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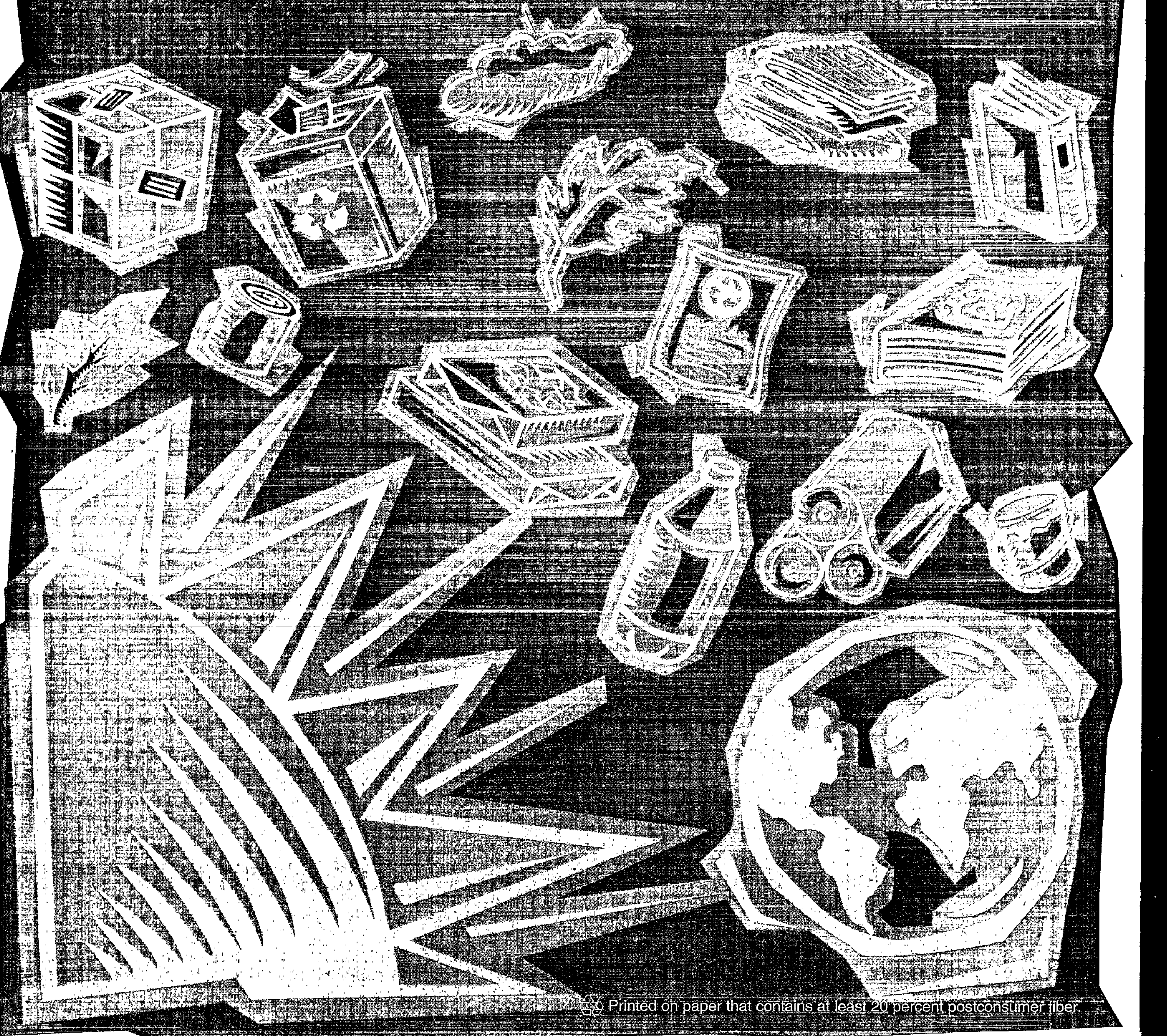
Greenhouse Gas Emissions From Management of Selected Materials in Municipal Solid Waste



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GREENHOUSE GAS EMISSIONS FROM MANAGEMENT OF SELECTED MATERIALS IN MUNICIPAL SOLID WASTE

FINAL REPORT

Prepared for the U.S. Environmental Protection Agency
under EPA Contract No. 68-W6-0029

September 1998

TABLE OF CONTENTS

BACKGROUND DOCUMENTS (Available in the docket in the RCRA Information Center)
DOCUMENT A - BACKGROUND DATA SUBMITTED BY FRANKLIN ASSOCIATES, Ltd.
ATTACHMENT 1 - A PARTIAL LIFE CYCLE INVENTORY OF PROCESS AND TRANSPORTATION ENERGY FOR BOXBOARD AND PAPER TOWELS
DOCUMENT B - BACKGROUND DATA SUBMITTED BY THE TELLUS INSTITUTE
DOCUMENT C - REVIEW PROCESS FOR THE REPORT
DOCUMENT D - COMMENT-RESPONSE DOCUMENT

EXECUTIVE SUMMARY: BACKGROUND AND FINDINGS

An important environmental challenge facing the United States (US) is management of municipal solid waste (MSW). In 1996, the US generated 210 million tons of MSW;[1] per-capita MSW generation rates have risen throughout most of the last decade. At the same time, the US recognizes climate change as a potentially serious issue, and is embarking on a number of actions to reduce the emissions of greenhouse gases (GHGs) that can cause it. This report examines how the two issues – MSW management and climate change – are related, by presenting material-specific GHG emission factors for various waste management options.

Among the efforts to slow the potential for climate change are measures to reduce emissions of carbon dioxide from energy use, reduce methane emissions, and change forestry practices to promote long-term storage of carbon in trees. Different management options for MSW provide many opportunities to affect these same processes, directly or indirectly. This report integrates, for the first time, a wealth of information on GHG implications of various MSW management options for some of the most common materials in MSW and for mixed MSW and mixed recyclables. The report's findings may be used to support 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, traps radiant heat from the Earth and helps warm the planet to a comfortable, livable temperature range. Without this natural "greenhouse effect," the average temperature on Earth would be approximately 5 degrees Fahrenheit, rather than the current 60 degrees Fahrenheit.[3]

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[1] U.S. EPA Office of Solid Waste, *Characterization of Municipal Solid Waste in the United States: 1997 Update*, EPA 530-R-9-001, p. 26.

[2] For more detailed information on climate change, please see *The Draft 1998 Inventory of US Greenhouse Gas Emissions and Sinks: 1990-1996*, (http://www.epa.gov/globalwarming/inventory/1998-inv.html) (March 1998); and *Climate Change 1995: The Science of Climate Change* (J.T. Houghton, *et al.*, eds.; Intergovernmental Panel on Climate Change [IPCC]; published by Cambridge University Press, 1996). To obtain a list of additional documents addressing climate change, call EPA's Climate Change "FAX on Demand" at (202) 260-2860 or access EPA's global warming web site at www.epa.gov/globalwarming.

[3] *Climate Change 1995: The Science of Climate Change* (*op. cit.*), pp. 57-58.

Many scientists, however, are alarmed by a significant increase in the concentration of carbon dioxide and other GHGs in the atmosphere. Since the pre-industrial era, atmospheric concentrations of carbon dioxide have increased by nearly 30 percent and methane concentrations have more than doubled. There is a growing international scientific consensus that this increase has been caused, at least in part, by human activity, primarily the burning of fossil fuels (coal, oil, and natural gas) for such activities as generating electricity and driving cars.[4]

Moreover, there is a growing consensus in international scientific circles that the buildup of carbon dioxide 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) impacts to ecosystems and possible loss in biological diversity, and (5) agricultural shifts such as impacts on crop yields and productivity. Although it is difficult to reliably detect trends in climate due to natural variability, the best current predictions suggest that the rate of climate change attributable to GHGs will far exceed any natural climate changes that have occurred during the last 10,000 years.[5]

Many of these changes appear to be occurring already. Global mean surface temperatures have already 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 have all been documented.[6]

Such important environmental changes pose potentially significant risks to humans, social systems, and the natural world. Of course, 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 the 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 is to stabilize GHG concentrations in the atmosphere at a level, and over a time frame, that will minimize man-made climate disruptions.

By signing the Convention, countries make a voluntary commitment to reduce GHGs or take other actions to stabilize emissions of GHGs at 1990 levels. All parties to the Convention are also required to develop, and periodically update, national inventories of their GHG emissions. The US ratified the Convention in October 1992. One year later, President Clinton issued the US *Climate Change Action Plan* (CCAP), which called for cost-effective domestic

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[4] *Ibid.*, pp. 3-5.

[5] *Ibid.*, pp. 6, 29-30, 156, and 371-372.

[6] *Ibid.*, pp. 26, 29-30, 156, and 171.

actions and voluntary cooperation with states, local governments, industry, and citizens to reduce GHG emissions.

Countries that ratified the Framework Convention on Climate Change met in Kyoto, Japan in December 1997, where they agreed to reduce global greenhouse gas emissions and set binding targets for developed nations. (For example, the emissions target for the US would be 7 percent below 1990 levels.) As of the publication of this report, the Kyoto agreement remains to be signed by the President and ratified by the US Senate; meanwhile, EPA continues to promote voluntary measures to reduce GHG emissions begun under the CCAP. The countries that ratified the Framework Convention will meet again in Buenos Aires in November, 1998, where the US will attempt to secure meaningful participation by developing countries.

The CCAP outlines over 50 voluntary initiatives to reduce GHG emissions in the US. One of the initiatives calls for *accelerated source reduction and recycling of municipal solid waste* through combined efforts by EPA, the Department of Energy, and the Department of Agriculture. Another waste related initiative is the Landfill Methane Outreach Program, which aims to reduce landfill methane emissions by facilitating the development of landfill gas utilization projects.[7]

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

What does municipal solid waste have to do with rising sea levels, higher temperatures, and GHG emissions? For many wastes, the materials that we dispose represent what is left over after a long series of steps including: (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.

At virtually every step along this "life cycle," the potential exists for GHG impacts. Waste management affects 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 carbon dioxide released when limestone is converted to lime (which is needed for aluminum and steel manufacturing).

(3) Methane 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 time periods or permanently. A store of sequestered carbon (e.g., a forest or coal deposit) is known as a carbon sink.

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[7] The Landfill Methane Outreach Program is a voluntary partnership between the EPA, state agencies, landfill gas-to-energy developers and energy users. The program has an Internet home page (http://www.epa.gov/landfill.html), and can be reached via a toll-free hotline number (1-800-782-7937).

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

Different wastes and waste management options have different implications for energy consumption, methane 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 WILL BE 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 CCAP. At that time, EPA estimated that its portion of the source reduction and recycling initiative could reduce annual GHG emissions by roughly 5.6 million metric tons of carbon equivalent (MTCE) by the year 2000, or about 5 percent of the overall goal of the Action Plan. To make these projections, EPA used limited data on energy consumption and forest carbon sequestration to estimate how a 5 percent increase in both source reduction and recycling would affect GHG emissions in 2000.

It was clear then that a rigorous analysis would be needed to more accurately gauge the total GHG emission reductions achievable through source reduction and recycling. Moreover, it was clear that all of the options for managing MSW should be considered. 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, the Office of Policy and the Office of Solid Waste launched a major research effort.

This research effort has been guided by contributions from many reviewers participating in three review cycles (as described in Background Document C). The first draft report was reviewed in 1995 by 20 EPA analysts from four offices (Air and Radiation; Policy; Research and Development; and Solid Waste) as well as analysts from the US Department of Energy and US Department of Agriculture, Forest Service. Comments resulting from these reviews were incorporated into a second draft of the report, completed in May 1996.

The 1996 draft was distributed to four researchers with academic and consulting backgrounds for a more intensive, external peer review. Based on their comments, another draft of the report was completed in March of 1997.

In March, 1997, EPA published the draft research in a report entitled *Greenhouse Gas Emissions from Municipal Waste Management: Draft Working Paper* (EPA530-R-97-010). As described in an accompanying Federal Register notice, public comment was solicited on the draft working paper.

This final report reflects comments from 23 individuals, representing trade associations, universities, industry, state offices, EPA offices, and other entities. Among the groups that provided detailed comments were:

- The American Forest and Paper Association,
- The American Plastics Council,
- The Steel Recycling Institute,
- The Integrated Waste Services Association,
- The Minnesota Office of Environmental Assistance, and
- The Missouri Department of Natural Resources.

Each comment on the draft working paper is specifically discussed in a comment response document, which is available in the public docket (F-97-GGEA-FFFFF). For each comment received, the comment response document summarizes both the comment and EPA's response. Among the changes made as a result of this review, EPA

- added two materials to the analysis—mixed paper and glass,
- revised system efficiencies for waste combustors, and provided a separate characterization of refuse-derived fuel (RDF) as a category of combustion,
- based GHG reductions from displaced electricity on GHGs from fossil-fuel-fired generation, rather than from the national average mix of fuels.

Each of these changes is discussed in more detail later in this report. In addition, this report updates many of the inputs to the calculations (such as the global warming potential for various greenhouse gases), and uses more recent information on waste composition and recycling rates.

The primary application of the GHG emission factors in this report is to support climate change mitigation accounting for waste management practices. Organizations interested in quantifying and voluntarily reporting GHG emission reductions associated with waste management practices may use these emission factors for that purpose. In conjunction with the Department of Energy, EPA has used these emission factors to develop guidance for voluntary reporting of GHG reductions, as authorized by Congress in Section 1605 (b) of the Energy Policy Act of 1992. EPA also plans to use these emission factors to evaluate its progress in reducing US GHG emissions—by promoting source reduction and recycling through voluntary programs such as WasteWi$e and Pay-as-You-Throw (PAYT)—as part of the US CCAP. The methodology presented in this report may also assist other countries involved in developing GHG emissions estimates for their solid waste streams.[8]

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

To measure the GHG impacts of municipal solid waste (MSW), one must first decide which wastes to analyze. We surveyed the universe of materials and products found in MSW and determined which were most likely to have the greatest impact on GHGs. These determinations were based on (1) the quantity generated, (2) differences in energy use for manufacturing a product from virgin versus recycled inputs, and (3) the potential contribution of materials to methane generation in landfills. By this process, we limited the analysis to the following 11 items:

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[8] 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.

- newspaper,
- office paper,
- corrugated cardboard,
- aluminum cans,
- steel cans,
- glass containers,
- HDPE (high density polyethylene) plastic,
- LDPE (low density polyethylene) plastic,
- PET (polyethylene terephthalate) plastic,
- food scraps, and
- yard trimmings.

The foregoing materials constitute 55 percent, by weight, of municipal solid waste, as shown in Exhibit ES-1.[9] We also examined the GHG implications of managing mixed MSW, mixed recyclables, and mixed paper.

Exhibit ES-1
Percentage of 1996 US Generation of MSW for Materials in This Report

Material	Percentage of MSW Generation (by Weight)
Newspaper	5.9%
Office paper	3.2%
Corrugated cardboard	13.8%
Aluminum cans	0.8%
Steel cans	1.3%
Glass containers	5.3%
HDPE plastic*	0.6%
LDPE plastic*	0.01%
PET plastic*	0.5%
Food scraps	10.4%
Yard trimmings	13.4%
TOTAL	55%

Source: Franklin Associates, Ltd., *Characterization of Municipal Solid Waste in the United States: 1997 Update*. EPA 530-R-98-007 (May 1998)
* Based on blow-molded containers.

- *Mixed MSW* is comprised of the waste material typically discarded by households and collected by curbside collection vehicles; it does not include white goods or industrial waste. This report analyzes mixed MSW on an "as disposed" (rather than "as generated") basis.
- *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 scraps 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 are recycled.
- *Mixed paper* is recycled in large quantities, and is an important class of scrap material in many recycling programs. However, it is difficult to present a single definition of mixed paper because each mill using recovered paper defines its own supply which varies with the availability and price of different grades of paper. Therefore, for purposes of this report, we identified three different definitions for

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[9] 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. In recognition of the variability in local conditions, EPA is developing the WAste Reduction Model (WARM), which may be used to estimate the GHG emissions of MSW management actions on a local and state level. For more information on the WARM model, contact the RCRA Hotline at 1-800-424-9346.

mixed paper according to their dominant source—broad (general sources), office, and residential.

