U.S. timber harvests, and the Aggregate Timberland Assessment System (ATLAS) model, which projects timber growth and changes in the U.S. forest inventory (where inventory is a function of both growth and harvests). The TAMM and ATLAS models are described more fully in Section 3.3. The TAMM and ATLAS models were run, using the NAPAP inputs, to generate estimates of U.S. harvest levels and forest inventories for each year through 2040, for both the baseline and high recovery scenarios.

(3) The outputs from TAMM and ATLAS for forest harvest levels and forest inventories in the two scenarios were used as inputs to the Forest Carbon (FORCARB) model, described in Section 3.4, which projects forest carbon sequestration. The FORCARB model produced, as outputs, estimates of U.S. forest carbon sequestration for each year through 2040, for both the baseline and high recovery scenarios.

(4) FORCARB outputs also were used as inputs to the WOODCARB (also known as HARVCARB, or Harvested Carbon) model, which tracks the flow of carbon in wood products (see Section 3.5).

For wood products, we used essentially the same process, but bypassed step 1 by creating a scenario involving increased recycling of wood, which causes a corresponding reduction in softwood harvest. This harvest forecast provided the basis for inputs to ATLAS, which in turn was linked to FORCARB and WOODCARB to evaluate carbon flows. As with paper, the increment in carbon storage between the base case scenario and the higher recycling scenario is calculated. This increment is divided by total tons of wood recycled to estimate a carbon storage rate (MTCE per ton of wood recycled).

3.2 THE NORTH AMERICAN PULP AND PAPER (NAPAP) MODEL

The NAPAP model is a linear optimization model[6] that uses forecasts of the U.S. economy (e.g., growth in population and the economy) to estimate the quantity of hardwood and softwood trees harvested for pulpwood in North America each year.[7] The model predicts the quantity of pulpwood harvested each year based on estimated demand and supply curves. The quantity harvested is the quantity at which these curves intersect.

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[6] A linear optimization model begins with a set of constraints (e.g., profits = revenues - costs; costs = labor costs + equipment costs + administrative costs + overhead costs) and an objective function (e.g., maximize profits). The model uses principles of matrix algebra to find the solution (e.g., the total level of output) at which the objective function is optimized (e.g., profits are maximized).

[7] A number of analyses have been conducted using results from the NAPAP models. These analyses include (1) USDA Forest Service. 1994. *RPA Assessment of the Forest and Rangeland Situation in the United States - 1993 Update*, USDA Forest Service Forest Resource Report No. 27 (Washington, DC: USDA Forest Service), 75 pp.; (2) Haynes, Richard W., Darius M. Adams, and John R. Mills. 1995. *The 1993 RPA Timber Assessment Update*, USDA Forest Service General Technical Report RM-GTR-259 (Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station), 66 pp.; (3) Ince, Peter J. 1995. *What Won't Get Harvested Where and When: The Effects of Increased Paper Recycling on Timber Harvest*, Yale School of Forestry and

3.2.1 Inputs to the NAPAP Model

The NAPAP model includes four major inputs:

- Macroeconomic forecast data (e.g., estimates of U.S. population growth and growth in per-capita gross domestic product);
- Paper manufacturing capacity as of a baseline year;[8]
- Manufacturing costs for each different paper manufacturing process; and
- Assumed levels of future harvests from public forests.

3.2.2 Equations and Assumptions Used in the NAPAP Model

The NAPAP model incorporates equations for the following functions and assumptions:

- Estimated pulpwood supply functions (reflecting an increasing supply of pulpwood at increasing market prices) for three U.S. regions (West, South, and North) and two regions in Canada;
- Estimated supply functions for four principal categories of recovered paper—newspaper, corrugated boxes, mixed papers, and the aggregate of pulp substitutes and high-grade de-inking—in each supply region (the supply functions reflect an increasing supply of recovered paper at increasing market prices);
- An unlimited supply of labor and energy at the market price in each supply region;
- A fixed-quantity supply function for residues from manufacture of solid wood products, such as lumber and plywood, mostly in the form of "pulp chips";
- Demand functions[9] for all 13 principal categories of paper and paperboard products produced in North America[10] (the demand functions reflect increasing demand due to population growth and growth in the gross domestic product, and decreasing demand due to increasing market prices);
- Functions for changes in paper manufacturing capacity (including capacity for both virgin and recycled inputs), assuming that when demand for paper increases, the investment in paper manufacturing capacity that is needed to meet demand will be made in those types of capacity where the ratio of profitability to capital cost is the highest; and

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Environmental Studies Program on Solid Waste Policy, Working Paper #3 (New Haven, CT: Yale University) 75 pp.; and (4) Environmental Defense Fund. 1995. *Paper Task Force Recommendations for Purchasing and Using Environmentally Preferable Paper: Final Report of the Paper Task Force* (New York, NY: Environmental Defense Fund), 245 pp.

[8] The baseline year for paper manufacturing capacity is 1986. The model predicts how capacity for each paper manufacturing process changes each year from 1986 onward. The model's predictions for paper manufacturing capacity in 1995, based on the 1986 baseline as updated, were within 5 percent of actual 1995 paper manufacturing capacity.

[9] Separate demand functions are incorporated for U.S. domestic demand, Canadian domestic demand, and demand from various trading regions for exported paper products from the United States and Canada.

[10] These paper grades include newspaper, coated and uncoated free sheet, coated and uncoated groundwood, linerboard, and corrugating medium.

- The ratio of the weight of paper recovered to the weight of the fiber actually used in manufacturing new paper, after accounting for discards during processing and losses during manufacturing.

The major assumptions of the NAPAP model include basic assumptions of economic analysis—i.e., that markets are perfectly competitive and that paper manufacturers seek to maximize their profits. Because owners of private forests may not always act to maximize their profits, NAPAP assumes that they will continue historical patterns of economic behavior (which USDA-FS has modeled through econometric methods). In addition, the model assumes (1) specific levels of harvests from public forests; and (2) specific future technology options.[11] Finally, the NAPAP pulpwood supply functions are the same for both the baseline and the high recycling scenario. In other words, the supply functions do not incorporate market feedbacks to account for changes in the age structure of forests or the acreage of forested land. The age structure of forests could change as increased paper recovery reduces tree harvests, so that on average trees grow longer. Forested acreage could change if higher paper recovery leads to decreased demand for pulpwood and lower pulpwood prices, leading some landowners to convert forested land to farmland or ranchland.[12]

For this analysis, the USDA-FS simulated different recovery rates for the two scenarios—for the year 2000, 50 percent in the baseline scenario and 55 percent in the high recovery scenario. The cumulative amounts of paper recovered under the baseline and high recovery scenarios are shown in Exhibit 3-2.

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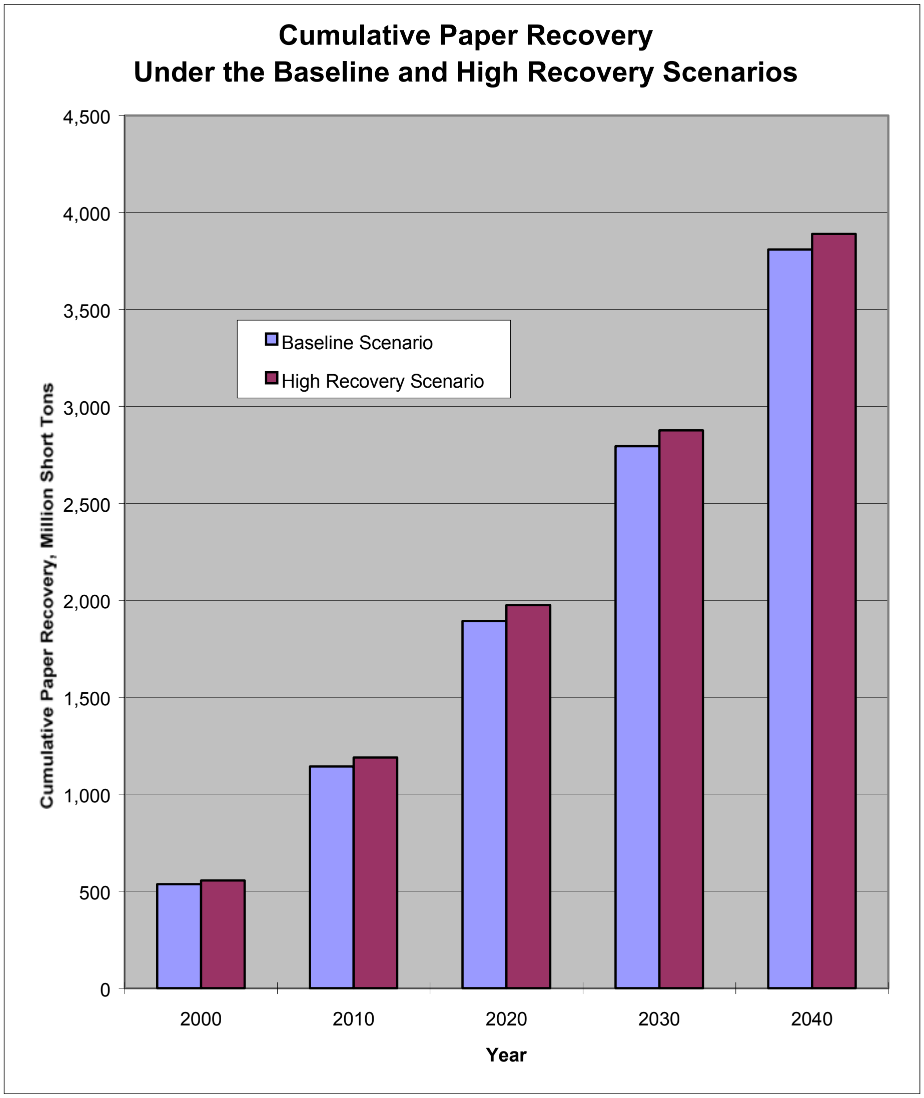
[11] The model assumes that certain technologies that existed in 1995 but were not yet commercialized (e.g., two newspaper processes with higher yields) would enter the commercial marketplace in the period from 1995-2000.

[12] The NAPAP pulpwood supply functions incorporate projections of timber inventories over time from a prior run of the linked TAMM and ATLAS models. Ideally, the NAPAP portion of this analysis would have used two separate projections of timber inventories over time: one projection based on the baseline paper recovery scenario and another based on the high paper recovery scenario. NAPAP recently has been revised so that it may now be run iteratively with TAMM and ATLAS; however, NAPAP did not have that capability at the time this analysis was conducted.

Exhibit 3-2
Cumulative Paper Recovery Under the Baseline and High Recovery Scenarios (Million Short Tons)

Year	2000	2010	2020	2030	2040
A. Baseline Scenario	536	1143	1893	2795	3808
B. High Recovery Scenario	556	1189	1975	2876	3890
C. Incremental Paper Recovery Under the High Recovery Scenario (B-A)	20	46	81	81	81



NAPAP scenarios generally are specified in terms of recovered fiber utilization rates, which differ somewhat from paper recovery rates. To assure that the model inputs for fiber utilization are consistent with paper production, recovery, and consumption projections prepared by the American Forest and Paper Association (AFPA), Franklin Associates, Ltd. developed a set of conversion factors. USDA-FS used these conversion factors to adjust the demand functions for paper products. The effect was to increase the projections of paper demand and increase the estimates of the equilibrium quantity of paper produced.[13]

Trade in forest products between the United States and Canada was assumed to be fixed at levels projected in recent USDA-FS studies. As a result, any change in *North American* pulpwood harvests due to increased U.S. paper recovery would be shown in the NAPAP outputs as a change in *U.S.* pulpwood harvests. Thus, the forest carbon effects of increased paper recovery in the United States were modeled as if those effects occur entirely in the United States.

3.2.3 Outputs of the NAPAP Model

The principal outputs of the NAPAP model, for each of the two scenarios modeled, are annual U.S. pulpwood harvests from the present to the year 2040. These harvests are broken down into four categories of pulpwood: (1) softwood roundwood; (2) softwood residues; (3) hardwood roundwood; and (4) hardwood residues. The NAPAP estimates of pulpwood harvests for each scenario—for selected years from 1995 to 2040—are shown in Exhibit 3-3. As the exhibit shows, the NAPAP model projected that higher paper recovery rates until the year 2016 would result in pulpwood harvests that would be substantially below the baseline from 1995 to 2000 (because of the recovered paper substitutes for pulp that would otherwise be made from trees). From 2005 to 2010, the higher recovery scenario would result in slightly higher pulpwood harvests than under the baseline.[14] From 2020 onward, annual pulpwood harvests would be the same under the baseline and high recovery scenarios (because after 2016 the paper recovery rates would be the same in both scenarios).

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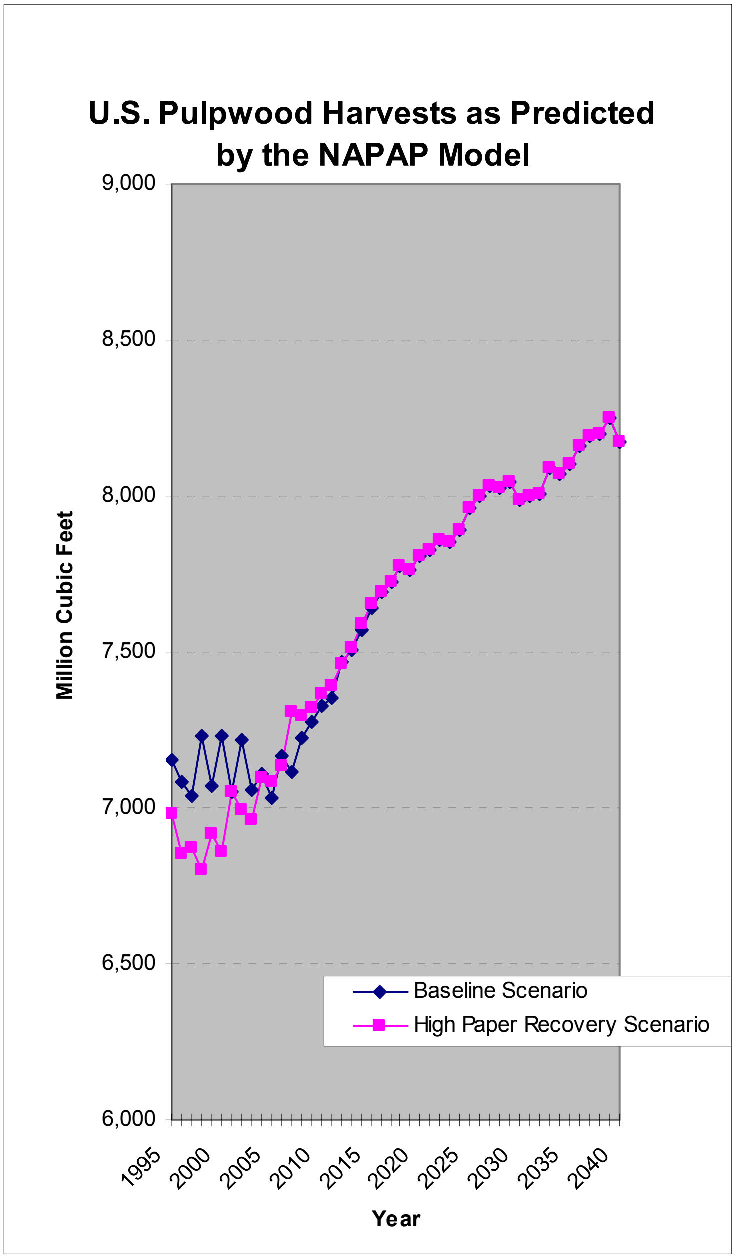
[13] Specifically, the USDA-FS adjusted the NAPAP model by increasing the elasticity of demand for paper products so that it reflected the historical relationship between (1) paper demand and (2) population and per capita gross domestic product. “Elasticity of demand” is the extent to which a change in the price of goods will affect the quantity of the goods demanded and is defined as the percentage change in quantity divided by the percentage change in price that induced the change in quantity. For example, if the quantity demanded goes down by 2 percent when the price goes up by 1 percent, the elasticity of demand is -2. Specifically, this is the “own-price elasticity” of demand because it is measured with respect to the price of the goods in question, as distinct from “cross-elasticity” of demand, which would be measured with respect to the price of different goods.

[14] Pulpwood harvests are projected to be higher between 2005 and 2010 under the high recycling scenario These harvests are expected to be higher due to the modeled consequences of reduced pulpwood harvests before 2005. Because pulpwood harvests before 2005 are projected to be lower under the high recycling scenario, more pulpwood remains to be harvested in later years. The increasing supply of pulpwood ready for harvest reduces pulpwood prices, leading to modeled increases in industry demand for non-paper uses. The increased industry demand results in slightly higher pulpwood harvests after 2005. However, it is important to note that under the baseline scenario, pulpwood harvests are projected to decline between 2000 and 2005. This decline is because the increase in paper recycling during this period is projected to be greater than the increase in paper consumption.

Exhibit 3-3
U.S. Pulpwood Harvests as Predicted by the NAPAP Model for Selected Years (Million Cubic Feet)

Year	1995	2000	2010	2020	2030	2040
Baseline Scenario	7,152	7,230	7,328	7,808	7,989	8,173
High Paper Recovery Scenario	6,982	6,858	7,362	7,808	7,989	8,173



3.3 THE TIMBER ASSESSMENT MARKET MODEL (TAMM) AND THE AGGREGATE TIMBERLAND ASSESSMENT SYSTEM (ATLAS)

TAMM and ATLAS are spatial equilibrium models.[15] TAMM models U.S. timber harvests through 2040, and ATLAS models changes in U.S. forest growth, and inventory of growing stock volume, through 2040.[16] The two models are interrelated, because timber harvests depend in part on timber inventory, and timber inventory depends in part on prior harvest levels. (This interrelationship is shown graphically in Exhibit 3-1 with arrows going in both directions between the two models.) To obtain consistency in the projections of the two models, an iterative process is used. TAMM outputs for timber removals are used as inputs to ATLAS, and the resulting ATLAS outputs for forest growth and inventory are used as inputs to TAMM. This cycle is continued until the difference in projections between one cycle and the next has been reduced to an acceptably small amount. To reduce the costs of modeling in this analysis, no hand linkages were made to transfer price estimates from TAMM back to the Area Models (see Exhibit 3-1), nor to transfer timberland area estimates from the Area Models back to ATLAS. Implicitly, the forested area was modeled as being unaffected by increased paper recovery rates.

TAMM's estimates of timber harvests are based on four factors: (1) estimated demand for solid forest products (such as softwood and hardwood lumber and panel products such as plywood) based on projected macroeconomic data (e.g., growth in population and in the economy); (2) estimates of pulpwood harvests from the NAPAP model; (3) estimates of fuelwood harvests (held constant at recent levels); and (4) estimates of annual forest growth from ATLAS.

The ATLAS estimates of forest growth and inventory are based on (1) the previous year's inventory, (2) timber harvests from TAMM, and (3) estimated forest growth parameters.

3.3.1 Inputs to the TAMM Model

The TAMM model is based on eight major inputs:[17]

- U.S. pulpwood harvests, from the NAPAP model;
- U.S. fuelwood harvests, from a fuelwood model;

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[15] A spatial equilibrium model is an optimization model (see footnote 6 in this chapter) that accounts for costs of transportation of products from producing regions to consuming regions.

[16] The descriptions of the TAMM and ATLAS models are drawn from Richard W. Haynes et al. 1993. *Alternative Simulations of Forestry Scenarios Involving Carbon Sequestration Options: Investigation of Impacts on Regional and National Timber Markets*, U.S. Department of Agriculture Forest Service, Pacific Northwest Station, August 5. Two articles which give a more detailed description of the TAMM model are (1) Adams, D.M. and R.W. Haynes. 1980. *The 1980 Softwood Timber Assessment Market Model: Structure, Projections, and Policy Simulations*, Forest Science Monograph No. 22 (Washington, DC: USDA Forest Service), 62 pp., and (2) Adams, D.M. and R.W. Haynes, *A Spatial Equilibrium Model of U.S. Forest Products Markets for Long-Range Projection and Policy Analysis*. In Andersson *et al.*, eds., "Systems Analysis in Forestry and Forest Industries," *TIMS Studies in the Management Sciences* 21(1986)73-87. Two journal articles which describe analyses based on the TAMM model are (1) Adams, D.M. and R.W. Haynes, *Softwood Timber Supply and the Future of the Southern Forest Economy*, *Southern Journal of Applied Forestry* 15(1991):31-37, and (2) Adams, D.M and R.W. Haynes. 1991. "Estimating the Economic Impacts of Preserving Old-Growth on Public Lands in the Pacific Northwest," *The Northwest Environmental Journal* 6(2):439-441.

[17] Inputs to the TAMM model are documented in: Haynes, R.W. 1990. *An Analysis of the Timber Situation in the United States: 1989-2040*, Gen. Tech. Rep. RM-199 (Ft. Collins, Colorado: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station), 286 pp.

- Assumed levels of future timber harvests from public forests, from USDA-FS harvest plans;
- U.S. net imports of forest products, from a trade model;
- Changes in U.S. forested acreage over time, from a prior run of forest Area Models;[18]
- Growth in forest inventory, from the ATLAS model;
- Macroeconomic forecast data, e.g., on U.S. housing starts, housing repairs, and remodeling; and
- Installed capacity as of 1990 for producing timber products, such as lumber or plywood, from harvested trees.

3.3.2 Equations and Assumptions Used in the TAMM Model

The TAMM model incorporates equations for the following:

- Estimated timber product supply functions (reflecting an increasing supply of timber products at increasing market prices) for eight U.S. regions; and
- Estimated demand functions for U.S. demand for all major uses of lumber and plywood (reflecting decreasing demand for such products at increasing market prices).

Also, changes in supply capacity for timber products are predicted by the model, based on anticipated changes in relative regional profitability or rate of return from capital investment.[19]

The TAMM model includes several major assumptions:[20]

- General assumptions of competitive markets, increasing demand for wood products with increasing economic activity, profit maximization by owners of lumber and plywood mills, and continued historical patterns of economic behavior by owners of forest land (these behavior patterns may not be strictly profit maximizing); and
- Specific assumptions regarding particular levels of public harvests and projected changes in technology.

In addition, TAMM and ATLAS assume (1) specified levels for net imports of softwood products, and (2) no net imports of hardwood lumber.

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[18] In the NAPAP portion of this analysis, timber inventories over time were not affected by the different paper recovery rates in the two different scenarios analyzed, but in the TAMM and ATLAS models, timber inventories were estimated independently for the two different scenarios.

[19] Specifically, TAMM uses an assumption that changes in capital investment are a function of past changes in output (i.e., that manufacturers' expectations about the profitability of capital investment are based on past changes in output).

[20] Assumptions of the TAMM model are documented in the following two reports: (1) Haynes, R.W. 1990. *An Analysis of the Timber Situation in the United States: 1989-2040*, Gen. Tech. Rep. RM-199. (Fort Collins, Colorado: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station), 286 pp.; and (2) Haynes, R.W., D.M. Adams, and J.R. Mills. 1995. *The 1993 RPA Timber Assessment Update*, Gen. Tech. Rep. RM-GTR-259 (Fort Collins, Colorado: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station), 66 pp.

3.3.3 Inputs to the ATLAS Model

The ATLAS model, for each simulation year, relies on four major inputs:

- Forest inventory at the beginning of the previous period, from a prior ATLAS model run;
- Forest removals during the previous period, from the TAMM model;
- Changes in forest acreage, from a prior run of a modified version of the Southern Area Model; and
- State-by-state data on the number of forested acres and the volume of timber per forested acre (shown as "Forest Inventory Data" in Exhibit 3-1).

3.3.4 Equations and Assumptions of the ATLAS Model

The ATLAS model incorporates equations that allow the model to simulate shifts in forest management intensities and consequent changes in yields. Projected shifts in forest management intensities are based on (1) the modeled prices of forest products, (2) the costs of various management practices, and (3) the timber yields associated with each management practice.

The only major assumption in the ATLAS model is that owners of private forests manage their forests at the level of intensity indicated by recent average forest planting rates. Otherwise, the model is very simple, relying on a basic mathematical proposition that forest inventory in any period equals forest inventory in the previous period, plus net growth, minus harvests. Net growth is gross growth less mortality from fire, storm, insects, and disease.

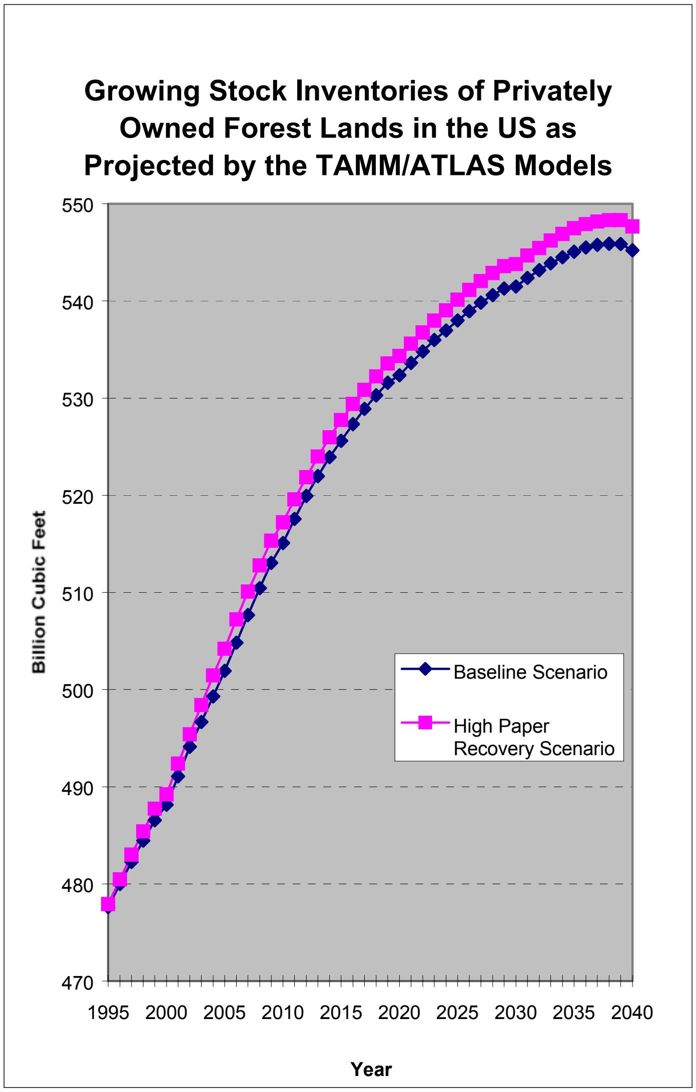
3.3.5 Outputs of the TAMM/ATLAS Models

The outputs of the linked TAMM and ATLAS models are projections, through 2040, of U.S. inventories of forest growing stock volumes (i.e., the volume of trees growing in forests), annual U.S. sawtimber harvests, and forest growth.

We used the TAMM/ATLAS data on forest growing stock inventories as inputs to FORCARB. Exhibit 3-4 shows the growing stock inventories of privately owned forest lands in the United States as projected by the TAMM/ATLAS models. As the exhibit shows, forest growing stock inventories range from 1 to 2 billion cubic feet higher under the high recovery scenario than under the baseline scenario for the entire simulation period.

Exhibit 3-4
Growing Stock Inventories of Privately Owned Forest Lands in the US As Projected by the TAMM/ATLAS Models (Billion Cubic Feet)

Year	1995	2000	2010	2020	2030	2040
Baseline Scenario	478	488	515	532	541	545
High Paper Recovery Scenario	478	489	517	534	544	548



3.4 THE FOREST CARBON MODEL (FORCARB)

The Forest Carbon Model (FORCARB) projects U.S. forest carbon sequestration (including soil, forest floor, and understory carbon) each year through 2040, based on outputs from the TAMM/ATLAS linked models.[21]

3.4.1 Inputs to the FORCARB Model

The major inputs to the FORCARB model are the following:

- Forest growing stock inventories—by tree species, age, and region—from the linked TAMM/ATLAS models; and
- The percentage carbon composition for different species of trees, as grown in different forest regions.

3.4.2 Assumptions of the FORCARB Model

The USDA-FS tracks information in TAMM/ATLAS in terms of growing stock volume, i.e., the merchantable portion of trees. Tree volume is larger than growing stock volume, due to additional volume in non-merchantable portions of the tree such as roots and branches. The FORCARB model uses the simplifying assumption that tree volume is a constant multiple of growing stock volume. Carbon in the tree volume in the U.S. forest industry then is estimated based on the percentage carbon content of different species of trees.

When a tree is harvested, FORCARB no longer counts the carbon remaining in the non-merchantable portion of the tree (e.g., tree roots) following harvest. In other words, FORCARB uses the simplifying modeling assumption that the carbon in the non-merchantable portion of the tree is no longer sequestered and is converted to CO_2 emissions.

3.4.3 Outputs of the FORCARB Model

As outputs, the FORCARB model produces estimates of total U.S. forest carbon inventories and estimates of sawtimber and pulpwood harvests for each year through 2040. The amount of forest carbon sequestration in a given year equals the increase in forest carbon inventories during that year. If forest carbon inventories decrease, net emissions, i.e., negative forest carbon sequestration, would occur.

Exhibit 3-5 shows the projected carbon inventories of U.S. forests, as projected by the FORCARB model, for the baseline and high paper recovery scenarios. The forest carbon inventories that served as the basis for these annual changes counted carbon in trees and understory (e.g., small trees), but not carbon in the soil and forest floor. These carbon stocks were not included because of the high level of uncertainty in estimating and modeling their carbon content.

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[21] The description of the FORCARB model here is drawn from Birdsey, Richard A., and Linda S. Heath. 1993. *Carbon Sequestration Impacts of Alternative Forestry Scenarios - Draft* (Radnor, PA: U.S. Department of Agriculture Forest Service, Global Change Research Program), pp. 47-51. A number of studies analyzing forest issues using the FORCARB and HARVCARB models have been published in journal articles. Among these are three that also explain the FORCARB and HARVCARB models. These three articles are (1) Plantinga, A.J. and R.A. Birdsey. 1993. "Carbon Fluxes Resulting from U.S. Private Timberland Management," *Climatic Change* 23:37-53; (2) 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; and (3) Heath, L.S. and R.A. Birdsey. 1993. "Impacts of Alternative Forest Management Policies on Carbon Sequestration on U.S. Timberlands," *World Resource Review* 5:171-179.

Exhibit 3-5
U.S. Forest Carbon Inventory, Trees, Understory, Soil, and Forest Floor As Predicted by the FORCARB Model (Million Metric Tons of Carbon)

Year	2000	2010	2020	2030	2040
A. Baseline Scenario	8,641	9,076	9,322	9,442	9,497
B. High Paper Recovery Scenario	8,665	9,118	9,364	9,480	9,537
C. Incremental Carbon Stored Under the High Paper Recovery Scenario (B-A)	24	42	42	38	40

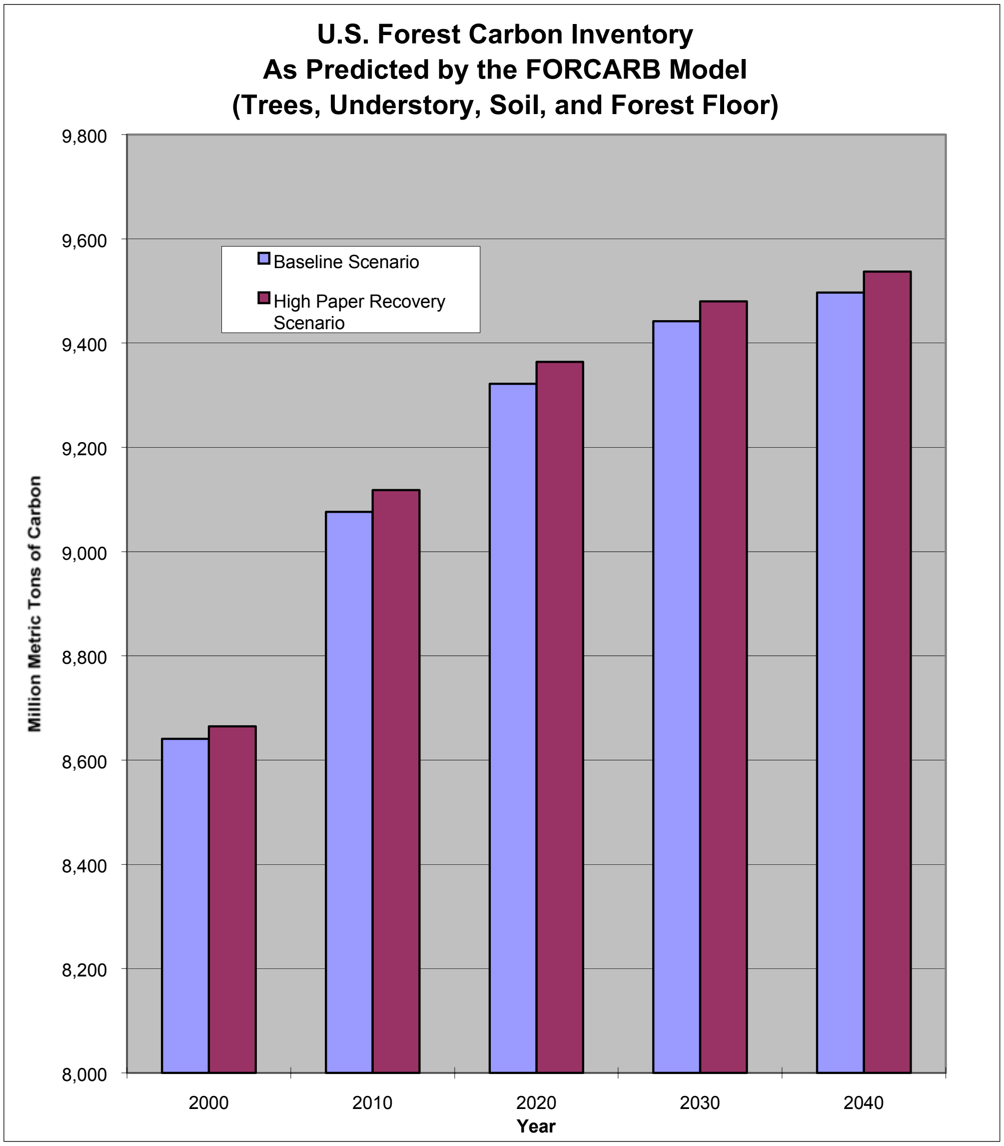

Exhibit 3-6 shows the *change* in U.S. forest carbon inventories, expressed as an annual average for decades from 2000 to 2040. Inventories increase more quickly under the high recycling scenario than under the baseline recycling scenario, through the decade ending 2010. After 2010, the rate of increase in forest carbon inventories is essentially the same for both scenarios. This consistency is because the paper recovery rate is modeled as converging in 2016 to the same rate in both scenarios.

3.5 THE HARVESTED CARBON MODEL (WOODCARB)

WOODCARB (also known as the Harvested Carbon Model, or HARVCARB) can be thought of as a spreadsheet model that projects the disposition of harvested wood across four different potential scenarios, for 50 years into the future.[22] The spreadsheet would include estimates of the percentage of four categories of wood that will be found in four potential fates at 10-year intervals: (1) products (a "wood-in-use" sink); (2) landfills; (3) combustion for energy; and (4) aerobic decomposition. Some change in the fate of a wood product occurs over time: wood products that are in use in the early years are likely to be landfilled or combusted in later years. The four different categories of wood considered in the model are softwood and hardwood pulpwood, and softwood and hardwood sawtimber. The model has separate fate estimates for three regions of the United States: west, south, and north.

We combined the average annual sawtimber and pulpwood harvest estimates from FORCARB with the fate estimates in the WOODCARB spreadsheet, to obtain estimates of the amount of carbon from harvested wood that would be found in each of the four potential fates for 50 years into the future.

3.5.1 Inputs to the WOODCARB Model

As the only input to the WOODCARB model, the USDA-FS used the annual sawtimber and pulpwood harvests from the FORCARB model.

3.5.2 Assumptions of the WOODCARB Model

The WOODCARB model assumes that the material management patterns for the four categories of wood over a 50-year period do not change (e.g., the model does not assume any change in the proportion of waste or disposed wood burned for energy).

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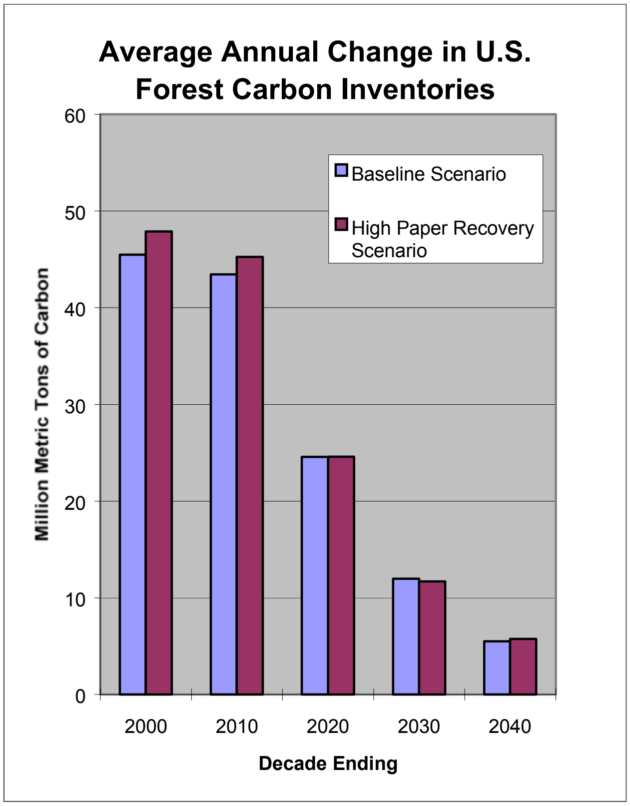
[22] This USDA-FS model is an adaptation of the HARVCARB model developed earlier (C. Row, and R.B. Phelps, 1990, "Tracing the flow of carbon through the U.S. forest products sector," Presentation at the 19th World Congress, International Union of Forestry Organizations, 5-11 August 1190, Montreal, Quebec), and described more fully in Row and Phelps, 1996, "Wood Carbon Flows and Storage after Timber Harvest," in Forests and Global Change. Vol 2, R. Neil Sampson and Dwight Hair, eds. American Forests, Washington, DC, p 27-58. This description of the USDA-FS implementation of the model is based on R.A. Birdsey and L.S. Heath, *op cit*, pp. 50-51.

Exhibit 3-6
Average Annual Change In U.S. Forest Carbon Inventories As Predicted by the FORCARB Model (Million Metric Tons of Carbon)

Time Period	Decade Ending 2000	Decade Ending 2010	Decade Ending 2020	Decade Ending 2030	Decade Ending 2040
A. Baseline Scenario	45.48	43.47	24.56	11.96	5.52
B. High Paper Recovery Scenario	47.89	45.25	24.59	11.70	5.74
C. Incremental Annual Forest Carbon Sequestration in the High Paper Recovery Scenario [B-A]	2.40	1.79	0.03	-0.26	0.22



3.5.3 Outputs of the WOODCARB Model

In this analysis, WOODCARB provided outputs for the amount of carbon (1) retained in wood-in-use sinks; (2) landfilled; (3) combusted for energy; and (4) aerobically decomposed, for each year from 1995 to 2040. Because other parts of our analysis address landfills and combustion, and aerobic decomposition has no GHG effects, we used only the estimates of the amount of carbon retained in wood-in-use sinks (a form of carbon sequestration). We included this amount in our estimate of total "forest carbon," even though this carbon is stored in locations outside of forests.

Exhibit 3-7 shows the wood-in-use sinks for the baseline and high recovery scenarios from 1990 to 2040, as predicted by the WOODCARB model. As shown in the exhibit, the wood-in-use sinks are slightly less under the high recovery scenario than under the baseline scenario. The WOODCARB model predicts this result because under the high recovery scenario, tree harvests are reduced. Under the fixed proportions of the fates of wood assumed in WOODCARB, less wood is available for each of the fates for wood products, including wood-in-use sinks. As noted above, WOODCARB uses fixed proportions for the disposition of harvested wood (e.g., paper, housing, and furniture). With increased paper recovery, wood prices would be expected to decline (due to reduced demand), and more wood probably would be used for housing and furniture. Because WOODCARB does not account for any change in the price of wood and its impacts on wood-in-use sinks, the values in Exhibit 3-7 are probably a slight underestimate of the amount of carbon in wood-in-use sinks under the high recovery scenario.

3.6 APPLYING THE MODELS FOR WOOD PRODUCTS

As the preceding discussion indicates, the USDA-FS modeling system is quite complex and requires extensive coordination between model components. The modeling of the effects of paper recycling and source reduction was conducted over a 2-year period and involved efforts of several experts. After publication of the first edition of this report, EPA received several requests to evaluate the effect of recycling and source reduction of solid wood products, especially dimensional lumber and medium-density fiberboard. For these products, the USDA-FS, EPA, and ICF Consulting conducted a more streamlined analysis to characterize forest carbon flows.

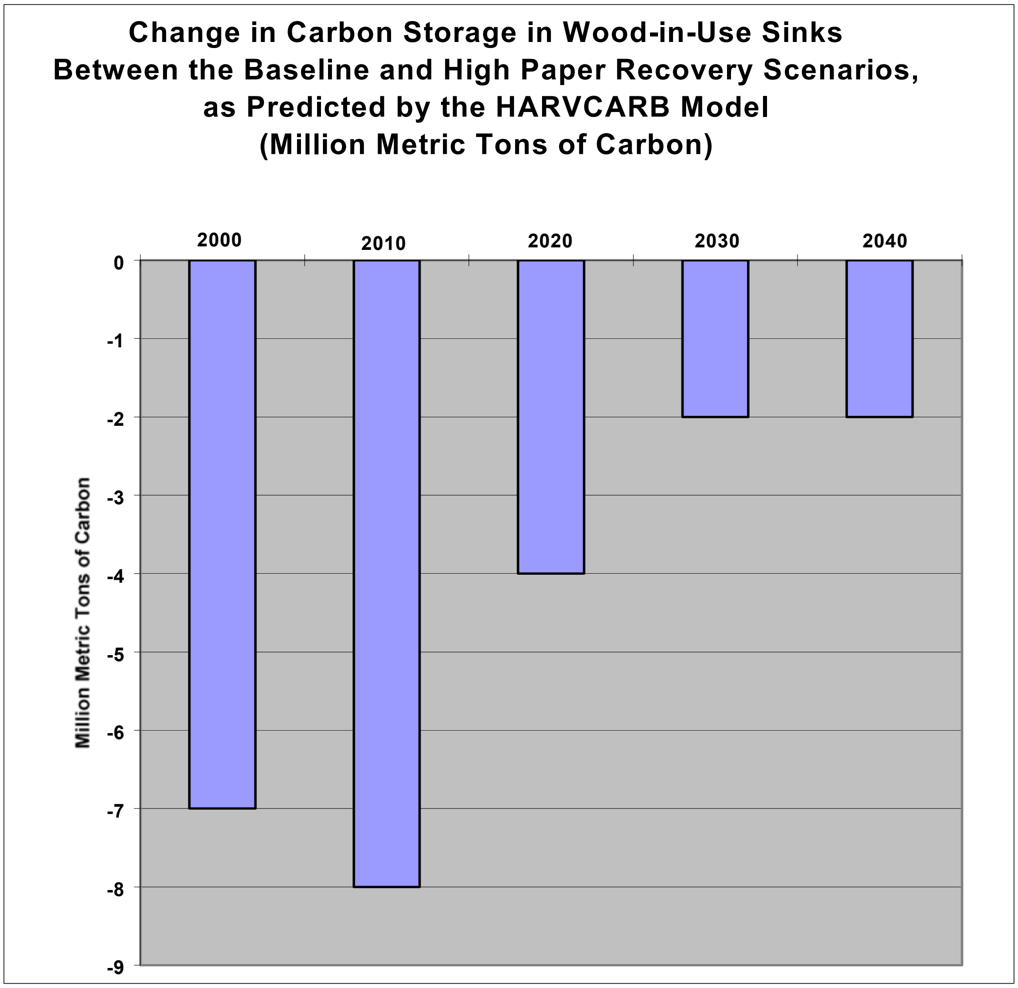
The streamlined analysis bypassed the use of NAPAP and TAMM. Rather than creating a market-based harvest scenario by using these models, a harvest scenario was developed based on the expert judgment of two USDA-FS experts in forest products and carbon flows: Dr. Ken Skog of the Forest Products Laboratory and Dr. Linda Heath of the Northeast Research Station. Dr. Skog indicated that the majority of solid wood products are derived from softwood, and a large-scale wood recycling program might result in a corresponding reduction in softwood harvest of about 1.7 percent. This harvest forecast provided the basis for inputs to ATLAS, which in turn was linked to FORCARB and WOODCARB to evaluate carbon flows.

The reductions were distributed throughout the USDA-FS regions in proportion to baseline harvest for the period 1998-2007. The cumulative reduction in softwood harvest was 26.4 million short tons.

The effect of this reduction in harvest is to increase carbon sequestration in forests. To be consistent with the approach for paper recycling, effects were analyzed only for the tree and understory components (and excluded forest floor and soils). The total carbon sequestration was converted to a rate per increment of (a) recycling or (b) source reduction. Dr. Skog provided the following rough estimates of the system efficiencies, on a mass basis, for producing wood products from virgin inputs or recycled inputs:

Exhibit 3-7
U.S. Cumulative (Since 1990) Wood-in-Use Sinks as Predicted by the HARVCARB Model (Million Metric Tons of Carbon)

Year	2000	2010	2020	2030	2040
A. Baseline Scenario	733	1,216	1,634	2,028	2,381
B. High Paper Recovery Scenario	726	1,208	1,630	2,026	2,379
C. Change in Carbon Storage in Wood-in-Use Sinks [B-A]	-7	-8	-4	-2	-2



- 1.1 tons roundwood input per ton finished product; and
- 1.25 tons recycled wood input per ton of finished product.

Based on these factors:

- For every ton of solid wood product that is source reduced, the reduction in timber harvest is 1.1 tons; and
- Assuming that overall demand for wood products is constant, increases in recycling reduce timber harvest so that for every ton of solid wood product recycled, the reduction in timber harvest is 0.88 tons (=1.1/1.25).

To develop estimates of the incremental forest carbon sequestration rates, we divided the change in forest carbon sequestration by the rates of recycling or source reduction that correspond to the reduced tonnages of softwood harvest.

The final step was to estimate effects on the product pool. For wood products, we assumed a carbon density of 0.531 tons C/ton wood (or 0.48 MTCE per short ton wood), corresponding to softwoods in a Southeast and South Central pine forest (one of the principal sources of softwood harvests), based on Birdsey 1992.[23] Other key assumptions were the following:

- For source reduction, every ton of wood product removed from the product pool results in a corresponding decline in carbon mass in that pool; and
- For increased recycling (i.e., at levels above the current rate), every 1 ton of wood recycled yields 0.8 ton of product (=1/1.25). According to Dr. Skog, it is reasonable to assume that the mass lost in the recycling process is burned. Thus the carbon loss from the product pool is (1 ton wood recycled - 0.8 ton wood retained) * 0.48 MTCE/ton wood = 0.10 MTCE/ton.

Note that the effect on the product pool from both source reduction and recycling is to decrease carbon sequestration. This decrease offsets some of the benefit of increasing sequestration in the forest pool.

3.7 RESULTS

As noted at the beginning of this chapter, we first obtained estimates of the forest carbon sequestration[24] from paper recycling, and then used those estimates to develop estimates of the forest carbon sequestration from source reduction of paper.

We estimated the forest carbon sequestration per ton of paper recycled at various points in the future by dividing the *cumulative difference* in forest carbon between the high recovery and baseline scenarios by the *cumulative difference* in the amount of paper recovered between the two scenarios. To estimate the forest carbon sequestration in each scenario, we summed the forest carbon sequestration estimates generated by the FORCARB model and the wood-in-use sink estimates generated by the WOODCARB model.

The USDA-FS projected forest carbon inventories under the baseline and high recovery scenarios at several points in time (i.e., 2000, 2010, 2020, 2030, and 2040). The estimates of incremental forest carbon sequestration per ton of paper recovered vary across time, as shown in Exhibit 3-8. Note that the estimates of incremental forest carbon sequestration decline from 2000 to 2020, and then stabilize.

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[23] Birdsey, Richard A. 1992. *Carbon Storage and Accumulation in the United States Forest Ecosystems*. USDA Forest Service. General Technical Report WO-59. Table 1.2

[24] As noted earlier, the term *forest carbon sequestration* is intended to include both the carbon stored in forests and the carbon stored in wood-in-use sinks.

We chose the forest carbon sequestration factor for the period ending in 2010 as the best approximation of the forest carbon benefits from increasing source reduction and recycling over the near term. This value—0.73 MTCE per short ton of paper recovered—falls between the higher value for 2000 and the lower values for later years in the simulation period. We selected this value to approximate the short-term carbon sequestration benefits of source reduction and recycling because it balances the following: (1) relatively high carbon sequestration benefits will be achievable in the near term; (2) forest carbon sequestration benefits drop somewhat over time; and (3) more uncertainty is associated with the long-term carbon sequestration effects and market response (because model predictions far into the future are more uncertain than near-term predictions). In sum, we believe that the value for the year 2010 strikes the best balance in capturing the relatively higher short-term benefits of forest carbon sequestration and recognizing that these benefits decline over time.[25]

Using the forest carbon sequestration estimate for paper recovery, we developed estimates for forest carbon sequestration associated with source reduction of paper, as shown in Exhibit 3-9. We 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.[26] We estimated that forest carbon sequestration for source reduction, assuming displacement of virgin inputs, is the same as for paper recovery. Although this approach for estimating the effects of source reduction does not consider the loss rates associated with paper recovery, we believe it is a reasonable first approximation. To estimate the forest carbon sequestration for source reduction assuming displacement of the current mix of inputs, we used an additional factor, i.e., the percentage of virgin inputs in the current mix of inputs. For this calculation (column "d" in Exhibit 3-9), we account for the fact that displacement of recycled inputs does not have any impact on forest carbon sequestration.

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[25] The impact of increased paper recycling and source reduction on forest growing stock inventories (3 billion cubic feet in addition to the baseline scenario of 541 cubic feet in 2030, as shown in Exhibit 3-4) is only 0.5 percent. This amount is less than the likely statistical error in measuring the inventories. Although the estimated effect is a small proportion of the total inventory, the relationship between recycling and stocks is clear, and the magnitude of the effect is plausible and is significant on a per-ton basis.

[26] 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.

Exhibit 3-8
Increased Forest Carbon Storage Per Ton of Paper Recovered

Cumulative Change Between the Baseline and High Paper Recovery Scenarios for:	**2000**	**2010**	**2020**	**2030**	**2040**
A. Forest Carbon Stocks* (million MTCE)	24.0	41.9	42.2	39.7	41.9
B. Wood-in-Use Stocks (million MTCE)	-7.0	-8.0	-4.0	-2.0	-2.0
C. Incremental Carbon Stored (million MTCE) [A+B]	17.0	33.9	38.2	37.7	39.9
D. Incremental Paper Recovery (million short tons)	19.7	46.2	81.4	81.4	81.4
E. Incremental Carbon Sequestration (MTCE/ton) [C/D]	0.9	0.7	0.5	0.5	0.5

*Includes trees and understory.

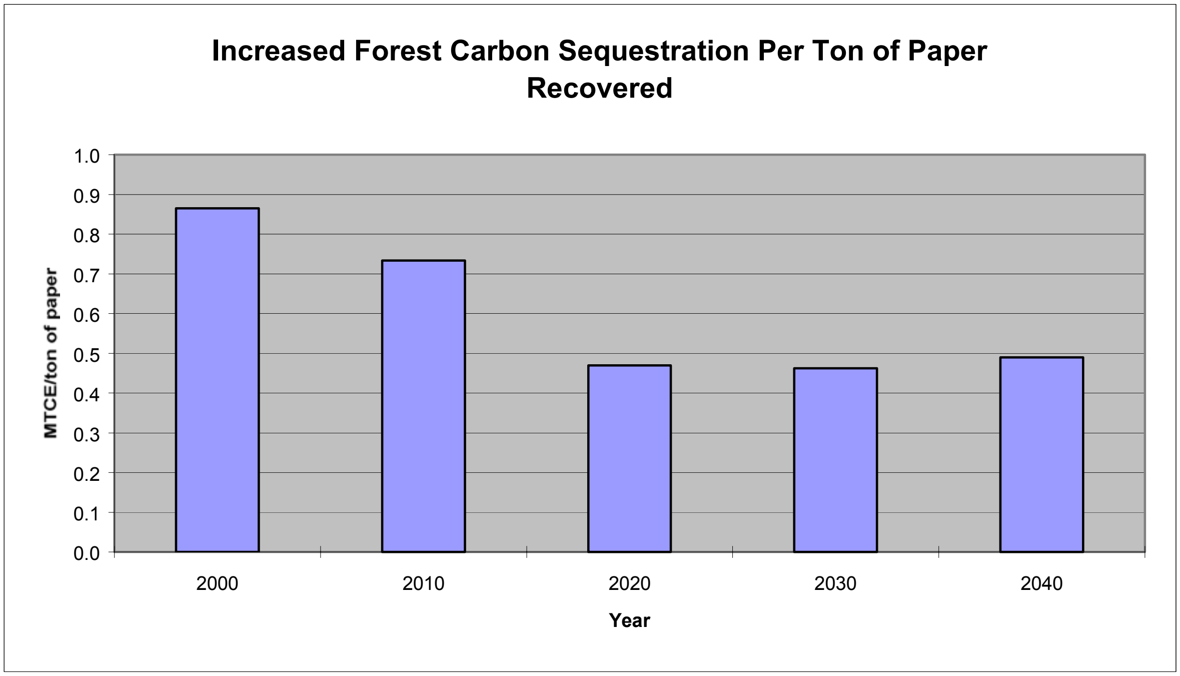

Exhibit 3-9
Forest Carbon Sequestration Per Ton of Paper Product Recycled or Source Reduced

(a) Material	(b) Recycling, Recovering 1 Incremental Ton of Paper (MTCE)	(c) Source Reduction, Assuming Displacement of 1 Ton of Paper Made from the Virgin Inputs (MTCE)	(d) Percent Virgin Inputs in the Current Mix of Inputs	(e) (e = b * d) Source Reduction, Assuming Displacement of One Ton of Paper Made From the Current Mix of Virgin and Recycled Inputs (MTCE)
Corrugated Cardboard	0.73	0.73	41%	-0.30
Magazines/ Third-class Mail	0.73	0.73	84%	-0.61
Newspaper	0.73	0.73	49%	-0.36
Office Paper	0.73	0.73	67%	-0.49
Phonebooks	0.73	0.73	89%	-0.66
Textbooks	0.73	0.73	87%	-0.64

Exhibit 3-10 displays the results of the analysis for dimensional lumber and medium-density fiberboard (the results are the same for both of these wood products). As shown in the top of the exhibit, the ratio of carbon stored per ton of reduced harvest is 0.99 MTCE/metric ton wood for 2010. Using the system efficiencies for wood products conversion rates and expressing emission factors in MTCE per short ton, the effects on the forest pool as of 2010 are the following:

- Recycling: 0.79 MTCE/ton
- Source reduction: 0.98 MTCE/ton

As noted earlier, recycling and source reduction would reduce the amount of carbon in the wood products pool; this effect is shown in the middle section of Exhibit 3-10. The bottom section shows the effect of summing the increase in forest carbon and the decrease in product pool carbon. Using 2010 as the most relevant period, the results are the following:

- Recycling: 0.69 MTCE/ton
- Source reduction: 0.50 MTCE/ton

Recycling has higher net carbon storage. Although it has a lower rate of forest carbon sequestration than source reduction, it also has a much smaller decrement in carbon storage in the product pool.

Exhibit 3-10
Increase in Forest Carbon per Unit Change in Harvest

Emission factor -- increase in forest carbon (trees + understory) per unit change in harvest
Based on density and carbon content of softwoods in Southeast & South Central Region, Pine Forest Type

	2000	2010	2020	2030	2040
Per ton reduced wood harvest (MT/MT)	0.96	0.99	0.99	0.99	0.97
Per ton reduced carbon harvest (MT/MT)	1.81	1.86	1.87	1.86	1.83
Per ton increased recycling (MT/short ton)	0.77	0.79	0.79	0.79	0.78
Per ton reduced prodn of solid wood product (source reduction) (MT/short ton)	0.96	0.98	0.99	0.98	0.97

Emission factor -- change in product pool carbon per unit change in recycling or source
Based on carbon content of softwoods in Southeast & South Central Region, Pine Forest Type

	2000	2010	2020	2030	2040
Per ton increased recycling (MT/short ton)	-0.10	-0.10	-0.10	-0.10	-0.10
Per ton reduced prodn of solid wood product (source reduction) (MT/short ton)	-0.48	-0.48	-0.48	-0.48	-0.48

Emission factor -- increase in forest + product pool carbon per unit change in recycling or
Based on carbon content of softwoods in Southeast & South Central Region, Pine Forest Type

	2000	2010	2020	2030	2040
Per ton increased recycling (MT/short ton)	0.67	0.69	0.70	0.69	0.68
Per ton reduced prodn of solid wood product (source reduction) (MT/short ton)	0.48	0.50	0.51	0.50	0.49

3.8 LIMITATIONS

Any analysis based on a complex system of models is subject to the limitations introduced by each model in the system. The limitations of each component model derive from (1) the assumptions made in developing the model; (2) the input equations used in the model; and (3) the potential impact of factors not included in the model. Because of these limitations, the actual behavior of markets for paper, wood, and other forest products (and the actual choices made by owners of private forestland) could differ from those predicted by the system of forest models. We believe that most of these limitations would tend to bias estimates under the baseline and high recycling scenarios in the same direction, so that the estimated *differences* between the two scenarios should be relatively accurate. Some limitations could result in unequal bias in the estimates, however, leading to biased estimates of the differences.

This section first discusses limitations associated with the geographic scope of the analysis. Secondly, we discuss limitations that could bias the estimates. Limitations that could bias both scenarios in the same direction are listed next. This section concludes with a brief discussion of the uncertainties introduced by the choice of a time period over which incremental forest carbon sequestration is estimated.

3.8.1 Limitations of Geographic Scope of Analysis and Results

Although the goal of this analysis is to estimate the impact of paper recycling and source reduction on GHG emissions in the *United States*, the actual effects would occur in Canada and other countries as well.

- The USDA-FS models treat forest product markets in the United States and Canada as a single integrated economic and biological system. But they do not treat Canadian forest inventories in the same way and degree of detail as U.S. forest inventories. The estimated impacts of increases in recycling and source reduction were treated as impacts on U.S. forests. Because much of the economically marginal paper production is from Canadian pulp sources, source reduction, in particular, would lower demand for Canadian timber. In any case, U.S. and Canadian forests actually would share the effects.
- More than 20 percent of the paper currently recovered in the two countries is exported. Some proportion of the increased amounts of recycled paper—probably more than 20 percent—would undoubtedly be exported. Current exports comprise 43 percent of the world trade in recovered paper. The major buyers of this paper are developing countries in Asia and Latin America, with Korea, Taiwan, and Mexico being major destinations. The alternative sources of fiber for the paper industry in these countries are pulp and fiber from non-forest sources (agricultural refuse, hemp, bamboo, and rubber and palm oil trees). Very little comes from forest harvests. Forests in these countries, however, are not necessarily managed on a sustainable basis. It is difficult to determine which of these effects would dominate—displacement of non-forest fiber (with no forest carbon impact) or displacement of unsustainably managed forest fiber (with a benefit larger than that in U.S. forests).[27]
- NAPAP does not account for any effects of lower pulpwood prices (due to higher paper recycling rates) on net exports of U.S. pulpwood to non-Canadian markets. Lower pulpwood prices would be expected to result in increased exports and possibly changes in foreign timber inventories. Though U.S. pulpwood exports are currently less than 1 percent of U.S. pulpwood production, some virgin pulp fiber is now being exported from southern and western ports in the form of pulp chips. The future potential for pulp chip exports is difficult to estimate.
- The competition to U.S. and Canadian exports of both recovered and newly manufactured paper is likely to come from two sources. First, all other developed countries are also likely to intensify recycling and source reduction programs, with additional recovery of paper fiber. Second, a major developing source of fiber for paper is the establishment of intensive forest plantations in tropical and southern hemisphere countries, particularly Australia, Brazil, Chile, Indonesia, New Zealand, and South Africa. The effect of additional world sources of paper fiber from developed countries on these forest plantation programs is difficult to estimate.

3.8.2 Limitations Expected to Bias the Results

Two limitations in the system of forest sector models could result in biased estimates of the incremental forest carbon sequestration from increased paper recycling. The limitations are as follows:

- The modeling system does not account for any conversion of U.S. forestland to farmland or rangeland that might occur in response to lower prices for pulpwood due to higher paper recycling rates. The NAPAP model does not account for potential changes in timber inventory in the near term due to lower harvests associated with higher paper recovery. Nor does it account for potential changes in forest acreage in the longer term if higher paper recovery depresses pulpwood prices enough to induce landowners to convert forested acreage

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[27] A comprehensive description of the world paper industry, its fiber sources, and environmental concerns can be found in International Institute for Environment and Development (IIED), 1996, *Towards a Sustainable Paper Cycle,* IIED: London, 258 pp. This study, prepared for the World Business Council for Sustainable Development, treats many of the issues covered in this chapter, but on a global basis.

to other uses. The TAMM and ATLAS models likewise do not allow for long-term changes in forested acreage due to increased paper recovery. These effects, however, may be small. Converting forestland to agriculture or to industrial, commercial, or residential uses is far more likely to result from much higher land values for crops or development, if the land is suitable or in a favorable location.

- This analysis did not consider carbon storage in forest soils and forest floors, because of the high level of uncertainty in projecting changes in carbon storage. Nonetheless, projections of carbon storage in forest soils and floors under the baseline and high recycling scenarios, as generated by the FORCARB model, suggest that incremental carbon storage under the high recycling scenario could be slightly higher than shown here, if storage in soils and the forest floor were included.

3.8.3 Limitations Not Expected to Bias the Results

We expect that several limitations in the system of forest models would bias—to about the same extent—the estimates of forest carbon sequestration in the baseline and high recycling scenarios. The limitations thus would not result in significant bias in the estimate of the *difference* in forest carbon sequestration between the two scenarios. These limitations are as follows:

- The macroeconomic forecasts used in the models (e.g., for population growth and growth in per-capita gross domestic product) are simply forecasts, and may turn out to be inaccurate;
- The historical supply and demand functions used in the models may change in the future. For example, (1) demand for newspaper may drop sharply due to competition from electronic news media, or (2) improved technologies or tree diseases not anticipated in the models may significantly change the cost of producing forest products; and
- Future harvests from public forestland may be different from those projected.

3.8.4 The Use of a Point Estimate for Forest Carbon Sequestration

As shown in Exhibit 3-8, estimates of forest carbon sequestration due to increased paper recycling vary over time. As noted above, in choosing a single point estimate, we selected the time period that best balances the competing criteria of (1) capturing the long-term forest carbon sequestration effects, and (2) limiting the uncertainty inherent in projections made well into the future. The range of forest carbon sequestration estimates over time, and the limitations of the analysis discussed above, indicate that there is considerable uncertainty in the point estimate selected. In comparison to the estimates of other types of GHG emissions and sinks developed in other parts of this analysis, the magnitude of forest carbon sequestration is relatively high. Based on these forest carbon sequestration estimates, source reduction and recycling of paper are found to have substantial net GHG reductions. Because paper products comprise the largest share of municipal waste generation (and the largest volumes of waste managed through recycling, landfilling, and combustion), it is important to bear in mind the uncertainty in the forest carbon sequestration values when evaluating the results of this report.

4. SOURCE REDUCTION AND RECYCLING

This chapter presents estimates of GHG emissions and carbon sequestration resulting from source reduction and recycling of 15 manufactured materials: aluminum cans, steel cans, glass containers, plastic containers (LDPE, HDPE, and PET), corrugated boxes, magazines/third-class mail, newspaper, office paper, phonebooks, textbooks, dimensional lumber, medium-density fiberboard, and mixed paper.

To estimate GHG emissions associated with source reduction and recycling (and other MSW management options), we 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 Chapter 3).

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

4.1 GHG IMPLICATIONS OF SOURCE REDUCTION

When a material is source reduced (i.e., less of the material is made), the GHG emissions associated with making the material and managing the post-consumer 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 for paper products (also treated as negative emissions, as estimated in Chapter 3); and (3) zero waste management GHG emissions. Exhibit 4-1 presents the GHG implications of source reduction. The values for forest carbon sequestration were copied from Exhibit 3-8.

In order to compare source reduction to other solid waste management alternatives, we 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 policy makers 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 (post-consumer) 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.

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[1] In this analysis, the values reported for source reduction apply to material lightweighting or extension of a product's useful life. We assume no substitution by another material or product, and thus we assume 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 4.3 below.

Exhibit 4-1
GHG Emissions for Source Reduction
(MTCE/Ton of Material Source Reduced)

	Avoided GHG Emissions from Raw Materials Acquistion and Manufacturing			Changes in Forest Carbon Storage		Net Emissions	Net Emissions
Material	For Current Mix of Inputs	For 100% Virgin Inputs	Post-consumer	For Current Mix of Inputs	For 100% Virgin Inputs	For Current Mix of Inputs	For 100% Virgin Inputs
Aluminum Cans	-2.49	-4.67	0.00	0.00	0.00	-2.49	-4.67
Steel Cans	-0.79	-1.01	0.00	0.00	0.00	-0.79	-1.01
Glass	-0.14	-0.16	0.00	0.00	0.00	-0.14	-0.16
HDPE	-0.49	-0.53	0.00	0.00	0.00	-0.49	-0.53
LDPE	-0.61	-0.64	0.00	0.00	0.00	-0.61	-0.64
PET	-0.49	-0.58	0.00	0.00	0.00	-0.49	-0.58
Corrugated Cardboard	-0.24	-0.22	0.00	-0.28	-0.73	-0.51	-0.96
Magazines/Third-class Mail	-0.46	-0.46	0.00	-0.58	-0.73	-1.04	-1.19
Newspaper	-0.46	-0.59	0.00	-0.35	-0.73	-0.81	-1.32
Office Paper	-0.31	-0.28	0.00	-0.50	-0.73	-0.80	-1.01
Phonebooks	-0.64	-0.67	0.00	-0.65	-0.73	-1.28	-1.40
Textbooks	-0.59	-0.59	0.00	-0.64	-0.73	-1.23	-1.32
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
Mixed Paper							
Broad Definition	NA	NA	NA	NA	NA	NA	NA
Residential Definition	NA	NA	NA	NA	NA	NA	NA
Office Paper Definition	NA	NA	NA	NA	NA	NA	NA
Mixed MSW	NA	NA	NA	NA	NA	NA	NA

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

4.2 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, several paper types are recycled in an open loop (i.e., they are recycled into more than one product) under the general heading of mixed paper.[3] 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, we 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 4-2. 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, catalogs, commercial printing, folding cartons, and a small amount of old corrugated containers. Mixed paper as characterized by the broad and residential definitions can be remanufactured via an open loop into recycled boxboard. Mixed paper from offices is typically used to manufacture commercial paper towels.