Next, 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.[10]

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, 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 change in forest carbon sequestration);
- manufacturing (fossil fuel energy emissions); and
- waste management (carbon dioxide emissions associated with combustion and methane emissions from landfills; these emissions are offset to some degree by avoided utility fossil fuel use and carbon sequestration in landfills).

At each of these points, we also considered transportation-related energy emissions.

GHG emissions associated with electricity used in the raw materials acquisition and manufacturing steps are estimated based on the current mix of energy sources, including fossil fuels, hydropower, and nuclear power. However, estimates of GHG emission reductions attributable to utility emissions avoided from waste management practices are based solely on the reduction of fossil fuel use.[11]

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, one could compare a baseline scenario, where 10 tons of office paper is manufactured, used, and landfilled, to an alternative scenario, where 10 tons is manufactured, used, and recycled.

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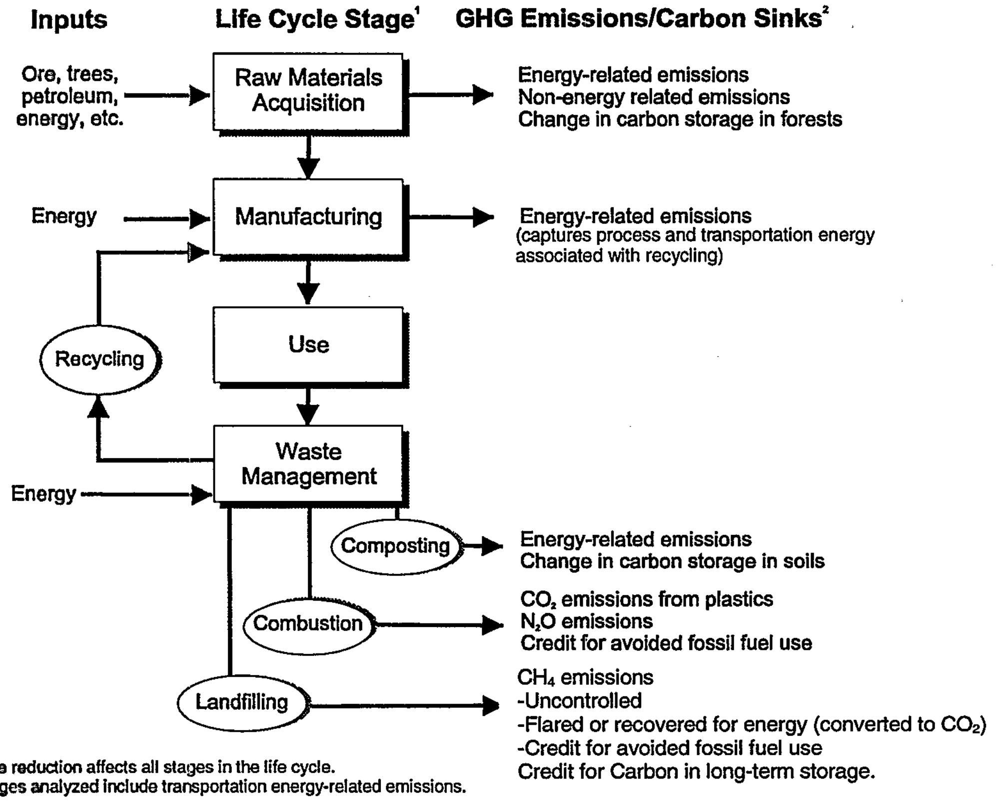
[10] EPA's Office of Research and Development (ORD) is performing a more extensive application of life cycle assessment for various waste management options for MSW. ORD's analysis will inventory a broader set of emissions (air, water, and waste) associated with these options. For more information on this effort, go to their project website at http://www.epa.gov/docs/crb/apb/apb.htm.

[11] We adopted this approach based on suggestions from several commenters 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
GHG Sources and Sinks Associated with Materials in the MSW Stream



[1] Note that source reduction affects all stages in the life cycle.
[2] All life cycle stages analyzed include transportation energy-related emissions.

In calculating emissions for the scenarios, two different reference points can be used:

- With a "raw material extraction" reference point (i.e., cradle-to-grave perspective), one can start at the point of raw material acquisition as the "zero point" for emissions, and add all emissions (and deduct sinks) from that point on through the life cycle.
- With a "waste generation" reference point (solid waste manager's perspective), one can begin accounting for GHG emissions at the point of waste generation. All subsequent emissions and sinks from waste management practices are then 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) impact these processes.

When developing an emission factor to account for GHG emissions from a waste management activity, the key question to ask is "What is the baseline management practice?" Because it is the difference in emissions between the baseline and alternate scenarios that is meaningful, using raw material extraction or waste generation reference points yields the same results. The March 1997 Draft Working Paper used the raw material extraction reference point to display GHG emissions because it is most consistent with standard life cycle inventory accounting techniques. Several commenters 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 more clarity for evaluating waste management options. Thus, this report uses the waste generation approach, and defines a 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. This standard raw material acquisition and manufacturing step is used to estimate the upstream impacts of source reduction and recycling.

Exhibit ES-3 shows how the GHG sources and sinks are affected by each waste management strategy using the waste generation reference point. For example, the top row of the exhibit shows that source reduction[12] (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.

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[12] 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, please see section 4.3.

Exhibit ES-3
Components of Net Emissions for Various Municipal Solid Waste Management Strategies

Municipal Solid Waste Management Strategy	Greenhouse Gas Sources and Sinks		
	Raw Materials Acquisition and Manufacturing	Change in Forest or Soil Carbon Storage	Waste Management
Source Reduction	Decrease in GHG emissions, relative to the baseline of manufacturing	Increase in forest carbon storage	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 storage	Process and transportation emissions associated with recycling are counted in the manufacturing stage
Composting (food scraps, yard trimmings)	No emissions/sinks	Increase in soil carbon storage	Compost machinery emissions and transportation emissions
Combustion	No change	No change	Nonbiogenic CO_2, N_2O emissions, avoided utility emissions, and transportation emissions
Landfilling	No change	No change	Methane 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 storage, and avoid landfill methane emissions. When waste is combusted, energy recovery displaces fossil fuel-generated electricity from utilities (thus reducing GHG emissions from the utility sector), and landfill methane emissions are avoided. Landfill methane emissions can be reduced by using gas recovery systems and by diverting organic materials from the landfill.

In order to support a broad portfolio of climate change mitigation activities covering a broad scope of greenhouse gases, many different emission estimation methodologies will need to be employed. The primary result of this research is the development of material-specific GHG emission factors which can be used to account for the climate change benefits of waste management practices. A spreadsheet accounting tool, the Waste Reduction Model (WARM), is being developed to allow for customizing of emission factors based on key variables which may better reflect local conditions.

Exhibit ES-4 presents the GHG impacts of source reduction, recycling, composting, combustion, and landfilling, on a per-ton managed basis, for the individual materials, mixed waste, and mixed recyclables, using the waste generation reference point. For comparison, Exhibit ES-5 shows the same results, using the raw material extraction reference point. In these tables, emissions for one ton of a given material are presented across different management options.[13] 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 Exhibit ES-6. This exhibit shows the GHG values for each of the first four management strategies, minus the GHG values for landfilling. With this exhibit, one may compare the GHG emissions of changing management of one 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 Exhibit ES-4 through ES-6 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 willdiffer from those summarized here.

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

- Source reduction, generally speaking, represents an opportunity to reduce GHG emissions in a significant way.[14] 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 all other options.
- Recycling generally has the second lowest GHG emissions. For most materials, recycling reduces enery-related CO_2 emissions in the manufacturing process (although not as dramatically as source reduction) and avoids emissions from waste management. Paper recycling increase storage of forest carbon.

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[13] 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.

[14] 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]
Newspaper	-0.91	-0.86	NA	-0.22	-0.23
Office Paper	-1.03	-0.82	NA	-0.19	0.53
Corrugated Cardboard	-0.78	-0.70	NA	-0.19	0.04
Mixed Paper					
Broad Definition	NA	-0.67	NA	-0.19	0.06
Residential Definition	NA	-0.67	NA	-0.19	0.03
Office Paper Definition	NA	-0.84	NA	-0.18	0.10
Aluminum Cans	-2.98	-3.88	NA	0.03	0.01
Steel Cans	-0.84	-0.57	NA	-0.48	0.01
Glass	-0.14	-0.08	NA	0.02	0.01
HDPE	-0.61	-0.37	NA	0.21	0.01
LDPE	-0.89	-0.49	NA	0.21	0.01
PET	-0.98	-0.62	NA	0.24	0.01
Food Scraps	NA	NA	0.00	-0.05	0.15
Yard Trimmings	NA	NA	0.00	-0.07	-0.11
Mixed MSW as Disposed	NA	NA	NA	-0.04	-0.02
Mixed Recyclables	NA	-0.76	NA	-0.18	0.03

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 projected national average methane recovery in year 2000.

Exhibit ES-5

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]
Newspaper	-0.43	-0.38	NA	0.26	0.25
Office Paper	-0.50	-0.30	NA	0.34	1.06
Corrugated Cardboard	-0.38	-0.30	NA	0.21	0.44
Mixed Paper					
Broad Definition	NA	-0.21	NA	0.26	0.51
Residential Definition	NA	-0.22	NA	0.26	0.48
Office Paper Definition	NA	-0.33	NA	0.33	0.61
Aluminum Cans	0.00	-0.90	NA	3.01	3.00
Steel Cans	0.00	0.26	NA	0.35	0.85
Glass	0.00	0.06	NA	0.17	0.15
HDPE	0.00	0.24	NA	0.81	0.62
LDPE	0.00	0.40	NA	1.10	0.90
PET	0.00	0.36	NA	1.21	0.99
Food Waste	NA	NA	-0.00	-0.05	0.15
Yard Waste	NA	NA	0.00	-0.07	-0.11
Mixed MSW as Disposed	NA	NA	NA	-0.04	-0.02
Mixed Recyclables	NA	-0.26	NA	0.33	0.53

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 food waste, yard waste, and mixed MSW.

Exhibit ES-6

Greenhouse Gas Emissions of MSW Management Options Compared to Landfilling[1]

(MTCE/Ton)

Material	Source Reduction[2] Net Emissions Minus Landfilling Net Emissions	Recycling Net Emissions Minus Landfilling Net Emissions	Composting[3] Net C Minus Landfilling Net Emissions	Combustion[4] Net Emissions Minus Landfilling Net Emissions
Newspaper	-0.68	-0.63	NA	0.01
Office Paper	-1.56	-1.35	NA	-0.72
Corrugated Cardboard	-0.82	-0.74	NA	-0.23
Mixed Paper				
Broad Definition	NA	-0.73	NA	-0.25
Residential Definition	NA	-0.69	NA	-0.22
Office Paper Definition	NA	-0.95	NA	-0.28
Aluminum Cans	-3.00	-3.89	NA	0.02
Steel Cans	-0.85	-0.58	NA	-0.49
Glass	-0.15	-0.09	NA	0.01
HDPE	-0.62	-0.38	NA	0.20
LDPE	-0.90	-0.51	NA	0.20
PET	-0.99	-0.63	NA	0.22
Food Scraps	NA	NA	-0.15	-0.20
Yard Trimmings	NA	NA	0.11	0.04
Mixed MSW as Disposed	NA	NA	NA	-0.02
Mixed Recyclables	NA	-0.79	NA	-0.20

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.

- Composting is a management option for food scraps and yard trimmings. The net GHG emissions from composting are lower than landfilling for food scraps (composting avoids methane emissions), and higher than landfilling for yard trimmings (landfilling is credited with the carbon storage that results from failure of certain yard trimmings to degrade fully in landfills). Overall, given the uncertainty in the analysis, the emission factors for composting or combusting these materials are similar.

- The net GHG emissions from combustion and landfilling are similar for mixed MSW. Because, in practice, combustors and landfills manage a mixed wastestream, net emissions are determined more by technology factors (e.g., landfill gas collection system efficiency, combustion energy conversion efficiency) 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,[15] but do count emissions from sources such as plastics, and (2) a series of assumptions on sequestration, future use of methane recovery systems, landfill gas recovery system efficiency, 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 results.

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) methane 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.[16] 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 US 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 baseline practice of landfilling (in a landfill with no gas collection system) to recycling 50 tons office paper and 2 tons of aluminum cans can reduce GHG emissions by over 100 MTCE.
- At the community level, a city of 100,000 with average waste generation (4.3 lb/day per capita) and recycling (27 percent), and baseline disposal in a landfill

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[15] 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.

[16] For details on the sensitivity analyses, see section 7.4 and Exhibits 7-7 and 7-8.

with no gas collection system, could increase the 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 are already 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 GHG emissions by 92,000 MTCE per year by managing waste in a mass burn combustor unit.
- A town of 50,000 landfilling 30,000 tons per year could install a landfill gas recovery system and reduce emissions by about 6,600 MTCE per year.
- At the national level, if the US attains the goal of a 35 percent recycling rate by 2005, emissions will be reduced by over 9 million MTCE per year compared to a baseline where we maintain the current 27 percent recycling rate and use the "national average" landfill for disposal.

ES.7 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 follow:

- The manufacturing GHG analysis is based on estimated industry averages for energy usage, and in some cases the estimates are based on limited data.[17] 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 US 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 was limited by the lack of data on methane generation and carbon sequestration resulting from composting; we relied on a theoretical approach to estimate the values.
- The combustion analysis uses national average values for several parameters; variability from site to site is not reflected in our estimate.

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[17] When EPA published this report as a draft working paper, the Agency specifically requested that commenters provide data on raw material acquisition and manufacturing. Although several commenters agreed that updated information would be important, none provided such data.

- The landfill analysis (1) incorporates considerable uncertainty on methane generation and carbon sequestration, due to limited data availability, and (2) uses as a baseline landfill methane recovery levels projected for the year 2000.

Finally, through 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 welcome readers to provide better 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

1.1 INTRODUCTION

This chapter provides an overview of the methodology we used to calculate the greenhouse gas (GHG) emissions associated with various management strategies for municipal solid waste (MSW). The chapter begins with a brief discussion of the life cycle framework used for the analysis. Next, it explains how we selected the ten materials that were analyzed. We then describe the specific GHG emissions and emission offsets considered in calculating the net emissions associated with particular waste management options. Finally, the chapter discusses the life cycle stages that we studied to identify the GHG impacts of MSW management options. Succeeding chapters will describe how we analyzed each step in the life cycle.

1.2 THE OVERALL FRAMEWORK: A STREAMLINED LIFE CYCLE INVENTORY

Early in our analysis of the GHG benefits of specific waste management practices, it became clear that there are opportunities to reduce GHG emissions from all waste management options, depending on the particular circumstances. Although source reduction and recycling are often the most advantageous waste management practices from a GHG perspective, it became clear that a material-specific comparison of all available waste management options would clarify where the greatest GHG benefits could be obtained for particular materials in MSW. This type of analysis is also intended to help policymakers identify the best options for GHG reductions. We determined that a streamlined application of life cycle assessment would be the best way to conduct such a comparative analysis.

A full life cycle assessment (LCA) is an analytical framework for understanding the material inputs, energy inputs, and environmental releases associated with manufacturing, using, and disposing 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 in all stages in the life of a product or process, and an inventory of environmental releases throughout the product lifecycle; (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 life cycle assessment is beyond the scope of this analysis. Rather, this report is a streamlined application of a life cycle assessment that is limited to an inventory of the emissions and other environmental impacts related to global warming; we did not assess air, water, or environmental impacts that did not have a direct bearing on climate change. Moreover, we did not attempt, as part of this analysis, to assess human health impacts or environmental improvements needed.[1]

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[1] EPA's Office of Research and Development (ORD) is performing a more extensive application of life cycle assessment for various waste management options for MSW. ORD's analysis will inventory a broader set of emissions (air, water, and waste) associated with these options. For more information on this effort, go to their project website at http://www.epa.gov/docs/crb/apb/apb.htm.