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 materials. Material losses are quantified and translated into loss rates. In this analysis, we used estimates of loss rates provided by Franklin Associates, Ltd. (FAL) for steel, dimensional lumber, and medium-density fiberboard (the same materials for which we used FAL's energy data, as described in Chapter 2). EPA's Office of Research and Development (ORD) provided loss rates for the other materials. These values are shown in Exhibit 4-3.

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.

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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. We made a preliminary estimate of the GHG emissions from paper sludge managed in landfills; our 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.

Exhibit 4-2
Summary of Mixed Paper Scenarios
(Composition as a percentage of total)

Paper Grade	**All Paper and Paperboard in MSW (1)**	**Mixed Paper: Broad Definition (2)**	**Mixed Paper: Offices (3)**	**Mixed Paper: Single-Family Residential (4)**
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%

(1) All grades of paper and paperboard in MSW.
(2) Excludes newspaper, old corrugated containers, tissue produce, paper plates and cups, converting and special industrial papers, non-packaging paperboard such as album covers and posterboard, and paper labels.
(3) Includes the high-grade papers (ledger and computer printout) as well as stationery, mail, magazines, and manila folders. Could be recovered as "File Stock."
(4) 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.

Exhibit 4-3
Loss Rates For Recovered Materials

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

* FAL provided data for column (c), while ORD provided data for column (d).

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.”

The results of our analysis are shown in Exhibit 4-4. In this exhibit, for each material we present the differences between manufacture from virgin and recycled inputs for (1) energy-related GHG emissions (both in manufacturing processes and transportation), (2) process non-energy-related GHG emissions, and (3) forest carbon sequestration. Our method of accounting for loss rates yields estimates of GHG emissions on the basis of metric tons of carbon equivalent (MTCE) per short ton of material *collected for recycling* (rather than emissions per ton of material *made with recycled inputs*).

We recognize that some readers may find it more useful to evaluate recycling in terms of tons of recyclables *as marketed* rather than tons of materials *collected*. To adjust the emission factors reported in Exhibit 4-4 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 4-3 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]

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[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).

$T_{recyc} = T_{prod}*(RC_p-RC_i)/L$, 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 4-3, 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.

In order to compare GHG emissions from recycling to those attributable to another solid waste management option such as landfilling, we 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 non-energy GHG emissions, recycling has lower GHG emissions than all other waste management options except for source reduction.

4.3 SOURCE REDUCTION WITH MATERIAL SUBSTITUTION

As noted above, our 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.

4.4 LIMITATIONS

Because the data presented in this chapter were developed earlier in Chapters 2 and 3, the limitations discussed in those chapters also apply to the values presented here. Five 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, we did not include them in our estimates. We did perform a screening analysis for paper sludge, however, based on (1) data on sludge generation rates and sludge composition (i.e., percentage of cellulose, hemicellulose, lignin, etc. in sludge),[5] 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. Our 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 non-energy 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 our 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 our 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, we assumed that increased recycling does not change overall demand for products. In other words, we 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.

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

Exhibit 4-4
GHG Emissions for Recycling
(MTCE/Ton of Material Recovered)

(a) Material	(b) Recycled Input Credit*: Process Energy	(c) Recycled Input Credit*: Transportation Energy	(d) Recycled Input Credit*: Process Non-Energy	(e) Forest Carbon Sequestration	(f) (f = b + c + d + e) GHG Reductions From Using Recycled Inputs Instead of Virgin Inputs
Aluminum Cans	-2.92	-0.14	-1.05	0.00	-4.11
Steel Cans	-0.48	-0.01	0.00	0.00	-0.49
Glass	-0.03	0.00	-0.04	0.00	-0.08
HDPE	-0.34	0.00	-0.04	0.00	-0.38
LDPE	-0.43	0.00	-0.04	0.00	-0.47
PET	-0.40	0.00	-0.02	0.00	-0.42
Corrugated Cardboard	0.04	-0.01	0.00	-0.73	-0.71
Magazines/Third-class Mail	0.00	0.00	0.00	-0.73	-0.74
Newspaper	-0.21	-0.01	0.00	-0.73	-0.95
Office Paper	0.06	0.00	0.00	-0.73	-0.68
Phonebooks	-0.18	0.00	0.00	-0.73	-0.91
Textbooks	-0.01	0.00	0.00	-0.73	-0.75
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	0.08	-0.02	0.00	-0.73	-0.67
Residential Definition	0.08	-0.02	0.00	-0.73	-0.67
Office Paper Definition	-0.08	-0.02	0.00	-0.73	-0.83

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

*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 a weighted average of closed- and open-loop recycling for mixed paper. All other estimates are for closed-loop recycling.

Explanatory notes for Exhibit 4-4: 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% virgin inputs and from 100% 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. We first estimated the values in columns “b” and “c” based on data provided by FAL and ORD, as shown in Exhibits 2-2 through 2-5. 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 differemce 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 non-energy GHG emissions from recycling, we used (1) data showing the difference in process non-energy GHG emissions between making 1 ton of the material from 100% virgin inputs and from 100% recycled inputs (as shown in the second-to-last column of Exhibits 2-2 and 2-4) 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 Chapter 3. The last column (column “f”) sums columns “b” through “e” to show the GHG implications of recycling each material.

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5. COMPOSTING

This chapter has been extensively revised since the first edition of this report. The revised chapter presents the results of an in-depth analysis to determine the net GHG impacts of composting yard trimmings and food discards. As research in the areas of erosion control, soil fertility, and bio-based products continues, we are likely to uncover additional GHG and other benefits of composting.

This chapter presents estimates of GHG emissions and sinks from composting yard trimmings and food discards.[1] The chapter is organized as follows:

Section 5.1 presents an estimate of potential CO_2 and CH_4 emissions from composting;

Section 5.2 quantifies the potential carbon storage benefits of applying compost to soils;

Section 5.3 presents net GHG emissions from composting; and

Section 5.4 discusses the limitations of this analysis.

Composting may result in (1) CH_4 emissions from anaerobic decomposition; (2) long-term carbon storage in the form of undecomposed carbon compounds; and (3) non-biogenic CO_2 emissions from collection and transportation of the organic materials to the central composting site, and from mechanical turning of the compost pile.[2] Composting also results in biogenic CO_2 emissions associated with decomposition, both during the composting process and after the compost is added to the soil. Because this CO_2 is biogenic in origin, however, it is not counted as a GHG in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*[3] (as explained in Section 1.4.2) and is not included in our accounting of emissions and sinks.

Our analysis suggests that composting, when managed properly, does not generate CH_4 emissions, but it does result in some carbon storage (associated with application of compost to soils), as well as minimal CO_2 emissions from transportation and mechanical turning of the compost piles. In order to maintain consistency with other chapters in this report, we selected point estimates from the range of emission factors—covering various compost application rates and time periods—developed in our analysis. The point estimates were chosen based on a "typical" compost application rate of 20 tons of compost per acre, averaged over three soil-crop scenarios. In terms of timing, the carbon storage values for the year 2010 were selected to be consistent with forest carbon storage estimates presented in Chapter 4 of this report. Overall, we estimate that centralized composting of organics results in net GHG storage of 0.05 MTCE/wet ton of organic inputs composted and applied to agricultural soil.

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[1] Although paper and mixed MSW can be composted, we did not analyze the GHG implications of composting them because of time and resource constraints.

[2] CO_2 emissions from delivery of compost to its final destination were not counted because compost is a marketable product, and CO_2 emissions from transportation of other marketable, finished goods to consumers have not been counted in other parts of this analysis.

[3] U.S. EPA. 2001. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*. U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC. EPA-236-R-01-001.

5.1 POTENTIAL GREENHOUSE GAS EMISSIONS

Two potential types of GHG emissions are associated with composting: (1) CH_4 from anaerobic decomposition; and (2) non-biogenic CO_2 from transportation of compostable materials, and turning of the compost piles.

5.1.1 CH_4

To research the issue of CH_4 emissions, we first conducted a literature search for articles on CH_4 generation from composting. We found very few articles specifically addressing CH_4 emissions from composting published between 1991 and 1999,[4] and thus decided not to continue searching for earlier articles. Because CH_4 emissions from composting are addressed only occasionally in the literature, we contacted several composting experts from universities and the U.S. Department of Agriculture to discuss the potential for CH_4 generation, based on the nature of carbon flows during composting. Our CH_4 analysis is based on their expert opinions.

The researchers we contacted stated that well-managed compost operations usually do not generate CH_4 because they typically maintain an aerobic environment with proper moisture content to encourage aerobic decomposition of the materials. The researchers also noted that even if CH_4 is generated in anaerobic pockets in the center of the compost pile, the CH_4 is most likely oxidized when it reaches the oxygen-rich surface of the pile, where it is converted to CO_2. Several of the researchers commented that anaerobic pockets are most apt to develop when too much water is added to the compost pile. They noted that this problem rarely occurs because compost piles are much more likely to be watered too little rather than too much.

We concluded from the available information that CH_4 generation from centralized compost piles is essentially zero.

5.1.2 CO_2 from Transportation of Materials and Turning of Compost

This study estimated the indirect CO_2 emissions associated with collecting and transporting organics to centralized compost facilities, and turning the compost piles. We began with estimates developed by Franklin Associates, Ltd. (FAL) for the amount of diesel fuel required to (1) collect and transport 1 ton of organics[5] to a central composting facility (363,000 Btu) and (2) turn the compost pile (221,000 Btu).[6] We converted these estimates to units of metric tons of carbon equivalent (MTCE) per ton of organics, based on a carbon coefficient of 0.02 MTCE per million Btu of diesel fuel. This resulted in an estimate of 0.01 MTCE of indirect CO_2 emissions per ton of material composted in a centralized facility.

5.2 POTENTIAL CARBON STORAGE

We also evaluated the effect of compost application on soil carbon storage. We did not find information on carbon storage associated with compost derived specifically from yard trimmings or food discards. Nevertheless, it is reasonable to expect that these materials are basically homogeneous with respect to the fate of their stored carbon, even though their initial moisture and carbon content differs.

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[4] Among the papers with pertinent information is that of H.J. Hellebrand, 1998, *Emission of Nitrous Oxide and other Trace Gases during Composting of Grass and Green Waste,* J. Agric. Engineering Research 69:365-375.

[5] Measured on a wet weight basis, as MSW is typically measured.

[6] Franklin Associates, Ltd. 1994. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful), pp. I-27, 30, and 31.

To develop carbon storage estimates for composted organics, we researched the processes that affect soil carbon storage, reviewed the results of experiments on the soil carbon impacts of applying organic amendments (e.g., compost, manure, biosolids, and crop residues), and interviewed experts on the potential carbon storage benefits of composting organics as compared to other methods of disposal. During this process, four hypotheses were proposed regarding the benefits of applying organics compost to soil:

1. Many soils have been depleted in organic matter through cultivation and other practices. Adding compost can raise soil carbon levels by increasing organic matter inputs. Soils degraded by intensive crop production, construction, mining, and other activities lose organic matter when decomposition rates and removals of carbon in harvests exceed the rate of new inputs of organic materials. Adding compost shifts the balance so that soil organic carbon levels are restored to higher levels. Some of the compost carbon is retained by the system.
2. Nitrogen in compost can stimulate higher productivity, thus generating more crop residues. This "fertilization effect" would increase soil carbon due to the larger volume of crop residues, which serve as organic matter inputs.
3. The composting process leads to increased formation of stable carbon compounds (e.g., humic substances, aggregates) that then can be stored in the soil for long (>50 years) periods of time. Humic substances comprise 60-80 percent of soil organic matter and are made up of complex compounds that render them resistant to microbial attack.[7] In addition to humic substances, soil organic carbon may be held in aggregates (i.e., stable organo-mineral complexes in which carbon is bonded with clay colloids and metallic elements) and protected against microbial attack.[8]
4. The application of compost produces a multiplier effect by qualitatively changing the dynamics of the carbon cycling system and increasing the retention of carbon from non-compost sources. Some studies of other compost feedstocks (e.g., farmyard manure, legumes) have indicated that the addition of organic matter to soil plots can increase the potential for storage of soil organic carbon. The carbon increase apparently comes not only from the organic matter directly, but also from retention of a higher proportion of carbon from residues of crops grown on the soil. This multiplier effect could enable compost to increase carbon storage by more than its own direct contribution to carbon mass accumulation.

Our research efforts did not yield any primary data that could be used to develop quantitative estimates of the soil carbon storage benefits of compost. Therefore, we developed modeling approaches to investigate the possible effects of compost application on soil carbon storage. Section 5.2.2 describes application of the CENTURY model to quantify soil carbon restoration and nitrogen fertilization associated with compost application to carbon-depleted soils. We conducted a bounding analysis, described in Section 5.2.6, to address the third hypothesis, incremental humus formation. Although several of the experts we spoke with cited persuasive qualitative evidence of the existence of a multiplier effect, we were unable to develop an approach to quantify this process. In that sense, our carbon storage estimates are likely to be conservative (i.e., understate carbon storage rates), at least for soils with high silt and/or clay content where this process is most likely to apply.

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[7] N. Brady and R. Weil. 1999. *The Nature and Properties of Soils* (Upper Saddle River, NJ: Prentice Hall).

[8] R. Lal et al. 1998. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, MI: Sleeping Bear Press, Inc).

Our analyses of soil carbon restoration, nitrogen fertilization, and incremental humus formation apply relatively simple models of very complex processes. These processes probably are controlled by a number of biological, physicochemical, and compost management factors, such as application (i.e., silviculture, horticulture, agriculture, and landscaping); application rate; regional and local climatic factors; soil type; and, to a lesser extent, compost feedstock (e.g., grass, leaves, branches, yard trimmings, food discards). In addition, the results are time-dependent, so the year in which benefits are assessed has an effect on the magnitude of carbon storage.

Note that the framework used here describes the soil carbon benefits of composting relative to landfilling and combustion. In all three management methods, yard trimmings are collected and removed from soils in residential or commercial settings. This removal may result in some loss of organic carbon from the "home soil." An estimate of the "absolute" soil carbon storage value would net out whatever loss occurs due to the removal of the yard trimmings. This effect is probably a negligible one, however, and we were unable to find empirical data on it. Because the decrement in carbon in "home soil" applies equally to all three management practices, and emission factors are intended to be viewed relative to other management practices (see Chapter 8), neglecting the carbon loss from the home soil does not compromise the validity of the results.

5.2.1 Modeling Soil Carbon Restoration and Nitrogen Fertilization

As mentioned above, this analysis included an extensive literature review and interviews with experts to consider whether the application of compost leads to long-term storage of carbon in soils. After determining that neither the literature review nor discussions with experts would yield a basis for a quantitative estimate of soil carbon storage, we evaluated the feasibility of a simulation modeling approach. We initially identified two simulation models with the potential to be applied to the issue of soil carbon storage from compost application: CENTURY[9] and the Rothamsted C (ROTHC-26.3)[10] model. Both are peer-reviewed models whose structure and application have been described in scores of publications. They share several features:

- Ability to run multi-year simulations;
- Capability to construct multiple scenarios covering various climate and soil conditions and loading rates; and
- Ability to handle interaction of several soil processes, environmental factors, and management scenarios such as carbon: nitrogen (C:N) ratios, aggregate formation, soil texture (e.g., clay content), and cropping regime.

Given the extensive application of CENTURY in the United States, its availability on the Internet, and its ability to address many of the processes important to compost application, we decided to use CENTURY rather than ROTHC-26.3.

5.2.2 CENTURY Model Framework

CENTURY is a Fortran model of plant-soil ecosystems that simulates long-term dynamics of carbon, nitrogen, phosphorus, and sulfur. It tracks the movement of carbon through soil pools—active, slow, and passive—and can show changes in carbon levels due to the addition of compost.

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[9] Metherell, A., L. Harding, C. Cole, W. Parton. 1993. CENTURY Agroecosystem Version 4.0, Great Plains System Research Unit Technical Report No. 4, USDA-ARS Global Climate Change Research Program, (Colorado State University: Fort Collins, CO).

[10] This model was developed based on long-term observations of soil carbon at Rothamsted, an estate in the United Kingdom where organic amendments have been added to soils since the 19th century.

In addition to soil organic matter pools, carbon can be found in surface (microbial) pools and in above- and below-ground litter pools. The above-ground and below-ground litter pools are divided into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. Carbon additions to the system flow through the various pools and can exit the system (e.g., as CO_2, dissolved carbon, or through crop removals).

The above-ground and below-ground litter pools are split into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. The active pool of soil organic matter includes living biomass, some of the fine particulate detritus,[11] most of the non-humic material, and some of the more easily decomposed fulvic acids. The active pool is estimated to have a mean residence time (MRT)[12] of a few months to 10 years.[13] The slow pool includes resistant plant material (i.e., high lignin content) derived from the structural pool and other slowly decomposable and chemically resistant components. It has an MRT of 15-100 years.[14] The passive pool of soil organic matter includes very stable materials remaining in the soil for hundreds to thousands of years.[15]

CENTURY does not simulate increased formation of humic substances associated with organic matter additions, nor does it allow for organic matter additions with high humus content to increase the magnitude of the passive pool directly. (Because CENTURY does not account for these processes, we developed a separate analysis, described in Section 5.2.6.)

CENTURY contains a submodel to simulate soil organic matter pools. Additional submodels address nitrogen, phosphorus, sulfur, the water budget, leaching, soil temperature, and plant production, as well as individual submodels for various ecosystems (e.g., grassland, cropland). The nitrogen submodel addresses inputs of fertilizer and other sources of nitrogen, mineralization of organic nitrogen, and uptake of nitrogen by plants.

5.2.3 Inputs

The CENTURY model simulates the long-term dynamics of various plant-soil ecosystems (e.g., grassland, agricultural land, forest, and savanna). The model uses a series of input files to specify modeling conditions: Crop, Harvest, Fertilization, Cultivation, Organic Matter Addition, Irrigation, Grazing, Fire, Tree Type, Tree Removal, Site, and Weather Statistics. A schedule file is used to specify the timing of events.

For this analysis, we developed a basic agricultural scenario where land was converted from prairie to farmland (growing corn) in 1921 and remains growing corn through 2030. We then evaluated more than 30 scenarios to examine the effect of several variables on soil carbon storage:

- Compost application rate and frequency;

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[11] Detritus refers to debris from dead plants and animals.

[12] The term "mean residence time (MRT)" is used interchangeably with "turnover time" and is the average time in which a unit (e.g., a carbon atom) resides within a "state" where there is both an input and an output. MRT is only strictly defined at steady-state (i.e., inputs = outputs), but as most soils systems have a continuing input of carbon and an approximately equal output through decomposition and transfer to other pools, MRT is often used to describe carbon dynamics in soils. Mathematically, it is the ratio of (a) mass in the pool to (b) throughput of carbon. For example, if a given carbon pool has a mass of 1,000 kg and the inflow is 1 kg/yr, the MRT is 1,000 kg / (1 kg/yr) = 1,000 yr.

[13] Metherell et al. 1993, Brady and Weil 1999.

[14] *Ibid.*

[15] *Ibid.*

- Site characteristics (rainfall, soil type, irrigation regime);
- Fertilization rate; and
- Crop residue management.

Compost application rates were adjusted using the organic matter (compost) files for each compost application rate included in our analysis. We compared the effect of applying compost annually for 10 years (1996-2005) at seven different application rates: 1.3, 3.2, 6.5, 10, 15, 20, and 40 wet tons compost/acre (corresponding to 60-1,850 grams of carbon per square meter).[16] We also investigated the effect of compost application frequency on the soil carbon storage rate and total carbon levels. We ran the model to simulate compost applications of 1.3 wet tons compost/acre and 3.2 wet tons compost/acre every year for 10 years (1996-2005) and applications of 1.3 wet tons compost/acre and 3.2 wet tons compost/acre applied every five years (in 1996, 2001, and 2006). The simulated compost was specified as having 33 percent lignin,[17] 17:1 carbon-to-nitrogen (C:N) ratio,[18] 60:1 carbon-to-phosphorus ratio, and 75:1 carbon-to-sulfur ratio.[19] We also ran a scenario with no compost application for each combination of site-fertilization-crop residue management. This scenario allowed us to control for compost application, i.e., to calculate the change in carbon storage attributable only to the addition of compost.

The majority of inputs needed to specify a scenario reside in the site file. The input variables in this file include the following:

- Monthly average maximum and minimum air temperature;
- Monthly precipitation;
- Lignin content of plant material;
- Plant nitrogen, phosphorus, and sulfur content;
- Soil texture;
- Atmospheric and soil nitrogen inputs; and
- Initial soil carbon, nitrogen, phosphorus, and sulfur levels.

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[16] The model requires inputs in terms of the carbon application rate in grams per square meter. The relationship between the carbon application rate and compost application rate depends on three factors: the moisture content of compost, the organic matter content (as a fraction of dry weight), and the carbon content (as a fraction of organic matter). Our inputs are based on values provided by Dr. Harold Keener of Ohio State University, who estimates that compost has a moisture content of 50 percent, an organic matter fraction (as dry weight) of 88 percent, and a carbon content of 48 percent (as a fraction of organic matter). Thus, on a wet weight basis, 21 percent of compost is carbon.

[17] Percent lignin was estimated based on the lignin fractions for grass, leaves, and branches specified by compost experts (particularly Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University, and lignin fractions reported in M.A. Barlaz, "Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale landfills," EPA 600/R-97-071, 1997. FAL provided an estimate of the fraction of grass, leaves, and branches in yard trimmings in a personal communication with ICF Consulting, November 14, 1995. Subsequently, FAL obtained and provided data showing that the composition of yard trimmings varies widely in different states. The percentage composition used here (50 percent grass, 25 percent leaves, and 25 percent branches on a wet weight basis) is within the reported range.

[18] The C:N ratio was taken from Brady and Weil, 1999, *The Nature and Property of Soils: Twelfth Edition*, Prentice Hall.

[19] C:P and C:S ratios were based on the literature and conversations with composting experts, including Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University.

Several sets of detailed site characteristics from past modeling applications are available to users. We chose two settings: an eastern Colorado site with clay loam soil and a southwestern Iowa site with silty clay loam soil. Both settings represent fairly typical Midwestern corn belt situations where agricultural activities have depleted soil organic carbon levels. The Colorado scenario is available as a site file on the CENTURY Web site;[20] Dr. Keith Paustian, an expert in the development and application of CENTURY, provided the specifications for the Iowa site (as well as other input specifications and results for several of the runs described here).

We also varied fertilization rate. As discussed earlier, one of our hypotheses was that the mineralization of nitrogen in compost could stimulate crop growth, leading to production of more organic residues, which in turn would increase soil organic carbon levels. The strength of this effect would vary depending on the availability of other sources of nitrogen. To investigate this hypothesis, we analyzed different rates of synthetic fertilizer addition ranging from zero up to a typical rate to attain average crop yield (90 lbs. N/acre for the Colorado site, 124 lbs. N/per acre for the Iowa site). We also analyzed fertilizer application at half of these typical rates.

Finally, we simulated two harvest regimes, one where the corn is harvested for silage (where 95 percent of the above-ground biomass is removed) and the other where corn is harvested for grain (where the “stover” is left behind to decompose on the field). These simulations enabled us to isolate the effect of the carbon added directly to the system in the form of compost, as opposed to total carbon inputs (which include crop residues).

5.2.4 Outputs

CENTURY is capable of providing a variety of output data, including carbon storage in soils, CO_2 emissions due to microbial respiration, and monthly potential evapotranspiration. The outputs we chose were carbon levels for each of the eight soil pools: structural carbon in surface litter, metabolic carbon in surface litter, structural carbon in soil litter, metabolic carbon in soil litter, surface pool, active pool, slow pool, and passive pool. Our output data cover the period from 1900 through 2030. In general, we focussed on the difference in carbon storage between a baseline scenario, where no compost was applied, and a with-compost scenario. We calculated the delta between the two scenarios to isolate the effect of compost application. Output data in grams of carbon per square meter were converted to MTCE by multiplying by area (in square meters).

To express results in units comparable to those for other sources and sinks, we divided the increase in carbon storage by the short tons of organics required to produce the compost.[21] That is, we express the factors as a carbon storage rate in units of MTCE per wet short ton of organic inputs (not MTCE per short ton of compost).

5.2.5 Results

The carbon storage rate declines with time after initial application. The rate is similar across application rates and frequencies, and across the site conditions we simulated. Exhibit 5-1 displays results for the Colorado and Iowa sites, for the 10-, 20-, and 40-ton per acre application rates. As indicated on the graph, the soil carbon storage rate varies from about 0.08 MTCE per wet ton organics immediately after compost application (in 1997) to about 0.02 MTCE per ton in 2030 (24 years after the last application in 2006).

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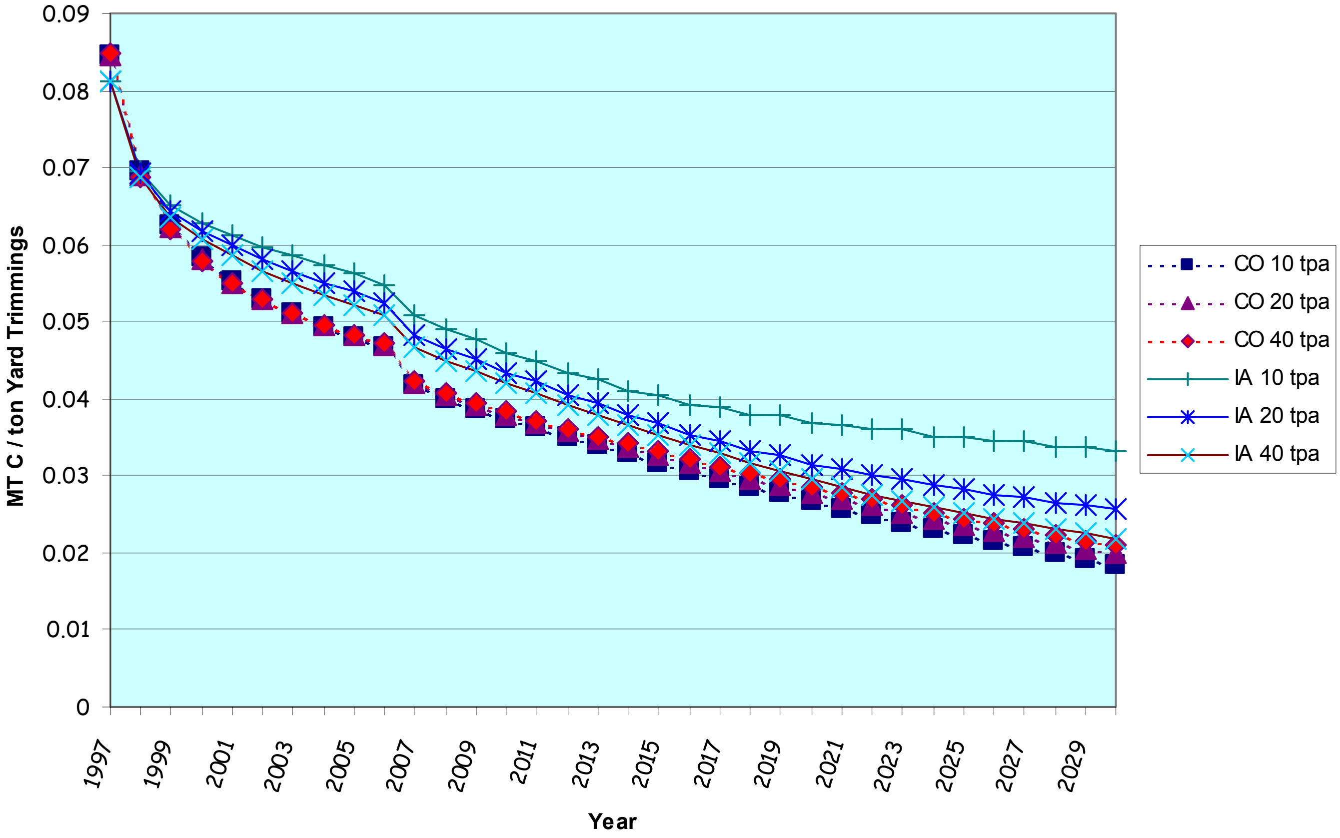
[20] http://www.nrel.colostate.edu/PROGRAMS/MODELING/CENTURY/CENTURY.html

[21] We assume 2.1 tons of yard trimmings are required to generate 1 ton of composted yard trimmings. Thus, to convert the results in this report (in MTCE per wet ton yard trimmings) to MTCE per wet ton of compost, multiply by 2.1. To convert to MTCE per dry ton compost, multiply values in this report by 4.2 (assuming 50 percent moisture content).

Exhibit 5-1 Soil C Storage-CO and IA sites; 10, 20, and 40 tpa application rates



The similarity across the various site conditions and application rates reflects the fact that the dominant process controlling carbon retention is the decomposition of organic materials in the various pools. As simulated by CENTURY, this process is governed by first-order kinetics, i.e., the rate is independent of organic matter concentration or the rate of organic matter additions.

Several secondary effects, however, result in some variation in the carbon storage rate.[22] We had hypothesized that where a crop's demand for nitrogen exceeds its availability from other sources, mineralization of compost nitrogen can stimulate increased productivity. Simulation of this effect showed that where there is a shortage of nitrogen, compost application can result in higher productivity, which translates into higher inputs of crop residues to the soil. These higher inputs in turn increase the carbon storage rate per unit of compost inputs. This effect is a relatively modest one, however.

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[22] In addition to the nitrogen fertilization effect, compost also affects moisture retention in soils, which in turn modifies the water balance relations simulated by CENTURY.

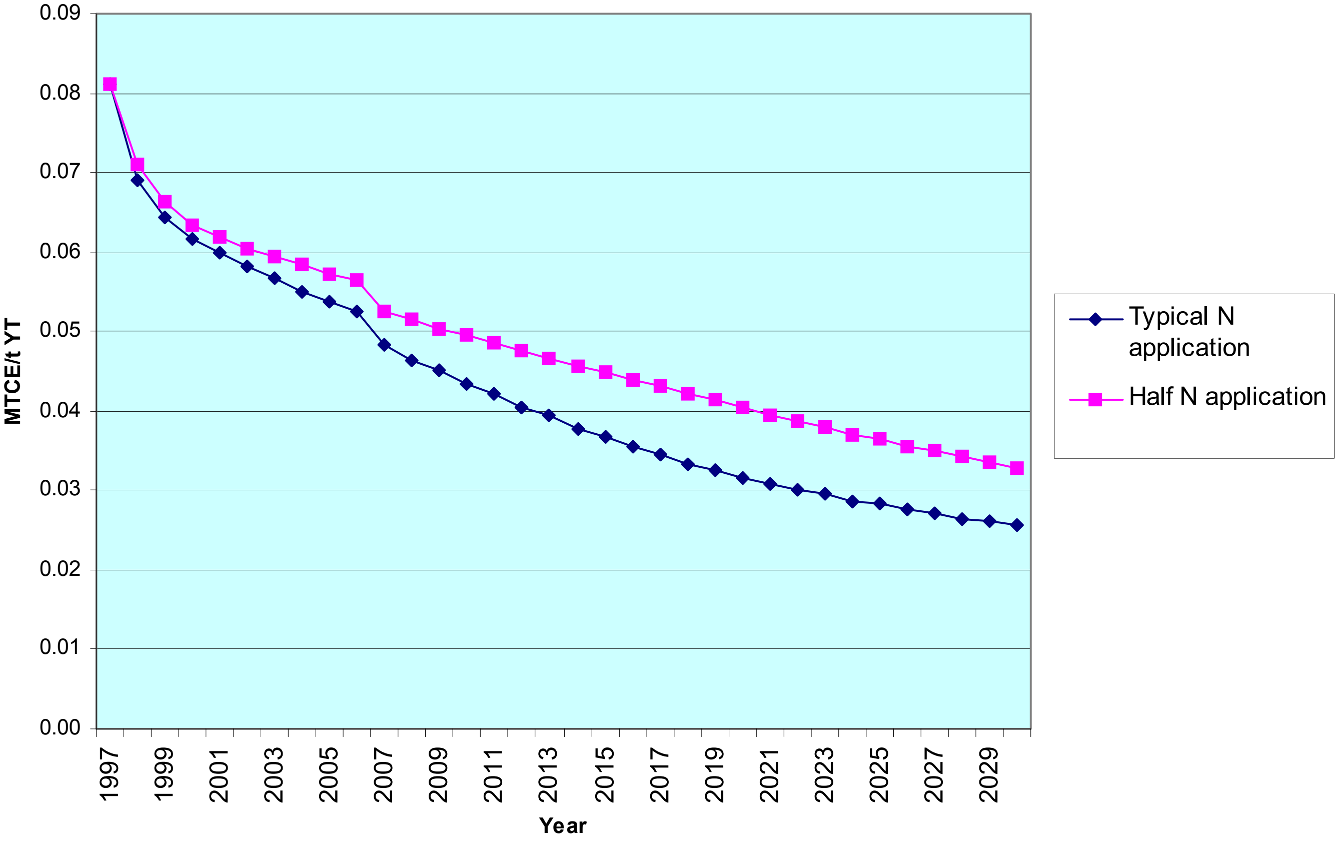
Exhibit 5-2 shows the carbon storage rate for the Iowa site and the effect of nitrogen fertilization. The two curves in the exhibit both represent the difference in carbon storage between (a) a with-compost scenario (20 tons per acre) and (b) a baseline where compost is not applied. The nitrogen application rates differ in the following ways:

- The curve labeled “Typical N application” represents application of 124 lbs. per acre, for both the compost and baseline scenario. Because the nitrogen added via compost has little effect when nitrogen is already in abundant supply, this curve portrays a situation where the carbon storage is attributable solely to the organic matter additions in the compost.
- The curve labeled “Half N application” represents application of 62 lbs. per acre. In this scenario, mineralization of nitrogen added by the compost has an incremental effect on crop productivity compared to the baseline. The difference between the baseline and compost application runs reflects both organic matter added by the compost and additional biomass produced in response to the nitrogen contributed by the compost.

Exhibit 5-2

Incremental Carbon Storage as a function of Nitrogen Application Rate

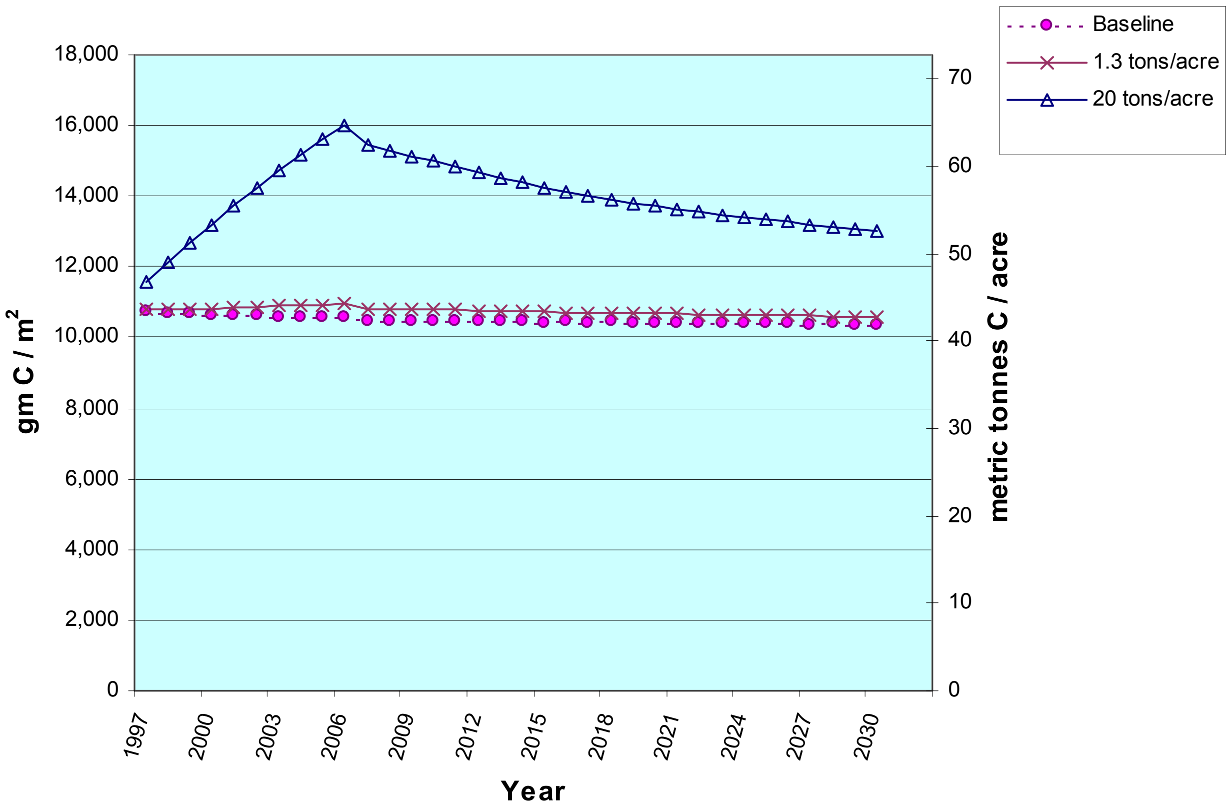
Iowa site, corn harvested for grain



The difference in incremental carbon storage rates between the two fertilization scenarios is less than 0.01 MTCE per ton, indicating that the nitrogen fertilization effect is small. Note that this finding is based on the assumption that farmers applying compost also will apply sufficient synthetic fertilizer to maintain economic crop yields. If this assumption is not well-founded, or in situations where compost is applied as a soil amendment for road construction, landfill cover, or similar situations, the effect would be larger.

When viewed from the perspective of total carbon, rather than as a storage rate per ton of inputs to the composting process, both soil organic carbon concentrations and total carbon stored per acre increase with increasing application rates (see Exhibit 5-3). Soil organic carbon concentrations increase throughout the period of compost application, peak in 2006 (the last year of application), and decline thereafter due to decomposition of the imported carbon. Exhibit 5-3 displays total carbon storage (including baseline carbon) in soils on the order of 40 to 65 metric tons per acre (the range would be higher with higher compost application rates or applications with a longer term).

Exhibit 5-3 Total Soil C
Iowa site, corn harvested for grain



5.2.6 Incremental Humus Formation

The third of the four hypotheses describing the benefits of composting, as compared to alternative management methods, is predicated on incremental formation of stable carbon compounds that can be stored in the soil for long periods of time. CENTURY does not simulate this process, i.e., it does not allow for organic matter additions with high humus content to directly increase the magnitude of the passive pool. Therefore, we used a bounding analysis to estimate the upper and lower limits of the magnitude of this effect. In this analysis, we evaluated the amount of long-term soil carbon storage when organics are composted and applied to soil.

During the process of decomposition, organic materials typically go through a series of steps before finally being converted to CO_2, water, and other reaction products. The intermediate compounds that are formed, and the lifetime of these compounds, can vary widely depending on a number of factors, including the chemical composition of the parent compound. Parent compounds range from readily degradable molecules such as cellulose and hemicellulose to molecules more resistant to degradation, such as lignin, waxes, and tannins.

Composting is designed to promote rapid decomposition of organics, thus reducing their volume. Some evidence suggests that composting produces a greater proportion of humus than that typically formed when organics are left directly on the ground. The conditions in the two phases are different. The heat generated within compost piles favors ‘thermophilic’ (heat-loving) bacteria, which tend to produce a greater proportion of stable, long-chain carbon compounds (e.g., humic substances) than do bacteria and fungi that predominate at ambient soil temperatures.

Increased humus formation associated with compost application is a function of two principal factors:

(1) The fraction of carbon in compost that is considered “passive” (i.e., very stable); and

(2) The rate at which passive carbon is degraded to CO_2.

Estimates for the first factor are based on experimental data compiled by Dr. Michael Cole of the University of Illinois. Dr. Cole found literature values indicating that between 4 and 20 percent of the carbon in finished compost degrades quickly.[23] Dr. Cole averaged the values he found in the literature and estimated that 10 percent of the carbon in compost can be considered “fast” (i.e., readily degradable). The remaining 90 percent of carbon in compost can be classified as either slow or passive. We were not able to locate experimental data that delineates the fractions of slow and passive carbon in compost; therefore, we developed upper and lower bound estimates based on Dr. Cole’s professional judgement. He suggested values of 30 percent slow and 60 percent passive, and 45 percent slow and 45 percent passive for the upper and lower bounds on passive content, respectively.[24]

For the second factor, we chose a mean residence time for passive carbon of 400 years based on the range of values specified in the literature.[25]

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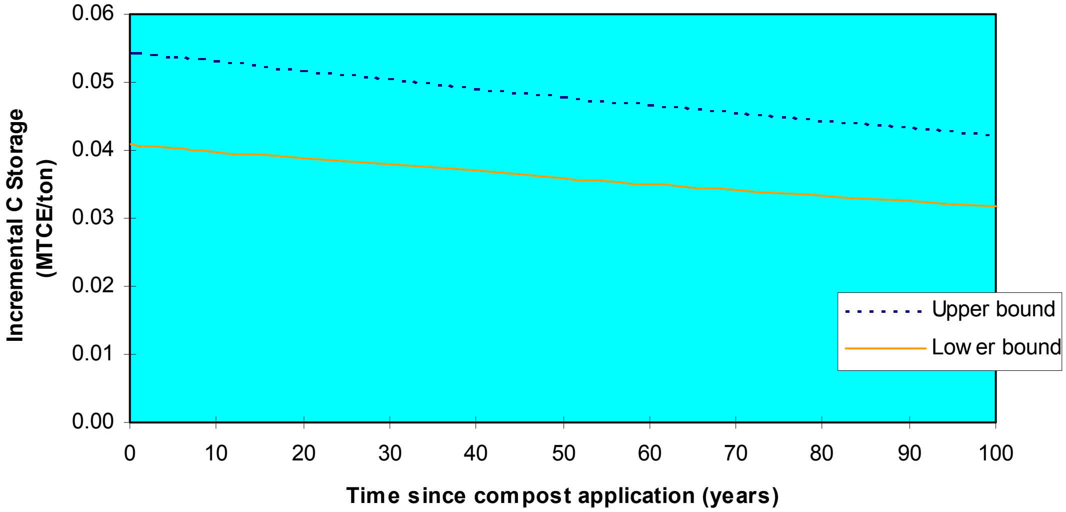
[23] Very little information is available on the characteristics of compost derived from yard trimmings or food discards. However, Dr. Cole found that the composition of composts derived from other materials is broadly consistent, suggesting that his estimates may be reasonably applied to yard trimmings or food scrap compost.

[24] We focussed only on the passive pool because (1) the CENTURY model does not allow for direct input of organic carbon into the passive pool, and (2) the model runs resulted in very little indirect (i.e., via other pools) formation of passive carbon. Although the first factor is also true for the slow pool, the second is not. Had we analyzed slow carbon in the same way as passive carbon, there would be potential for double-counting (see discussion in Section 5.3).

[25] Metherell et al. 1993, Brady and Weil 1999.

Combining the two bounds for incremental humus formation (60 percent passive and 45 percent passive), we estimated the incremental carbon storage implied by each scenario (see Exhibit 5-4).

Exhibit 5-4 Incremental Carbon Storage: MTCE/wet ton vs time



The upper bound on the incremental carbon storage from composting is more than 0.05 MTCE per ton of organics (shown in the top left of the graph); the lower bound is approximately 0.03 MTCE per ton (shown in the bottom right of the graph) after about 100 years. Incremental storage is sensitive to the fraction of carbon in compost that is passive but is not very sensitive to the degradation rate (within a 100-year time horizon, over the range of rate constants appropriate for passive carbon).

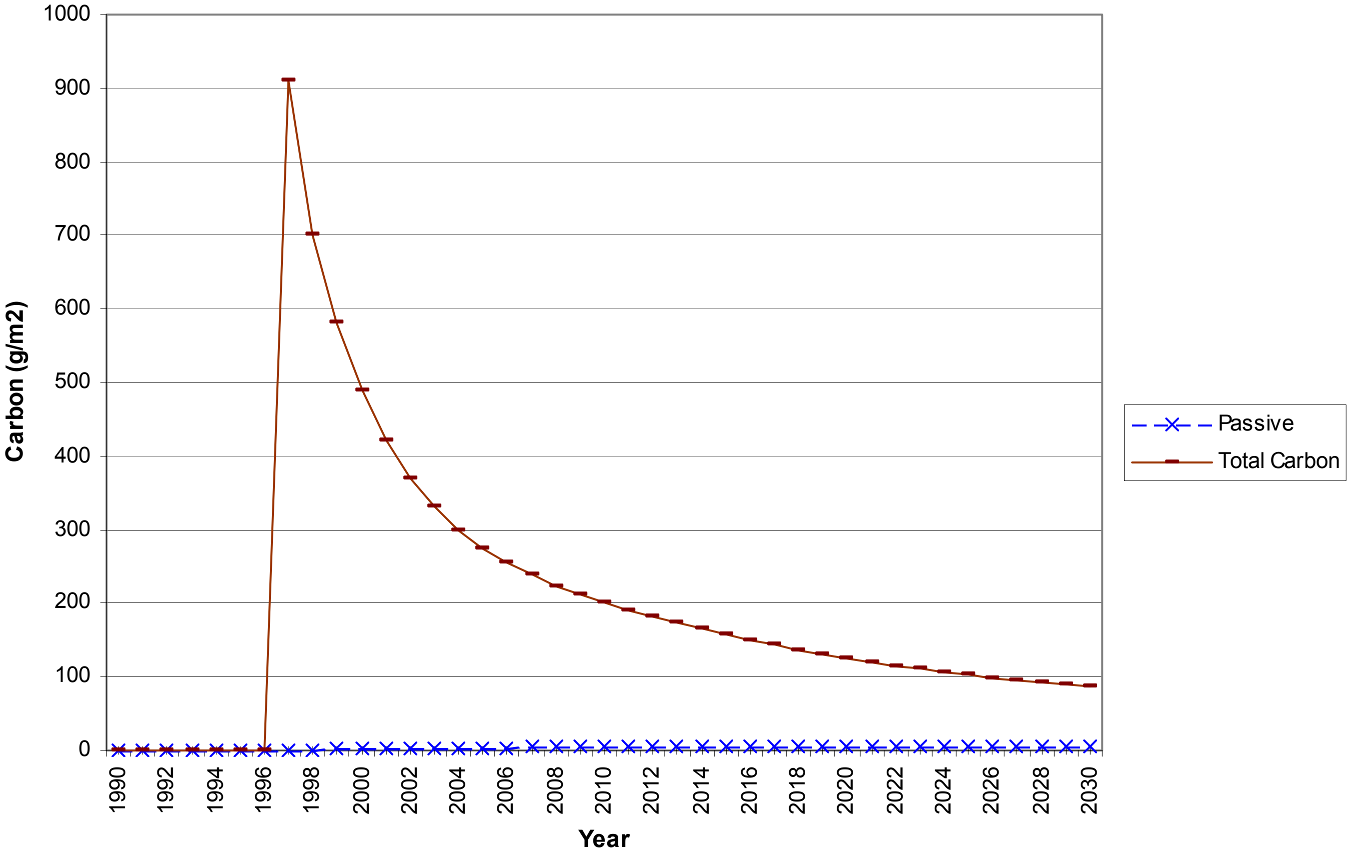
To select a point estimate for the effect of incremental humus formation, we took the average storage value across the two bounding scenarios, when time equals 10 years (i.e., approximately 2010). The resulting value is 0.05 MTCE/ton. The 2010 time frame was chosen for this analysis because the forest carbon estimates presented in Chapter 3 of this report are for the period ending in 2010.

5.3 NET GHG EMISSIONS FROM COMPOSTING

The approaches described in Section 5.2 were adopted to capture the range of carbon storage benefits associated with compost application. However, this dual approach creates the possibility of double counting. In an effort to eliminate double counting, we evaluated the way that CENTURY partitions compost carbon once it is applied to the soil.

To do so, we ran a CENTURY model simulation of compost addition during a single year and compared the results to a corresponding reference case (without compost). We calculated the difference in carbon in each of the CENTURY pools for the two simulations and found that the change in the passive pool represented less than 0.01 percent of the change in total carbon. Therefore, CENTURY is not adding recalcitrant carbon directly to the passive pool. Next, we graphed the change in the passive pool over time to ensure that the recalcitrant compost carbon was not being cycled from the faster pools into the passive pool several years after the compost is applied. As Exhibit 5-5 shows, CENTURY does not introduce significant increments (over the base case) of recalcitrant carbon into the passive pool at any time.

Exhibit 5-5 Difference in Carbon Storage Between Compost Addition and Base Case yearly application with 20 tons compost



Based on our analysis, it appears that CENTURY is appropriately simulating carbon cycling and storage for all but the passive carbon introduced by compost application. Because passive carbon represents approximately 52 percent of carbon in compost (the midpoint of 45 percent and 60 percent), we scaled the CENTURY results by 48 percent to reflect the proportion of carbon that can be classified as fast or slow (i.e., not passive).

Exhibit 5-6 shows the soil carbon storage and transportation-related emissions and sinks, and sums these to derive estimates of a net GHG emission factor, using the same sign convention as our broader analysis. A negative value denotes carbon storage; a positive value denotes emissions.

Summing the values corresponding to typical application rate and the 2010 time frame for soil carbon restoration (-0.02 MTCE/ton), increased humus formation (-0.05 MTCE/ton), and transportation emissions (0.01 MTCE/ton), the result is –0.05 MTCE/ton.[26]

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[26] The addends do not sum to the total, due to rounding.

Exhibit 5-6
Net GHG Emissions from Composting
(In MTCE Per Short Ton of Yard Trimmings Composted)

Emission/ Storage Factor (for 2010)					
Soil Carbon Restoration			Increased Humus Formation	Transportation Emissions	Net Carbon Flux
Unweighted	Proportion of C that is not passive	Weighted estimate			
-0.04	48%	-0.02	-0.05	0.01	-0.05

5.4 LIMITATIONS

Due to data and resource constraints, this chapter does not explore the full range of conditions under which compost is managed and applied, and how these conditions would affect the results of this analysis. Instead, this study attempts to provide an analysis of GHG emissions and sinks associated with centralized composting of yard trimmings and food discards (henceforth, organics) under a limited set of scenarios. Our analysis was limited by the lack of primary research on carbon storage and CH_4 generation associated with composting. The limited availability of data forced us to rely on two modeling approaches, each with its own set of limitations. In addition, our analysis was limited by the scope of the report, which is intended to present life-cycle GHG emissions of waste management practices for selected material types, including food discards and yard trimmings.

5.4.1 Limitations of Modeling Approaches

Due to data and resource constraints, we were unable to use CENTURY to evaluate the variation in carbon storage impacts for a wide range of compost feedstocks (e.g., yard trimmings mixed with food discards, food discards alone). As noted earlier, resource constraints limited the number of soil types, climates, and compost applications simulated. The CENTURY results also incorporate the limitations of the model itself, which have been well documented elsewhere. Perhaps most importantly, the model's predictions of soil organic matter levels are driven by four variables: annual precipitation, temperature, soil texture, and plant lignin content. Beyond these, the model is limited by its sensitivity to several factors for which data are difficult or impossible to obtain (e.g., presettlement grazing intensity, nitrogen input during soil development).[27] The model's monthly simulation intervals limit its ability to fully address potential interactions between nitrogen supply, plant growth, soil moisture, and decomposition rates, which may be sensitive to conditions that vary on a shorter time scale.[28] In addition, the model is not designed to capture the hypothesis that, due to compost application, soil ecosystem dynamics change so that more carbon is stored than is actually being added to the soil (i.e., the multiplier effect).

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[27] Parton, W., D.Schimel, C. Cole, and D. Ojima. 1987. "Analysis of Factors Controlling Soil Organic Matter Levels in Great Plains Grasslands." *Soil Sci. Soc. Am. J.* Vol. 51 (1173-1179).

[28] Paustian, K., W. Parton, and Jan Persson. 1992. "Modeling Soil Organic Matter in Organic-Amended and Nitrogen-Fertilized Long-Term Plots." *Soil Sci. Soc. Am. J.* Vol. 56 (476-488).

CENTURY simulates carbon movement through organic matter pools. Although the model is designed to evaluate additions of organic matter in general, to our knowledge it has not been applied in the past to evaluate the application of organics compost. CENTURY is parameterized to partition carbon to the various pools based on ratios of lignin to nitrogen and lignin to total carbon, not on the amount of organic material that has been converted to humus already. We addressed this limitation by developing an "add-on" analysis to evaluate humus formation in the passive pool, scaling the CENTURY results, and summing the soil carbon storage values. There is some potential for double-counting, to the extent that CENTURY is routing some carbon to various pools that is also accounted for in the incremental humus analysis. We believe that this effect is likely to be minor.

The bounding analysis used to analyze increased humus formation is limited by the lack of data specifically dealing with composts composed of yard trimmings or food discards. This analysis is also limited by the lack of data on carbon in compost that is passive. The approach of taking the average value from the two scenarios is simplistic but appears to be the best available option.

5.4.2 Limitations Related to the Scope of the Report

As indicated above, this chapter presents our estimates of the GHG-related impacts of composting food discards and yard trimmings. These estimates were developed within the framework of the larger report; therefore, our presentation of results, estimation of emissions and sinks, and description of ancillary benefits was not comprehensive. The remainder of this section describes specific limitations of our compost analysis.

As in the other chapters of this report, the GHG impacts of composting reported in this chapter are relative to other possible disposal options for yard trimmings (i.e., landfilling and combustion). In order to present absolute GHG emission factors for composted yard trimmings that could be used to compare composting to a baseline of leaving yard trimmings on the ground where they fall, we would need to analyze the home soil. In particular, the carbon storage benefits of composting would need to be compared to the impact that removal of yard trimmings has on the home soil.

As mentioned in Section 5.4.1, due to data and resource constraints, our analysis considers a small sampling of feedstocks and a single compost application (i.e., agricultural soil). We analyzed two types of compost feedstocks—yard trimmings and food discards—although sewage sludge, animal manure, and several other compost feedstocks also may have significant GHG implications. Similarly, we assumed that compost was applied to degraded agricultural soils, despite widespread use of compost in land reclamation, silviculture, horticulture, and landscaping.

This analysis did not consider the full range of soil conservation and management practices that could be used in combination with compost and the impacts of those practices on carbon storage. Some research indicates that adding compost to agricultural soils in conjunction with various conservation practices enhances the generation of soil organic matter to a much greater degree than applying compost alone. Examples of these conservation practices include conservation tillage, no tillage, residue management, crop rotation, wintering, and summer fallow elimination. Research suggests that allowing crop residues to remain on the soil rather than turning them over helps to protect and sustain the soil while simultaneously enriching it. Alternatively, conventional tillage techniques accelerate soil erosion, increase soil aeration, and hence lead to greater GHG emissions.[29]

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[29] R. Lal et al. 1998. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, MI: Sleeping Bear Press, Inc).

As is the case in other chapters, the methodology used to estimate GHG emissions from composting did not allow for variations in transportation distances. We recognize that the density of landfills versus composting sites in any given area would have an effect on the extent of transportation emissions derived from composting. For example, in states that have a higher density of composting sites, the hauling distance to such a site would be less and would require less fuel than transportation to a landfill. Alternatively, transporting compost from urban areas, where compost feedstocks may be collected, to farmlands, where compost is typically applied, potentially would require more fuel because of the large distance separating the sites.

Emission factors presented in this chapter do not capture the full range of possible GHG emissions from compost. Some of the nitrogen in compost is volatilized and released into the atmosphere as N_2O shortly after application of the compost. Based on a screening analysis, we estimated N_2O emissions to be less than 0.01 MTCE per wet ton of compost inputs and thus considered this effect to be negligible.

Addressing the possible GHG emission reductions and other environmental benefits achievable by applying compost instead of chemical fertilizers, fungicides, and pesticides was beyond the scope of this report. Manufacturing these agricultural products requires energy. To the extent that compost may replace or reduce the need for these substances, composting may result in reduced energy-related GHG emissions. Although we understand that compost is generally applied for its soil amendment properties rather than for pest control, compost has been effective in reducing the need for harmful or toxic pesticides and fungicides.[30]

In addition to the carbon storage benefits of adding compost to agricultural soils, composting can lead to improved soil quality, improved productivity, and cost savings. As discussed earlier, nutrients in compost tend to foster soil fertility.[31] In fact, composts have been used to establish plant growth on land previously unable to support vegetation. In addition to these biological improvements, compost also may lead to cost savings associated with avoided waste disposal, particularly for feedstocks such as sewage sludge and animal manure.

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[30] For example, the use of compost may reduce or eliminate the need for soil fumigation with methyl bromide (an ozone-depleting substance) to kill plant pests and pathogens.

[31] N. Brady and R. Weil. 1999. *The Nature and Properties of Soils* (Upper Saddle River, NJ: Prentice Hall).

6. COMBUSTION

This chapter presents estimates of the net GHG emissions from combustion of each of the materials considered in this analysis and several categories of mixed waste streams (e.g., mixed paper, mixed recyclables, and mixed MSW). Combustion of MSW results in emissions of CO_2 (because nearly all of the carbon in MSW is converted to CO_2) and N_2O. Note that CO_2 from burning biomass sources (such as paper products and yard trimmings) is not counted as a GHG because it is biogenic (as explained in Section 1.4).

Combustion of MSW with energy recovery in a waste-to-energy (WTE) plant also results in *avoided* CO_2 emissions at utility and metals production facilities. First, the electricity produced by a WTE plant displaces electricity that would otherwise be provided by an electric utility power plant. Because most utility power plants burn fossil fuels and thus emit CO_2, the electricity produced by a WTE plant reduces utility CO_2 emissions. These avoided GHG emissions must be subtracted from the GHG emissions associated with combustion of MSW. Second, most MSW combusted with energy recovery in the United States is combusted in WTE plants that recover ferrous metals (e.g., steel) and non-ferrous materials (e.g., non-ferrous metals and glass).[1] The recovered ferrous metals and non-ferrous materials then are recycled.[2] As discussed in Chapter 4, processes using recycled inputs require less energy than processes using virgin inputs. In measuring GHG implications of combustion, one also must account for the change in energy use due to recycling associated with metals recovery.

WTE facilities can be divided into three categories: (1) mass burn, (2) modular, or (3) refuse-derived fuel (RDF). A mass burn facility generates electricity and/or steam from the combustion of mixed MSW. In the United States, about 70 mass burn facilities process approximately 21 million tons of MSW annually.[3] Modular WTE plants generally are smaller than mass burn plants and are prefabricated off-site so that they can be assembled quickly where they are needed. Because of their similarity to mass burn facilities, modular facilities are treated as part of the mass burn category for the purposes of this analysis.

An RDF facility combusts MSW that has undergone varying degrees of processing, from simple removal of bulky and noncombustible items to more complex processes (shredding and material recovery), which result in a finely divided fuel. Processing MSW into RDF yields a more uniform fuel that has a higher heating value than is produced by mass burn or modular WTE.[4] In the United States, approximately 12 facilities process and combust RDF, 7 facilities combust RDF using off-site processing,

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[1] We did not consider any recovery of materials from the MSW stream that may occur before MSW is delivered to the combustor. We considered such prior recovery to be unrelated to the combustion operation—unlike recovery of steel from combustor ash, an activity that is an integral part of the operation of many combustors.

[2] Note that material recovery at WTE facilities has increased in recent years, and this trend may continue as more facilities install material recovery systems. According to the Integrated Waste Services Association's *2000 Waste-to-Energy Directory of United States Facilities* (www.wte.org), ferrous metal recovery at WTE facilities increased from more than 773,000 tons in 1999 to more than 788,000 tons in 2000. During the same period, on-site recycling more than doubled, from approximately 462,000 tons to 939,000 tons.

[3] Integrated Waste Services Association, *The 2000 IWSA Waste-To-Energy Directory of United States Facilities*, Table 1. This estimate assumes that 92 percent of combustion system capacity gets utilized, per e-mail correspondence with Maria Zannes of IWSA (June 12, 2001).

[4] MSW processing into RDF involves both manual and mechanical separation to remove materials such as glass and metals that have little or no fuel value.

and 7 facilities process RDF for combustion off-site. These 26 facilities process approximately 8 million tons of MSW annually.[5]

This study analyzed the net GHG emissions from combustion of mixed waste streams, and the following individual materials at mass burn and RDF facilities:

- Aluminum Cans;
- Steel Cans;
- Glass Containers;
- HDPE Plastic;
- LDPE Plastic;
- PET Plastic;
- Corrugated Cardboard;
- Magazines and Third-class Mail;
- Newspaper;
- Office Paper;
- Phonebooks;[6]
- Textbooks;[7]
- Dimensional Lumber;
- Medium-density Fiberboard;
- Food Discards; and
- Yard Trimmings.

Net emissions consist of (1) emissions of non-biogenic CO_2 and N_2O minus (2) avoided GHG emissions from the electric utility sector and from processing with recycled inputs (e.g., steel produced from recycled inputs requires less energy than steel from virgin inputs). There is some evidence that as combustor ash ages, it absorbs CO_2 from the atmosphere. We did not count absorbed CO_2, however, because we estimated the quantity to be less than 0.01 MTCE per ton of MSW combusted.[8] Similarly, the residual waste from processing MSW into RDF is typically landfilled. Some potential exists for the organic fraction of this residual waste to yield GHG emissions when landfilled. We did not count these emissions, however, because the quantity emitted is estimated to be less than 0.01 MTCE per ton of MSW processed into RDF.[9]

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[5] Integrated Waste Services Association, *The 2000 IWSA Waste-To-Energy Directory of United States Facilities*, Table 1.

[6] Newspaper used as proxy, as material-specific data were unavailable.

[7] Office paper used as proxy, as material-specific data were unavailable.

[8] Based on data provided by Dr. Jurgen Vehlow, of the Institut fur Technische Chemie in Karlsruhe, Germany, we estimated that the ash from 1 ton of MSW would absorb roughly 0.004 MTCE of CO_2.

[9] Based on data provided by Karen Harrington, principal planner for the Minnesota Office of Environmental Assistance, we estimated that landfilling the residual waste would emit roughly 0.003 MTCE of CO_2

The results showed that combustion of mixed MSW has small negative net GHG emissions (in absolute terms). Combustion of paper products, dimensional lumber, medium-density fiberboard, food discards, and yard trimmings results in negative net GHG emissions. Processing steel cans at a combustor, followed by recycling the ferrous metal, likewise results in negative net GHG emissions. Combustion of plastic produces positive net GHG emissions, and combustion of aluminum cans and glass results in small positive net GHG emissions. The reasons for each of these results are discussed in the remainder of this chapter.[10]

6.1 METHODOLOGY

The study's general approach was to estimate the (1) gross emissions of CO_2 and N_2O from MSW and RDF combustion (including emissions from transportation of waste to the combustor and ash from the combustor to a landfill) and (2) CO_2 emissions avoided due to displaced electric utility generation and decreased energy requirements for production processes using recycled inputs.[11] To obtain an estimate of the *net* GHG emissions from MSW and RDF combustion, we subtracted the GHG emissions avoided from the direct GHG emissions. We estimated the net GHG emissions from waste combustion per ton of mixed MSW and per ton of each selected material in MSW. The remainder of this section describes how we developed these estimates.

6.1.1 Estimating Direct CO_2 Emissions from MSW Combustion

The carbon in MSW has two distinct origins. Some of it is derived from sustainably harvested biomass (i.e., carbon in plant and animal matter that was converted from CO_2 in the atmosphere through photosynthesis). The remaining carbon in MSW is from non-biomass sources, e.g., plastic and synthetic rubber derived from petroleum.

For reasons described in Section 1.4, this study did not count the biogenic CO_2 emissions from combustion of biomass. On the other hand, we did count CO_2 emissions from combustion of non-biomass components of MSW—plastic, textiles, and rubber. Overall, only a small portion of the total CO_2 emissions from combustion are counted as GHG emissions.

For mixed MSW, we used the simplifying assumptions that (1) all carbon in textiles is non-biomass carbon, i.e., petrochemical-based plastic fibers such as polyester (this is a worst-case assumption); and (2) the category of "rubber and leather" in EPA's MSW characterization report[12] is composed almost entirely of rubber. Based on these assumptions, this study estimated that there are 0.11 pounds of non-biogenic carbon in the plastic, textiles, rubber, and leather contained in 1 pound of mixed MSW.[13] We assumed that 98 percent of this carbon would be converted to CO_2 when the waste is

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per ton of MSW processed into RDF. Facsimile from Karen Harrington, Minnesota Office of Environmental Assistance to ICF Consulting, October 1997.

[10] Note that Exhibits 6-1, 6-2, and 6-5 do not show mixed paper. Mixed paper is shown in the summary exhibit (Exhibit 6-6). The summary values for mixed paper are based on the proportions of the four paper types (newspaper, office paper, corrugated cardboard, and magazines/third-class mail) that comprise the different "mixed paper" definitions.

[11] A comprehensive evaluation also would consider the fate of carbon remaining in combustor ash. Depending on its chemical form, carbon may be aerobically degraded to CO_2, anaerobically degraded to CH_4, or remain in a relatively inert form and be stored. Unless the ash carbon is converted to CH_4 (which we considered to be unlikely), the effect on the net GHG emissions would be very small.

[12] U.S. EPA Office of Solid Waste. 2002. *Municipal Solid Waste in the United States: 2000 Facts and Figures*. EPA 530-R-02-001.

[13] ICF Consulting. 1995. Memorandum. "Work Assignment 239, Task 2: Carbon Sequestration in Landfills," April 28, Exhibit 2-A, column "o."

combusted, with the balance going to the ash. Then we converted the 0.11 pounds of non-biomass carbon per pound of mixed MSW to units of MTCE per ton of mixed MSW combusted. The resulting value for mixed MSW is 0.10 MTCE per ton of mixed MSW combusted,[14] as shown in Exhibit 6-1.