1.3 THE REVIEW PROCESS

Prior drafts of this report were reviewed in three peer review cycles, the details of which are provided in Background Document C.[2] The 1995 draft report was reviewed by 20 EPA analysts from four offices (Air and Radiation; Policy, Planning and Evaluation; Research and Development; and Solid Waste). In addition, the 1995 draft was reviewed by four analysts from the Department of Energy (DOE), Argonne National Laboratory, and DOE's National Renewable Energy Laboratory. Comments resulting from these reviews were incorporated into a second draft of the report, completed in May of 1996.

The 1996 draft was distributed to four researchers with academic and consulting backgrounds for a more intensive, external peer review. None of the researchers chosen was involved in the preparation of the report. Based on the comments received from these reviewers, another draft of the report was completed in March of 1997.

In March, 1997, EPA published the draft research in a report entitled *Greenhouse Gas Emissions from Municipal Waste Management: Draft Working Paper* (EPA530-R-97-010). As described in an accompanying Federal Register notice, public comment was solicited on the draft working paper. Twenty-three individuals, representing trade associations, universities, industry, state offices, EPA offices, and other entities provided comments. The most extensive comments were made by

- American Forest and Paper Association,
- American Plastics Council,
- Integrated Waste Services Association,
- Steel Recycling Institute,
- Minnesota Office of Environmental Assistance, and
- Missouri Department of Natural Resources.

Each comment pertaining to the 1997 draft, and an explanation of how the comment was taken into account in this report, is specifically addressed in a comment response document (Background Document D).

Among the changes made as a result of this review, EPA

- added two materials to the analysis—mixed paper and glass,
- revised system efficiencies for waste combustors, and provided a separate characterization of refuse-derived fuel (RDF) as a category of combustion,
- based GHG reductions from displaced electricity on GHGs from fossil-fuel-fired generation, rather than from the national average mix of fuels, and
- added a "waste generation" reference point for GHG accounting, where before only a "raw material extraction" reference point was provided.

In addition, the revised working paper updates many of the inputs to the calculations (such as the global warming potential for various greenhouse gases), and uses more recent information on waste composition and recycling rates.

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[2] All background documents and supporting memoranda cited in this report are provided in the docket at the Resource Conservation and Recovery Act (RCRA) Information Center.

1.4 MSW MATERIALS CONSIDERED IN THE STREAMLINED LIFE CYCLE INVENTORY

Source reduction and recycling have been part of the President's Climate Change Action Plan since its inception. In 1993, we made initial rough estimates of the potential for source reduction and recycling of MSW to reduce GHG emissions. However, it was clear that a more rigorous analysis would be needed to determine the GHG emissions associated with source reduction and recycling and to identify which materials in MSW were most likely to reduce GHG emissions if source reduced or recycled.

Each material in MSW has different GHG impacts depending on how it is made and disposed. To determine which materials in MSW had the greatest potential to reduce GHG emissions if source reduced or recycled, we performed a screening analysis of 37 of the most common materials and products found in MSW.[3] The screening analysis compared: (1) the GHG emissions from manufacturing each of the 37 materials from virgin or recycled inputs (based on the process and transportation energy requirements, and fuel mix for each material); and (2) the projected source reduction and recycling rates for each material. The information on energy requirements, fuel mix, and recycling rates was estimated independently by two groups with experience in MSW and life cycle assessment: Franklin Associates, Ltd. and the Tellus Institute. The materials were ranked by their potential for GHG reductions. For each material, we (1) averaged the two estimates for energy requirements and fuel mix, then (2) used those averages, together with estimates of the GHG emissions per unit of fuel used, to estimate GHG reductions per ton of material source reduced or recycled, and finally (3) used the estimated GHG reductions per ton, together with the averaged estimates of the potential tonnage of source reduction and recycling achievable for each material, to estimate the total GHG reduction potential for each material.[4]

While the screening analysis was general in nature and employed many assumptions, the underlying data provided by Franklin Associates and the Tellus Institute pointed toward the same general results. The energy and recycling data provided by both groups indicated that the same eight manufactured materials had the greatest potential to reduce GHG emissions if they were source reduced or recycled. We initially limited the life cycle assessment to these eight materials:

- newspaper,
- office paper,[5]

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[3] Materials and products in the screening analysis included, in addition to the materials and products covered in this report, the following: 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).

[4] Note that the comparative analysis among materials may vary for different units of measure. For example, a comparison between two packaging materials based on the GHG impacts per thousand packages will differ from a comparison based on the GHG impacts per ton of packaging material; the former comparison will account for the different weights of different types of packages. However, we chose to compare materials on a per-ton basis because this report's analysis focuses on greenhouse gas impacts from waste management, and waste is typically measured in tons.

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

- corrugated cardboard,
- aluminum cans,
- steel cans,[6]
- HDPE (high density polyethylene) plastic blow-molded containers,
- LDPE (low density polyethylene) plastic blow-molded containers, and
- PET (polyethylene terephthalate) plastic blow-molded containers.

We also examined the GHG implications of various management strategies for food scraps, yard trimmings, mixed MSW, and mixed recyclables. Finally, in response to several public comments, we later added mixed paper and glass containers to the analysis.

1.5 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 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 greenhouse gas accounting framework in terms of timing and levels of production. Each of these factors warrants further discussion.

GHGs Emissions Relevant to Waste: The most important GHGs for purposes of analyzing MSW management options are carbon dioxide, methane, nitrous oxide, and perfluorocarbons. Of these, carbon dioxide (CO_2) is by far the most common GHG emitted in the US. Most carbon dioxide emissions result from energy use, particularly fossil fuel combustion. A great deal of energy is consumed when a product is made 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. We estimated energy-related GHG emissions at all of these stages, except for transportation of products to consumers (because GHG emissions from transportation to consumers will vary little among the options considered). Much of this report is devoted to explaining how we quantified the energy used – and the resulting carbon dioxide emissions – at each stage in the life cycle of any given material in MSW. Energy consumed in

Comparing GHGs

Carbon dioxide, methane, and nitrous oxide are very different gases when it comes to their heat-trapping potential. An international protocol has established carbon dioxide as the reference gas for measurement of heat-trapping potential (also known as global warming potential or GWP). By definition, the GWP of one kilogram (kg) of carbon dioxide is 1.

Methane has a GWP of 21. This means that one kg of methane has the same heat-trapping potential as 21 kg of CO_2.

Nitrous oxide has a GWP of 310. Perfluorocarbons are the most potent greenhouse gases covered by this analysis; GWPs are 6,500 for CF_4 and 9,200 for C_2F_6.

In this report, emissions of carbon dioxide, methane, nitrous oxide, and perfluorocarbons have been converted to their "carbon equivalents." Because CO_2 is 12/44 carbon by weight, one metric ton of CO_2 is equal to 12/44 or 0.27 metric tons of carbon equivalent (MTCE). The MTCE value for one 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.)

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[6] Other steel materials may also be recycled, but we limited our analysis to steel cans from households.

connection with consumer use of products is not evaluated, because it is assumed that 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 about the same whether the product was made from virgin or recycled inputs.

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

Nitrous oxide (N_2O) results from the use of commercial and organic fertilizers and fossil fuel combustion, as well as other sources. For this analysis, we estimated nitrous oxide 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) in which 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 and Carbon Sequestration Relevant to Waste: Carbon, like many other elements, cycles throughout earth's air, water, land, and biota. A carbon stock (or sink) is a point in the carbon cycle where carbon is stored. While the carbon is stored, it is not in the atmosphere contributing to the "greenhouse effect" (i.e., the trapping of heat close to the earth's surface). Examples of carbon stocks are forests, oceans, oil fields, and landfills.

"Carbon sequestration" is the opposite of GHG emissions. With carbon sequestration, carbon is removed from the carbon cycle and added to a carbon stock. For example, when a forest removes carbon from the atmosphere and converts it to wood at a faster pace than the trees are harvested (or decompose), this is known as forest carbon sequestration. Likewise, if organic matter added to a landfill does not decompose into methane or carbon dioxide, and enters into long-term storage, it is said to be "sequestered."

The baseline against which changes in carbon stocks are measured is a projection by the US Forest Service of forest growth, harvests, mortality, and removals under anticipated market conditions for forest products. One of the assumptions on which the projections is based is that US 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).[8] Thus, we assume in the baseline that harvesting trees at current levels results in no diminution of the forest carbon stock and no additional carbon dioxide in the atmosphere. On the other hand, forest carbon

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[7] US EPA, *Draft Inventory of US Greenhouse Gas Emissions and Sinks: 1990-1996*, April 1998.

[8] Assuming a sustainable harvest in the US is reasonable because from 1952 to 1992 US 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.

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 (composting, combustion, and landfilling) do not.

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 sequestration. Plastic in a landfill represents merely 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, there has been no change in the overall amount of carbon stored. On the other hand, that 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.

While 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 Relevant to Waste: When a waste is used to generate electricity (either through waste combustion or recovery of methane from landfills), it displaces utility fossil fuels that would otherwise be consumed. Fossil fuel combustion is the single largest source of GHGs in the US. 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: For most parts of the analysis, we selected as the baseline year the most recent year for which data were available. However, for the landfill methane recovery rate, and system efficiency and ferrous recovery rate at waste combustors, we used values projected for the year 2000. For paper recovery, we made annual projections through 2010 that enabled us to develop an average value for the period from 1996 through 2010.[9] In these cases, we developed future scenarios because some of the underlying factors that affect GHG emissions are changing rapidly, and we are seeking to define relationships (e.g., between tonnage of waste landfilled and methane emissions) that represent an average over the next several years.

- In the case of landfill methane, there are three EPA programs that reduce methane emissions: one that requires landfill gas recovery at large landfills; one that promotes recovery of landfill methane on a voluntary basis at smaller landfills; and another that promotes source reduction and recycling (which results in less methane-producing waste being landfilled). In estimating the landfill methane emission reductions due to source reduction and recycling, we needed to account for the planned increase in landfill methane capture. Otherwise, EPA would count landfill methane emissions reductions twice: once for capturing landfill methane, and once for avoiding methane production through source reduction and recycling. Because the programs to regulate landfill gas and promote

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

voluntary methane recovery aim to become fully effective by 2000 (dramatically increasing methane recovery), by using a baseline year of 2000 we avoided double counting.

- Although the current population of US municipal waste combustors includes a few small facilities that do not recover energy, we assumed that these would be closed in the near future. Thus, we represented all combustors as having energy recovery. We also used an estimate provided by the combustion industry for anticipated levels of ferrous recovery.
- For paper recovery, earlier analyses had indicated that the marginal impact of increased paper recovery on forest carbon sequestration changes over time; the impact also differs depending on the initial paper recovery rate and how that rate changes over time. To estimate the impact of increased paper recovery on forest carbon sequestration, we needed to account for these influences. First, we developed a baseline projection for paper recovery rates. We began with a projection, from the American Forest and Paper Association, that paper recovery rates will continue to increase from about 35 percent in 1994 to 50 percent by 2000. Then we developed a baseline scenario for paper recovery whose trajectory passes through 50 percent in 2000, with continued modest increases in the following years. Because we needed to estimate the effect of efforts (e.g., by EPA) to enhance recovery beyond the baseline projected rates, we developed a plausible scenario for enhanced paper recovery rates, and then compared the predicted forest carbon sequestration under the two scenarios.[10] (Our approach is fully described in chapter 3).

1.6 HOW THESE INPUTS ARE TALLIED AND COMPARED

Exhibit 1-1 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.

To calculate the net GHG implications of a waste management strategy for a given material, one must first establish a baseline scenario and an alternative scenario. For example, one could compare a baseline scenario, where 10 tons of office paper is manufactured, used, and landfilled, to an alternative scenario, where 10 tons is manufactured, used, and recycled. Then, 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 these emissions. The formula for net GHG emissions is as follows:

$$\text{Net GHG emissions} = \text{Gross GHG emissions} - (\text{increase in carbon stocks} + \text{avoided utility GHG emissions})$$

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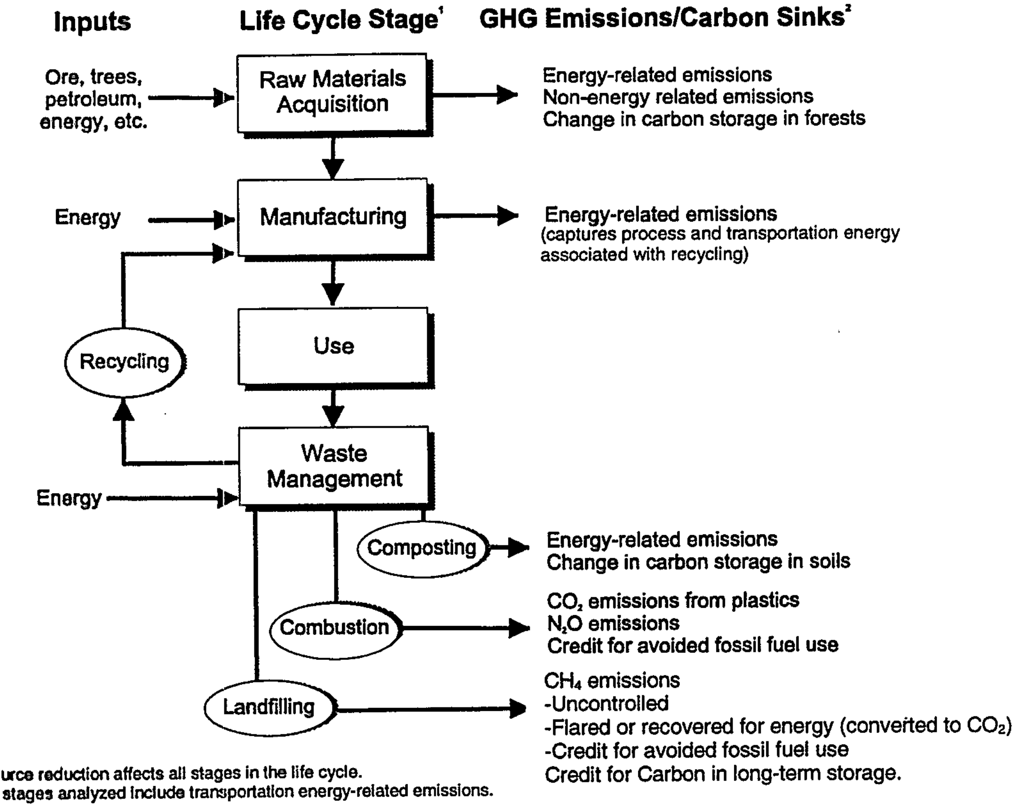
[10] Note that this estimate is necessary for analyzing the scenarios, however, it does not represent a plan of action by EPA.

Exhibit 1-1

GHG Sources and Sinks Associated with Materials in the MSW Stream



[1] Note that source reduction affects all stages in the life cycle.
[2] All life cycle stages analyzed include transportation energy-related emissions.

Comparing net GHG emissions for the two scenarios allows one to identify which has the lowest net GHG emissions. 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. Generally, recycling reduces GHG emissions because, in most cases, manufacturing a product from recycled inputs requires less fossil energy than making the product from virgin inputs, and thus reduces energy-related GHG emissions. Another GHG issue in the case of paper is that paper recycling results in additional carbon sequestration in forests.

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, there are GHG emissions associated with making the material/product. These GHG emissions may be augmented by methane emissions from landfills (which themselves may be offset to some degree by energy recovery at landfills or landfill carbon sequestration). If the wastes are combusted, there may be an offset for avoided utility emissions.

In calculating emissions for the life cycle scenarios, two different reference points can be used:

- In a "raw material extraction" approach (i.e., cradle-to-grave perspective), one can start at the point of raw material acquisition as the "zero point" for emissions, and add all emissions (and deduct sinks) from that point on through the life cycle.

- In a "waste-generation" approach (solid waste manager's perspective), one can begin accounting for GHG emissions at the point of waste generation. All subsequent emissions and sinks from waste management practices are then 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) impact 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 life cycle inventory accounting techniques. Several commenters 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 more clarity for evaluating waste management options. Thus, this report uses the waste generation approach, and defines 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.[11]

Exhibit 1-2 indicates how the GHG sources and sinks have been counted for each MSW management strategy 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.

1.7 SUMMARY OF THE LIFE CYCLE STAGES

The following sections explain the life cycle diagram and components presented in Exhibits 1-1 and 1-2, 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.

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[11] 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.