The study estimated that HDPE and LDPE are 84 percent carbon, while PET is 57 percent carbon (based on a moisture content of 2 percent). We assumed that 98 percent of the carbon in the plastic is converted to CO_2 during combustion. The values for CO_2 emissions, converted to units of MTCE per ton of plastic combusted, are shown in column "b" of Exhibit 6-1.

6.1.2 Estimating N_2O Emissions from Combustion of Waste

Studies compiled by the Intergovernmental Panel on Climate Change (IPCC) show that MSW combustion results in measurable emissions of N_2O, a GHG with a high global warming potential (GWP).[15] The IPCC compiled reported ranges of N_2O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. This study averaged the midpoints of each range and converted the units to MTCE of N_2O per short ton of MSW. The resulting estimate is 0.01 MTCE of N_2O emissions per ton of mixed MSW combusted. Because the IPCC did not report N_2O values for combustion of individual components of MSW, we used the 0.01 value not only for mixed MSW, but also as a proxy for all components of MSW, except for aluminum cans, steel cans, glass, HDPE, LDPE, and PET.[16]

6.1.3 Estimating Indirect CO_2 Emissions from Transportation of Waste to the WTE Plant

Next, this study estimated the indirect CO_2 emissions from the transportation of waste. For the indirect CO_2 emissions from transporting waste to the WTE plant, and ash from the WTE plant to a landfill, we used an estimate for mixed MSW developed by Franklin Associates, Ltd. (FAL).[17] We then converted the FAL estimate from pounds of CO_2 per ton of mixed MSW to MTCE per ton of mixed MSW. This resulted in an estimate of 0.01 MTCE of CO_2 emissions from transporting 1 ton of mixed MSW and the resulting ash. We assumed that transportation of any individual material in MSW would use the same amount of energy as transportation of mixed MSW.

6.1.4 Estimating Gross GHG Emissions from Combustion

To estimate the gross GHG emissions per ton of waste combusted, we summed the values for emissions from combustion CO_2, combustion N_2O, and transportation CO_2. The gross GHG emission estimates, for mixed MSW and for each individual material, are shown in column "e" of Exhibit 6-1.

6.1.5 Estimating Utility CO_2 Emissions Avoided

Most WTE plants in the United States produce electricity. Only a few cogenerate electricity and steam. In this analysis, we assumed that the energy recovered with MSW combustion would be in the form of electricity. This analysis is shown in Exhibit 6-2. We used three data elements to estimate the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy

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[14] Note that if we had used a best-case assumption for textiles, i.e., assuming they have no petrochemical-based fibers, the resulting value for mixed MSW would have been 0.09 MTCE per ton of mixed MSW combusted.

[15] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual, Volume 3,* (undated) p. 6-33. The GWP of N_2O is 310 times that of CO_2.

[16] This exception was made because at the relatively low combustion temperatures found in MSW combustors, most of the nitrogen in N_2O emissions is derived from the waste, not from the combustion air. Because aluminum and steel cans do not contain nitrogen, we concluded that running these metals through an MSW combustor would not result in N_2O emissions.

[17] Franklin Associates, Ltd. 1994. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful, Inc.), p. I-24.

Exhibit 6-1
Gross Emissions of GHGs from MSW Combustion (MTCE/Ton)

(a) Material Combusted	(b) Combustion CO_2 Emissions From Non-Biomass Per Ton Combusted	(c) Combustion N_2O Emissions Per Ton Combusted	(d) Transportation CO_2 Emissions Per Ton Combusted	(e) (e = b + c + d) Gross GHG Emissions Per Ton Combusted
Aluminum Cans	0.00	0.00	0.01	0.01
Steel Cans	0.00	0.00	0.01	0.01
Glass	0.00	0.00	0.01	0.01
HDPE	0.76	0.00	0.01	0.77
LDPE	0.76	0.00	0.01	0.77
PET	0.56	0.00	0.01	0.56
Corrugated Cardboard	0.00	0.01	0.01	0.02
Magazines/Third-class Mail	0.00	0.01	0.01	0.02
Newspaper	0.00	0.01	0.01	0.02
Office Paper	0.00	0.01	0.01	0.02
Phonebooks	0.00	0.01	0.01	0.02
Textbooks	0.00	0.01	0.01	0.02
Dimensional Lumber	0.00	0.01	0.01	0.02
Medium-density Fiberboard	0.00	0.01	0.01	0.02
Food Discards	0.00	0.01	0.01	0.02
Yard Trimmings	0.00	0.01	0.01	0.02
Mixed MSW	0.10	0.01	0.01	0.12
Carpet	0.47	0.00	0.01	0.48
Personal Computers	0.75	0.00	0.01	0.76

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
Note that Exhibits 6-1, 6-2, and 6-5 show coated paper but not mixed paper;
mixed paper is shown in the summary exhibit (Exhibit 6-6).
The summary values for mixed paper are based on the proportions of the four paper types (newspaper, office paper, corrugated cardboard, and coated paper) that comprise the different "mixed paper" definitions.
The values for phone books and textbooks are proxies, based on newspaper and office paper, respectively.

Exhibit 6-2
Avoided Utility GHG Emissions from Combustion at Mass Burn and RDF Facilities

(a) Material Combusted	(b) Energy Content (Btu Per Pound)	(c) Energy Content (Million Btu Per Ton)	(d) Mass Burn Combustion System Efficiency (Percent)	(e) RDF Combustion System Efficiency (Percent)	(f) Emission Factor for Utility-Generated Electricity (MTCE/ Million Btu of Electricity Delivered)	(g) (g = c * d * f) Avoided Utility CO_2 Per Ton Combusted at Mass Burn Facilities (MTCE)	(h) (h = c * e * f) Avoided Utility CO_2 Per Ton Combusted at RDF Facilities (MTCE)
Aluminum Cans	-335 a	-0.7	17.8%	16.3%	0.081	-0.01 *	-0.01 *
Steel Cans	-210 a	-0.4	17.8%	16.3%	0.081	-0.01 *	-0.01 *
Glass	-235 a	-0.5	17.8%	16.3%	0.081	-0.01 *	-0.01 *
HDPE	18,687 b	37.4	17.8%	16.3%	0.081	0.54	0.49
LDPE	18,687 b	37.4	17.8%	16.3%	0.081	0.54	0.49
PET	9,702 c,d	19.4	17.8%	16.3%	0.081	0.28	0.25
Corrugated Cardboard	7,043 b	14.1	17.8%	16.3%	0.081	0.20	0.18
Magazines/Third-class Mail	5,258 d	10.5	17.8%	16.3%	0.081	0.15	0.14
Newspaper	7,950 b	15.9	17.8%	16.3%	0.081	0.23	0.21
Office Paper	6,800 b,f	13.6	17.8%	16.3%	0.081	0.20	0.18
Phonebooks	7,950 g	15.9	17.8%	16.3%	0.081	0.23	0.21
Textbooks	6,800 h	13.6	17.8%	16.3%	0.081	0.20	0.18
Dimensional Lumber	8,300 i	16.6	17.8%	16.3%	0.081	0.24	0.22
Medium-density Fiberboard	8,300 i	16.6	17.8%	16.3%	0.081	0.24	0.22
Food Discards	2,370 b	4.7	17.8%	16.3%	0.081	0.07	0.06
Yard Trimmings	2,800 j	5.6	17.8%	16.3%	0.081	0.08	0.07
Mixed MSW**	5,000 k	10.0	17.8%	16.3%	0.081	0.14	0.13

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
* The amount of energy absorbed by 1 ton of steel, aluminum cans, or glass in an MSW combustor would, if not absorbed, result in less than 0.01 MTCEof avoided utility CO2.
** Mixed MSW represents the entire waste stream as disposed of.

a We developed these estimates based on data on the specific heat of aluminum, steel, and glass and calculated the energy required to raise the temperature of aluminum, steel, and glass from ambient temperature to the temperature found in a combustor (about 750° Celsius). We obtained the specific heat data from Incropera, Frank P.and David P. DeWitt, Introduction to Heat Transfer, Second Edition (New York: John Wiley & Sons) 1990, pp. A3-A4.
b MSW Fact Book.
c Gaines and Stodolsky.
d For PET plastic, we converted the value of 9,900 Btu/pound dry weight, to 9,702 Btu/pound wet weight, to account for a moisture content of 2 percent.
e We used Franklin Associates, Ltd.'s value for magazines as a proxy for the value for coated paper.
f We used the MSW Fact Book's value for mixed paper as a proxy for the value for office paper.
g. We used newspapers as a proxy for phonebooks.
h We used office paper as a proxy for textbooks.
i We used the higher end of the Btu factor for Basswood from the USFS. Basswood is a relatively soft wood so its high end Btu content should be most similar to an average factor for all wood types. Fons, W. L.; Clements, H. B.; Elliott, E. R.; George, P. M. 1962. Project Fire Model. Summary Progress Report-II. Period May 1, 1960, to April 30, 1962. Macon, GA: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Southern Forest Fire Laboratory. 58 p. [16824]
j Procter and Redfern, Ltd. and ORTECH International.
k Telephone conversation among IWSA, American Ref-Fuel, and ICF Consulting, October 28, 1997.

content of mixed MSW and of each separate waste material considered, (2) the combustion system efficiency in converting energy in MSW to delivered electricity, and (3) the electric utility CO_2 emissions avoided per kilowatt-hour of electricity delivered by WTE plants.

Energy content: For the energy content of mixed MSW, we used a value of 5,000 Btu per pound of mixed MSW combusted, which is a value commonly used in the WTE industry.[18] This estimate is within the range of values (4,500 to 6,500 Btu per pound) reported by FAL[19] and is slightly higher than the 4,800 Btu per pound value reported in EPA's *MSW Fact Book*.[20] For the energy content of RDF, we used a value of 5,700 Btu per pound of RDF combusted.[21] This estimate is within the range of values (4,800 to 6,400 Btu per pound) reported by the DOE's National Renewable Energy Laboratory (NREL).[22] For the energy content of specific materials in MSW, we consulted three sources: (1) EPA's *MSW Fact Book* (a compilation of data from primary sources), (2) a report by Environment Canada,[23] and (3) a report by Argonne National Laboratories.[24] We assume that the energy contents reported in the first two of these sources were for materials with moisture contents typically found for the materials in MSW (the sources implied this but did not explicitly state it). The Argonne study reported energy content on a dry weight basis.

Combustion system efficiency: To estimate the combustion system efficiency of mass burn plants, we used a net value of 550 kilowatt-hours (kwh) generated by mass burn plants per ton of mixed MSW combusted.[25] To estimate the combustion system efficiency of RDF plants, we evaluated three sources: (1) data supplied by an RDF processing facility located in Newport, Minnesota; (2) the Integrated Waste Services Association (IWSA) report *Waste-to-Energy Directory: Year 2000*; and (3) the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory. We used the Newport Processing Facility's reported net value of 572 kwh generated per ton of RDF for two reasons.[26] First,

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[18] Telephone conversation among representatives of Integrated Waste Services Association, American Ref-Fuel, and ICF Consulting, October 28, 1997.

[19] Franklin Associates, Ltd. 1994. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful, Inc.), pp. 1-16.

[20] U.S. Environmental Protection Agency, Office of Solid Waste. 1995. *MSW Fact Book, Version 2.0* (Washington, D.C.: U.S. Environmental Protection Agency).

[21] Note that this is a value reported by an RDF facility located in Newport, Minnesota; the data were provided by the Minnesota Office of Environmental Assistance. Facsimile from Karen Harrington, Minnesota Office of Environmental Assistance to ICF Consulting, October 1997.

[22] U.S. Department of Energy, National Renewable Energy Laboratory. 1992. *Data Summary of Municipal Solid Waste Management Alternatives Volume IV: Appendix B - RDF Technologies* (Springfield, VA: National Technical Information Service, NREL/TP-431-4988D), p. B-5.

[23] Procter and Redfern, Ltd. and ORTECH International. 1993. *Estimation of the Effects of Various Municipal Waste Management Strategies on Greenhouse Gas Emissions, Part II* (Ottawa, Canada: Environment Canada, Solid Waste Management Division, and Natural Resources Canada, Alternative Energy Division).

[24] Gaines, Linda, and Frank Stodolsky. 1993. *Mandated Recycling Rates: Impacts on Energy Consumption and Municipal Solid Waste Volume* (Argonne, IL: Argonne National Laboratory), pp. 11 and 85.

[25] Note that this is the value reported by Integrated Waste Services Association in its comments to the draft version of the first edition of this report. This value is within the range of values reported by others in response to this draft. Letter received from Maria Zannes, Integrated Waste Services Association, Washington, DC, August 25, 1997.

[26] The net energy value reported accounts for the estimated energy required to process MSW into RDF and the estimated energy consumed by the RDF combustion facility.

this value is within the range of values reported by the other sources. Second, the Newport Processing Facility provided a complete set of data for evaluating the overall system efficiency of RDF plants.[27]

Next, we considered losses in transmission and distribution of electricity. Using a transmission and distribution loss rate of 5 percent,[28] we estimated that 523 kwh are delivered per ton of waste combusted at mass burn facilities, and 544 kwh are delivered per ton of waste input at RDF facilities

We then used the value for the delivered kwhs per ton of waste combusted to derive the implicit combustion system efficiency (i.e., the percentage of energy in the waste that is ultimately delivered in the form of electricity). To determine this efficiency, we first estimated the Btu of MSW needed to deliver 1 kwh of electricity. We divided the Btu per ton of waste by the delivered kwh per ton of waste to obtain the Btu of waste per delivered kwh. The result is 19,200 Btu per kwh for mass burn and 21,000 Btu per kwh for RDF. Next we divided the physical constant for the energy in 1 kwh (3,412 Btu) by the Btu of MSW and RDF needed to deliver 1 kwh, to estimate the total system efficiency at 17.8 percent for mass burn and 16.3 percent for RDF (Exhibit 6-2, columns "d" and "e").[29]

<u>Electric utility carbon emissions avoided</u>: To estimate the avoided utility CO_2 from waste combustion, we used the results in columns "c" and "d," together with a "carbon coefficient" of 0.081 MTCE emitted per million Btu of utility-generated electricity (delivered), based on the national average fossil fuel mix used by utilities[30] as shown in Exhibits 6-3 and 6-4. This approach uses the average fossil fuel mix as a proxy for the fuels displaced at the margin when utility-generated electricity is displaced by electricity from WTE plants. In other words, we assume that nuclear, hydropower, and other non-fossil sources generate electricity at essentially fixed rates; marginal demand is met by fossil sources.[31] The actual carbon reductions could vary depending on which type of fuel used to generate electricity is displaced at the margin. The resulting estimates for utility carbon emissions avoided for each material are shown in columns "g" and "h" of Exhibit 6-2.

6.1.6 Approach to Estimating CO_2 Emissions Avoided Due to Increased Steel Recycling

Next, the study estimated the avoided CO_2 emissions from increased steel recycling made possible by steel recovery from WTE plants for (1) mixed MSW and (2) steel cans. Note that we did not credit increased recycling of non-ferrous materials, because of lack of data on the proportions of those materials being recovered. The result tends to overestimate net GHG emissions from combustion.

For mixed MSW, we estimated the amount of steel recovered per ton of mixed MSW combusted, based on (1) the amount of MSW combusted in the United States, and (2) the amount of steel recovered, post-combustion. Ferrous metals are recovered at approximately 83 WTE facilities in the United States

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[27] The data set included estimates on the composition and amount of MSW delivered to the processing facility, as well as estimates for the heat value of RDF, the amount of energy required to process MSW into RDF, and the amount of energy used to operate the RDF facility.

[28] Personal communication among representatives of Integrated Waste Services Association, American Ref-Fuel, and ICF Consulting, October 28, 1997.

[29] Note that the total system efficiency is the efficiency of translating the energy content of the fuel into the energy content of delivered electricity. The estimated system efficiencies of 17.8 and 16.3 percent reflect losses in (1) converting energy in the fuel into steam, (2) converting energy in steam into electricity, and (3) delivering electricity. The losses in delivering electricity are the transmission and distribution losses, estimated at 5 percent.

[30] Value estimated using data from the Energy Information Administration, *Annual Energy Review 2000* (Washington, DC: U.S. Government Printing Office, DOE/EIA-0384(2000)) August 2001.

[31] Non-fossil sources are expected to meet baseload energy requirements because of the financial incentive for these energy sources to generate at capacity. In general, the marginal cost of producing more power from these sources is minimal compared to the capital costs associated with establishing the facility.

and at seven RDF processing facilities that do not generate power on-site. These facilities recovered a total of nearly 789,000 tons per year of ferrous metals in 2000.[32] By dividing 789,000 tons (total U.S. steel recovery at combustors) by total U.S. combustion of MSW, which is approximately 30 million tons, we estimated that 0.03 tons of steel are recovered per ton of mixed MSW combusted (as a national average).

For steel cans, we first estimated the national average proportion of steel cans entering WTE plants that would be recovered. As noted above, approximately 90 percent of MSW destined for combustion goes to facilities with a ferrous recovery system. At these plants, approximately 98 percent of the steel cans would be recovered. We multiplied these percentages to estimate the weight of steel cans recovered per ton of steel cans combusted—about 0.88 tons per ton.

Finally, to estimate the avoided CO_2 emissions due to increased recycling of steel, we multiplied (1) the weight of steel recovered by (2) the avoided CO_2 emissions per ton of steel recovered. The result was an estimated avoided CO_2 emissions of approximately 0.43 MTCE per ton for steel cans and 0.01 MTCE per ton for mixed MSW, as shown in column "d" of Exhibit 6-5.

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[32] Integrated Waste Services Association, *The 2000 IWSA Waste-To-Energy Directory of United States Facilities.*

Exhibit 6-3

Estimating the Emission Factor for Utility-Generated Electricity

	Value	Value	Source
Electric Utility Consumption of Fossil Fuels to Generate Electricity			
Coal (Quadrillion Btu)	17.5		DOE, EIA, "Annual Energy Review: 2000," July 2001, Diagram 5.
Natural Gas (Quadrillion Btu)	3.1		DOE, EIA, "Annual Energy Review: 2000," July 2001, Diagram 5.
Petroleum (Quadrillion Btu)	0.8		DOE, EIA, "Annual Energy Review: 2000," July 2001, Diagram 5.
Total (Quadrillion Btu)	21.4		The sum of coal, natural gas, and petroleum.
Energy Value of one Quadrillion Btu (measured in Kilowatt-hours)	2.9E+11		DOE, EIA, "Form EIA 1605 (1997)," Appendix E.
Total (Billion kwh)	6,268		(21.44 Quad Btu) x (2.92875x10^{11} kWh/Quad Btu) / (10^9 kwh/Billion kwh)
Net Generation: Before Transmission and Distribution Losses (Fossil Fuels Only)			
Coal (Billion kwh)	1,692		DOE, EIA, "Annual Energy Review: 2000," August 2001, Table 8.3.
Natural Gas (Billion kwh)	290		DOE, EIA, "Annual Energy Review: 2000," August 2001, Table 8.3.
Petroleum (Billion kwh)	72		DOE, EIA, "Annual Energy Review: 2000," August 2001, Table 8.3.
Total (Billion kwh)	2,054		The sum of coal, natural gas, and petroleum.
Generation Efficiency (Fossil Fuels Only)			
Generation Output (Billion kwh)	2,054		Calculated above.
Consumption (Billion kwh)	6,268		Calculated above.
Efficiency (Percent)	33%		Generation Output / Consumption, i.e. 2,067 / 6,279.
Efficiency of Energy Conversion From Fossil Fuels to Delivered Electricity			
Transmission and Distribution Losses (TDL) (Percent)	9%		DOE, EIA, "Annual Energy Review: 2000," August 2001, "Electricity Notes."
Delivered Electricity Efficiency (Percent)	91%		Calculated as 100 percent (Deliverable Electricity) - 9 percent (TDL)
Efficiency of Energy Conversion and Delivery for Fossil Fuels (Percent)	30%		Generation Efficiency x Delivered Electricity Efficiency, i.e., 0.33 x 0.91.
Estimated Emission Factor for Delivered Electricity (MTCE/MBtu of Electricity Delivered)			
Weighted Average Emission Factor of the U.S. Mix of Fuels Used to Generate Electricity	**All Fuels**	**Fossil Fuels Only**	
(Kilograms of Carbon in CO_2 per Million Btu Consumed)	16.38	24.04	Exhibit 6-4 of this report.
Weighted Average Emission Factor (MTCE/million Btu)	0.01638	0.02404	Converting kilograms of carbon (kg C) to metric tons of carbon (MTC).
Efficiency of Energy Conversion and Delivery (Percent)	30%	30%	Calculated above.
Emission Factor for Delivered Electricity (MTCE/million Btu)	**0.05493**	**0.08060**	Weighted Average Emission Factor (MTCE/million Btu) / Conversion Efficiency.

Exhibit 6-4

Estimating the Weighted Average Carbon Coefficient of the U.S. Average Mix of Fuels Used to Generate Electricity (MTCE/Million Btu)

Fuel	Net Generation* (Billion kwh)	Percentage of Generation: All Fuels (%)	Percentage of Generation: Fossil Fuels (%)	Carbon Coefficents** (Kg CE Emitted Per Million Btu Consumed)
Coal	1,692	56.1%	82%	25.78
Natural Gas	290	9.6%	14%	14.48
Petroleum***	72	2.4%	4%	21.51
Nuclear	705	23.4%		0
Hydroelectric	253	8.4%		0
Other	2	0.1%		0
Total	3,015	100%	100%	NA
Weighted Average - All Fuels				16.38
Weighted Average - Fossil Fuels				24.04

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

* Source: EIA's *Annual Energy Review: 2000,* "Table 8.3 Electricity Net Generation at Electric Utilities, 1949-2000," for 2000.

** Values include fugitive methane emissions (weighted by the GWP of methane).

*** The carbon coefficient for residual fuel is used as a proxy for petroleum.

Exhibit 6-5

Avoided GHG Emissions Due to Increased Steel Recovery from MSW at WTE Facilities

(a) Material Combusted	(b) Tons of Steel Recovered Per Ton of Waste Combusted (Tons)	(c) Avoided CO_2 Emissions Per Ton of Steel Recovered (MTCE/Ton)	(d) Avoided CO_2 Emissions Per Ton of Waste Combusted (MTCE/Ton)
Aluminum Cans	0.00	0.00	0.00
Steel Cans	0.88	0.49	0.43
Glass	0.00	0.00	0.00
HDPE	0.00	0.00	0.00
LDPE	0.00	0.00	0.00
PET	0.00	0.00	0.00
Corrugated Cardboard	0.00	0.00	0.00
Magazines/Third-class Mail	0.00	0.00	0.00
Newspaper	0.00	0.00	0.00
Office Paper	0.00	0.00	0.00
Phonebooks	0.00	0.00	0.00
Textbooks	0.00	0.00	0.00
Dimensional Lumber	0.00	0.00	0.00
Medium-density Fiberboard	0.00	0.00	0.00
Food Discards	0.00	0.00	0.00
Yard Trimmings	0.00	0.00	0.00
Mixed MSW	0.02	0.49	0.01

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

*The value in column "d" is a national average and is weighted to reflect 98 percent recovery at the 90 percent of facilities that recover ferrous metals.

6.2 RESULTS

The results of this analysis are shown in Exhibit 6-6. The results from the last columns of Exhibits 6-1, the last two columns of Exhibit 6-2, and the last column of Exhibit 6-3 are shown in columns "b" through "e" in Exhibit 6-6. The net GHG emissions from combustion of each material at mass burn and RDF facilities are shown in columns "f" and "g," respectively. These net values represent the gross GHG emissions (column "b"), minus the avoided GHG emissions (columns "c," "d," and "e"). As stated earlier, these estimates of net GHG emissions are expressed for combustion in absolute terms. They are not values relative to some other waste management option. They are expressed in terms of short tons of waste input (i.e., tons of waste prior to processing).

We estimate that combustion of mixed MSW at mass burn and RDF facilities reduces net post-consumer GHG emissions to -0.04 and -0.03 MTCE per ton, respectively. Combustion of paper products has negative net post-consumer GHG emissions ranging from -0.14 to -0.22 MTCE per ton at mass burn facilities and from -0.13 to -0.20 MTCE per ton at RDF facilities. Net GHG emissions are negative because CO_2 emissions from burning paper are not counted (because they are biogenic) and fossil fuel burning by utilities to generate electricity is avoided. Likewise, combustion of medium-density fiberboard and dimensional lumber also results in negative net GHG emissions, with both equaling -0.23 MTCE at mass burn facilities and -0.21 at RDF facilities. Finally, net GHG emissions for food discards and yard trimmings (two other forms of biomass) are also negative, but of a smaller magnitude (-0.05 and -0.07 MTCE per ton of material, respectively, for mass burn and -0.05 and -0.06 MTCE per ton of material, respectively, for RDF).

Combustion of plastics results in substantial net GHG emissions, estimated from 0.21 to 0.27 MTCE per ton of material combusted for mass burn facilities, and from 0.25 to 0.30 MTCE per ton of material input to RDF facilities. This result is primarily because of the high content of non-biomass carbon in plastics. Also, when combustion of plastic results in electricity generation, the utility carbon emissions avoided (due to displaced utility fossil fuel combustion) are much lower than the carbon emissions from the combustion of plastic. This result is largely due to the lower system efficiency of WTE plants, compared with electric utility plants. Recovery of ferrous metals at combustors results in negative net GHG emissions, estimated at -0.42 MTCE per ton of steel cans, due to the increased steel recycling made possible by ferrous metal recovery at WTE plants.

6.3 LIMITATIONS OF THE ANALYSIS

The certainty of the analysis presented in this chapter is limited by the reliability of the various data elements used. The most significant limitations are as follows:

- Combustion system efficiency of WTE plants may be improving. If efficiency improves, more utility CO_2 will be displaced per ton of waste combusted (assuming no change in utility emissions per kwh), and the net GHG emissions from combustion of MSW will decrease.
- Data for the RDF analysis were provided by the Minnesota Office of Environmental Assistance and were obtained from a single RDF processing facility and a separate RDF combustion facility. Research indicates that each RDF processing and combustion facility is different. For example, some RDF combustion facilities may generate steam for sale off-site, which can affect overall system efficiency. In addition, the amount of energy required to process MSW into RDF and the amount of energy used to operate RDF combustion facilities can be difficult to quantify and can vary among facilities on a daily, seasonal, and annual basis. Thus, the values used for the RDF analysis should be interpreted as approximate values.

Exhibit 6-6
Net GHG Emissions from Combustion at WTE Facilities

(a) Material Combusted	(b) Gross GHG Emissions Per Ton Combusted (MTCE/Ton)	(c) Avoided Utility CO_2 Per Ton Combusted at Mass Burn Facilities (MTCE/Ton)	(d) Avoided Utility CO_2 Per Ton Combusted at RDF Facilities (MTCE/Ton)	(e) Avoided CO_2 Emissions Per Ton Combusted Due to Steel Recovery (MTCE/Ton)	(f) (f = b - c - e) Net GHG Emissions from Combustion at Mass Burn Facilities (MTCE/Ton)	(g) (g = b - d- e) Net GHG Emissions from Combustion at RDF Facilities (MTCE/Ton)
Aluminum Cans	0.01	-0.01	-0.01	0.00	0.02	0.02
Steel Cans	0.01	-0.01	-0.01	0.43	-0.42	-0.42
Glass	0.01	-0.01	-0.01	0.00	0.01	0.01
HDPE	0.77	0.54	0.49	0.00	0.23	0.28
LDPE	0.77	0.54	0.49	0.00	0.23	0.28
PET	0.56	0.28	0.25	0.00	0.28	0.31
Corrugated Cardboard	0.02	0.20	0.18	0.00	-0.19	-0.17
Magazines/Third-class Mail	0.02	0.15	0.14	0.00	-0.13	-0.12
Newspaper	0.02	0.23	0.21	0.00	-0.21	-0.19
Office Paper	0.02	0.20	0.18	0.00	-0.18	-0.16
Phonebooks	0.02	0.23	0.21	0.00	-0.21	-0.19
Textbooks	0.02	0.20	0.18	0.00	-0.18	-0.16
Dimensional Lumber	0.02	0.24	0.22	0.00	-0.22	-0.20
Medium-density Fiberboard	0.02	0.24	0.22	0.00	-0.22	-0.20
Yard Trimmings	0.02	0.08	0.07	0.00	-0.06	-0.06
Food Discards	0.02	0.07	0.06	0.00	-0.05	-0.04
Mixed Paper						
Broad Definition	0.02	0.20	0.19	NA	-0.19	-0.17
Residential Definition	0.02	0.20	0.18	NA	-0.18	-0.17
Office Paper Definition	0.02	0.19	0.17	NA	-0.17	-0.15
Mixed MSW	0.12	0.14	0.13	0.01	-0.04	-0.02

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

The reported ranges for N_2O emissions were broad. In some cases the high end of the range was 10 times the low end of the range. Research has indicated that N_2O emissions vary with the type of waste burned. Thus, the average value used for mixed MSW and for all MSW components should be interpreted as an approximate value.

- For mixed MSW, the study assumed that all carbon in textiles is from synthetic fibers derived from petrochemicals (whereas, in fact, some textiles are made from cotton, wool, and other natural fibers). Because we assumed that all carbon in textiles is non-biogenic, we counted all of the CO_2 emissions from combustion of textiles as GHG emissions. This assumption will slightly overstate the net GHG emissions from combustion of mixed MSW, but the magnitude of the error is small because textiles represent only a small fraction of the MSW stream. Similarly, the MSW category of "rubber and leather" contains some biogenic carbon from leather. By not considering this small amount of biogenic carbon, the analysis slightly overstates the GHG emissions from MSW combustion.
- Because the makeup of a given community's mixed MSW may vary from the national average, the energy content also may vary from the national average energy content used in this analysis. For example, MSW from communities with a higher- or lower-than-average recycling rate may have a different energy content, and MSW with more than the average proportion of dry leaves and branches will have a higher energy content.
- In this analysis, we used the national average recovery rate for steel. Where waste is sent to a WTE plant with steel recovery, the net GHG emissions for steel cans will be slightly lower (i.e., more negative). Where waste is sent to a WTE plant without steel recovery, the net GHG emissions for steel cans will be the same as for aluminum cans (i.e., close to zero). We did not credit increased recycling of non-ferrous materials, because of a lack of information on the proportions of those materials. This assumption tends to result in overstated net GHG emissions from combustion.
- This analysis used the national average fossil fuel mix for electricity as the proxy for fuel displaced at the margin when WTE plants displace utility electricity. If some other fuel or mix of fuels is displaced at the margin (e.g., coal), the avoided utility CO_2 would be different (e.g., for coal, the avoided utility CO_2 would be about 0.01 MTCE per ton higher for mixed MSW, and the net GHG emissions would be -0.05 MTCE instead of -0.04 MTCE per ton).

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7. LANDFILLING

This chapter presents estimates of GHG emissions and carbon storage from landfilling the materials considered in this analysis. For this study, we estimated the CH_4 emissions, transportation-related CO_2 emissions, and carbon storage that will result from landfilling each type of organic waste and mixed MSW. The GHG accounting principles used in the analysis follow.[1]

- When food discards, yard trimmings, paper, and wood are landfilled, anaerobic bacteria degrade the materials, producing CH_4 and CO_2. CH_4 is counted as an anthropogenic GHG, because even though it is derived from sustainably harvested biogenic sources, degradation would not result in CH_4 emissions if not for deposition in landfills. The CO_2 is not counted as a GHG in this context because if it were not emitted from landfills, it would be produced through natural decomposition. Because metals do not contain carbon, they do not generate CH_4 when landfilled. Plastics do not biodegrade, and therefore do not generate any CH_4.
- Transportation of waste materials to a landfill results in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes.
  Because food discards, yard trimmings, and paper are not completely decomposed by anaerobic bacteria, some of the carbon in these materials is stored in the landfill. Because this carbon storage would not normally occur under natural conditions (virtually all of the organic material would degrade to CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic sink.[2]

We developed separate estimates of emissions from landfills without gas recovery systems, those that flare CH_4, those that combust CH_4 for energy recovery, and from the national average mix of these three categories. Our national average emission estimate accounts for the extent to which CH_4 will be flared at some landfills and combusted for energy recovery at others.[3]

From the standpoint of post-consumer GHG emissions, landfilling some materials—including magazines/third-class mail, newspaper, phonebooks, dimensional lumber, medium-density fiberboard, leaves, and branches—results in net storage (i.e., carbon storage exceeds CH_4 plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present. At the other extreme, office paper, textbooks, and food discards result in net emissions regardless of landfill gas collection and recovery practices. The remaining materials have net post-consumer emissions that are either very low (aluminum, steel cans, and plastics have transportation-related emissions of 0.01 MTCE per ton, regardless of whether gas collection is present) or borderline, depending on whether the landfill has gas recovery (e.g., mixed MSW has net emissions at landfills without gas recovery, but net carbon storage at landfills with gas recovery).

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[1] These principles are described in broad terms in Section 1.5 of this report.

[2] However, carbon in plastic that remains in the landfill is not counted as stored carbon, because it is of fossil origin.

[3] Currently, most landfill CH_4 recovery in the United States—both for flaring and electricity—is occurring in response to a 1996 EPA rule that requires a well-designed and well-operated landfill gas collection system at landfills that (1) have a design capacity of at least 2.5 million metric tons or 2.5 million cubic meters; (2) are calculated to emit more than 50 metric tons of non-CH_4 organic compounds per year; and (3) received waste on or after November 11, 1987 (Federal Register, Vol. 61, No. 49, p. 9905, March 12, 1996). For the year 2000, an estimated 43 percent of landfill CH_4 was generated at landfills with landfill gas recovery systems subject to these requirements or installed on a voluntary basis.