Exhibit 1-2
Components of Net Emissions for Various Municipal Solid Waste Management Strategies

Municipal Solid Waste Management Strategy	Greenhouse Gas Sources and Sinks		
	Process and Transportation GHGs from Raw Materials Acquisition and Manufacturing	Change in Forest or Soil Carbon Storage	Waste Management GHGs
Source Reduction	Decrease in GHG emissions, relative to the baseline of manufacturing	Increase in forest carbon storage	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 storage	Process and transportation emissions are counted in the manufacturing stage
Composting	No emissions/sinks*	No change	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	Methane emissions, long-term carbon storage, avoided utility emissions, and transportation emissions

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

GHG Emissions and Carbon Sinks Associated With Raw Materials Acquisition and Manufacturing

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

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 box 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 – for example, "lightweighting," double-sided photocopying, or 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).[12]

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[12] Although material substitution is not quantitatively addressed in the report, it is discussed from a methodological standpoint in Chapter 2, and is also briefly discussed in Chapter 4, Section 4.3. Material substitution is an important issue for future research.

The GHG emissions associated with raw materials acquisition and manufacturing are: (1) process energy GHG emissions, (2) transportation energy GHG emissions, and (3) process non-energy GHG emissions (for aluminum, steel, plastics, and office paper.) Each type of emission is described below. Changes in carbon storage in forests are also 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 box on CO_2 Emissions from Biogenic Sources, below).

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 is also needed to extract the oil or mine the coal that is ultimately used to produce energy, and to transport these fuels to 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 are also counted.

To estimate process energy GHG emissions, we first obtained estimates of both the total amount of process energy used per ton of product (measured in British thermal units or BTUs), and the fuel mix (e.g., diesel oil, natural gas, fuel oil). Next, we used emissions factors for each type of fuel to convert the amount of each type of fuel used to the GHG emissions that are produced. 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 our 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. We based our estimates of transportation energy emissions on: 1) the amounts of raw material inputs and intermediate products used in manufacturing one 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, we used data on the average fuel consumption per ton-mile for each mode of transportation.[13] Then we used an emission factor for each type of fuel to convert the amount of each type of fuel consumed to the GHG emissions produced.

More detail on our 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, we refer to these emissions 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 $CaCO_3$); the manufacture of lime results in CO_2 emissions. Other process non-energy GHG emissions are associated with production of plastics, office paper, and tissue paper. In some cases, process non-energy GHG

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[13] These data are found in the Background Document A.

emissions are only associated 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 in the stages of raw materials acquisition and manufacturing is the additional carbon sequestration in trees associated with source reduction or recycling of paper products. Our methodology for estimating forest carbon sequestration is described in Chapter 3.

GHG Emissions and Carbon Sinks Associated With Waste Management

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

In this analysis, source reduction is measured by the amount of material that would otherwise be produced but is not being produced because of 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. Thus, 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). There are no GHG emissions at the MSW management stage because the recycled material is diverted from waste management facilities.[14] (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.

Most of the materials considered in this analysis are modeled as being recycled in a "closed loop" (e.g., newspapers are recycled into new newspapers). However, office paper and corrugated boxes are modeled as being recycled in an "open loop" (i.e., they are recycled into more than one product):

- Office paper is modeled as being recycled into either office paper or tissue paper; and
- Corrugated boxes are modeled as being recycled into either corrugated boxes or folding boxes.

In addition, 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. We recognize that other materials are recycled in open loop processes, but due to limited resources, we could not analyze all open loop processes.[15]

Composting: When organic materials are composted, most of their organic mass quickly decomposes to CO_2. The materials that may be composted (e.g., leaves, brush, grass, food waste,

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

[15] 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 US and all other parties to the Framework Convention on Climate Change 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, *IPCC Guidelines for National Greenhouse Gas Inventories* (three volumes), 1997.) In selecting the methodologies used in this report to evaluate emissions and sinks of GHGs, we attempted to be consistent with IPCC's 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 eventually cycle back to the atmosphere 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 Framework Convention on Climate Change is on anthropogenic emissions - emissions resulting from human activities and subject to human control - because it is these emissions that 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.

Thus, for processes with CO_2 emissions, if (a) the emissions are from biogenic materials and (b) the materials are grown on a sustainable basis, then those emissions are considered to simply close the loop in the natural carbon cycle -- that is, they return to the atmosphere CO_2 which 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 scraps.) 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).

newspapers) are all originally produced by trees or other plants. As described in the text box above, the CO_2 emitted from these materials during composting is biogenic CO_2, and thus is not counted in GHG emissions.

There is some potential for the composting of yard trimmings to result in production of more humic material (natural organic polymers, which degrade at a slow rate) than is produced when yard trimmings are left to decompose in the yard. This process may act to enhance long-term carbon storage in soils to which compost is applied.

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

Because the CO_2 emissions from composting are biogenic, and there are generally no methane emissions, the only GHG emissions from composting result from transportation of compostable materials to composting facilities, and mechanical turning of the compost piles. Carbon cycling in compost operations is 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 methane, a GHG. Some of the organic matter never decomposes at all; instead it becomes sequestered carbon. (Landfilling of metals and plastics does not result in either methane emissions or carbon sequestration).

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

2. RAW MATERIALS ACQUISITION AND MANUFACTURING

To estimate the GHG emissions and sinks for the full life cycle of MSW materials, we needed to estimate the GHG emissions associated with raw materials acquisition and manufacturing. This chapter describes how we estimated these emissions for ten materials: newspaper, office paper, corrugated boxes, mixed paper, aluminum cans, steel cans, glass containers, and three types of plastic (LDPE, HDPE, and PET).

In manufacturing, substantial amounts of energy are used in the acquisition of raw materials and in the manufacturing process itself. In general, the majority of energy necessary for these activities comes from fossil fuels. Combustion of fossil fuels results in emissions of CO_2, a greenhouse gas, and trace amounts of other GHGs that are not included in the analysis. 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 GHGs.

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 to fuel a blast furnace. Because fuel is also needed for "pre-combustion" activities (such as oil exploration and extraction, coal mining and beneficiation, and natural gas production), CO_2 emissions from "pre-combustion" activities are also counted in this category. When electricity is used in manufacturing, the CO_2 emissions from the fuels burned to produce the electricity are also counted. In general, making a material from recycled inputs requires less process energy than making the material from virgin inputs.

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 also generally include the energy used to process the inputs at a MRF. Transportation of finished manufactured goods to consumers is not included in the analysis. We did not consider the global warming impacts of

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[1] Note, however, that CO_2 emissions from combustion of biomass are not counted as GHG emissions (as described in Chapter 1). For example, paper manufacturing uses biomass as a fuel.

transportation emissions of nitrogen oxides (NO_x); such emissions contribute indirectly to climate change.[2] This omission would tend to slightly understate the GHG impacts from transportation.

We also considered the methane emissions associated with producing, processing, and transporting coal, oil, and natural gas. Methane is emitted during the various stages of fossil fuel production because methane is trapped within coal and oil deposits, and because natural gas consists largely of methane.

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.

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 one 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 one ton of newspaper from virgin inputs, we multiplied the amount of each type of fuel used (as measured in million British thermal units, or BTUs) times the carbon coefficient for that type of fuel (as measured in metric tons of carbon equivalent, or MTCE, per million BTUs). Each of these multiplications yielded an estimate, for one of the fuels used to make newspaper, of the amount of GHGs emitted (in MTCE) from the combustion of that fuel when one ton of newspaper is made. The total process energy GHG emissions from making one ton of newspaper are simply the sum of the GHG estimates across the different fuels used. To estimate the GHG emissions when electricity is used, we used the national average mix of fuels used to make electricity.

We estimated GHGs from the energy used to transport raw materials for making one 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 count "pre-combustion" energy, we scaled up the amount of each fuel combusted during manufacture by the amount of energy needed to produce that fuel.[3] In this approach, we used the simplifying assumption that when oil is produced, oil is used as the energy source in oil production, while natural gas is used for natural gas production, etc.

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[2] Because the Intergovernmental Panel on Climate Change (IPCC) has not established a method for estimating the global warming implications of emissions of nitrogen oxides, we have not attempted such an estimation.

[3] The proportion of precombustion energy, as a percent of total combustion energy, varies among fuels. The following values represent the percentage of total combustion energy, for each source category, attributable to precombustion energy. The precombustion energy equals 18.5 percent of the combustion energy for diesel, 20.5 percent for gasoline, 17.2 percent for residual fuel oil 18.5 percent for distillate fuel oil, 12.1 percent for natural gas, and 2.4 to 2.7 percent for coal. Source, Franklin Associates, Ltd.

We developed GHG estimates for raw materials acquisition and manufacturing for each of the ten manufactured materials considered in this report. We then developed GHG estimates for tissue paper and folding boxes to enable us to estimate the GHG implications of increased recycling of office paper and corrugated boxes, respectively, in an "open loop." We also developed GHG estimates for boxboard and paper towels to enable us to estimate the GHG implications of recycling mixed paper in an "open loop."[4] Thus, the exhibits in this chapter show data not only for the ten materials of interest, but also for tissue paper, folding boxes, boxboard, and paper towels. For steel cans, we developed GHG estimates for virgin production using the basic oxygen furnace process,[5] and for recycled production using the electric arc furnace process.[6]

For the amounts of each type of fuel used for process and transportation energy, we obtained two independent sets of estimates from two consulting firms that have expertise in lifecycle analysis: Franklin Associates Ltd. (FAL), and the Tellus Institute (Tellus). For carbon coefficients, we used data from the Energy Information Administration of the US Department of Energy[7] for all fuels except diesel fuel and electricity; for the latter fuels we used data from the American Council for an Energy-Efficient Economy.[8] The carbon coefficient for electricity was based on the weighted average carbon coefficients for all fuels used to generate electricity in the US.[9]

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[4] Note that only Franklin Associates, Ltd. provided virgin and recycled manufacturing and transportation data for boxboard and paper towels. For virgin boxboard, there is only one type of product manufactured, as shown in Exhibits 2-3 and 2-4. For recycled boxboard, there are two types of products for which 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 with respect to their recycled material inputs only (i.e., the proportion of newsprint, 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. In other words, there would be no reason to distinguish between boxboard "A" and boxboard "B" if one considers virgin inputs only; in this case, there would only be one type of product—virgin boxboard (as stated above).

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

[6] 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 are made into some other steel product. By modeling recovery of steel cans as a closed loop process, we implicitly assumed that each ton of steel produced from recovered steel cans in an electric arc furnace displaces a 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.)

[7] Energy Information Administration, US Department of Energy, Draft *Emissions of Greenhouse Gases in the United States 1989-1994*, DOE/EIA-0573-annual (Washington, D.C.: US Department of Energy), in press 1995, cited in US Environmental Protection Agency, *Draft Inventory of US Greenhouse Gas Emissions and Sinks: 1990-1996* (Washington, D.C.: US EPA),April 1998.

[8] R. Neal Elliott, Carbon Reduction Potential from Recycling in Primary Materials Manufacturing, (Berkeley, CA: American Council for an Energy-Efficient Economy), February 8, 1994, p. 14.

[9] FAL and Tellus reported the BTU value for electricity in terms of the BTUs 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 factory. Thus, FAL and Tellus had already accounted for the efficiency of converting fuels to electricity, and the

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 methane 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 GHG emissions associated with US production of coal, oil, and natural gas. The resulting average estimates for GHG emissions from fossil fuel production were 0.92 kilograms of carbon equivalent per million BTUs (kg CE/million BTU) for coal, 0.10 kg CE/million BTU for oil, and 0.70 kg CE/million BTU for natural gas.[10]

The carbon coefficients that reflect both CO_2 and methane emissions are provided 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 based on the FAL data, and then repeated the summation using the Tellus data. Both sets of summed estimates are listed in Exhibit 2-2 in columns "b" (for virgin inputs) and "c" (for recycled inputs).[11] Although these estimates do not represent minimum or maximum values, we believe that they do portray the variability in actual industry values for each material.

We also estimated the energy-related GHG emissions from manufacturing each material from the current mix of virgin and recycled inputs. To do so, we averaged the two estimates for each material based on FAL and Tellus data; the results are shown in column "e." (The remaining two columns of Exhibit 2-2 are discussed later in this chapter.)

The FAL and Tellus values for energy use are provided in Exhibits 2-3 through 2-10. Exhibits 2-3 through 2-6 present the FAL data – providing, in turn, the data used to estimate energy-related GHG emissions for products manufactured from virgin inputs, and then the data for energy-related GHG emissions for products manufactured from recycled inputs.[12] Exhibits 2-7 through 2-10 present the Tellus data, which are organized in the same way.[13]

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losses in transmission and distribution of electricity; and we did not need to account for these factors in the carbon coefficient for electricity.

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

[11] Note that in Exhibit 2-2, only Franklin Associates, Ltd. provided virgin and recycled data for boxboard, paper towels, and glass containers.

[12] Note that when paper is made from virgin inputs, a substantial amount of biomass fuel (e.g., black liquor from the digestion process and tree bark) is used. However, when paper is made from recycled inputs, no biomass fuel is used.

[13] Note that in Exhibits 2-7 and 2-9, Tellus included values for the energy content of steam used in manufacturing. We translated these steam energy values into fuel inputs as follows: (1) we assumed that the energy content of the fuels combusted was converted into steam energy at a conversion efficiency of 85 percent; (2) for paper products, made from virgin or recycled inputs, we used a fuel mix for steam of 40 percent oil, 33 percent biomass, 17 percent natural gas, and 10 percent coal; and (3) for non-paper products made from virgin or recycled inputs, we used a fuel mix for steam of 50 percent natural gas, 25 percent coal, and 25 percent oil (based on ICF professional judgment).

For most materials, both FAL and Tellus provided data for fuels used in manufacturing processes that use (1) 100 percent virgin inputs and (2) 100 percent recycled inputs.[14] To estimate the types and amounts of fuels used for process and transportation energy, FAL and Tellus relied on published data (such as engineering handbooks and published production data), and on personal contacts with industry experts. FAL and Tellus counted all energy, no matter where it was used. For example, much aluminum produced in the US is made 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. In addition, it does not matter where recycled inputs are made into remanufactured products. For example, if office paper that is recovered in the US is remanufactured into paper products in Asia, the energy savings from remanufacture using recycled rather than virgin inputs are counted.

Neither the FAL nor the Tellus 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.

After FAL and Tellus had developed their initial estimates of process energy intensity and fuel mix, we reviewed and verified the data by analyzing significant discrepancies between the estimates provided by the two firms. Where discrepancies were found, we reviewed the most critical assumptions and data elements that each firm used, and identified circumstances where it would be appropriate for one firm to revise its assumptions or update its data sources.[15] The effect of this process was to arrive at estimates by the two firms that were closer to each other and, we expect, more accurately reflect the energy used in raw materials acquisition and manufacturing of the materials 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, 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.

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[14] The three exceptions were (1) the FAL data for corrugated boxes made from virgin inputs, for which FAL provided data for manufacture from 90.2 percent virgin inputs and 9.8 percent recycled inputs, (2) the FAL 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, and (3) the Tellus data for steel cans made from virgin inputs, for which Tellus provided data for manufacture from 90 percent virgin inputs and 10 percent recycled inputs. We extrapolated from these 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.

[15] For example, some of the data issues that we reviewed and decided on were (1) the fuel mix to assume for electricity used to manufacture aluminum (the national average fuel mix for generating electricity was used, because electricity generated from all types of fuel is sold as a single commodity through interconnected regional grids meaning that, while aluminum is largely processed in the West where hydropower is abundant, aluminum processing draws from the grid so all power sources are mixed), (2) whether to include the "pre-combustion" energy for fossil fuels, i.e., the energy required to extract, refine, and deliver the fuels (pre-combustion energy was counted), (3) whether to use data for use of recovered materials in "closed loop" or "open loop" processes (we used a "closed loop" model for most materials), and (4) what loss rates should be used (we averaged the FAL and Tellus loss rates).

In order to make the best use of all available data for each material, we averaged the FAL and Tellus estimates of GHG emissions for manufacturing the material from (1) virgin inputs, and (2) recycled inputs. These averaged values are used in all of the computations displayed in the executive summary and in Chapter 8, which present overall results of the analysis.