7.1 EXPERIMENTAL VALUES FOR CH_4 GENERATION AND CARBON STORAGE

To estimate CH_4 emissions and carbon storage from landfilling of specific materials, we used data from laboratory experiments conducted by Dr. Morton Barlaz.[4] The experiments provided data on (1) the amount of CH_4 generated by each type of organic material, when digested by bacteria in anaerobic conditions simulating those in a landfill; and (2) the amount of carbon remaining, undecomposed (i.e., stored) at the end of the experiment.

7.1.1 Experimental Design

Dr. Barlaz placed each type of organic waste and mixed MSW in separate reactor vessels, in which he maintained anaerobic conditions similar to those in a landfill, but controlled to favor maximum CH_4 generation. Dr. Barlaz measured the amount of CH_4 generated in each reactor and the amount of undecomposed carbon remaining in each reactor at the end of the experiment. Each material was tested in four reactors, and the results from each reactor were averaged.[5]

At the start of the experiment, Dr. Barlaz dried a sample of each material and analyzed the amount of cellulose, hemicellulose, and lignin (and, for food discards, protein) in each material. Cellulose, hemicellulose, and protein partly decompose in a landfill, resulting in CH_4 generation. Lignin is relatively stable and non-decomposable under anaerobic conditions.

Portions of each material were weighed, placed in two-liter plastic containers (i.e., reactors), and allowed to decompose anaerobically under warm, moist conditions designed to accelerate decomposition. The reactors were seeded with a small amount of well-decomposed refuse containing an active population of CH_4-producing microorganisms (the "seed"), to ensure that CH_4 generation was not limited due to an insufficient population of microorganisms. To promote degradation, water was cycled through each reactor. Nitrogen and phosphorus were added so that CH_4 generation would not be limited by a lack of these nutrients.

The reactors were allowed to run for periods varying from three months to two years. The experiment ended for each reactor when one of two conditions was met: (1) no measurable CH_4 was being emitted (i.e., any CH_4 that was being emitted was below the detection limits of the analytical equipment); or (2) a curve generated mathematically from an analysis of the reactor's prior CH_4 generation indicated that the reactor had produced at least 95 percent of the CH_4 that it would produce if allowed to run indefinitely.

Dr. Barlaz measured the amount of CH_4 generated during the experimental period and subtracted the amount of CH_4 attributable to the seed. At the end of the experiment, he opened the reactors, drained the leachate, dried and weighed the contents, and analyzed the percentage composition of cellulose, hemicellulose, and lignin (and, for food discards, protein) in the remaining contents. He then measured the percentage of total volatile solids in the remaining contents. This amount included the cellulose, hemicellulose, lignin, and protein, and any other carbon-containing components such as waxes and tannins.

The experimental results were used to estimate the amount of carbon remaining in the reactor that was attributable to the seed[6] and the amount attributable to the material. The experiment was assumed to reflect actual landfill conditions, and the organic carbon remaining undegraded in the reactors was assumed to remain undegraded over the long term in landfills, i.e., it would be stored.

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[4] Barlaz, M.A. 1997. "Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills," EPA 600/R-97-071. Dr. Barlaz's work was funded by EPA's Air and Energy Engineering Research Laboratory.

[5] Barlaz, op. cit.

[6] Dr. Barlaz tested seed alone to be able to control for the amount of CH_4 generation and carbon storage that was attributable to the seed.

Dr. Barlaz's experiment did not specifically test all of the paper grades described in this report. He did evaluate four specific grades: newspaper, corrugated boxes, office paper, and coated paper. We identified proxies for five additional material types for which we had no experimental data. We assumed that magazines placed in a landfill will have characteristics similar to those observed for coated paper. Similarly, we assumed that phonebooks and textbooks would behave in the same way as newspaper and office paper, respectively. Experimental results for branches were used as a proxy for dimensional lumber and medium-density fiberboard.

As discussed in Section 4.2, we included the following three definitions of mixed paper among the materials analyzed in this report:

- Broadly defined mixed paper, which includes almost all printing-writing paper, folding boxes, and most paper packaging;
- Residential mixed paper, which includes the typical mix of papers from residential curbside pick-up (e.g., high-grade office paper, magazines, catalogs, commercial printing, folding cartons, and a small amount of old corrugated containers); and
- Mixed paper from offices, which includes copy and printer paper, stationary and envelopes, and commercial printing.

To develop estimates of CH_4 emissions and carbon storage for these three categories of mixed paper, we used the detailed characterization of mixed paper (shown in Exhibit 4-2) developed by Franklin Associates, Ltd., and we assigned analogs among the four paper grades tested by Dr. Barlaz. Exhibit 7-1 characterizes the composition of the two products made from mixed paper: boxboard (made using either a broad or a residential mix of recycled paper) and paper towels (made from recycled office paper). Emissions were calculated using these characterizations of the mixed paper grades and the values obtained from Dr. Barlaz's experiment for newspaper, corrugated boxes, office paper, and coated paper.[7]

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[7] Note that Exhibits 7-2 through 7-4 do not show mixed paper; however, mixed paper is shown in Exhibits 7-6 through 7-8. Exhibits 7-2 through 7-8 appear at the end of the chapter.

Exhibit 7-1

Proxies for Composition Mixed Paper (Percent)

Paper Grade	**Broad Definition for Mixed Paper**	**Mixed Paper from Residential Sources**	**Mixed Paper from Offices**
Newspaper[1]	24	23	21
Corrugated Boxes [2]	48	53	5
Office Paper [3]	20	14	38
Coated Paper [4]	8	10	36
Total	100	100	100

Explanatory Notes:

[1] Includes newspaper, uncoated groundwood paper, recycled folding boxes, and set-up boxes.

[2] Includes virgin and recycled corrugated boxes.

[3] Includes uncoated free sheet paper, cotton fiber paper, bleached bristols, unbleached kraft folding boxes, bleached kraft folding boxes, bleached bags and sacks, unbleached bags and sacks, and unbleached wrapping paper.

[4] Includes coated free sheet paper and coated groundwood paper.

7.1.2 CH_4 Generation: Experimental Data and Adjusted Values

The amount of CH_4 generated by each type of organic material (after deducting the CH_4 attributable to the seed), is shown in column "b" of Exhibit 7-2.

As a check on his experimental results, Dr. Barlaz estimated the amount of CH_4 that would have been produced if all of the cellulose, hemicellulose, and protein from the waste material that was decomposed during the experiment had been converted to equal parts of CH_4 and CO_2 (CH_4-producing microorganisms generate equal amounts, by volume, of CH_4 and CO_2 gas).[8] Dr. Barlaz referred to this amount as the material's "CH_4 potential." He then calculated the percentage of the CH_4 potential for each material accounted for by the sum of (1) the measured CH_4 generation, and (2) the amount of CH_4 that could be formed from the carbon in the leachate that was removed from the reactor and from the carbon in the refuse that remained in the reactor at the end of the experiment.[9] The resulting percentages of the CH_4 potential are shown in column "c" of Exhibit 7-2. CH_4 potential not accounted for could be due to either (1) leaks of CH_4; (2) measurement error; or (3) carbon in the cell mass of microorganisms (which was not measured).

CH_4 recovery was below 85 percent of the CH_4 potential for five materials: coated paper, office paper, food discards, leaves, and branches. In using Dr. Barlaz's data, we needed to make a choice regarding how to allocate this missing carbon. We chose to assume that some of it had been converted to microorganism cell mass, and the remainder had been degraded. Dr. Barlaz postulated a higher CH_4 yield based on assumptions that (1) 5 percent of the carbon in cellulose and hemicellulose (and protein in the case of food discards) that was degraded was converted into the cell mass of the microbial population; and (2) 90 percent of the carbon-containing compounds that were degraded but not converted to cell mass were converted to equal parts of CH_4 and CO_2. The "corrected yields," based on these assumptions, are shown in column "d" of Exhibit 7-2.

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[8] *Ibid.* Lignin was not considered in this check because cellulose, hemicellulose, and protein account for nearly all of the CH_4 generated.

[9] Note that any carbon that was converted to cell mass in microorganisms was not considered in this calculation.

We decided, in consultation with Dr. Barlaz, to use the "corrected yields" for leaves, branches, and office paper because we believed that these values were more realistic than the measured yields.[10, 11]

The CH_4 values that we used for each material (either the measured yield, or the "corrected" yield) are shown again in column "f" of Exhibit 7-2. In order to maintain consistent units with the other parts of our analysis, we converted the units for CH_4 generation from milliliters per dry gram of waste, to MTCE per wet ton of waste.[12] The resulting values are shown in column "g" of Exhibit 7-2. The value for yard trimmings is a weighted average of the values for grass, leaves, and branches, based on an assumption that yard trimmings are composed of 50 percent grass, 25 percent leaves, and 25 percent branches (on a wet weight basis).

7.1.3 Carbon Storage: Experimental Data and Calculations

Carbon storage was estimated by calculating the amount of carbon remaining in each reactor at the end of the experiment and then subtracting the amount of carbon remaining that was attributable to the seed. The difference between the two values is the amount of carbon from the waste material that remained in the reactor, undecomposed, at the end of the experiment. Because the conditions in the reactor simulated landfill conditions (favorable to optimized decomposition), approximately this amount of carbon would be stored if the material were landfilled. Carbon storage for each material is presented in Exhibit 7-3.[13]

7.2 FATES OF LANDFILL CH_4: CONVERSION TO CO_2, EMISSIONS, AND FLARING OR COMBUSTION WITH ENERGY RECOVERY

In this analysis, we accounted for (1) the conversion in the landfill of some portion of landfill CH_4 to CO_2 and (2) the capture of CH_4, either for flaring or for combustion with energy recovery (in either case, the captured CH_4 is converted to CO_2).[14] Exhibit 7-4 presents this analysis.

The exhibit begins with the CH_4 generation per wet ton of each material, which is shown in column "b" (the values were simply copied from the last column of Exhibit 7-2). Columns "c" through "k" calculate net GHG emissions from CH_4 generation for each of three categories of landfills: (1) landfills without landfill gas (LFG) recovery; (2) landfills with LFG recovery that flare LFG; and (3) landfills with LFG recovery, which generate electricity from the LFG. Columns "l" through "n" show the

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[10] The corrected yield was not available for coated paper/magazines. For food discards, even though the CH_4 potential recovery percentage was lower than 85 percent, we used the measured yield, as shown in column "b." We made this choice for food discards because the "corrected yield" for food discards was greater than the maximum possible yield (shown in column "e" of the exhibit). Dr. Barlaz had calculated the maximum possible yield for each material based on the CH_4 yield if all of the cellulose, hemicellulose, and protein in the material (1) decomposed and (2) was converted to equal parts of CH_4 and CO_2.

[11] Note that EPA's Office of Research and Development (ORD) uses the same data as the basis for its estimation of CH_4 yields. In that analysis, ORD does not use "corrected" values for materials with low CH_4 recovery, but rather uses observed experimental values for all materials.

[12] To make the conversion, we used the ratio of dry weight to wet weight for each material and a global warming potential of 21 for CH_4.

[13] The approach for estimating carbon storage is more fully described in, Barlaz, Morton, "Carbon Storage During Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills," paper submitted for publication, Department of Civil Engineering, North Carolina State University, Raleigh, NC, 1997.

[14] The CO_2 that is emitted is not counted as a GHG because it is biogenic in origin (as described in "CO_2 Emissions from Biogenic Sources: in Chapter 1).

estimated percentage of landfills in each category in 2000.[15,16] The final column shows the weighted average GHG emissions from CH_4 generation across all types of landfills.

To estimate MSW CH_4 emissions from each category of landfill, we first estimated the percentage of landfill CH_4 that is oxidized near the surface of the landfill. We estimated that 10 percent of the landfill CH_4 generated is either chemically oxidized or converted by bacteria to CO_2, [17] and the remaining 90 percent is available for atmospheric CH_4 emissions.

To estimate MSW CH_4 emissions from landfills with LFG recovery, we used the assumption that these landfills have an average LFG recovery efficiency of 75 percent.[18] We then calculated avoided utility GHG emissions from landfills with electricity generation. Because energy recovery systems experience down time, during which CH_4 is flared rather than used to generate electricity, we incorporated a 15 percent system efficiency loss into our estimates for avoided utility emissions.[19]

We also estimated the percentage of MSW disposed in each category of landfill in 2000. According to our estimates, 49 percent of all landfill CH_4 was generated at landfills with recovery systems, and the remaining 51 percent was generated at landfills without LFG recovery.[20] Of the 49 percent of all CH_4 generated at landfills with LFG recovery, 49 percent (or 24 percent of all CH_4) was generated at landfills that use LFG to generate electricity, and 51 percent (or 25 percent of all CH_4) at landfills that flare LFG.[21, 22]

Our results are shown in the final column of Exhibit 7-4. The materials with the highest rates of *net* GHG emissions from CH_4 generation, as shown in column "o"—corrugated boxes, office paper, and textbooks—also have the highest *gross* CH_4 generation, as shown in column "b." The recovery of CH_4 at landfills reduces the CH_4 emissions for each material in proportionate amounts but does not change the

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[15] Draft *U.S. Climate Action Report – 2001* (CAR). At the time of publication of this report, the CAR was still being reviewed; however, EPA expected that these estimates will not change in the final version.

[16] Note that estimates of percent CH_4 generation at landfills with recovery have decreased since the first edition of this report was published (in the first edition, we estimated that 54 percent of CH_4 would be generated at landfills with recovery). This difference is because the first edition relied on 1995 projections of year 2000 generation and recovery, whereas this version uses the most recent estimates of conditions in 2000.

[17] An oxidation rate of 10 percent is cited by Liptay, K., J. Chanton, P. Czepiel, and B. Mosher, "Use of Stable Isotopes to Determine Methane Oxidation in Landfill Cover Soils," *Journal of Geophysical Research*, April 1998, 103(D7), pp. 8243-8250; and Czepiel, P.M., B. Mosher, P.M. Crill, and R.C. Harriss. 1996. "Quantifying the Effects of Oxidation on Landfill Methane Emissions," *Journal of Geophysical Research*, 101, pp. 16721-16729.

[18] Several commenters on the draft version of the first edition of this report suggested a range of values; 75 percent was most often cited as a best estimate. Moreover, EPA has used this figure in its most recent publications [see, for example, *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions* (Washington, D.C.: U.S. EPA) September 1999].

[19] EPA. 1999. *Landfill Gas-to-Energy Project Opportunities: Background Information on Landfill Profiles*, Office of Air and Radiation, EPA 430-K-99-002, pp. 3-13.

[20] Based on data on (1) year 2000 MSW landfill CH_4 generation of 72.7 million MTCE (from draft *U.S. Climate Action Report – 2001*), (2) year 2000 landfill CH_4 recovery of 26.7 million MTCE (also from draft *U.S. Climate Action Report – 2001*), and (3) estimated landfill CH_4 recovery efficiency of 75 percent (from *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*).

[21] Draft *U.S. Climate Action Report – 2001.*

[22] The assumption that 49 percent of landfills recovering CH_4 will use it to generate electricity is subject to change over time based upon changes in the cost of recovery and the potential payback. Additionally, new technologies may arise that use recovered CH_4 for purposes other than generating electricity.

ranking of materials by CH_4 emissions. Leaves, branches, and the two wood products have the lowest rates of net GHG emissions from CH_4 generation.

7.3 UTILITY CO_2 EMISSIONS AVOIDED

Exhibit 7-5 presents a list of conversion factors and physical constants used to convert CH_4 combusted for electricity production to avoided CO_2 emissions. Using data on Btu per cubic feet of CH_4, kwh of electricity generated and delivered per Btu, and kilograms of utility carbon avoided per Btu delivered, we estimated that 0.18 MTCE is avoided per MTCE of CH_4 combusted. This figure then was incorporated into exhibit 7-4 to estimate net GHG emissions from landfills with electricity generation. As mentioned earlier in this chapter, our analysis assumes that 24 percent of landfills in the United States combust landfill CH_4 for electricity generation. We also assume a 15 percent system efficiency loss, reflecting the fact that landfill gas-to-energy facilities incur some system "down time," as shown in column 1.

7.4 NET GHG EMISSIONS FROM LANDFILLING

To determine the net GHG emissions from landfilling each material, we summed the net GHG emissions from CH_4 generation, carbon storage (treated as negative emissions), and transportation CO_2 emissions. The results are shown in Exhibit 7-6. The four columns under section "e" of the exhibit may be used by local MSW planners to estimate GHG emissions from MSW in a given community.

As the exhibit shows, the post-consumer results for organic materials vary widely. For some materials—in particular, magazines/third-class mail, newspaper, phonebooks, dimensional lumber, medium-density fiberboard, and yard trimmings (in particular, leaves and branches)—landfilling results in substantial net GHG reductions. For others—including corrugated cardboard, office paper, textbooks, and food discards—net emissions are significant. For the rest, net emissions and reductions are relatively small.

7.5 LIMITATIONS

Perhaps the most important caveat to the analysis of GHG emissions and storage associated with landfilling is that the results are based on a single set of laboratory experiments, those conducted by Dr. Morton Barlaz. Although researchers other than Dr. Barlaz have conducted laboratory studies that track the degradation of mixed MSW, his experiments were the only ones we identified that rigorously tested materials on an individual basis. Dr. Barlaz is recognized as an expert on the degradation of different fractions of MSW under anaerobic conditions, and his findings with respect to the CH_4 potential of mixed MSW are within the range used by landfill gas developers. Nevertheless, given the sensitivity of the landfill results to estimated CH_4 generation and carbon storage, we recognize that more research is needed in this area.

Another important caveat relates to our estimate that 49 percent of MSW landfill CH_4 is generated at landfills with LFG recovery systems. The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate. Because of the high global warming potential of CH_4, small changes in the LFG recovery rate (for the national average landfill) could have a large effect on the net GHG impacts of landfilling each material and the ranking of landfilling relative to other MSW management options. The effects of different rates of LFG recovery are shown in Exhibit 7-7. Column "b" of the exhibit shows net GHG emissions if 20 percent of waste was disposed of at landfills with recovery. The remaining columns show net GHG emissions at increasing LFG recovery rates, up to a 60 percent rate. As the exhibit shows, the net post-consumer GHG emissions for landfilling mixed MSW decline significantly as recovery increases. At the local level, the GHG emissions from landfilling MSW depend on whether the local landfill has LFG recovery, as shown in Exhibit 7-6.

Because the national average estimate of emissions is based on estimated year 2000 LFG recovery levels, there are several limitations associated with the use of this emission factor. First, because landfill CH_4 generation occurs over time and has significant timing delays (i.e., CH_4 generation may not begin until a few years after the waste is deposited in the landfill and can continue for many years after the landfill is closed), the values listed in this chapter represent total CH_4 generated, over time, per ton of waste landfilled. To the extent that LFG recovery rates shift dramatically over time, these shifts are not reflected in the analysis. Second, landfills with LFG recovery may be permitted, under EPA regulations, to remove the LFG recovery equipment when three conditions are met: (1) the landfill is permanently closed, (2) LFG has been collected continuously for at least 15 years, and (3) the landfill emits less than 50 metric tons of non-CH_4 organic compounds per year.[23] Although the removal of LFG recovery equipment will permit CH_4 from closed landfills to escape into the atmosphere, the amounts of CH_4 emitted should be relatively small, because of the relatively long time period required for LFG collection before LFG recovery equipment is removed. Third, several methodological issues are associated with applying the CH_4 generation estimates from the Climate Action Report to develop the national average emission factors:

(1) The generation estimates in the CAR include closed landfills (generation is modeled as a function of waste in place), whereas the estimates used in this report apply to ongoing generation (which is routed to open landfills);

(2) Likewise, both the flaring and landfill gas-to-energy estimates also include closed landfills; and

(3) The distribution of waste in place is not a perfect proxy for the destination of ongoing waste generation.

CH_4 oxidation rate and landfill gas collection system efficiency are also important factors driving results. We used values of 10 percent and 75 percent, respectively, as best estimates for these factors. Reviewers who commented on the draft of the first edition of this report and sources in the literature have reported estimates ranging from about 5 percent to 40 percent for oxidation, and from about 60 to 95 percent for collection system efficiency. We investigated the sensitivity of our results to these assumptions, and our results are shown in Exhibit 7-8. We portray the sensitivity as a bounding analysis; i.e., we use the combinations of variables yielding the upper bound emission factor (5 percent oxidation, 60 percent collection efficiency) and the lower bound (40 percent oxidation, 95 percent efficiency).[24] As the exhibit shows, the materials most sensitive to these variables are those with the highest CH_4 generation potential, i.e., corrugated cardboard, office paper, textbooks, food discards, and mixed paper. Sensitivity varies: the difference between upper and lower bounds ranges from 0.06 MTCE/ton for leaves and branches to 0.43 MTCE/ton for office paper and textbooks. The post-consumer emission factors of several materials and mixed material combinations—corrugated cardboard, grass, mixed paper, and mixed MSW—change from having net storage under the lower bound to having net emissions under the upper bound.

Ongoing shifts in the use of landfill cover and liner systems are likely to influence the rate of CH_4 generation and collection. As more landfills install effective covers and implement controls to keep water and other liquids out, conditions will be less favorable for degradation of organic wastes. Over the long term these improvements may result in a decrease in CH_4 generation and an increase in carbon storage. Moreover, Dr. Barlaz believes that the CH_4 yields from his laboratory experiments are likely to be higher than CH_4 yields in a landfill, because the laboratory experiments were designed to generate the maximum

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[23] Federal Register, Vol. 61, No. 49, p. 9907.

[24] The table also reports two intermediate combinations, including the best estimate values.

amount of CH_4 possible. If the CH_4 yields used in this analysis were higher than yields in a landfill, the net GHG emissions from landfilling organic materials would be lower than estimated here.

We assumed that once wastes are disposed in a landfill, they are never removed. In other words, we assumed that landfills are never “mined.” A number of communities have mined their landfills—removing and combusting the waste—in order to create more space for continued disposal of waste in the landfill. To the extent that landfills are mined in the future, it is incorrect to assume that carbon stored in a landfill will remain stored. For example, if landfilled wastes are later combusted, the carbon that was stored in the landfill will be oxidized to CO_2 in the combustor.

Our estimate of carbon avoided utility GHG emissions per unit of CH_4 combusted assumes that all landfill gas-to-energy projects are electricity producing. In reality, some projects are “direct gas” projects, in which CH_4 is piped directly to the end user for use as fuel. In these cases, the CH_4 essentially replaces natural gas as a fuel source. Because natural gas use is less GHG-intensive than average electricity production, direct gas projects will tend to offset fewer GHG emissions than electricity projects will—a fact not reflected in our analysis.

For landfilling of yard trimmings (and other organic materials), we assumed that all carbon storage in a landfill environment is incremental to the storage that occurs in a non-landfill environment. In other words, we assumed that in a baseline where yard trimmings are returned to the soil (i.e., in a non-landfill environment), all of the carbon is decomposed relatively rapidly (i.e., within several years) to CO_2, and there is no long-term carbon storage. To the extent that long-term carbon storage occurs in the baseline, the estimates of carbon storage reported here are overstated, and the net post-consumer GHG emissions are understated.

Finally, our spreadsheet analysis is limited by the assumptions that were made at various steps in the analysis, as described throughout this chapter. The key assumptions that have not already been discussed as limitations are the assumptions used in developing “corrected” CH_4 yields for organic materials in MSW. Because of the high global warming potential of CH_4, a small difference between estimated and actual CH_4 generation values would have a large effect on the GHG impacts of landfilling and the ranking of landfilling relative to other MSW management options.

Exhibit 7-2
Methane Yield for Solid Waste Components

(a) Material	(b) Average Measured Methane Yield (ml per dry gm)	(c) Percentage of "Methane Potential" Accounted for	(d) "Corrected" Methane Yield (ml per dry gram)	(e) Maximum Possible Methane Yield (ml per dry gram)	(f) Selected Methane Yield (ml per dry gm)	(g) Selected Methane Yield (MTCE/Wet Ton)
Corrugated Cardboard	152.3	87.7	NA	279.7	152.3	0.537
Magazines/Third-class Mail	84.4	83.7	NA	NA	84.4	0.294
Newspaper	74.2	98.0	NA	239.4	74.2	0.259
Office Paper	217.3	55.5	346.0	398.2	346.0	1.207
Food Discards	300.7	77.4	386.2	357.6	300.7	0.335
Yard Trimmings						0.191
Grass	144.3	89.3	NA	153.2	144.3	0.214
Leaves	30.5	75.2	56.0	108.0	56.0	0.166
Branches	62.6	82.8	76.3	224.9	76.3	0.170
Mixed MSW	92.0	97.6	NA	157.6	92.0	0.286

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

Note that Exhibits 7-1 to 7-3 show coated paper but not mixed paper; mixed paper is shown in Exhibits 7-5 and 7-6. The values for the different types of mixed paper are based on the proportion of the four paper types (newspaper, office paper, corrugated cardboard, and coated paper) that comprise the different "mixed paper" definitions.

Exhibit 7-3
Carbon Storage for Solid Waste Components

(a) **Material**	(b) **Ratio of Carbon Storage to Dry Weight (gm C/dry gm)**	(c) **Ratio of Dry Weight to Wet Weight**	(d) **(d = b * c) Ratio of Carbon Storage to Wet Weight (gm C/wet gm)**	(e) **Amount of Carbon Stored (MTCE per Wet Ton)**
Corrugated Cardboard	0.26	0.95	0.25	0.22
Magazines/Third-class Mail	0.34	0.94	0.32	0.29
Newspaper	0.42	0.94	0.39	0.36
Office Paper	0.05	0.94	0.05	0.04
Food Discards	0.08	0.30	0.02	0.02
Yard Trimmings			0.23	0.21
Grass	0.32	0.40	0.13	0.12
Leaves	0.54	0.80	0.43	0.39
Branches	0.38	0.60	0.23	0.21
Mixed MSW	0.13	0.84	0.11	0.10

Note that more digits may be displayed than are significant.

Explanatory Notes for Exhibit 7-3:
(1) Because MSW is typically measured in terms of its wet weight, we needed to convert the ratios for carbon stored as a fraction of dry weight to carbon stored as a fraction of wet weight. To do this, we used the estimated ratio of dry weight to wet weight for each material. These ratios are shown in column "c" of the exhibit. For most of the materials, we used data from an engineering handbook.[25] For grass, leaves, and branches, we used data provided by Dr. Barlaz.

(2) For consistency with the overall analysis, we converted the carbon storage values for each material to units of MTCE stored per short ton of waste material landfilled. The resulting values are shown in column "e" of the exhibit.

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[25] Tchobanoglous, George, Hilary Theisen, and Rolf Eliassen. 1977. *Solid Wastes: Engineering Principles and Management Issues* (New York: McGraw-Hill Book Co.), pp. 58 and 60.

Exhibit 7-4
Net GHG Emissions from CH_4 Generation

				Methane from Landfills With LFG Recovery and:											
		Methane from Landfills Without Methane Recovery		Flaring			Electricity Generation			Percentage of Methane from Each Type of Landfill in 2000			Net Methane Generation	Avoided CO_2 from Energy Recovery	TOTAL
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(l)	(m)	(n)	(o)	(p)	(q)
Material	CH_4 Generation (MTCE/Wet Ton)	Percentage of CH_4 Not Oxidized to CO_2	Net GHG Emissions From CH_4 Generation (MTCE/Wet Ton)	Percentage of CH_4 Not Recovered (100% Minus LFG Collection System Efficiency)	Percentage of CH_4 Not Recovered That Is Not Oxidized to CO_2	Net GHG Emissions From CH_4 Generation (MTCE/Wet Ton)	Utility CO_2 Emissions Avoided per MTCE CH_4 Combusted (MTCE)	Percentage of CH_4 Recovered for Electricity Generation Not Utilized Due to System "Down Time"	Utility CO_2 Emissions Avoided (MTCE/Wet Ton)	Percentage of CH_4 From Landfills Without LFG Recovery in 2000	Percentage of CH_4 From Landfills With LFG Recovery And Flaring in 2000	CH_4 From Landfills With LFG Recovery and Electricity Generation in 2000	Net CH_4 Emissions from Landfilling (MTCE/Wet Ton)	Net Avoided CO_2 Emissions from Landfilling (MTCE/Wet Ton)	Net GHG Emissions From Landfilling (MTCE/Wet Ton)
Corrugated Cardboard	0.537	90%	0.48	25%	90%	0.12	-0.18	0.15	-0.06	51%	25%	24%	0.31	-0.01	0.29
Magazines/Third-class Mail	0.294	90%	0.26	25%	90%	0.07	-0.18	0.15	-0.03	51%	25%	24%	0.17	-0.01	0.16
Newspaper	0.259	90%	0.23	25%	90%	0.06	-0.18	0.15	-0.03	51%	25%	24%	0.15	-0.01	0.14
Office Paper	1.207	90%	1.09	25%	90%	0.27	-0.18	0.15	-0.14	51%	25%	24%	0.69	-0.03	0.66
Phonebooks	0.259	90%	0.23	25%	90%	0.06	-0.18	0.15	-0.03	51%	25%	24%	0.15	-0.01	0.14
Textbooks	1.207	90%	1.09	25%	90%	0.27	-0.18	0.15	-0.14	51%	25%	24%	0.69	-0.03	0.66
Dimensional Lumber	0.170	90%	0.15	25%	90%	0.04	-0.18	0.15	-0.02	51%	25%	24%	0.10	0.00	0.09
Medium-density Fiberboard	0.170	90%	0.15	25%	90%	0.04	-0.18	0.15	-0.02	51%	25%	24%	0.10	0.00	0.09
Food Discards	0.335	90%	0.30	25%	90%	0.08	-0.18	0.15	-0.04	51%	25%	24%	0.19	-0.01	0.18
Yard Trimmings	0.191	90%	0.17	25%	90%	0.04	-0.18	0.15	-0.02	51%	25%	24%	0.11	-0.01	0.10
Grass	0.214	90%	0.19	25%	90%	0.05	-0.18	0.15	-0.02	51%	25%	24%	0.12	-0.01	0.12
Leaves	0.166	90%	0.15	25%	90%	0.04	-0.18	0.15	-0.02	51%	25%	24%	0.09	0.00	0.09
Branches	0.170	90%	0.15	25%	90%	0.04	-0.18	0.15	-0.02	51%	25%	24%	0.10	0.00	0.09
Mixed MSW	0.28601	90%	0.26	25%	90%	0.06	-0.18	0.15	-0.03	51%	25%	24%	0.16	-0.01	0.16

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

Exhibit 7-5

Calculation to Estimate Utility GHGs Avoided through Combustion of Landfill CH_4

Step	Value	Source
Metric tons CH_4/MTCE CH_4	0.17	1/((12/44)*Global warming potential of CH_4)
Grams CH_4/metric ton CH_4	1.00E+06	Physical constant
Cubic ft. CH_4/gram CH_4	0.05	1/20: 20 grams per cubic foot of methane at standard temperature and pressure
Btu/cubic ft. CH_4	1,000	"Opportunity for LF Gas Energy Recovery in Kentucky," OAR September 97, pp. 2-12
kwh Electricity generated/Btu	0.00008	1/13,000: from "Opportunity" report p. 2-11, assumes use of internal combustion engines
kwh electricity delivered/kwh electricity generated	0.95	Telephone conversation among IWSA, American Ref-Fuel, and ICF Consulting, October 28, 1997.
Btu/kwh electricity delivered	3,412	Physical constant
Kg utility C avoided/Btu delivered electricity	8.060E-05	0.08349 MTCE/mmBtu delivered electricity, from Exhibit 6-3. This assumes that LFG energy recovery displaces fossil fuel generation.
Metric Tons avoided utility C/kg utility C	0.001	1000 kg per metric ton
Ratio of MTCE avoided utility C per MTCE CH_4	0.18	Product from multiplying all factors

Exhibit 7-6
Net GHG Emissions from Landfilling

(a)	(b) Net GHG Emissions from CH_4 Generation (MTCE/Wet Ton)				(c)	(d)	(e) (e = b + c + d) Net GHG Emissions from Landfilling (MTCE/Wet Ton)			
Material	Landfills Without LFG Recovery	Landfills With LFG Recovery and Flaring	Landfills With LFG Recovery and Electric Generation	Year 2000 National Average	Net Carbon Storage (MTCE/Wet Ton)	GHG Emissions From Transportation (MTCE/Wet Ton)	Landfills Without LFG Recovery	Landfills With LFG Recovery and Flaring	Landfills With LFG Recovery and Electric Generation	Year 2000 National Average
Aluminum Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Steel Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Glass	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
HDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
LDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
PET	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Corrugated Cardboard	0.48	0.12	0.06	0.29	-0.22	0.01	0.27	-0.09	-0.15	0.08
Magazines/Third-class Mail	0.26	0.07	0.03	0.16	-0.29	0.01	-0.02	-0.21	-0.25	-0.12
Newspaper	0.23	0.06	0.03	0.14	-0.36	0.01	-0.12	-0.29	-0.32	-0.21
Office Paper	1.09	0.27	0.14	0.66	-0.04	0.01	1.05	0.24	0.10	0.62
Phonebooks	0.23	0.06	0.03	0.14	-0.36	0.01	-0.12	-0.29	-0.32	-0.21
Textbooks	1.09	0.27	0.14	0.66	-0.04	0.01	1.05	0.24	0.10	0.62
Dimensional Lumber	0.15	0.04	0.02	0.09	-0.21	0.01	-0.04	-0.16	-0.18	-0.10
Medium-density Fiberboard	0.15	0.04	0.02	0.09	-0.21	0.01	-0.04	-0.16	-0.18	-0.10
Food Discards	0.30	0.08	0.04	0.18	-0.02	0.01	0.29	0.06	0.03	0.17
Yard Trimmings	0.17	0.04	0.02	0.10	-0.21	0.01	-0.03	-0.15	-0.18	-0.09
Grass	0.19	0.05	0.02	0.12	-0.12	0.01	0.09	-0.06	-0.08	0.01
Leaves	0.15	0.04	0.02	0.09	-0.39	0.01	-0.23	-0.34	-0.36	-0.29
Branches	0.15	0.04	0.02	0.09	-0.21	0.01	-0.04	-0.16	-0.18	-0.10
Mixed Paper										
Broad Definition	0.53	0.13	0.07	0.32	-0.23	0.01	0.31	-0.08	-0.15	0.10
Residential Definition	0.49	0.12	0.06	0.29	-0.24	0.01	0.26	-0.10	-0.16	0.07
Office Paper Definition	0.58	0.15	0.07	0.35	-0.21	0.01	0.38	-0.05	-0.12	0.15
Mixed MSW	0.26	0.06	0.03	0.16	-0.10	0.01	0.17	-0.02	-0.06	0.07

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

Exhibit 7-7
Net GHG Emissions from CH_4 Generation at Landfills

Sensitivity Analysis: Varying the Percentage of Waste Disposed at Landfills with Methane Recovery

(a) Material	(b) 17% of Waste Disposed At Landfills With LFG Recovery	(c) 20% of Waste Disposed At Landfills With LFG Recovery	(d) 49% of Waste Disposed At Landfills With LFG Recovery	(e) 55% of Waste Disposed At Landfills With LFG Recovery	(f) 60% of Waste Disposed at Landfills With LFG Recovery
Corrugated Cardboard	0.20	0.19	0.06	0.04	0.02
Magazines/Third-class Mail	-0.05	-0.06	-0.13	-0.14	-0.15
Newspaper	-0.15	-0.16	-0.21	-0.23	-0.24
Office paper	0.89	0.87	0.59	0.54	0.49
Phonebooks	-0.15	-0.16	-0.21	-0.23	-0.24
Textbooks	0.89	0.87	0.59	0.54	0.49
Dimensional Lumber	-0.07	-0.07	-0.11	-0.12	-0.12
Medium-density Fiberboard	-0.07	-0.07	-0.11	-0.12	-0.12
Food Discards	0.25	0.24	0.16	0.15	0.13
Yard Trimmings	-0.05	-0.06	-0.10	-0.11	-0.11
Grass	0.06	0.05	0.01	0.00	-0.01
Leaves	-0.25	-0.26	-0.30	-0.30	-0.31
Branches	-0.07	-0.07	-0.11	-0.12	-0.12
Mixed Paper					
Broad Definition	0.23	0.22	0.09	0.06	0.04
Residential Definition	0.19	0.18	0.06	0.03	0.01
Office Paper Definition	0.30	0.28	0.14	0.11	0.08
Mixed MSW	0.13	0.12	0.06	0.05	0.03

Exhibit 7-8

Net GHG Emissions from CH_4 Generation at Landfills

Sensitivity Analysis: Varying Oxidation and Gas Collection Efficiency Rates. Based on Estimated National Mix of Landfill Gas Recovery Systems in 2000.

Oxidation Rate:	**40%**	**25%**	**10%**	**5%**
Collection Efficiency:	**95%**	**85%**	**75%**	**60%**
Material	**Lower-bound Emissions**	**Conservative (High) Emissions**	**Best Estimate**	**Upper-bound Emissions**
Corrugated Cardboard	0.15	0.22	0.29	0.35
Magazines/Third-class Mail	0.08	0.12	0.16	0.19
Newspaper	0.07	0.11	0.14	0.17
Office Paper	0.35	0.49	0.66	0.78
Phonebooks	0.07	0.11	0.14	0.17
Textbooks	0.35	0.49	0.66	0.78
Dimensional Lumber	0.05	0.07	0.09	0.11
Medium-density Fiberboard	0.05	0.07	0.09	0.11
Food Discards	0.10	0.14	0.18	0.22
Yard Trimmings	0.05	0.08	0.10	0.12
Grass	0.06	0.09	0.12	0.14
Leaves	0.05	0.07	0.09	0.11
Branches	0.05	0.07	0.09	0.11
Mixed Paper				
Broad Definition	0.17	0.24	0.32	0.38
Residential Definition	0.16	0.22	0.29	0.35
Office Paper Definition	0.19	0.26	0.35	0.42
Mixed MSW	0.08	0.12	0.16	0.19

8. ACCOUNTING FOR EMISSION REDUCTIONS

Earlier chapters of this report examined GHG emissions from each of five waste management options. This chapter recapitulates the emission factors for each option, explains the analytic framework for applying emission factors, and reviews opportunities for GHG emission reductions.

In the discussion that follows, we focus on national average conditions. For example, we represent landfills as having the national average landfill gas recovery systems, and we represent combustors based on mass burn units with the national average system efficiency for collection of ferrous metal. As shown in the previous chapters, GHG emissions are sensitive to many variables, including several that are site-specific. At specific locations, the GHG emission factors can differ from those described below. To allow for customizing of emission factors to better reflect local conditions, EPA has developed a spreadsheet accounting tool, the Waste Reduction Model (WARM), which enables users to input several key variables (e.g., information on landfill gas collection systems, electric utility fuel mix, transportation distances).[1] We encourage readers to take advantage of this model when assessing their waste management options.

8.1 NET GHG EMISSIONS FOR EACH WASTE MANAGEMENT OPTION

This section presents the net life-cycle GHG emissions for each waste management option for each material considered. These emissions are shown in 12 exhibits that summarize the GHG emissions and sinks in MTCE/ton and $MTCO_2E$/ton, which are described in detail in earlier chapters. In these exhibits, emission factors are shown for mixed plastics, mixed recyclables, and mixed organics. We developed the emission factor for mixed recyclables by calculating the average (weighted by tons recycled in 2000) of emission factors for aluminum cans, steel cans, HDPE, LDPE, PET, corrugated cardboard, magazines/third-class mail, newspaper, office paper, phonebooks textbooks, and wood products. The emission factor for mixed plastics is the average (weighted by tons recycled in 2000) of emission factors for HDPE, LDPE, and PET. The mixed organics emission factor is the average (weighted by tons composted in 2000) of emission factors for yard trimmings and food discards.[2]

As mentioned in Chapter 1, we used a waste generation reference point for measuring GHG emissions; i.e., we begin accounting for GHG emissions at the point of waste generation. All subsequent emissions and sinks from waste management practices then are counted. Changes in emissions and sinks from raw material acquisition and manufacturing processes are captured to the extent that certain waste management practices (i.e., source reduction and recycling) affect these processes (for reference, GHG emissions from raw materials acquisition and manufacturing are shown in the first column of several exhibits in this chapter). Negative emission factors indicate that from the point of waste generation, some MSW management options can reduce GHG emissions.

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[1] Microsoft Excel© and Web-based versions of this tool are available online at the following Web site: http://www.epa.gov/globalwarming/actions/waste/tools.html.

[2] All data on recycling and compost rates are from U.S. EPA Office of Solid Waste. 2002. *Municipal Solid Waste in the United States: 2000 Facts and Figures*, EPA 530-R-02-001.

Exhibits 8-1 and 8-2 show the life-cycle GHG reductions associated with source reduction, presented in MTCE/ton and $MTCO_2E$/ton, respectively. In brief, the exhibits show that, for all of the manufactured materials evaluated, source reduction results in GHG emission reductions. On a per-ton basis, aluminum cans and several paper grades have the greatest potential for emission reduction, due primarily to reductions in energy use in the raw material acquisition and manufacturing step and (for paper) forest carbon sequestration.

Exhibits 8-3 and 8-4 show the life-cycle GHG emissions associated with recycling in MTCE/ton and $MTCO_2E$/ton, respectively. The third through fifth columns in the exhibits show the GHG reductions associated with using recycled inputs in place of virgin inputs when the material is remanufactured. As the final column indicates, recycling results in negative emissions (measured from the point of waste generation) for all the materials considered in this analysis. Emission reductions associated with recycling are due to several factors, including avoided waste management emissions and reduced process energy emissions.[3] In addition, emission reductions from recycling paper products (when measured at the point of waste generation) are due in part to the forest carbon sequestration benefits of recycling paper.

Exhibits 8-5 and 8-6 present the life-cycle GHG emissions from composting food discards, yard trimmings, and mixed organics in MTCE/ton and $MTCO_2E$/ton, respectively. The exhibits show that composting these materials results in net emissions of -0.05 MTCE/ton, or -0.20 $MTCO_2E$/ton, based on the difference between the emissions associated with transporting the materials to the composting facility and the soil carbon sequestration benefits.

Exhibits 8-7 and 8-8 present the life-cycle GHG emissions from combusting each of the materials considered in MTCE/ton and $MTCO_2E$/ton, respectively. These exhibits show emissions for mass burn facilities with the national average rate of ferrous recovery. Results for RDF facilities are similar. As the exhibits show, mixed MSW combustion has net emissions of -0.04 MTCE/ton, or -0.16 $MTCO_2E$/ton. Net GHG emissions are positive for plastics, aluminum, and glass, and negative for the other materials.

GHG emissions from landfilling each of the materials in MTCE/ton are shown in Exhibit 8-9. Exhibit 8-10 presents these values in $MTCO_2E$/ton. The values in the final columns indicate that net GHG emissions from landfilling mixed MSW, under national average conditions in 2000, are positive. Among individual materials, emissions are lowest for newspaper, phonebooks, magazines/third-class mail, wood products, and yard trimmings, and highest for office paper, textbooks, and food discards.

As discussed in Chapter 7 and shown in Exhibit 7-6, the results for landfills are very sensitive to site-specific factors. Landfill gas collection practices significantly influence the net GHG emissions from landfilling the organic materials. For mixed MSW, net emissions are 0.17 MTCE/ton in landfills without landfill gas collection, and -0.06 MTCE/ton in landfills with landfill gas collection and energy recovery. The largest differences attributable to landfill gas recovery are for office paper and textbooks (both have a range of approximately 1 MTCE/ton), corrugated cardboard, and mixed paper. The CH_4 oxidation rate and gas collection system efficiency also have a strong influence on the estimated net emissions for mixed waste and the organic materials.

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[3] Process energy emissions for recycled corrugated cardboard, office paper, wood products (i.e., dimensional lumber and medium-density fiberboard), and mixed paper (broad and residential definitions) are actually higher than those for virgin production because production with recycled inputs tends to use fossil fuel-derived energy, while production with virgin inputs uses higher proportions of biomass fuel (CO_2 from such fuel is not counted in GHG inventories). In the case of dimensional lumber, production with recycled inputs requires more energy than virgin production.

Exhibits 8-11 and 8-12 display the national average emissions for each management option and each material in MTCE/ton and $MTCO_2E$/ton, respectively. When reviewing the emission factors, it is important to recall caveats that appear throughout this report. In particular, these estimates do not reflect site-specific variability, and they are not intended to compare one material to another. Rather, these estimates are designed to support accounting for GHG emissions and sinks from waste management practices. A brief recap of how to apply the emission factors appears in the following section.

8.2 APPLYING EMISSION FACTORS

The net GHG emission estimates presented in Exhibits 8-1 through 8-10 (and the more detailed estimates in the preceding chapters) provide emission factors that may be used by organizations interested in quantifying and voluntarily reporting emissions reductions associated with waste management practices. In conjunction with the U.S. Department of Energy (DOE), EPA has used these estimates as the basis for developing guidance for voluntary reporting of GHG reductions, as authorized by Congress in Section 1605(b) of the Energy Policy Act of 1992. Other applications have included evaluating the progress of voluntary programs aimed at source reduction and recycling, such as EPA's WasteWise and Pay-as-You-Throw programs.

EPA has also assisted the Climate Neutral Network by using the methods and data described in this report to develop company-specific GHG "footprints." As part of the program, companies develop GHG footprints, which include "downstream" waste management activities, for their specific product lines or facilities. These footprints then are used to determine the reductions or offsets that are necessary to become GHG-neutral. Companies may use changes in waste management practices as part of their offset portfolio.

Additionally, EPA worked with the International Council for Local Environmental Initiatives (ICLEI) to incorporate GHG emission factors into its municipal GHG accounting software. Currently, 350 communities participate in ICLEI's Cities for Climate Protection Campaign, which helps cities and towns establish a GHG emissions reduction target and implement a comprehensive local action plan designed to achieve that target. The program has resulted in 7.5 million metric tons of annual GHG emissions reductions.

In order to apply the emission factors presented in this report, one must first establish two scenarios: (1) a baseline scenario that represents current management practices (e.g., disposing 10 tons per year of office paper in a landfill with national average characteristics in terms of LFG collection); and (2) an alternative scenario that represents the alternative management practice (e.g., recycling the same 10 tons of office paper).[4] The emission factors developed in this report then can be used to calculate emissions under both the baseline and the alternative management practices. Once emissions for the two scenarios have been determined, the next step is to calculate the difference between the alternative scenario and the baseline scenario. The result represents the GHG emission reductions or increases attributable to the alternative waste management practice.

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[4] The emission factors are expressed in terms of GHG emissions per ton of material managed. In the case of recycling, we define 1 ton of material managed as 1 ton *collected* for recycling. As discussed in Chapter 4, the emission factors can be adjusted to calculate GHG emissions in terms of tons of recycled materials *as marketed* (reflecting losses in collection and sorting processes), or changes in the *recycled content* of products.

Applying Emission Factors: Non-linear Relationship between Recycling and Emission Reductions and Forest Carbon Leakage

Two caveats should be considered when applying the emission factors to analyze large-scale shifts in waste management. First, increased recycling and GHG emission reductions may have a non-linear relationship, such that emission reductions increase at a *declining rate* as recycling increases. This decline may be due to three factors: (1) energy use in manufacturing processes may be non-linear with respect to recycled content; (2) manufacturing capacity for recycled materials may be limited in the short term, so that large-scale increases in recycling would require additional capital investment in capacity; and (3) market penetration of recyclables may have limits (e.g., due to performance characteristics), such that recyclables cannot completely replace virgin inputs in the short term.

In terms of the second caveat, the forest carbon sequestration benefits of paper and wood source reduction and recycling are based on the assumption that reduced demand for a given paper or wood product translates directly into reduced tree harvesting. Given that pulpwood and roundwood can be used for many products, some of the forest carbon sequestration benefits may be lost by an increase in harvests for these other products. This phenomenon is a form of what is sometimes termed “leakage” in the context of GHG mitigation projects.

Although both of these issues are important considerations in applying the emission factors in this report, we note that the emission factors are primarily designed for use by local waste managers. The factors are intended to assess the GHG impacts of waste management decisions at a small-to-moderate scale. Readers should be cautious when applying the emission factors at a larger scale, however, since the non-linear nature of the factors and the issue of leakage become most relevant in the larger context.

Exhibits 8-13 and 8-14 illustrate the results of this procedure in a scenario where the baseline management scenario is disposal in a landfill with national average conditions (i.e., the weighted average in terms of landfill gas recovery practice). Alternative scenarios involve source reduction, recycling, composting, or combustion. The values in the cells of the matrix are expressed in MTCE/ton in Exhibit 8-13 and in MTCO$_2$E/ton in Exhibit 8-14, and represent the *incremental change* in GHG emissions. For example, recycling 1 ton of office paper, rather than landfilling it, reduces GHG emissions by 1.30 MTCE, or 4.76 MTCO$_2$E (see the “Recycling” columns of the exhibits). Continuing the example from the previous paragraph, if a business implements an office paper recycling program and annually diverts 10 tons of office paper (that would otherwise be landfilled) to recycling, the GHG emission reductions are:

10 tons/yr * -1.30 MTCE/ton = -13.0 MTCE/yr

Under the sign convention used in this report, the negative value indicates that emissions are reduced.

Due to resource and data limitations, emission factors have not been developed for all material types reported by WasteWise partners, the Voluntary Reporting of Greenhouse Gas Program—or 1605(b) as it is commonly called—and other parties interested in reporting voluntary emission reductions. However, existing emission factors will continue to be updated and improved and new emission factors will be developed as more data becomes available. The latest emission factors, reflecting these ongoing revisions, can be found on the EPA Global Warming Web site <http://www.epa.gov/globalwarming/actions/waste/w-online.htm>.

In cases where parties have been using source reduction or recycling techniques for materials not specifically analyzed in this report, it is possible to estimate the GHG emission reductions by assigning surrogate materials. A list of materials not specifically analyzed, and their corresponding surrogates, is presented in Exhibit 8-15. Surrogates are assigned based on consideration of similarities in characteristics likely to drive life-cycle GHG emissions, such as similarities in energy consumption during the raw material acquisition and manufacturing life-cycle stages. Note that the use of these surrogates involves considerable uncertainty.

Exhibit 8-15 Recommended Surrogates for Voluntary Reporting

Material Source Reduced	Surrogate Material
Metal (type unknown)	Average of Aluminum and Steel
Mixed Metals	Average of Aluminum and Steel
Copper	Steel Cans
Iron	Steel Cans
Other Ferrous Metals	Steel Cans
Other Non-Ferrous Metals	Steel Cans
Steel	Steel Cans
Plastic (resin unknown)	(PET+HDPE+LDPE)/3
PVC/Vinyl	(PET+HDPE+LDPE)/3
Polypropylene	(PET+HDPE+LDPE)/3
Polystyrene	(PET+HDPE+LDPE)/3
Other plastic (resin known, but not 41-46)	(PET+HDPE+LDPE)/3
Rubber	(PET+HDPE+LDPE)/3
Textiles	(PET+HDPE+LDPE)/3
Boxboard	Corrugated Cardboard
Kraft Paper	Corrugated Cardboard
Coated Paper	Magazines/Third-class Mail
High Grade Paper	Office Paper
Paper (type unknown)	Mixed Paper – Broad Definition
Wood	Dimensional Lumber
Food	Food Discards
Organics (type unknown)	Yard Trimmings
Other Yard Waste	Yard Trimmings

In our effort to continually expand and update life-cycle GHG emission factors for MSW materials, we are in the process of developing emission factors for carpet and personal computers. The emission factors will be based on data compiled by Franklin Associates, Ltd. These emission factors will differ from the other emission factors presented in this report because they are for products, each of which contain a variety of individual materials. In turn, the life-cycle emission factors will need to account for GHG emissions associated with the life cycle of each component material. Given the complexity of this task and the relatively limited life-cycle data on components of these products, EPA welcomes input from industry stakeholders to augment or verify the activity data that will be the basis for new emission factors for these products.

8.3 OTHER LIFE-CYCLE GHG ANALYSES AND TOOLS

Life-cycle analysis is increasingly being used to quantify the GHG impacts of private and public sector decisions. In addition to the life-cycle analyses that underpin the emission factors in this report, Environmental Defense,[5] ICLEI, Ecobilan, and others have analyzed the life-cycle environmental impacts of various industry processes (e.g., manufacturing) and private and public sector practices (e.g., waste management). In many cases, the results of life-cycle analyses are packaged into life-cycle software tools that distill the information according to a specific user's needs.

As mentioned earlier, the WARM model was designed as a tool for waste managers to weigh the GHG impacts of their waste management practices. As a result, the model focuses exclusively on waste sector GHG emissions, and the methodology used to estimate emissions is consistent with international and domestic GHG accounting guidelines. Life-cycle tools designed for broader audiences necessarily include other sectors and/or other environmental impacts, and are not necessarily tied to the Intergovernmental Panel on Climate Change (IPCC) guidelines for GHG accounting or the methods used in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.

- WARM covers 21 types of materials and 5 waste management options: source reduction, recycling, combustion, composting, and landfilling. WARM accounts for upstream energy and non-energy emissions, transportation distances to disposal and recycling facilities, carbon sequestration, and utility offsets that result from landfill gas collection and combustion. The tool provides participants in DOE's 1605(b) program with the option to report results by year, by gas, and by year and by gas. WARM software is available free of charge in both a Web-based calculator format and a Microsoft Excel© spreadsheet. The tool is ideal for waste planners interested in tracking and reporting voluntary GHG emission reductions from waste management practices and comparing the climate change impacts of different approaches. To access the tool, visit: <http://www.epa.gov/globalwarming/actions/waste/warm.htm>. The latest version of WARM has the additional capacity to calculate energy savings resulting from waste management decisions.
- The Cities for Climate Protection (CCP) Campaign's Greenhouse Gas Emission Software was developed by Torrie Smith Associates for ICLEI. This Windows-based tool, targeted for use by local governments, can analyze emissions and emission reductions on a community-wide basis and for municipal operations alone. The community-wide module looks at residential, commercial, and industrial buildings, transportation activity, and community-generated waste. The municipal operations module considers municipal buildings, municipal fleets, and waste from municipal in-house operations. In addition to computing GHG emissions, the CCP software estimates reductions in criteria air pollutants, changes in energy consumption, and financial costs and savings associated with energy use and other emission reduction initiatives. A version of the software program was made available for use by private businesses and institutions during the summer of 2001. CCP software subscriptions, including technical support, are available to governments participating in ICLEI for a subsidized price of $240. The full retail price of the software in the United States is $2,000. For more information, visit: <http://www.iclei.org/us/ccpsoftware.html> or contact the U.S. ICLEI office at (510)-540-8843, iclei_usa@iclei.org.

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[5] Blum, L., Denison, R.A., and Ruston, V.F. 1997. "A Life-Cycle Approach to Purchasing and Using Environmentally Preferable Paper: A Summary of the Paper Task Force Report," *Journal of Industrial Ecology*; Volume 1; No. 3; pp, 15-46. Denison, R.A. 1996. "Environmental Life-Cycle Comparison of Recycling, Landfilling, and Incineration: A Review of Recent Studies;" Annual Review of Energy and the Environment; Volume 21, Chapter 6, pp.191-237.

- The MSW Decision Support Tool (DST) and life-cycle inventory database for North America have been developed through funding by EPA's Office of Research and Development (ORD) through a cooperative agreement with the Research Triangle Institute (CR823052). The methodology is based on a multi-media, multi-pollutant approach and includes analysis of GHG emissions as well as a broader set of emissions (air, water, and waste) associated with MSW operations. The MSW-DST is available for site-specific applications and has been used to conduct analyses in several states and 15 communities, including use by the U.S. Navy in the Pacific Northwest. The tool is intended for use by solid waste planners at state and local levels to analyze and compare alternative MSW management strategies with respect to cost, energy consumption, and environmental releases to the air, land, and water. The costs are based on full-cost accounting principles and account for capital and operating costs using an engineering economics analysis. The MSW-DST calculates not only projected emissions of GHGs and criteria air pollutants, but also emissions of more than 30 air- and water-borne pollutants. The DST models emissions associated with all MSW management activities, including waste collection and transportation, transfer stations, materials recovery facilities, compost facilities, landfills, combustion and refuse-derived fuel facilities, utility offsets, material offsets, and source reduction. The differences in residential, multi-family, and commercial sectors can be evaluated individually. The software has optimization capabilities that enable one to identify options that evaluate minimum costs as well as solutions that can maximize environmental benefits, including energy conservation and GHG reductions.

  At the time of the publication of this report, the LCI database for North America was to be released in the winter of 2002. All supporting documentation for the MSW-DST and LCI database is to be released by spring 2002. Plans to develop a Web-based version are being considered. The MSW-DST provides extensive default data for the full range of MSW process models and requires minimum input data. The defaults can be tailored to the specific communities using site-specific information. For further information, refer to the project Web site at http://www.rti.org/units/ese/p2/lca.cfm#life. The MSW-DST also includes a calculator for source reduction and carbon sequestration using a methodology that is consistent with the IPCC in terms of the treatment of biogenic CO_2 emissions. For more information, refer to the project Web site: <http://www.rti.org/units/ese/p2/lca.cfm#life> or contact Susan Thornloe, U.S. EPA, (919)-541-2709, thornloe.susan@epamail.epa.gov, or Keith Weitz, Research Triangle Institute, (919)-541-6973, kaw@rti.org.

- The Tool for Environmental Analysis and Management (TEAM), developed by Ecobilan, simulates operations associated with product design, processes and, activities associated with several industrial sectors. The model considers energy consumption, material consumption, transportation, waste management, and other factors in its evaluation of environmental impacts. Many firms and some government agencies have used the model. Users pay a licensing fee of $3,000 and an annual maintenance contract of $3,000. This model is intended for use in Europe and was not developed for use in North America. For more information, visit: <http://www.ecobalance.com/software/gb_software.html>.

8.4 OPPORTUNITIES FOR GHG REDUCTIONS

Although this report has focused on the five most common waste management practices—source reduction, recycling, composting, combustion, and landfilling—for select materials, future quantification efforts may include a number of emerging practices:

- Co-firing waste biomass. For utilities and power generating companies with coal-fired capacity, co-firing with waste biomass may represent one of the least-cost renewable energy options. Co-firing involves replacing a portion of the coal with biomass at an existing power plant boiler. This replacement can be achieved by either mixing biomass with coal before fuel is introduced into the boiler or by using separate fuel feeds for coal and biomass. Specific biomass feedstocks include agricultural and wood waste, MSW, and industrial wastes. Given the increasing use of co-firing technology as an energy source, understanding its GHG benefits will likely be an important future EPA effort.

- Compost as landfill cover. Using compost as landfill cover on closed landfills provides an excellent environment for the bacteria that oxidize CH_4. Under optimal conditions, compost covers can practically eliminate CH_4 emissions. Furthermore, the covers offer the possibility of controlling these emissions in a cost-effective manner. This technology is particularly promising for small landfills, where landfill gas collection is not required and the economics of landfill gas-to-energy projects are not attractive. Ancillary benefits also might arise in the compost market from this technique if using compost as a landfill cover becomes a widespread practice. An increase in composting could reduce the quantity of organic waste disposed of at MSW landfills, thereby reducing CH_4 emissions. Given the recent development of this practice, quantifying its GHG impacts will likely prove useful as landfill owners consider adopting the technology.
- Bioreactors. Bioreactors are a form of controlled landfilling with the potential to provide reliable energy generation from solid waste, as well as significant environmental and solid waste management benefits. The concept is to accelerate the decomposition process of landfill waste through controlled additions of liquid and leachate recirculation, which enhances the growth of the microbes responsible for solid waste decomposition. The result is to shorten the time frame for landfill gas generation, thereby rendering projections of landfill gas generation rates and yields that are much more reliable for landfill gas recovery.
- Anaerobic digestion. Several facilities are using this technique to produce CH_4 from mixed waste, which is then used to fuel energy recovery. The approach generates CH_4 more quickly and captures it more completely than in a landfill environment, and thus, from a GHG perspective, offers a potentially attractive waste management option.[6]
- The paperless office. The rise of computer technology for research, communications, and other everyday workplace functions has presented a major opportunity for source reduction in the modern office. Today's offices are commonly equipped with all the necessary technologies to bypass paper entirely and rely instead on electronic communication. This form of "comprehensive" source reduction comes with significant GHG benefits, as described in Chapter 4. Therefore, attempting to quantify and communicate these benefits to the business community will be an important task in the coming years.
- Product stewardship. Increasingly, companies are taking responsibility for the environmental impacts associated with the full life cycle of their products. Two industries in particular—carpet and electronics—have been on the forefront of product stewardship efforts.

  Carpet: Currently, more than 6 billion pounds of carpet are shipped each year, of which approximately 200 million pounds are recycled. Although carpet is difficult to recycle due to its varied make-up, any incremental increase in recycling could have significant climate benefits. As a result, EPA is working with a group of carpet industry representatives, state environmental agencies, and non-profit recycling organizations to reach voluntary agreement on a phase-out of carpet disposal. This product stewardship activity has focused on setting rates and dates for carpet recovery over the next 10 years and encouraging the carpet industry

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[6] Environment Canada. 2001. *Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions.* Submitted by ICF Consulting, Torrie-Smith Associates, and Enviros-RIS.

to develop a new third-party organization to help coordinate industry efforts. The carpet industry and states have signed a memorandum of understanding that outlines the process and guiding framework for developing a 10-year plan on carpet disposal phase-out. EPA will continue to facilitate this effort in the coming years.[7]

Electronics: Understanding GHG emissions associated with waste management options for electronics products is important for a number of reasons. First, electronics are among the most rapidly growing categories of the U.S. waste stream. Sales of electronics have been increasing dramatically, and, due to the fairly short period between purchase and discard, the quantity of electronics discarded is expected to grow significantly in the future. Second, electronics contain valuable materials that can be reused and/or recycled. Third, many electronics products contain toxic materials that are covered by hazardous waste regulations. These three factors have motivated interest on the part of electronics manufacturers, waste managers, and others in recycling. Electronics will therefore become an increasingly essential addition to the list of materials analyzed in this report.

EPA will continue to evaluate new opportunities to reduce emissions from waste management as they become known. We also encourage readers to consider creative approaches to waste management, particularly those with associated life-cycle energy benefits or carbon storage implications.

All of the exhibits presented so far in this report have expressed GHG emissions in units of MTCE or $MTCO_2E$, calculated as the sum of the individual gases (CO_2, CH_4, N_2O, and PFCs) weighted by their global warming potential. In the Voluntary Reporting of Greenhouse Gas Program—also known as the 1605(b) program—established by DOE's Energy Information Administration, reporting companies are asked to provide emission reductions for each of the individual gases. In addition, the 1605(b) program requires emission reductions to be reported in the year they are achieved and does not allow participants to take credit for future emission reductions. Because the GHG emission factors presented in this report reflect the "present value" of future emissions and sinks as well as emissions and sinks occurring in the reporting year, our emission factors are not directly transferrable to the 1605(b) program. For purposes of supporting the program, we developed a revised set of 1605(b) program emission factors that reflect emissions by gas and by year. These emission factors provide incremental emissions for a baseline of landfilling and alternative scenarios of source reduction and recycling. Detailed reporting instructions and forms are available on DOE's Web site at http://www.eia.doe.gov/oiaf/1605/forms.html.

* * * * *

We close with a final note about the limitations of the GHG emission estimates in this report. We based our analysis on what we believed to be the best available data; where necessary, we made assumptions that we believe are reasonable. The accuracy of the estimates is limited, however, by the use of these assumptions and limitations in the data sources, as discussed throughout this report. Where possible, the emission factors reported here can be improved by substituting process- or site-specific data to increase the accuracy of the estimates. For example, a commercial firm with a large aluminum recycling program may have better data on the specific fuel mix of its source of aluminum and could thus calculate a more exact value for the emission factor. Despite the uncertainty in the emission factors, they provide a reasonable first approximation of the GHG impacts of solid waste management, and we believe that they provide a sound basis for evaluating voluntary actions to reduce GHG emissions in the waste management arena.

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[7] Additional information on this activity is available on the Minnesota Office of Environmental Assistance Web site at http://www.moea.state.mn.us/carpet/care.cfm.