Complete documentation of the FAL and Tellus data on the types and amounts of fuels used for process and transportation energy, including data sources, is provided in Background Documents A and B, available in the docket at the RCRA Information Center.

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

We also accounted for three additional sources of GHGs in manufacturing processes that are not related to energy use:

- 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.
- Methane 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.

In most cases, process non-energy GHG emissions are only associated 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. Our source for all these data, except the perfluorocarbon emissions, is an appendix to a report prepared for the EPA Office of Policy, Planning, and Evaluation.[16] Our source for the perfluorocarbon emissions is a memorandum prepared by ICF.[17]

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").

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

[17] Memorandum from ICF to US EPA, "Perfluorocarbon Emissions from Aluminum Smelting," March 27, 1996. Memorandum from ICF to US EPA, "Perfluorocarbon Emissions from Aluminum Smelting," March 27, 1996.

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 through 2-10 (the last columns of Exhibits 2-3 and 2-5 show the total process energy GHG emissions).

Because we had two independent sets of data on the amounts of each type of fuel used in making each product, we were able to develop both range estimates and point estimates of the energy-related GHG values for manufacturing each material from virgin or recycled inputs, and from the current mix of virgin and recycled inputs. In this report, for purposes of analyzing the GHG emissions associated with the manufacturing stage of the product lifecycle, we are using the values in column "g" of Exhibit 2-2 for total manufacturing GHG emissions (i.e., averages of point estimates). Depending on the inputs being considered, the appropriate value for total GHG emissions is used (i.e., the value for manufacture from virgin inputs, recycled inputs, or the current mix of virgin and recycled inputs).

2.4 LIMITATIONS OF THE ANALYSIS

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 methane emissions from natural gas pipelines and natural gas processing. Natural gas pipeline methane emissions are determined by the operating pressure in natural gas pipelines, and the number and size of leaks in the pipeline. 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 methane 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 percent 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.

Although we developed two sets of energy data for most of the materials, we obtained only one set (from Franklin Associates, Ltd.) for virgin and recycled energy use for boxboard, paper towels, and glass containers. Similarly, very limited data were available for the typical proportions of virgin and recycled inputs for tissue paper, folding boxes, boxboard, paper towels, and glass.

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 dating back to the early 1980s. Therefore, the data do not necessarily reflect recent trends in industrial energy efficiency or changes in the fuel mix. Although the limitations in the energy data have been fully acknowledged in earlier versions of this report, and we have specifically encouraged reviewers to provide updated or more complete data, no additional energy data was brought to our attention as a result of the review process.

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 BTUs	kg Carbon Equivalent (CE) from Combustion Per Million BTUs	Metric Tons of Fugitive Methane Emissions Per Million BTUs	kg CE from Fugitive Methane Emissions Per Million BTUs	kg CE Emitted Per Million BTUs Consumed
Gasoline	0.07	19.54	0.00002	0.098	19.64
LPG	0.06	17.13	0.00002	0.10	17.23
Distillate Fuel	0.07	20.06	0.00002	0.10	20.16
Residual Fuel	0.08	21.60	0.00002	0.10	21.70
Diesel	0.08	20.91	0.00002	0.10	21.01
Oil/Lubricants	0.07	20.35	0.00002	0.10	20.45
Steam (non-paper products)	0.07	18.73	0.00011	0.61	19.33
Steam (paper products)	0.05	13.16	0.00004	0.25	13.41
National Average Fuel Mix for Electri	0.06	16.21	0.00010	0.58	16.80
National Average Fossil Fuel Mix for	0.09	24.14	0.00015	0.87	25.01
Coal Used for Electricity	0.09	25.71	0.00016	0.92	26.63
Coal Used by Industry (Non-Coking	0.09	25.61	0.00016	0.92	26.53
Natural Gas	0.05	14.47	0.00012	0.70	15.17
Other (Petroleum Coke)	0.10	27.96	0.00002	0.10	28.06

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.

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

(a)	(b)		(c)		(d)		(e)		(f)			(g)		
	Virgin Input Combined Process and Transportation Energy Emissions (MTCE Per Ton of Product Made With Virgin Inputs)		Recycled Input Combined Process and Transportation Energy Emissions (MTCE Per Ton of Product Made With Virgin Inputs)		Percent Recycled Inputs in the Current Mix of Virgin and Recycled Inputs		Current Mix Combined Process and Transportation Energy Emissions (MTCE Per Ton of Product Made with the Current Mix of Virgin and Recycled Inputs)		Process Non-Energy Emissions (MTCE Per Ton of Product)			Average Combined Process and Transportation Energy and Process Non-Energy Emissions (MTCE Per Ton of Product)		
Type of Product	FAL Est.	Tellus Est.	FAL Est.	Tellus Est.	FAL Est.	Tellus Est.	FAL Est.	Tellus Est.	Virgin Inputs	Recycled Inputs	Current Mix	Virgin Inputs	Recycled Inputs	Current Mix
Newspaper	0.54	0.55	0.39	0.38	44%	39%	0.47	0.48	0.00	0.00	0.00	0.55	0.38	0.48
Office Paper	0.57	0.53	0.50	0.42	31%	32%	0.55	0.50	0.01	0.00	0.01	0.56	0.46	0.53
Tissue Paper	0.66	0.51	0.59	0.36	NA	NA	0.66	0.51	0.01	0.00	0.01	0.59	0.48	0.59
Corrugated Boxes	0.27	0.48	0.40	0.53	46%	51%	0.33	0.51	0.00	0.00	0.00	0.38	0.47	0.42
Folding Boxes	0.42	0.51	0.45	0.56	NA	NA	0.42	0.51	0.00	0.00	0.00	0.46	0.50	0.46
Mixed Paper														
Boxboard "A" *	0.33	NA	0.44	NA	NA	NA	0.33	NA	0.00	0.00	0.00	0.33	0.44	0.33
Boxboard "B" *	0.33	NA	0.44	NA	NA	NA	0.33	NA	0.00	0.00	0.00	0.33	0.44	0.33
Paper Towels	0.95	NA	0.78	NA	NA	NA	0.95	NA	0.00	0.00	0.00	0.95	0.78	0.95
Aluminum Cans	3.91	3.71	0.68	0.75	52%	51%	2.22	2.20	1.59	0.00	0.76	5.39	0.72	2.97
Steel Cans	0.79	0.97	0.28	0.30	45%	51%	0.56	0.63	0.24	0.24	0.24	1.12	0.53	0.83
Glass Containers	0.12	NA	0.07	NA	25%	NA	0.11	NA	0.04	0.00	0.03	0.16	0.07	0.14
HDPE	0.51	0.79	0.25	0.32	24%	22%	0.45	0.68	0.05	0.00	0.04	0.70	0.28	0.61
LDPE	0.63	1.05	0.23	0.42	0%	0%	0.63	1.05	0.05	0.00	0.05	0.89	0.33	0.89
PET	0.98	1.29	0.40	0.50	27%	25%	0.82	1.09	0.03	0.00	0.02	1.16	0.45	0.98

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.

* For virgin Boxboard, there is one type of product manufactured for which we obtained manufacturing and transportation data. For recycled Boxboard, there are two types of products for which we obtained two different sets of manufacturing and transportation data. Boxboard "A" and Boxboard "B" differ with respect to their recycled material inputs only (i.e., the proportion of newsprint, corrugated boxes, office paper, and coated paper used to manufacture either Boxboard "A" or Boxboard "B"). If one does not consider the current mix of virgin and recycled inputs, then there is no reason to distinguish between Boxboard "A" and Boxboard "B"; in this case, there is only one product to consider--virgin Boxboard (as stated above).

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 first summed the estimates for process and transportation GHG emissions based on the FAL data, and then repeated the summation using the Tellus data. These summed estimates are shown above in columns "b" (for virgin inputs) and "c" (for recycled inputs). Two summed estimates are shown for each material in each column: the "FAL estimate" and the "Tellus estimate." However, for boxboard, paper towels, and glass, we obtained data from FAL only.

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 FAL estimate of the percentage of recycled inputs in the current mix, together with the FAL estimates for GHG emissions from manufacture using virgin or recycled inputs, to develop FAL estimates of GHG emissions from manufacture using the current mix of virgin and recycled inputs (labeled "FAL estimate" in column "e"). We repeated the process using the Tellus data (labeled "Tellus estimate" in

Explanatory notes for Exhibit 2-2 (continued): column "e"). However, for tissue paper, folding boxes, boxboard "A", boxboard "B", paper towels, and glass, we were unable to obtain estimates of the proportions of recycled and virgin inputs used in the current manufacturing mix.

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. To obtain these values, we first developed two estimates of the GHG emissions for each material and each set of inputs. One estimate is based on FAL data, and the other is based on Tellus data (these estimates included both energy-related GHG emissions and process non-energy GHG emissions). The values in column "g" are the averages of the estimates based on FAL and Tellus data.

Exhibit 2-3 (Franklin Data)
GHG Emissions Per Ton of Product Manufactured from Virgin Inputs
Process GHGs Only

Type of Product	Process Energy (Million BTUs Per Ton of Product)	Average Fuel Mix (in Percent)										Process Energy Carbon Emissions (MTCE/Ton of Product)	Process Non-Energy Carbon Emissions (MTCE/Ton of Product)	Total Process Carbon Emissions (MTCE/Ton of Product)
		Gasoline	LPG	Distillate Fuel	Residual Fuel	Biomass	Diesel	Electricity	Coal	Natural Gas	Total			
Newspaper	33.96	0.00	0.06	0.08	0.49	6.53	0.82	57.54	1.07	33.41	100.00	0.52	0.00	0.52
Office Paper	54.80	1.99	0.00	0.01	4.34	50.07	0.00	24.75	9.78	9.06	100.00	0.52	0.01	0.53
Tissue Paper	52.09	2.29	0.00	3.35	13.19	40.88	0.00	18.90	11.95	9.44	100.00	0.61	0.01	0.62
Corrugated Boxes	30.01	0.00	0.00	0.01	1.62	56.06	1.21	19.67	8.75	12.68	100.00	0.24	0.00	0.24
Folding Boxes	40.12	2.79	0.00	1.44	5.88	47.87	0.00	18.22	10.29	13.52	100.00	0.40	0.00	0.40
Boxboard	32.26	0.00	0.00	0.00	0.94	59.34	1.36	5.32	24.01	9.02	100.00	0.29	0.00	0.30
Paper Towels	73.44	0.00	0.00	0.01	1.80	24.89	0.45	28.15	2.93	41.78	100.00	0.91	0.00	0.91
Aluminum Cans	226.85	0.00	0.01	0.23	1.25	0.00	0.22	84.18	0.25	13.86	100.00	3.78	1.59	5.37
Steel Cans	31.58	0.21	0.00	5.06	0.35	0.00	0.00	21.02	53.90	19.45	100.00	0.69	0.24	0.93
Glass	6.62	0.54	0.00	1.40	0.45	0.27	0.00	10.65	7.52	79.15	100.00	0.11	0.04	0.15
HDPE	30.71	0.10	0.03	0.23	0.72	0.00	0.00	42.46	0.00	56.46	100.00	0.49	0.05	0.54
LDPE	37.68	0.08	0.03	0.19	0.58	0.00	0.00	51.11	0.00	48.01	100.00	0.60	0.05	0.66
PET	50.51	0.05	0.05	5.88	15.56	0.00	0.00	51.66	6.14	20.67	100.00	0.91	0.03	0.94

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

Exhibit 2-4 (Franklin Data)
GHG Emissions Per Ton of Product Manufactured from Virgin Inputs
Transportation GHGs Only

Type of Product	Transportation Energy (Million BTUs Per Ton of Product)	Average Fuel Mix (in Percent)					Transportation Energy Carbon Emissions (Metric Tons of Carbon Equivalent Per Ton of Product)
		Diesel	Residual Oil	Natural Gas	Electricity	Total	
Newspaper	0.77	98.59	1.14	0.17	0.10	100.00	0.02
Office Paper	2.46	99.43	0.43	0.11	0.03	100.00	0.05
Tissue Paper	2.46	99.43	0.43	0.11	0.03	100.00	0.05
Corrugated Boxes	1.43	99.79	0.18	0.02	0.01	100.00	0.03
Folding Boxes	1.01	99.19	0.59	0.20	0.02	100.00	0.02
Boxboar	1.79	99.93	0.05	0.01	0.00	100.00	0.04
Paper	2.07	99.46	0.52	0.02	0.01	100.00	0.04
Aluminum Cans	5.73	37.53	62.07	0.00	0.40	100.00	0.12
Steel Cans	4.60	98.24	1.76	0.00	0.00	100.00	0.10
Glass	0.58	88.96	2.64	6.51	1.90	100.00	0.01
HDPE	1.15	54.50	19.32	24.66	1.52	100.00	0.02
LDPE	1.15	54.50	19.32	24.66	1.52	100.00	0.02
PET	3.27	79.65	16.63	2.42	1.31	100.00	0.07

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

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

Type of Product	Process Energy (Million BTUs Per Ton of Product)	Average Fuel Mix (in Percent)										Process Energy Carbon Emissions (MTCE/Ton of Product)	Process Non-Energy Carbon Emissions (MTCE/Ton of Product)	Total Process Carbon Emissions (MTCE/Ton of Product)
		Gasoline	LPG	Distillate Fuel	Residual Fuel	Biomass	Diesel	Electricity	Coal	Natural Gas	Total			
Newspaper	23.01	0.00	0.22	0.12	0.05	0.00	0.00	59.65	0.95	39.02	100.00	0.37	0.00	0.37
Office Paper	26.46	0.00	0.00	14.29	13.26	0.00	0.00	48.64	0.00	23.81	100.00	0.46	0.00	0.46
Tissue Paper	26.46	0.00	0.00	14.29	13.26	0.00	0.00	48.64	0.00	23.81	100.00	0.46	0.00	0.46
Corrugated Boxes	15.95	0.00	0.13	0.01	1.29	0.00	0.66	44.81	30.08	23.00	100.00	0.31	0.00	0.31
Folding Boxes	18.90	0.00	0.00	0.00	3.22	0.00	0.00	36.23	22.45	38.10	100.00	0.35	0.00	0.35
Boxboard*	22.53	0.00	0.03	0.02	0.36	0.00	0.49	67.46	24.36	7.25	99.98	0.43	0.00	0.43
Boxboard**	22.53	0.00	0.03	0.02	0.36	0.00	0.49	67.46	24.36	7.25	99.98	0.43	0.00	0.43
Paper Towels***	51.69	0.00	0.00	0.00	0.45	6.94	0.15	36.32	0.98	55.14	99.99	0.77	0.00	0.77
Aluminum Cans	40.34	0.00	0.00	0.00	3.10	0.00	0.00	39.96	0.00	56.94	100.00	0.65	0.00	0.65
Steel Cans	11.78	0.01	0.17	0.07	0.03	0.00	0.00	77.28	0.65	21.80	100.00	0.19	0.24	0.43
Glass	4.37	0.55	0.00	0.39	0.25	0.25	0.00	5.49	0.53	92.54	100.00	0.07	0.00	0.07
HDPE	12.68	0.00	0.21	0.00	0.00	0.00	0.00	99.79	0.00	0.00	100.00	0.21	0.00	0.21
LDPE	11.43	0.00	0.23	0.00	0.00	0.00	0.00	99.77	0.00	0.00	100.00	0.19	0.00	0.19
PET	21.87	0.00	0.12	0.00	0.00	0.00	0.00	99.88	0.00	0.00	100.00	0.37	0.00	0.37

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, and10 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 (Franklin Data)
GHG Emissions Per Ton of Product Manufactured from Recycled Inputs
Transportation GHGs Only

Type of Product	Transportation Energy (Million BTUS Per Ton of Product)	Average Fuel Mix (in Percent)					Transportation Energy Carbon Emissions (Metric Tons of Carbon Equivalent Per Ton of Product)
		Diesel	Residual Oil	Natural Gas	Electricity	Total	
Newspaper	0.75	98.67	1.08	0.15	0.10	100	0.02
Office Paper	1.61	100.00	0.00	0.00	0.00	100	0.03
Tissue Paper	1.61	100.00	0.00	0.00	0.00	100	0.12
Corrugated Boxes	1.23	99.90	0.10	0.00	0.00	100	0.09
Folding Boxes	1.29	99.92	0.08	0.00	0.00	100	0.10
Boxboard*	0.38	100.00	0.00	0.00	0.00	100	0.01
Boxboard**	0.38	100.00	0.00	0.00	0.00	100	0.01
Paper Towels***	0.44	97.58	2.31	0.08	0.06	100	0.01
Aluminum Cans	1.65	100.00	0.00	0.00	0.00	100	0.03
Steel Cans	4.03	99.99	0.01	0.00	0.00	100	0.08
Glass	0.34	88.61	2.61	6.53	1.95	100	0.01
HDPE	1.74	100.00	0.00	0.00	0.00	100	0.04
LDPE	1.74	100.00	0.00	0.00	0.00	100	0.04
PET	1.74	100.00	0.00	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.

* 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, and10 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 2-7 (Tellus Data)

GHG Emissions Per Ton of Product Manufactured from Virgin Inputs

Process GHGs Only

Type of Product	Process Energy (Million BTUs Per Ton of Product)	Average Mix of Energy Sources (percent)									Process Energy Carbon Emissions (Metric Tons of Carbon Equivalent Per Ton of Product)
		Gasoline	Diesel	Oil	Steam	Electricity	Coal	Natural Gas	Other Fuels	Total	
Newspaper	34.11	0.46	0.35	0.27	28.45	70.47	0.00	0.00	0.00	100.00	0.54
Office Paper	35.18	0.89	0.71	5.00	77.00	16.41	0.00	0.00	0.00	100.00	0.51
Tissue Paper	33.22	0.94	0.75	5.29	74.17	18.84	0.00	0.00	0.00	100.00	0.48
Corrugated Boxes	32.07	0.86	0.70	4.90	82.58	10.95	0.00	0.00	0.00	100.00	0.46
Folding Boxes	34.05	0.81	0.66	4.61	80.82	13.09	0.00	0.00	0.00	100.00	0.49
Aluminum Cans	216.24	0.00	0.00	1.93	1.08	72.01	1.25	23.68	0.05	100.00	3.60
Steel Cans	42.10	0.03	0.36	2.35	6.15	34.66	0.33	5.71	50.41	100.00	0.95
Glass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HDPE	37.29	0.00	8.10	0.00	1.69	23.09	0.00	42.27	24.85	100.00	0.72
LDPE	51.78	0.00	6.91	0.00	5.03	31.21	0.00	35.81	21.03	100.00	0.98
PET	62.51	0.00	5.61	0.00	27.37	34.99	0.00	10.89	21.14	100.00	1.25

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

Exhibit 2-8 (Tellus Data)
GHG Emissions Per Ton of Product Manufactured from Virgin Inputs
Transportation GHGs Only

Type of Product	Transportation Energy (Million BTUs Per ton of Product)	Average Fuel Mix (in Percent)			Transportation Energy Carbon Emissions (Metric Tons of Carbon Equivalent Per Ton of Product)
		Diesel	Natural Gas	Total	
Newspaper	0.58	100.00	0.00	100.00	0.01
Office Paper	1.21	100.00	0.00	100.00	0.03
Tissue Paper	1.21	100.00	0.00	100.00	0.03
Corrugated Boxes	1.08	100.00	0.00	100.00	0.02
Folding Boxes	1.08	100.00	0.00	100.00	0.02
Aluminum Cans	5.29	100.00	0.00	100.00	0.11
Steel Cans	0.91	100.00	0.00	100.00	0.02
Glass	0.00	100.00	0.00	100.00	0.00
HDPE	3.72	53.25	46.75	100.00	0.07
LDPE	3.83	53.19	46.81	100.00	0.07
PET	2.48	57.44	42.56	100.00	0.05

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

Exhibit 2-9 (Tellus Data)
GHG Emissions Per Ton of Product Manufactured from Recycled Inputs
Process GHGs Only

Type of Product	Process Energy (Million BTUs Per Ton of Product)	Average Mix of Energy Sources (percent)									Process Energy Carbon Emissions (Metric Tons of Carbon Equivalent Per Ton of Product)
		Gasoline	Diesel	Oil	Steam	Electricity	Coal	Natural Gas	Other Fuels	Total	
Newspaper	18.52	0.00	0.26	0.00	41.88	57.86	0.00	0.00	0.00	100.00	0.33
Office Paper	20.80	0.00	0.23	0.00	62.85	36.92	0.00	0.00	0.00	100.00	0.38
Tissue Paper	0.94	0.00	0.24	0.00	58.66	41.10	0.00	0.00	0.00	100.00	0.36
Corrugated Boxes	27.31	0.00	0.17	0.00	69.47	30.36	0.00	0.00	0.00	100.00	0.51
Folding Boxes	29.23	0.00	0.16	0.00	67.11	32.72	0.00	0.00	0.00	100.00	0.54
Aluminum Cans	46.04	0.00	0.10	2.57	0.00	35.51	0.00	61.82	0.00	100.00	0.73
Steel Cans	17.01	0.00	0.35	0.00	0.00	97.92	0.48	1.25	0.00	100.00	0.29
Glass	1.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HDPE	17.85	0.00	0.27	0.00	0.00	99.73	0.00	0.00	0.00	100.00	0.30
LDPE	23.29	0.00	0.20	0.00	0.00	99.80	0.00	0.00	0.00	100.00	0.39
PET	27.84	0.00	0.17	0.00	0.00	99.83	0.00	0.00	0.00	100.00	0.47

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

Exhibit 2-10 (Tellus Data)
GHG Emissions Per Ton of Product Manufactured from Recycled Inputs
Transportation GHGs Only

Type of Product	Transportation Energy (Million BTUs Per Ton of Product)	Average Fuel Mix (in Percent)			Transportation Energy Carbon Emissions (Metric Tons of Carbon Equivalent Per Ton of Product)
		Diesel	Natural Gas	Total	
Newspaper	2.13	100.00	0.00	100.00	0.04
Office Paper	1.87	100.00	0.00	100.00	0.04
Tissue Paper	0.00	100.00	0.00	100.00	0.00
Corrugated Boxes	1.33	100.00	0.00	100.00	0.03
Folding Boxes	0.83	100.00	0.00	100.00	0.02
Aluminum Cans	0.90	100.00	0.00	100.00	0.02
Steel Cans	0.82	100.00	0.00	100.00	0.02
Glass	0.00	100.00	0.00	100.00	0.00
HDPE	0.83	100.00	0.00	100.00	0.02
LDPE	1.56	100.00	0.00	100.00	0.03
PET	1.56	100.00	0.00	100.00	0.03

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

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3. FOREST CARBON SEQUESTRATION

This chapter presents estimates of the forest carbon sequestration that result from recycling or source reducing newspaper, office paper, and corrugated cardboard.

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 US, uptake by forests has exceeded release since about 1977, primarily due to forest management activities and the reforestation of previously cleared areas. This net storage 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 US forests was about 75 million metric tons of carbon equivalent (MMTCE) in 1996,[1] offsetting about 5 percent of US energy-related CO_2 emissions. In addition, about 18 million metric tons of carbon was stored in wood products.

When paper products are source reduced or recycled, trees that would otherwise be harvested are left standing. In the short term, this results in a larger amount of carbon remaining sequestered, because the standing trees continue to store carbon, whereas paper production 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 there would otherwise be, so that there is comparatively less forest acreage in trees that are growing rapidly (and thus sequestering carbon rapidly).[3,4,5]

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[1] US EPA, *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-96,* April 1998. Note that the estimate cited includes only carbon storage in trees and understory; this report also includes estimates for forest floor and soils.

[2] The basic relation is that 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).

[3] Note also that when a ton of paper is source reduced or recycled, less timber is harvested to make new paper. In general, as the demand for timber falls with increased source reduction and recycling, the price of timber also falls. Consequently, increased harvesting for solid wood products (such as lumber or plywood used in construction) may result.

[4] Note that some analysts project that in the long run, global demand for forest products will increase more rapidly than global paper recovery rates, so that even with increased paper recovery, forested acreage is likely to increase in the long run to meet increased demand.

[5] Some analysts have suggested that more efficient municipal waste combustors and increased paper combustion rates, combined with more intensive tree planting, could result in reduced GHG emissions [Electric Power Research Institute, "Paper Recycling: Impact on Electricity-Use, Electro-Technology Opportunities," Report RP-3228-06 (1993), cited in Gaines, Linda L. and Frank Stodolsky, "Energy Implications of Recycling Packaging Materials" (Argonne, IL: Argonne National Laboratory) 1994]. However, a comprehensive examination of the

Considering the importance of forest carbon sequestration as a process affecting net US GHG emissions, and given the fact that paper products are a large and growing portion of the forest products market, we recognized that a thorough examination of forest carbon sequestration was warranted for this study. Moreover, the complexity and long time frame of carbon storage in forests, coupled with the importance of market dynamics that determine land use behavior, dictated the use of best available models to evaluate the effect of source reduction and recycling of paper products on forest carbon sequestration. This chapter describes our method for applying models to estimate the effect of forest carbon sequestration associated with paper source reduction and recovery for recycling. We used the results from our analysis of paper recovery to estimate the effect of recycling and source reduction on forest carbon sequestration.

We worked with the US Department of Agriculture Forest Service (USDA-FS) to use a system of models of the US forest sector to estimate the amount of forest carbon sequestration per incremental ton of newspaper, office paper, and corrugated cardboard 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 allow us to separately estimate the forest carbon sequestration associated with recovery of each of the three types of paper, we obtained a single estimate for the sequestration from recovering <u>any</u> type of paper.

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 to those of a baseline scenario (such as the analysis described in this chapter), the USDA-FS model results are probably reasonable. This is because 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.

In brief, we found a relationship exists between recycling rates and carbon sequestration, and that recovering one ton of paper results in incremental forest carbon sequestration of 0.73 metric tons of carbon equivalent (MTCE).[6] We converted this single estimate for recovering any type of paper into separate estimates for source reducing each of three different types of paper. We developed separate estimates for source reduction based on the inputs displaced by source reduction - either 100 percent virgin inputs, or a mix of virgin and recycled inputs (this mix is different for each type of paper).

If one assumes that source reduction displaces 100 percent virgin inputs in paper manufacture, forest carbon effects would be the same as for recycling, i.e., sequestration of 0.73 MTCE per ton. If source reduction displaces the mix of virgin and recycled inputs currently used in manufacturing, the benefits would be somewhat reduced—source reduction of one ton of newspaper, office paper, or corrugated cardboard results in forest carbon sequestration of, respectively, 0.48, 0.56, and 0.44 MTCE.

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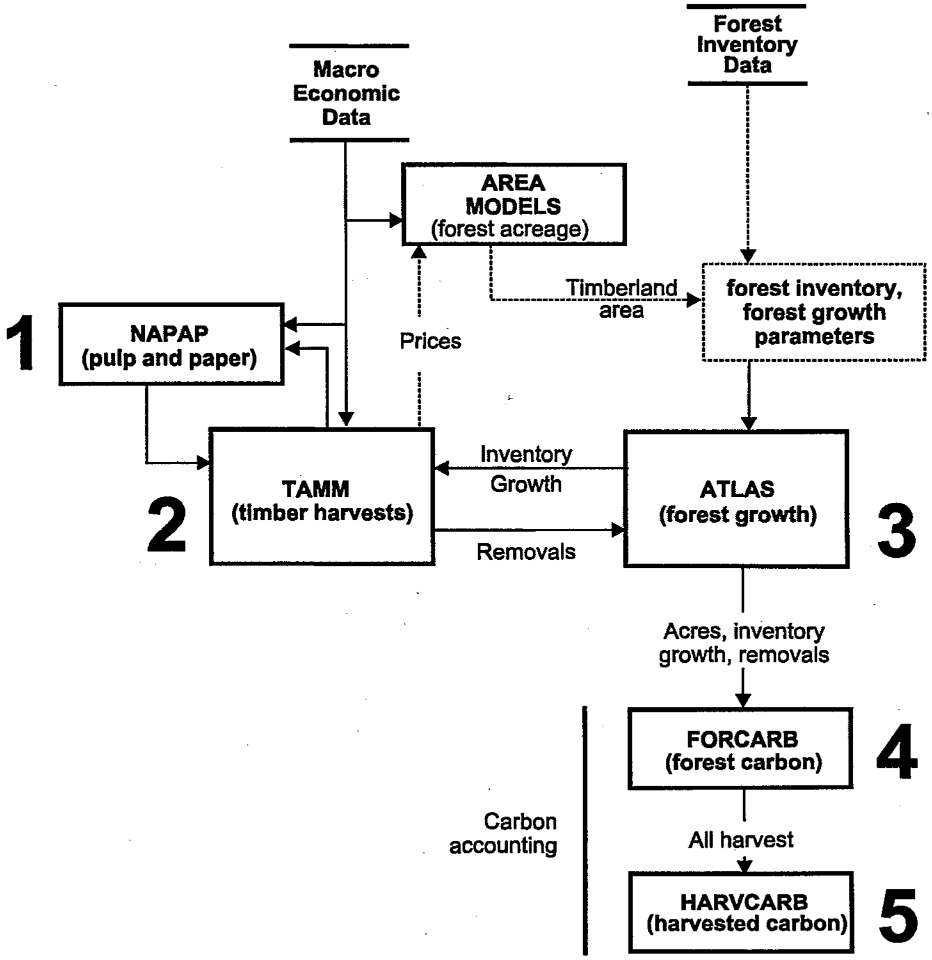
interactions between combustion and forest dynamics was beyond the scope of this report. Likewise the use of recovered paper for non-paper uses, such as molded pulp products and insulation, was not analyzed.

[6] 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.

Exhibit 3-1
USFS Models of the Forest Sector



------------------ Denotes 'hand' linkages between models/modelers requiring manipulation of data.

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 analysis. Sections 3.2 through 3.5 describe the five models in greater detail, and briefly discuss the inputs, assumptions, and outputs for each model. Section 3.6 presents the results of the analysis, and Section 3.7 discusses the limitations of individual models, and of the analysis as a whole.

3.1 MODELING FRAMEWORK

Working with USDA-FS, we used five linked models of the forest sector to estimate the impacts of increased recovery and source reduction of paper products on forest carbon sequestration.[7] The first model projects the decline in US 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 US timber harvests and increased timber inventories.[8] 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.

Our overall analysis proceeded as follows:

1) We developed two future recovery scenarios - a projected 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 the North American Pulp and Paper (NAPAP) model (the model is described in Section 3.2). A 50 percent recovery rate was used for the baseline scenario because the paper industry projects a 50 percent recovery rate by the year 2000 in the absence of further government policies to promote recycling. 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 corresponds to EPA's goal of increasing recovery of MSW in the original (1993) Climate Change Action Plan. We assumed that EPA policies to promote source reduction and recycling would end in 2000, and 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 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 were then 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 was then 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 US timber harvests, and the Aggregate Timberland Assessment System (ATLAS) model, which projects timber growth and changes in the US 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 US harvest levels and forest inventories for each year through 2040, for both the baseline and high recovery scenarios.

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[7] The Forest Service models and data bases were last completely revised in 1987, and updated in 1993. The Forest Service expects to publish a complete revision in December 1998.

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

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 US forest carbon sequestration for each year through 2040, for both the baseline and high recovery scenarios.

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

3.2 THE NORTH AMERICAN PULP AND PAPER (NAPAP) MODEL

The NAPAP model is a linear optimization model,[9] which uses forecasts of the US economy (e.g., growth in population and in the economy) to estimate the quantity of hardwood and softwood trees harvested for pulpwood in North America each year.[10] 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.

Inputs to the NAPAP Model

Major inputs to the NAPAP model are:

- macroeconomic forecast data (e.g., estimates of US population growth, and growth in per-capita gross domestic product),
- paper manufacturing capacity as of a baseline year,[11]
- manufacturing costs for each different paper manufacturing process, and
- assumed levels of future harvests from public forests.

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[9] 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).