Exhibit 8-1
GHG Emissions for Source Reduction (MTCE/Ton of Material Source Reduced)

Emissions Measured from a Waste Generation Reference Point[1]

	(a) Raw Materials Acquisition and Manufacturing		(b) Forest Carbon Sequestration		(c)	(d = a + b + c) (d) Net Emissions	
Material	**Source Reduction Displaces Current Mix of Virgin and Recycled Inputs**	**Source Reduction Displaces Virgin Inputs**	**Source Reduction Displaces Current Mix of Virgin and Recycled Inputs**	**Source Reduction Displaces Virgin Inputs**	**Waste Management Emissions**	**Source Reduction Displaces Current Mix of Virgin and Recycled Inputs**	**Source Reduction Displaces Virgin Inputs**
Aluminum Cans	-2.49	-4.67	0.00	0.00	0.00	-2.49	-4.67
Steel Cans	-0.79	-1.01	0.00	0.00	0.00	-0.79	-1.01
Glass	-0.14	-0.16	0.00	0.00	0.00	-0.14	-0.16
HDPE	-0.49	-0.53	0.00	0.00	0.00	-0.49	-0.53
LDPE	-0.61	-0.64	0.00	0.00	0.00	-0.61	-0.64
PET	-0.49	-0.58	0.00	0.00	0.00	-0.49	-0.58
Corrugated Cardboard	-0.24	-0.22	-0.28	-0.73	0.00	-0.51	-0.96
Magazines/Third-class Mail	-0.46	-0.46	-0.58	-0.73	0.00	-1.04	-1.19
Newspaper	-0.46	-0.59	-0.35	-0.73	0.00	-0.81	-1.32
Office Paper	-0.31	-0.28	-0.50	-0.73	0.00	-0.80	-1.01
Phonebooks	-0.64	-0.67	-0.65	-0.73	0.00	-1.28	-1.40
Textbooks	-0.59	-0.59	-0.64	-0.73	0.00	-1.23	-1.32
Dimensional Lumber	-0.05	-0.05	-0.50	-0.50	0.00	-0.55	-0.55
Medium-density Fiberboard	-0.10	-0.10	-0.50	-0.50	0.00	-0.60	-0.60
Food Discards	NA	NA	NA	NA	NA	NA	NA
Yard Trimmings	NA	NA	NA	NA	NA	NA	NA
Mixed Paper							
Broad Definition	NA	NA	NA	NA	NA	NA	NA
Residential Definition	NA	NA	NA	NA	NA	NA	NA
Office Paper Definition	NA	NA	NA	NA	NA	NA	NA
Mixed Plastics	NA	NA	NA	NA	NA	NA	NA
Mixed Recyclables	NA	NA	NA	NA	NA	NA	NA
Mixed Organics	NA	NA	NA	NA	NA	NA	NA
Mixed MSW (as disposed)	NA	NA	NA	NA	NA	NA	NA

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

Exhibit 8-2
GHG Emissions for Source Reduction
($MTCO_2E$/Ton of Material Source Reduced)

Emissions Measured from a Waste Generation Reference Point[1]

	(a) Raw Materials Acquisition and Manufacturing		(b) Forest Carbon Sequestration		(c)	(d = a + b + c) (d) Net Emissions	
Material	**Source Reduction Displaces Current Mix of Virgin and Recycled Inputs**	**Source Reduction Displaces Virgin Inputs**	**Source Reduction Displaces Current Mix of Virgin and Recycled Inputs**	**Source Reduction Displaces Virgin Inputs**	**Waste Management Emissions**	**Source Reduction Displaces Current Mix of Virgin and Recycled Inputs**	**Source Reduction Displaces Virgin Inputs**
Aluminum Cans	-9.15	-17.11	0.00	0.00	0.00	-9.15	-17.11
Steel Cans	-2.89	-3.69	0.00	0.00	0.00	-2.89	-3.69
Glass	-0.50	-0.57	0.00	0.00	0.00	-0.50	-0.57
HDPE	-1.79	-1.95	0.00	0.00	0.00	-1.79	-1.95
LDPE	-2.25	-2.34	0.00	0.00	0.00	-2.25	-2.34
PET	-1.78	-2.14	0.00	0.00	0.00	-1.78	-2.14
Corrugated Cardboard	-0.88	-0.82	-1.01	-2.69	0.00	-1.89	-3.50
Magazines/Third-class Mail	-1.69	-1.69	-2.11	-2.69	0.00	-3.80	-4.38
Newspaper	-1.69	-2.15	-1.29	-2.69	0.00	-2.97	-4.84
Office Paper	-1.13	-1.02	-1.82	-2.69	0.00	-2.95	-3.71
Phonebooks	-2.33	-2.44	-2.37	-2.69	0.00	-4.70	-5.13
Textbooks	-2.15	-2.16	-2.35	-2.69	0.00	-4.49	-4.85
Dimensional Lumber	-0.17	-0.17	-1.84	-1.84	0.00	-2.01	-2.01
Medium-density Fiberboard	-0.36	-0.36	-1.84	-1.84	0.00	-2.20	-2.20
Food Discards	NA	NA	NA	NA	NA	NA	NA
Yard Trimmings	NA	NA	NA	NA	NA	NA	NA
Mixed Paper							
Broad Definition	NA	NA	NA	NA	NA	NA	NA
Residential Definition	NA	NA	NA	NA	NA	NA	NA
Office Paper Definition	NA	NA	NA	NA	NA	NA	NA
Mixed Plastics	NA	NA	NA	NA	NA	NA	NA
Mixed Recyclables	NA	NA	NA	NA	NA	NA	NA
Mixed Organics	NA	NA	NA	NA	NA	NA	NA
Mixed MSW (as disposed)	NA	NA	NA	NA	NA	NA	NA

Note that totals may not add due to rounding and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

Exhibit 8-3
Recycling
(GHG Emissions in MTCE/Ton)

Emissions Measured from a Waste Generation Reference Point[1]

	Raw Materials Acquisition and Manufacturing (RMAM)		Recycled Input Credit[2]					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h) (h = b+c+d+e+f+g)
Material	RMAM Emissions Not Included in Baseline[3] (current mix of inputs)	Waste Generation Baseline	Process Energy	Transportation Energy	Process Non-Energy	Forest Carbon Sequestration	Waste Management Emissions	Net Emissions
Aluminum Cans	2.49	0.00	-2.92	-0.14	-1.05	0.00	0.00	-4.11
Steel Cans	0.79	0.00	-0.48	-0.01	0.00	0.00	0.00	-0.49
Glass	0.14	0.00	-0.03	0.00	-0.04	0.00	0.00	-0.08
HDPE	0.49	0.00	-0.34	0.00	-0.04	0.00	0.00	-0.38
LDPE	0.61	0.00	-0.43	0.00	-0.04	0.00	0.00	-0.47
PET	0.49	0.00	-0.40	0.00	-0.02	0.00	0.00	-0.42
Corrugated Cardboard	0.24	0.00	0.04	-0.01	0.00	-0.73	0.00	-0.71
Magazines/Third-class Mail	0.46	0.00	0.00	0.00	0.00	-0.73	0.00	-0.74
Newspaper	0.46	0.00	-0.21	-0.01	0.00	-0.73	0.00	-0.95
Office Paper	0.31	0.00	0.06	0.00	0.00	-0.73	0.00	-0.68
Phonebooks	0.64	0.00	-0.18	0.00	0.00	-0.73	0.00	-0.91
Textbooks	0.59	0.00	-0.01	0.00	0.00	-0.73	0.00	-0.75
Dimensional Lumber	0.05	0.00	0.02	0.00	0.00	-0.69	0.00	-0.67
Medium-density Fiberboard	0.10	0.00	0.01	0.00	0.00	-0.69	0.00	-0.67
Food Discards	NA	0.00	NA	NA	NA	NA	0.00	NA
Yard Trimmings	NA	0.00	NA	NA	NA	NA	0.00	NA
Mixed Paper								
Broad Definition	0.38	0.00	0.08	-0.02	0.00	-0.73	0.00	-0.67
Residential Definition	0.38	0.00	0.08	-0.02	0.00	-0.73	0.00	-0.67
Office Paper Definition	0.85	0.00	-0.08	-0.02	0.00	-0.73	0.00	-0.83
Mixed Plastics	0.51	0.00	-0.38	0.00	-0.03	0.00	0.00	-0.41
Mixed Recyclables	0.36	0.00	-0.10	-0.01	-0.02	-0.63	0.00	-0.76
Mixed Organics	NA	NA	NA	NA	NA	NA	NA	NA
Mixed MSW (as disposed)	NA	NA	NA	NA	NA	NA	NA	NA

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

[2] 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

Exhibit 8-4

Recycling

(GHG Emissions in $MTCO_2E$/Ton)

Emissions Measured from a Waste Generation Reference Point[1]

	Raw Materials Acquisition and Manufacturing (RMAM)		Recycled Input Credit[2]					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
								(h = b+c+d+e+f+g)
Material	**RMAM Emissions Not Included in Baseline[3] (Current Mix of Inputs)**	**Waste Generation Baseline**	**Process Energy**	**Transportation Energy**	**Process Non-Energy**	**Forest Carbon Sequestration**	**Waste Management Emissions**	**Net Emissions**
Aluminum Cans	9.15	0.00	-10.70	-0.51	-3.86	0.00	0.00	-15.07
Steel Cans	2.89	0.00	-1.75	-0.04	0.00	0.00	0.00	-1.79
Glass	0.50	0.00	-0.12	-0.02	-0.14	0.00	0.00	-0.28
HDPE	1.79	0.00	-1.26	0.00	-0.15	0.00	0.00	-1.40
LDPE	2.25	0.00	-1.57	0.00	-0.15	0.00	0.00	-1.71
PET	1.78	0.00	-1.48	0.00	-0.08	0.00	0.00	-1.55
Corrugated Cardboard	0.88	0.00	0.13	-0.04	-0.01	-2.69	0.00	-2.60
Magazines/Third Class Mail	1.69	0.00	-0.01	0.00	0.00	-2.69	0.00	-2.70
Newspaper	1.69	0.00	-0.76	-0.03	0.00	-2.69	0.00	-3.48
Office Paper	1.13	0.00	0.22	0.00	-0.02	-2.69	0.00	-2.48
Phonebooks	2.33	0.00	-0.65	0.00	0.00	-2.69	0.00	-3.34
Textbooks	2.15	0.00	-0.05	0.00	0.00	-2.69	0.00	-2.74
Dimensional Lumber	0.17	0.00	0.07	0.01	0.00	-2.53	0.00	-2.45
Medium-density Fiberboard	0.36	0.00	0.05	0.02	0.00	-2.53	0.00	-2.47
Food Discards	NA	0.00	NA	NA	NA	NA	0.00	NA
Yard Trimmings	NA	0.00	NA	NA	NA	NA	0.00	NA
Mixed Paper		0.00						
Broad Definition	1.38	0.00	0.29	-0.06	0.00	-2.69	0.00	-2.47
Residential Definition	1.39	0.00	0.29	-0.06	0.00	-2.69	0.00	-2.47
Office Paper Definition	3.12	0.00	-0.29	-0.07	0.00	-2.69	0.00	-3.05
Mixed Plastics	1.85	0.00	-1.40	0.00	-0.12	0.00	0.00	-1.51
Mixed Recyclables	1.32	0.00	-0.38	-0.04	-0.09	-2.30	0.00	-2.80
Mixed Organics	NA	NA	NA	NA	NA	NA	NA	NA
Mixed MSW (as disposed)	NA	NA	NA	NA	NA	NA	NA	NA

Note that totals may not add due to rounding and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisitionand manufacturing phase).

[2] 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

Exhibit 8-5
Composting
(GHG Emissions in MTCE/Ton)

Values are for Mass Burn Facilities with National Average Rate of Ferrous Recovery. Emissions Measured from a Waste Generation Reference Point[1]

	Raw Materials Acquisition and Manufacturing (RMAM)				
	(a)	(b)	(c)	(d)	(e) (e = b+c+d)
Material	RMAM Emissions Not Included in Baseline[2]	Waste Generation Baseline	Transportation to Composting	Soil Carbon Sequestration	Net Emissions (Post-Consumer)
Aluminum Cans	-2.49	0.00	NA	NA	NA
Steel Cans	-0.79	0.00	NA	NA	NA
Glass	-0.14	0.00	NA	NA	NA
HDPE	-0.49	0.00	NA	NA	NA
LDPE	-0.61	0.00	NA	NA	NA
PET	-0.49	0.00	NA	NA	NA
Corrugated Cardboard	-0.24	0.00	NA	NA	NA
Magazines/Third-class Mail	-0.46	0.00	NA	NA	NA
Newspaper	-0.46	0.00	NA	NA	NA
Office Paper	-0.31	0.00	NA	NA	NA
Phonebooks	-0.64	0.00	NA	NA	NA
Textbooks	-0.59	0.00	NA	NA	NA
Dimensional Lumber	-0.05	0.00	NA	NA	NA
Medium-density Fiberboard	-0.10	0.00	NA	NA	NA
Food Discards	NA	0.00	0.01	-0.07	-0.05
Yard Trimmings	NA	0.00	0.01	-0.07	-0.05
Mixed Paper					
Broad Definition	0.38	0.00	NA	NA	NA
Residential Definition	0.38	0.00	NA	NA	NA
Office Paper Definition	0.85	0.00	NA	NA	NA
Mixed Plastics	0.51	0.00	NA	NA	NA
Mixed Recyclables	0.36	0.00	NA	NA	NA
Mixed Organics	NA	0.00	0.01	-0.07	-0.05
Mixed MSW (as disposed)	NA	NA	NA	NA	NA

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

[2] The value for mixed MSW is the weighted average of the RMAM emissions for those materials we studied.

Exhibit 8-6
Composting
(GHG Emissions in $MTCO_2E$/Ton)

Values are for Mass Burn Facilities with National Average Rate of Ferrous Recovery. Emissions Measured from a Waste Generation Reference Point[1]

Material	Raw Materials Acquisition and Manufacturing (RMAM)		(c)	(d)	(e)
	(a) RMAM Emissions Not Included in Baseline[2]	(b) Waste Generation Baseline	Transportation to Composting	Soil Carbon Sequestration	(e = b+c+d) Net Emissions (Post-Consumer)
Aluminum Cans	-9.15	0.00	NA	NA	NA
Steel Cans	-2.89	0.00	NA	NA	NA
Glass	-0.50	0.00	NA	NA	NA
HDPE	-1.79	0.00	NA	NA	NA
LDPE	-2.25	0.00	NA	NA	NA
PET	-1.78	0.00	NA	NA	NA
Corrugated Cardboard	-0.88	0.00	NA	NA	NA
Magazines/Third-class Mail	-1.69	0.00	NA	NA	NA
Newspaper	-1.69	0.00	NA	NA	NA
Office Paper	-1.13	0.00	NA	NA	NA
Phonebooks	-2.33	0.00	NA	NA	NA
Textbooks	-2.15	0.00	NA	NA	NA
Dimensional Lumber	-0.17	0.00	NA	NA	NA
Medium-density Fiberboard	-0.36	0.00	NA	NA	NA
Food Discards	NA	0.00	0.04	-0.24	-0.20
Yard Trimmings	NA	0.00	0.04	-0.24	-0.20
Mixed Paper		0.00			
Broad Definition	1.38	0.00	NA	NA	NA
Residential Definition	1.39	0.00	NA	NA	NA
Office Paper Definition	3.12	0.00	NA	NA	NA
Mixed Plastics	1.85	0.00	NA	NA	NA
Mixed Recyclables	1.32	0.00	NA	NA	NA
Mixed Organics	NA	0.00	0.04	-0.24	-0.20
Mixed MSW (as disposed)	NA	NA	NA	NA	NA

Note that totals may not add due to rounding and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

[2] The value for mixed MSW is the weighted average of the RMAM emissions for those materials we studied.

Exhibit 8-7
Combustion
(GHG Emissions in MTCE/Ton)

Values are for Mass Burn Facilities with National Average Rate of Ferrous Recovery. Emissions Measured from a Waste Generation Reference Point[1]

	Raw Materials Acquisition and Manufacturing (RMAM)							
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h) (h = b+c+d+e+f+g)
Material	RMAM Emissions Not Included in Baseline[2]	Waste Generation Baseline	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Avoided Utility Emissions	Ferrous Recovery	Net Emissions (Post-Consumer)
Aluminum Cans	-2.49	0.00	0.01	0.00	0.00	0.01	0.00	0.02
Steel Cans	-0.79	0.00	0.01	0.00	0.00	0.01	-0.43	-0.42
Glass	-0.14	0.00	0.01	0.00	0.00	0.01	0.00	0.01
HDPE	-0.49	0.00	0.01	0.76	0.00	-0.54	0.00	0.23
LDPE	-0.61	0.00	0.01	0.76	0.00	-0.54	0.00	0.23
PET	-0.49	0.00	0.01	0.56	0.00	-0.28	0.00	0.28
Corrugated Cardboard	-0.24	0.00	0.01	0.00	0.01	-0.20	0.00	-0.19
Magazines/Third-class Mail	-0.46	0.00	0.01	0.00	0.01	-0.15	0.00	-0.13
Newspaper	-0.46	0.00	0.01	0.00	0.01	-0.23	0.00	-0.21
Office Paper	-0.31	0.00	0.01	0.00	0.01	-0.20	0.00	-0.18
Phonebooks	-0.64	0.00	0.01	0.00	0.01	-0.23	0.00	-0.21
Textbooks	-0.59	0.00	0.01	0.00	0.01	-0.20	0.00	-0.18
Dimensional Lumber	-0.05	0.00	0.01	0.00	0.01	-0.24	0.00	-0.22
Medium-density Fiberboard	-0.10	0.00	0.01	0.00	0.01	-0.24	0.00	-0.22
Food Discards	NA	0.00	0.01	0.00	0.01	-0.07	0.00	-0.05
Yard Trimmings	NA	0.00	0.01	0.00	0.01	-0.08	0.00	-0.06
Mixed Paper								
Broad Definition	0.38	0.00	0.01	0.00	0.01	-0.20	0.00	-0.19
Residential Definition	0.38	0.00	0.01	0.00	0.01	-0.20	0.00	-0.18
Office Paper Definition	0.85	0.00	0.01	0.00	0.01	-0.19	0.00	-0.17
Mixed Plastics	0.51	0.00	0.01	0.67	0.00	-0.43	0.00	0.25
Mixed Recyclables	0.36	0.00	0.01	0.02	0.01	-0.18	-0.02	-0.17
Mixed Organics	NA	0.00	0.01	0.00	0.01	-0.07	0.00	-0.06
Mixed MSW (as disposed)	NA	0.00	0.01	0.10	0.01	-0.14	-0.01	-0.04

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

[2] The value for mixed MSW is the weighted average of the RMAM emissions for those materials we studied.

Exhibit 8-8
Combustion
(GHG Emissions in $MTCO_2E$/Ton)

Values are for Mass Burn Facilities with National Average Rate of Ferrous Recovery. Emissions Measured from a Waste Generation Reference Point[1]

	Raw Materials Acquisition and Manufacturing (RMAM)							
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
								(h = b+c+d+e+f+g)
Material	**RMAM Emissions Not Included in Baseline[2]**	**Waste Generation Baseline**	**Transportation to Combustion**	**CO_2 from Combustion**	**N_2O from Combustion**	**Avoided Utility Emissions**	**Ferrous Recovery**	**Net Emissions (Post-Consumer)**
Aluminum Cans	-9.15	0.00	0.03	0.00	0.00	0.04	0.00	0.06
Steel Cans	-2.89	0.00	0.03	0.00	0.00	0.02	-1.58	-1.53
Glass	-0.50	0.00	0.03	0.00	0.00	0.02	0.00	0.05
HDPE	-1.79	0.00	0.03	2.79	0.00	-1.97	0.00	0.85
LDPE	-2.25	0.00	0.03	2.79	0.00	-1.97	0.00	0.85
PET	-1.78	0.00	0.03	2.04	0.00	-1.02	0.00	1.04
Corrugated Cardboard	-0.88	0.00	0.03	0.00	0.04	-0.74	0.00	-0.68
Magazines/Third-class Mail	-1.69	0.00	0.03	0.00	0.04	-0.55	0.00	-0.49
Newspaper	-1.69	0.00	0.03	0.00	0.04	-0.84	0.00	-0.77
Office Paper	-1.13	0.00	0.03	0.00	0.04	-0.72	0.00	-0.65
Phonebooks	-2.33	0.00	0.03	0.00	0.04	-0.84	0.00	-0.77
Textbooks	-2.15	0.00	0.03	0.00	0.04	-0.72	0.00	-0.65
Dimensional Lumber	-0.17	0.00	0.03	0.00	0.04	-0.87	0.00	-0.81
Medium-density Fiberboard	-0.36	0.00	0.03	0.00	0.04	-0.87	0.00	-0.81
Food Discards	NA	0.00	0.03	0.00	0.04	-0.25	0.00	-0.19
Yard Trimmings	NA	0.00	0.03	0.00	0.04	-0.30	0.00	-0.23
Mixed Paper								
Broad Definition	1.38	0.00	0.03	0.00	0.04	-0.74	0.00	-0.68
Residential Definition	1.39	0.00	0.03	0.00	0.04	-0.74	0.00	-0.68
Office Paper Definition	3.12	0.00	0.03	0.00	0.04	-0.68	0.00	-0.62
Mixed Plastics	1.85	0.00	0.03	2.47	0.00	-1.56	0.00	0.93
Mixed Recyclables	1.32	0.00	0.03	0.06	0.03	-0.67	-0.06	-0.61
Mixed Organics	NA	0.00	0.03	0.00	0.04	-0.27	0.00	-0.21
Mixed MSW (as disposed)	NA	0.00	0.03	0.37	0.04	-0.53	-0.04	-0.13

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

[2] The value for mixed MSW is the weighted average of the RMAM emissions for those materials we studied.

Exhibit 8-9
Landfilling
(GHG Emissions in MTCE/Ton)

Values for Landfill Methane and Net Emissions Reflect Projected National Average Methane Recovery in year 2000. Emissions Measured from a Waste Generation Reference Point[1]

	Raw Materials Acquisition and Manufacturing (RMAM)					
	(a)	(b)	(c)	(d)	(e)	(f) (f=b+c+d+e)
Material	RMAM Emissions Not Included in Baseline[2]	Waste Generation Baseline	Transportation to Landfill	Net Landfill CH_4	Landfill Carbon Sequestration	Net Emissions
Aluminum Cans	2.49	0.00	0.01	0.00	0.00	0.01
Steel Cans	0.79	0.00	0.01	0.00	0.00	0.01
Glass	0.14	0.00	0.01	0.00	0.00	0.01
HDPE	0.49	0.00	0.01	0.00	0.00	0.01
LDPE	0.61	0.00	0.01	0.00	0.00	0.01
PET	0.49	0.00	0.01	0.00	0.00	0.01
Corrugated Cardboard	0.24	0.00	0.01	0.31	-0.22	0.09
Magazines/Third-class Mail	0.46	0.00	0.01	0.17	-0.29	-0.11
Newspaper	0.46	0.00	0.01	0.15	-0.36	-0.20
Office Paper	0.31	0.00	0.01	0.69	-0.04	0.66
Phonebooks	0.64	0.00	0.01	0.15	-0.36	-0.20
Textbooks	0.59	0.00	0.01	0.69	-0.04	0.66
Dimensional Lumber	0.05	0.00	0.01	0.10	-0.21	-0.10
Medium-density Fiberboard	0.10	0.00	0.01	0.10	-0.21	-0.10
Food Discards	NA	0.00	0.01	0.19	-0.02	0.18
Yard Trimmings	NA	0.00	0.01	0.11	-0.21	-0.09
Mixed Paper						
Broad Definition	0.38	0.00	0.01	0.33	-0.23	0.12
Residential Definition	0.38	0.00	0.01	0.31	-0.24	0.08
Office Paper Definition	0.85	0.00	0.01	0.37	-0.21	0.17
Mixed Plastics	0.51	0.00	0.01	0.00	0.00	0.01
Mixed Recyclables	0.36	0.00	0.01	0.26	-0.21	0.06
Mixed Organics	NA	0.00	0.01	0.15	-0.12	0.04
Mixed MSW (as disposed)	NA	0.00	0.01	0.16	-0.10	0.07

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

[2] The value for mixed MSW is the weighted average of the RMAM emissions for those materials we studied.

Exhibit 8-10

Landfilling

(GHG Emissions in $MTCO_2E$/Ton)

Values for Landfill Methane and Net Emissions Reflect Projected National Average Methane Recovery in year 2000. Emissions Measured from a Waste Generation Reference Point[1]

	Raw Materials Acquisition and Manufacturing (RMAM)					
	(a)	(b)	(c)	(d)	(e)	(f)
						(f=b+c+d+e)
Material	RMAM Emissions Not Included in Baseline[2]	Waste Generation Baseline	Transportation to Landfill	Net Landfill CH_4	Landfill Carbon Sequestration	Net Emissions
Aluminum Cans	9.15	0.00	0.04	0.00	0.00	0.04
Steel Cans	2.89	0.00	0.04	0.00	0.00	0.04
Glass	0.50	0.00	0.04	0.00	0.00	0.04
HDPE	1.79	0.00	0.04	0.00	0.00	0.04
LDPE	2.25	0.00	0.04	0.00	0.00	0.04
PET	1.78	0.00	0.04	0.00	0.00	0.04
Corrugated Cardboard	0.88	0.00	0.04	1.12	-0.82	0.34
Magazines/Third-class Mail	1.69	0.00	0.04	0.61	-1.07	-0.41
Newspaper	1.69	0.00	0.04	0.54	-1.32	-0.74
Office Paper	1.13	0.00	0.04	2.52	-0.16	2.40
Phonebooks	2.33	0.00	0.04	0.54	-1.32	-0.74
Textbooks	2.15	0.00	0.04	2.52	-0.16	2.40
Dimensional Lumber	0.17	0.00	0.04	0.35	-0.76	-0.37
Medium-density Fiberboard	0.36	0.00	0.04	0.35	-0.76	-0.37
Food Discards	NA	0.00	0.04	0.70	-0.08	0.66
Yard Trimmings	NA	0.00	0.04	0.40	-0.76	-0.33
Mixed Paper						
Broad Definition	1.38	0.00	0.04	1.22	-0.83	0.43
Residential Definition	1.39	0.00	0.04	1.13	-0.87	0.30
Office Paper Definition	3.12	0.00	0.04	1.35	-0.76	0.63
Mixed Plastics	1.85	0.00	0.04	0.00	0.00	0.04
Mixed Recyclables	1.32	0.00	0.04	0.95	-0.75	0.24
Mixed Organics	NA	0.00	0.04	0.54	-0.43	0.15
Mixed MSW (as disposed)	NA	0.00	0.04	0.60	-0.37	0.27

Note that totals may not add due to rounding and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

[2] The value for mixed MSW is the weighted average of the RMAM emissions for those materials we studied.

Exhibit 8-11

Net GHG Emissions from Source Reduction and MSW Management Options (MTCE/Ton)

Emissions Measured from a Waste Generation Reference Point[1]

Material	Source Reduction[2]	Recycling	Composting	Combustion[3]	Landfilling[4]
Aluminum Cans	-2.49	-4.11	NA	0.02	0.01
Steel Cans	-0.79	-0.49	NA	-0.42	0.01
Glass	-0.14	-0.08	NA	0.01	0.01
HDPE	-0.49	-0.38	NA	0.23	0.01
LDPE	-0.61	-0.47	NA	0.23	0.01
PET	-0.49	-0.42	NA	0.28	0.01
Corrugated Cardboard	-0.51	-0.71	NA	-0.19	0.08
Magazines/Third-class Mail	-1.04	-0.74	NA	-0.13	-0.12
Newspaper	-0.81	-0.95	NA	-0.21	-0.21
Office Paper	-0.80	-0.68	NA	-0.18	0.62
Phonebooks	-1.28	-0.91	NA	-0.21	-0.21
Textbooks	-1.23	-0.75	NA	-0.18	0.62
Dimensional Lumber	-0.55	-0.67	NA	-0.22	-0.10
Medium-density Fiberboard	-0.60	-0.67	NA	-0.22	-0.10
Food Discards	NA	NA	-0.05	-0.05	0.17
Yard Trimmings	NA	NA	-0.05	-0.06	-0.09
Mixed Paper					
Broad Definition	NA	-0.67	NA	-0.19	0.10
Residential Definition	NA	-0.67	NA	-0.18	0.07
Office Paper Definition	NA	-0.83	NA	-0.17	0.15
Mixed Plastics	NA	-0.41	NA	0.25	0.01
Mixed Recyclables	NA	-0.76	NA	-0.17	0.05
Mixed Organics	NA	NA	-0.05	-0.06	0.03
Mixed MSW (as disposed)	NA	NA	NA	-0.04	0.07

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

[2] Source reduction assumes displacement of current mix of virgin and recycled inputs.

[3] Values are for mass burn facilities with national average rate of ferrous recovery.

[4] Values reflect projected national average methane recovery in year 2000.

Exhibit 8-12
Net GHG Emissions from Source Reduction and MSW Management Options ($MTCO_2E$/Ton)

Emissions Measured from a Waste Generation Reference Point[1]

Material	Source Reduction[2]	Recycling	Composting	Combustion[3]	Landfilling[4]
Aluminum Cans	-9.15	-15.07	NA	0.06	0.04
Steel Cans	-2.89	-1.79	NA	-1.53	0.04
Glass	-0.50	-0.28	NA	0.05	0.04
HDPE	-1.79	-1.40	NA	0.85	0.04
LDPE	-2.25	-1.71	NA	0.85	0.04
PET	-1.78	-1.55	NA	1.04	0.04
Corrugated Cardboard	-1.89	-2.60	NA	-0.68	0.28
Magazines/Third-class Mail	-3.80	-2.70	NA	-0.49	-0.44
Newspaper	-2.97	-3.48	NA	-0.77	-0.76
Office Paper	-2.95	-2.48	NA	-0.65	2.28
Phonebooks	-4.70	-3.34	NA	-0.77	-0.76
Textbooks	-4.49	-2.74	NA	-0.65	2.28
Dimensional Lumber	-2.01	-2.45	NA	-0.81	-0.38
Medium-density Fiberboard	-2.20	-2.47	NA	-0.81	-0.38
Food Discards	NA	NA	-0.20	-0.19	0.62
Yard Trimmings	NA	NA	-0.20	-0.23	-0.34
Mixed Paper					
Broad Definition	NA	-2.47	NA	-0.68	0.37
Residential Definition	NA	-2.47	NA	-0.68	0.25
Office Paper Definition	NA	-3.05	NA	-0.62	0.56
Mixed Plastics	NA	-1.51	NA	0.93	0.04
Mixed Recyclables	NA	-2.80	NA	-0.61	0.19
Mixed Organics	NA	NA	-0.20	-0.21	0.12
Mixed MSW (as disposed)	NA	NA	NA	-0.13	0.24

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

[2] Source reduction assumes displacement of current mix of virgin and recycled inputs.

[3] Values are for mass burn facilities with national average rate of ferrous recovery.

[4] Values reflect projected national average methane recovery in year 2000.

Exhibit 8-13
Net GHG Emissions of MSW Management Options Compared to Landfilling[1]
(MTCE/Ton)

Negative values indicate emission reductions.

	Source Reduction Net Emissions Minus Landfilling Net Emissions		Recycling Net Emissions Minus Landfilling Net Emissions	Composting Net Emissions Minus Landfilling Net Emissions	Combustion[2] Net Emissions Minus Landfilling Net Emissions
Material	**Current Mix of Inputs**	**100% Virgin Inputs**			
Aluminum Cans	-2.50	-4.68	-4.12	NA	0.01
Steel Cans	-0.80	-1.02	-0.50	NA	-0.43
Glass	-0.15	-0.17	-0.09	NA	0.00
HDPE	-0.50	-0.54	-0.39	NA	0.22
LDPE	-0.63	-0.65	-0.48	NA	0.22
PET	-0.50	-0.59	-0.43	NA	0.27
Corrugated Cardboard	-0.59	-1.03	-0.79	NA	-0.26
Magazines/Third-class Mail	-0.92	-1.07	-0.62	NA	-0.01
Newspaper	-0.60	-1.11	-0.74	NA	0.00
Office Paper	-1.43	-1.63	-1.30	NA	-0.80
Phonebooks	-1.07	-1.19	-0.70	NA	0.00
Textbooks	-1.85	-1.94	-1.37	NA	-0.80
Dimensional Lumber	-0.44	-0.44	-0.56	NA	-0.12
Medium-density Fiberboard	-0.50	-0.50	-0.57	NA	-0.12
Food Discards	NA	NA	NA	-0.22	-0.22
Yard Trimmings	NA	NA	NA	0.04	0.03
Mixed Paper					
Broad Definition	NA	NA	-0.78	NA	-0.29
Residential Definition	NA	NA	-0.74	NA	-0.25
Office Paper Definition	NA	NA	-0.99	NA	-0.32
Mixed Plastics	NA	NA	-0.42	NA	0.24
Mixed Recyclables	NA	NA	-0.82	NA	-0.22
Mixed Organics	NA	NA	NA	-0.09	-0.09
Mixed MSW (as disposed)	NA	NA	NA	NA	-0.10

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Values for landfilling reflect projected national average methane recovery in year 2000.

[2] Values are for mass burn facilities with national average rate of ferrous recovery.

Exhibit 8-14

Net GHG Emissions of MSW Management Options Compared to Landfilling[1] (MTCO_2E/Ton)

Negative values indicate emission reductions.

	Source Reduction Net Emissions Minus Landfilling Net Emissions		Recycling Net Emissions Minus Landfilling Net Emissions	Composting Net Emissions Minus Landfilling Net Emissions	Combustion[2] Net Emissions Minus Landfilling Net Emissions
Material	Current Mix of Inputs	100% Virgin Inputs			
Aluminum Cans	-9.18	-17.15	-15.11	NA	0.02
Steel Cans	-2.92	-3.72	-1.83	NA	-1.57
Glass	-0.54	-0.61	-0.32	NA	0.01
HDPE	-1.82	-1.99	-1.44	NA	0.81
LDPE	-2.29	-2.38	-1.75	NA	0.81
PET	-1.82	-2.18	-1.59	NA	1.00
Corrugated Cardboard	-2.17	-3.79	-2.88	NA	-0.96
Magazines/Third-class Mail	-3.36	-3.94	-2.26	NA	-0.05
Newspaper	-2.21	-4.07	-2.72	NA	-0.01
Office Paper	-5.23	-5.99	-4.77	NA	-2.94
Phonebooks	-3.94	-4.37	-2.57	NA	-0.01
Textbooks	-6.78	-7.13	-5.03	NA	-2.94
Dimensional Lumber	-1.63	-1.63	-2.07	NA	-0.43
Medium-density Fiberboard	-1.82	-1.82	-2.09	NA	-0.43
Food Discards	NA	NA	NA	-0.82	-0.81
Yard Trimmings	NA	NA	NA	0.15	0.11
Mixed Paper					
Broad Definition	NA	NA	-2.84	NA	-1.06
Residential Definition	NA	NA	-2.72	NA	-0.93
Office Paper Definition	NA	NA	-3.62	NA	-1.18
Mixed Plastics	NA	NA		NA	0.90
Mixed Recyclables	NA	NA	-2.99	NA	-0.80
Mixed Organics	NA	NA	NA	-0.32	-0.33
Mixed MSW (as disposed)	NA	NA	NA	NA	-0.38

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[1] Values for landfilling reflect projected national average methane recovery in year 2000.

[2] Values are for mass burn facilities with national average rate of ferrous recovery.