[10] A number of analyses have been conducted using results from the NAPAP models. These include: (1) USDA Forest Service, *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) 1994, 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) 1995, 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 Environmental Studies Program on Solid Waste Policy, Working Paper #3 (New Haven, CT: Yale University) 75 pp.; and (4) Environmental Defense Fund, *Paper Task Force Recommendations for Purchasing and Using Environmentally Preferable Paper: Final Report of the Paper Task Force* (New York, NY: Environmental Defense Fund) 1995, 245 pp.

[11] 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 five percent of actual 1995 paper manufacturing capacity.

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 regions in the US (west, south, and north) and two regions in Canada,
- estimated supply functions for four principal categories of recovered paper – newspapers, corrugated boxes, mixed papers, and the aggregate of pulp substitutes and high-grade de-inking categories – 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[12] for all thirteen principal categories of paper and paperboard products produced in North America[13] (the demand functions reflect increasing demand due to population growth and growth in the gross domestic product, and decreasing demand at 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
- 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) particular levels of harvests from public forests, and (2) specific future technology options.[14] Finally, the NAPAP pulpwood supply functions are

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[12] Separate demand functions are incorporated for US domestic demand, Canadian domestic demand, and demand from various trading regions for exported paper products from the US and Canada.

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

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

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 led to decreased demand for pulpwood and lower pulpwood prices, leading some landowners to convert forested land to farmland or ranchland).[15]

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.

NAPAP scenarios are generally specified in terms of recovered fiber utilization rates, which differ somewhat from paper recovery rates. To assure that the model inputs for fiber utilization were consistent with paper production, recovery, and consumption projections prepared by the American Forest and Paper Association (AFPA), Franklin Associates, Ltd. (FAL) 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.[16]

Trade in forest products between the US 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 US paper recovery would be shown in the NAPAP outputs as a change in US pulpwood harvests. Thus, the forest carbon effects of increased paper recovery in the US were modeled as if those effects occur entirely in the US.

Outputs of the NAPAP Model

The principal outputs of the NAPAP model, for each of the two scenarios modeled, are annual US 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

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[15] 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 has recently 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.

[16] 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 a good will affect the quantity of the good 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 one 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 good in question, as distinct from "cross-elasticity" of demand - which would be measured with respect to the price of a different good.)

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

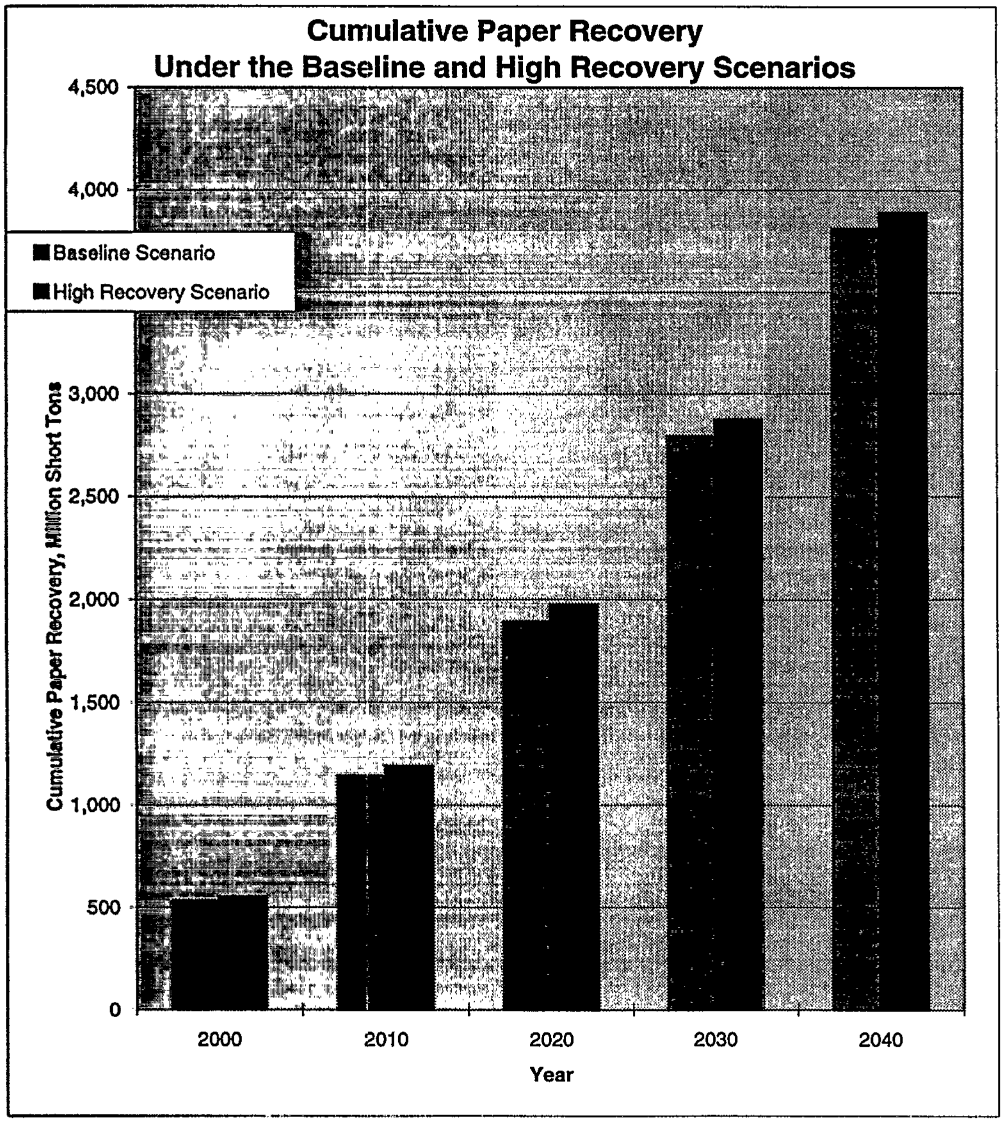
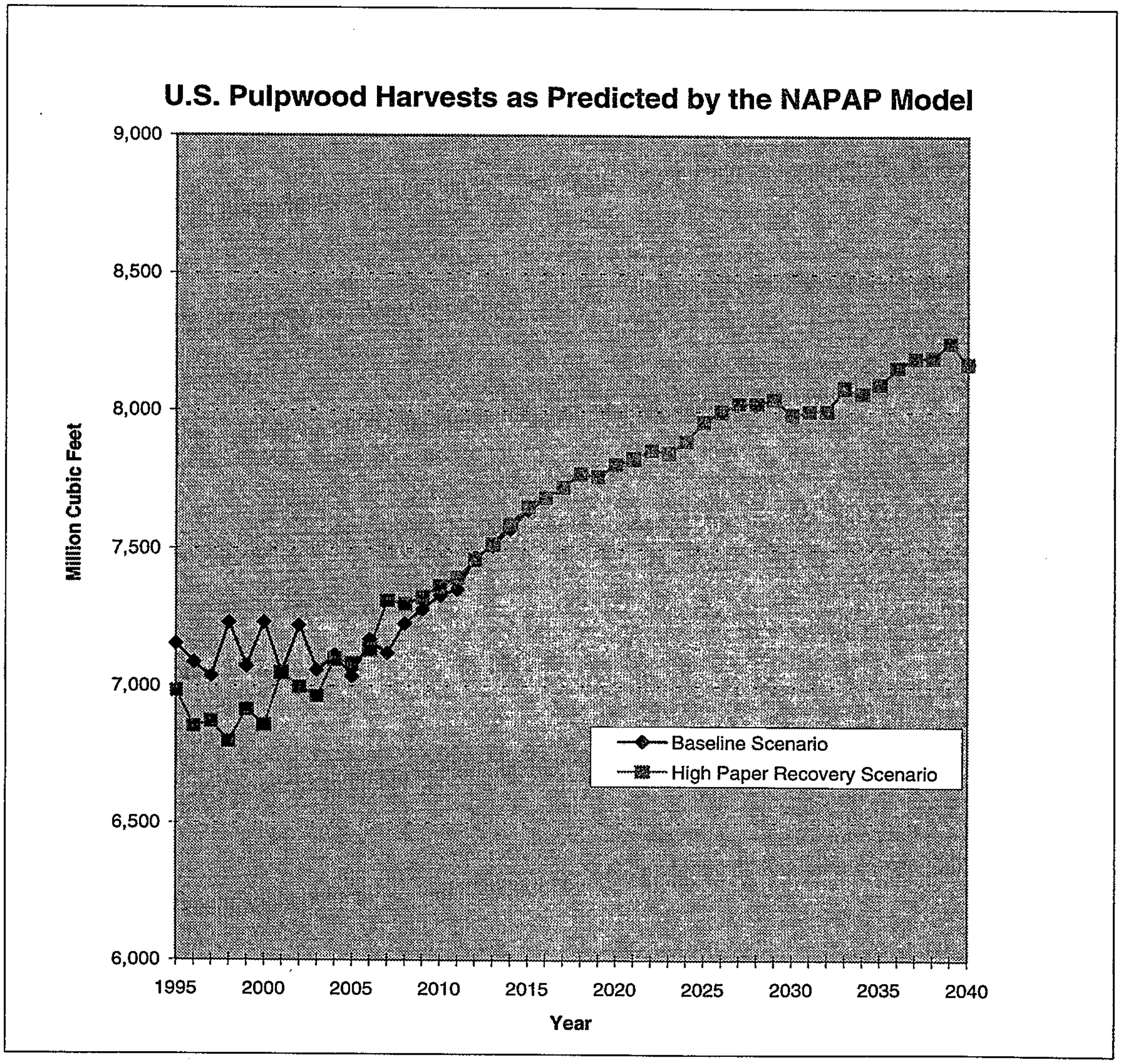


Exhibit 3-3
U.S. Pulpwood Harvests as Predicted by the NAPAP Model for Selected Years (Million Cubic Feet)

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



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,[17] and 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).

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

TAMM and ATLAS are spatial equilibrium models.[18] TAMM models US timber harvests through 2040, and ATLAS models changes in US forest growth, and inventory of growing stock volume, through 2040.[19] 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. Note that, 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

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[17] 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 is because the increase in paper recycling during this period is projected to be greater than the increase in paper consumption.

[18] A spatial equilibrium model is an optimization model (see footnote 9 in this chapter) that accounts for costs of transportation of products from producing regions to consuming regions.

[19] The descriptions of the TAMM and ATLAS models are drawn from Richard W. Haynes et al, *Alternative Simulations of Forestry Scenarios Involving Carbon Sequestration Options: Investigation of Impacts on Regional and National Timber Markets*, US Department of Agriculture Forest Service, Pacific Northwest Station, August 5, 1993. Two articles which give a more detailed description of the TAMM model are (1) Adams, D.M. and R.W. Haynes, *The 1980 Softwood Timber Assessment Market Model: Structure, Projections, and Policy Simulations*, Forest Science Monograph No. 22 (Washington, DC: USDA Forest Service) 1980, 62 pp., and (2) Adams, D.M. and R.W. Haynes, *A Spatial Equilibrium Model of US 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.

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.

Inputs to the TAMM Model

Major inputs to the TAMM model are:[20]

- US pulpwood harvests, from the NAPAP model,
- US fuelwood harvests, from a fuelwood model,
- assumed levels of future timber harvests from public forests, from USDA-FS harvest plans,
- US net imports of forest products, from a trade model,
- changes in US forested acreage over time, from a prior run of forest area models,[21]
- growth in forest inventory, from the ATLAS model,
- macroeconomic forecast data, e.g., on US housing starts, housing repairs, and remodeling, and
- installed capacity as of 1990 for producing timber products, such as lumber or plywood, from harvested trees.

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 regions in the US, and
- estimated demand functions for US 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.[22]

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[20] Inputs to the TAMM model are documented in Haynes, R.W., *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) 1990, 286 pp.

[21] Although 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, in the TAMM and ATLAS models, timber inventories were estimated independently for the two different scenarios.

[22] Specifically, TAMM uses an assumption that changes in capital investment are a function of past changes

The major assumptions of the TAMM model include:[23]

- 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.

Inputs to the ATLAS Model

Major inputs to the ATLAS model, for each simulation year, are:

- 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).

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 upon (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.

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in output (i.e., that manufacturers' expectations about the profitability of capital investment are based on past changes in output).

[23] Assumptions of the TAMM model are documented in the following two reports: (1) Haynes, R.W., *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) 1990, 286 pp.; and (2) Haynes, R.W., D.M. Adams, and J.R. Mills, *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) 1995, 66 pp.

Outputs of the TAMM/ATLAS Models

The outputs of the linked TAMM and ATLAS models are projections, through 2040, of US inventories of forest growing stock volumes (i.e., the volume of trees growing in forests), annual US 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 US as projected by the TAMM/ATLAS models. As the exhibit shows, forest growing stock inventories range from one to two billion cubic feet higher under the high recovery scenario than under the baseline scenario for the entire simulation period.

3.4 THE FOREST CARBON MODEL (FORCARB)

The Forest Carbon Model (FORCARB) projects US forest carbon storage (including soil, forest floor, and understory carbon) each year through 2040, based on outputs from the TAMM/ATLAS linked models.[24]

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.

Assumptions of the FORCARB Model

The Forest Service 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 US forest industry is then 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 immediately lost from storage, i.e., converted to CO_2 emissions.

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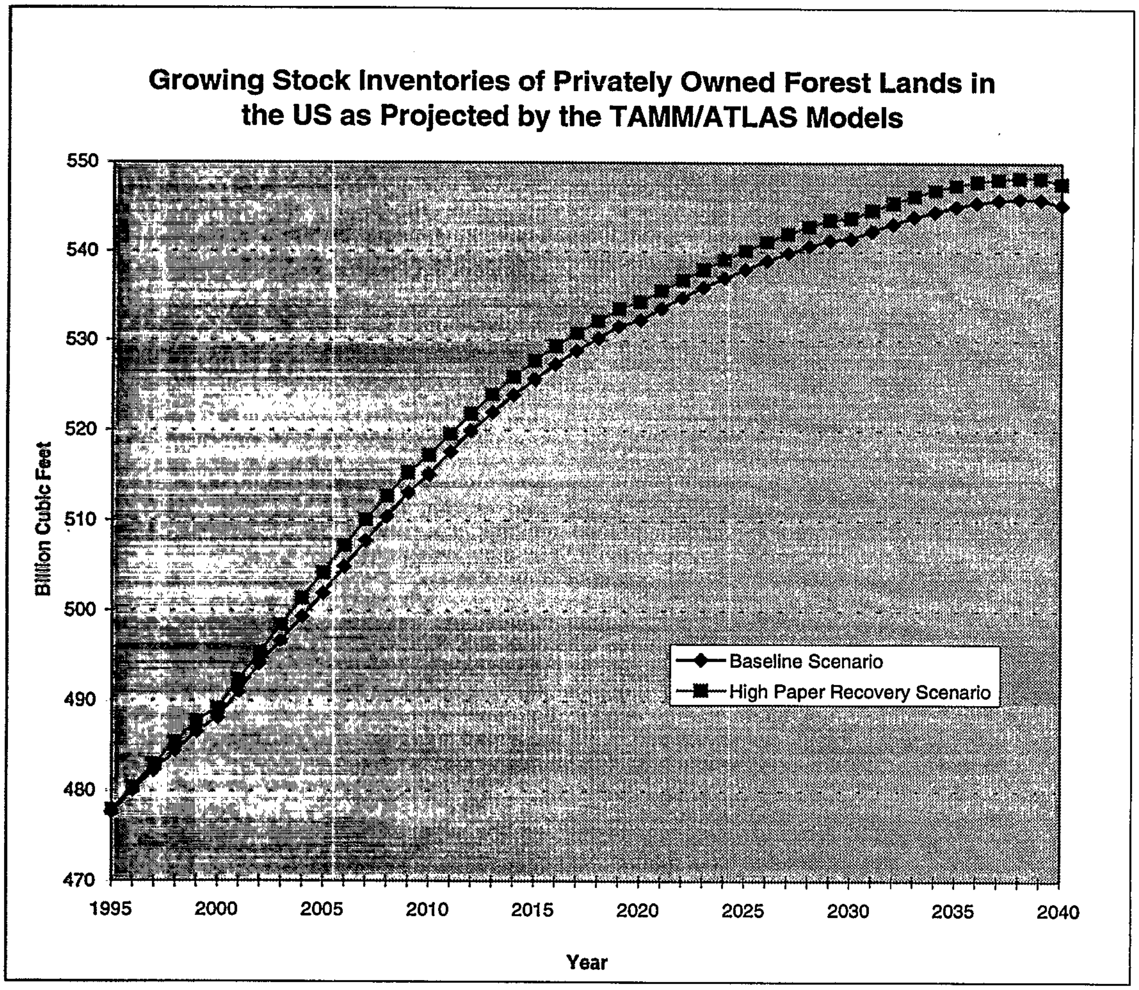
[24] The description of the FORCARB model here is drawn from Birdsey, Richard A., and Linda S. Heath, *Carbon Sequestration Impacts of Alternative Forestry Scenarios – Draft* (Radnor, PA: US Department of Agriculture Forest Service, Global Change Research Program), April 1993, pp. 47-51. A number of studies analyzing forest issues using the FORCARB and HARVCARB models have been published in journal articles. Among these are three which also explain the FORCARB and HARVCARB models. These three articles are: (1) Plantinga, A.J. and R.A. Birdsey, 1993, "Carbon fluxes resulting from US 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 US timberlands," *World Resource Review* 5:171-179.

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



Outputs of the FORCARB Model

The FORCARB model produces as outputs estimates of total US 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, there would be net emissions, i.e., negative forest carbon sequestration.

Exhibit 3-5 shows the projected carbon inventories of US forests, as predicted by the FORCARB model, for the baseline and high paper recovery scenarios. The forest carbon inventories on which these annual changes were based 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.

Exhibit 3-6 shows the *change* in US 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 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 (HARVCARB)

The Harvested Carbon Model (HARVCARB) can be thought of as a spreadsheet model that projects the disposition of harvested wood across four different potential fates, for 50 years into the future.[25] The spreadsheet would consist of estimates of the percentage of each of four types of wood that will be found in each of four potential fates at ten-year intervals. The four potential fates are (1) products (a "wood-in-use" sink), (2) landfills, (3) combustion for energy, and (4) aerobic decomposition. There is some change in the fate of a wood product 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 types 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 US – west, south, and north.

We combined the average annual sawtimber and pulpwood harvest estimates from FORCARB, with the fate estimates in the HARVCARB 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.

Inputs to the HARVCARB Model

For this analysis the USDA-FS used, as the only input to the HARVCARB model, the annual sawtimber and pulpwood harvests (from the FORCARB model).

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[25] This Forest Service 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 Forest Service's implementation of the model is based on R.A. Birdsey and L.S. Heath, *op cit*, pp. 50-51.

Exhibit 3-5
US 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

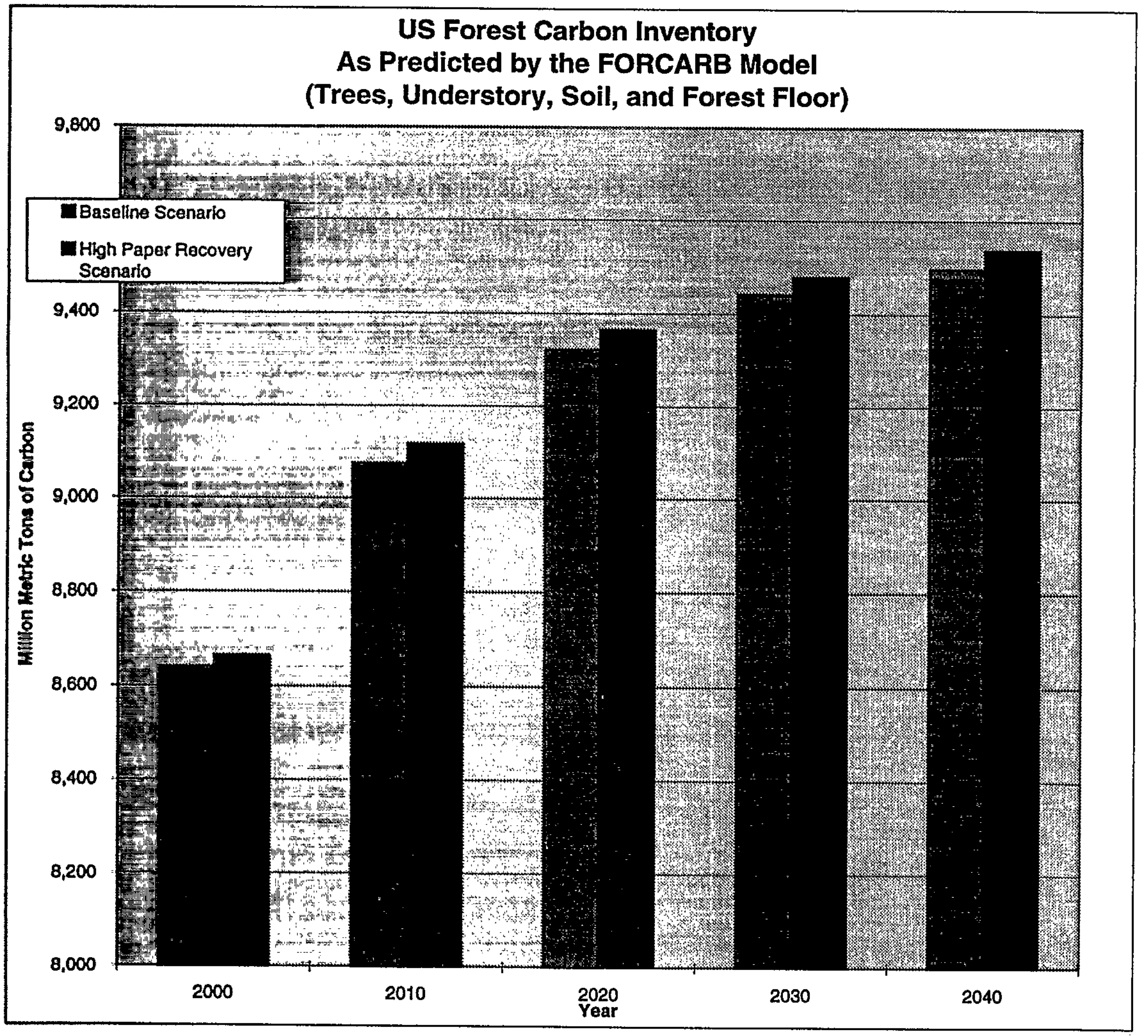
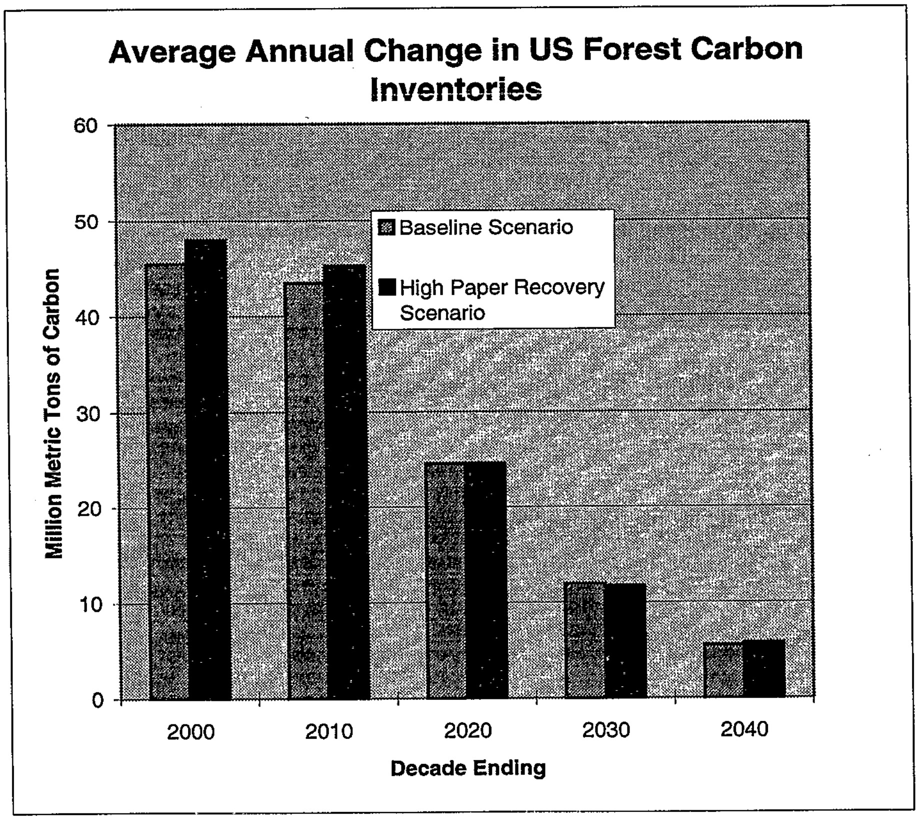


Exhibit 3-6
Average Annual Change In US Forest Carbon Inventories As Predicted by the FORCARB Model (Million Metric Tons of Carbon)

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



Assumptions of the HARVCARB Model

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

Outputs of the HARVCARB Model

In this analysis, HARVCARB 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 HARVCARB 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 HARVCARB model predicts this result because under the high recovery scenario, tree harvests are reduced; thus, under the fixed proportions of the fates of wood assumed in HARVCARB, less wood is available for each of the fates for wood products, including wood-in-use sinks. As noted above, HARVCARB 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 would probably be used for housing and furniture. Because HARVCARB 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 RESULTS

As noted in the introduction to this chapter, we first obtained estimates of the forest carbon sequestration[26] from recovery of paper, 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 recovered 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 HARVCARB 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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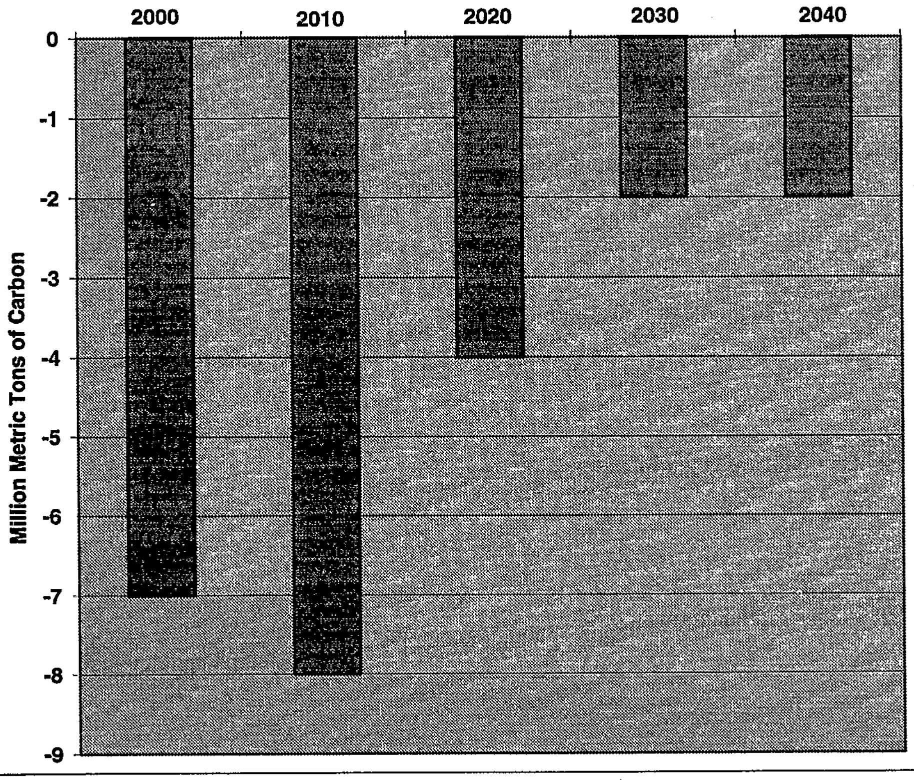
[26] As noted earlier, the term *forest carbon sequestration* is intended to include both the carbon stored in forests and the carbon stored in wood-in-use sinks.

Exhibit 3-7
US 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 Scenar	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

Change in Carbon Storage in Wood-in-Use Sinks Between the Baseline and High Paper Recovery Scenarios, as Predicted by the HARVCARB Model (Million Metric Tons of Carbon)



An important goal of this analysis is to develop "emission factors" or point estimates that enable policymakers and the public to quantify and compare the GHG impacts from managing specific waste materials in specific ways. Originally, these emission factors were intended to estimate progress made by the US in meeting its commitment to reduce GHG emissions by the year 2000. However, in December 1997, the parties to the UN Framework Convention on Climate Change agreed to an historic Protocol on climate change, the Kyoto protocol. The protocol establishes a US target of reducing GHG emissions to a level 7 percent below 1990 emissions over a 5 year period from 2008 through 2012. If the US ratifies the Kyoto protocol, these emissions factors may be used to help the US evaluate progress in meeting the emission reductions set forth in the protocol. The emission factors developed here are also intended to aid in the evaluation of voluntary programs, which, in a time of uncertain but inevitable reductions in emissions, are especially important. Given the uncertainty of the analysis, the timeframes chosen for developing emission factors are appropriate for the evaluation of voluntary programs.

In developing these estimates, 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 by the year 2000. 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 by the year 2000; (2) actions taken to bring about increases in source reduction and recycling by the year 2000 will have lingering effects beyond the year 2000, (3) forest carbon sequestration benefits drop somewhat over time; and (4) there is more uncertainty 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.[27] In addition, if the US ratifies the Kyoto protocol, 2010 fits well with the proposed timeframe for achieving emission reductions.

As noted above, we did not consider in this analysis carbon sequestration in forest soils or the forest floor. Research on forest soils is much more speculative than the characterization of the carbon in trees. It seems more likely than not that some quantity of carbon is sequestered in forest soils (and should be added to the forest carbon sequestration totals, but there are no reliable estimates of the actual amounts.

Using the forest carbon sequestration estimate for paper recovery, we developed estimates for forest carbon sequestration associated with source reduction, 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.[28] We estimated that forest carbon sequestration for source reduction, assuming displacement of virgin inputs, is the same as for paper

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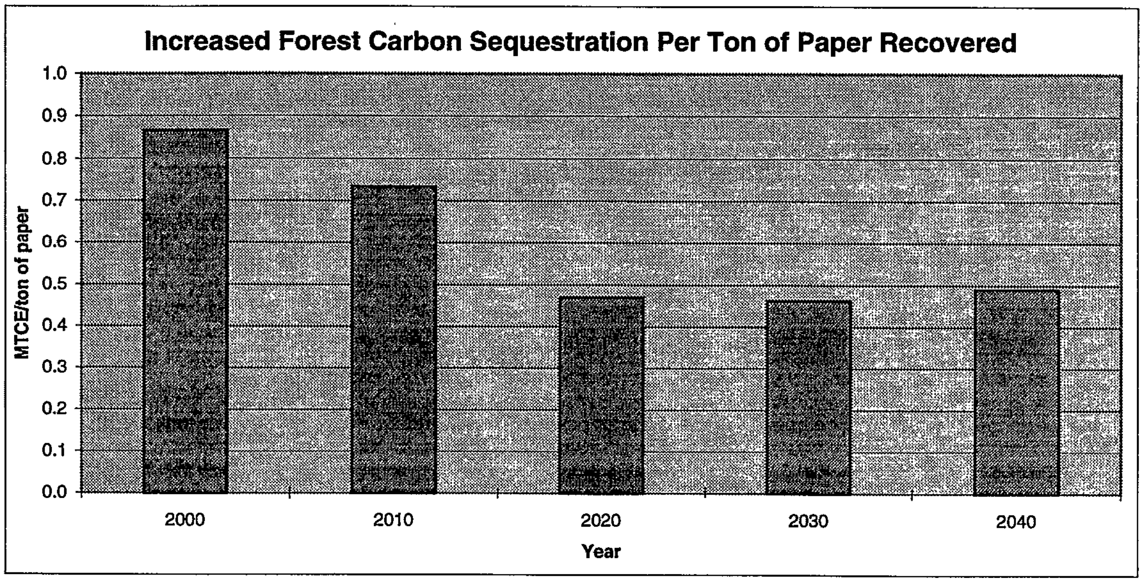
[27] The impact of increased paper recycling and source reduction on forest growing stock inventories (3 billion cubic feet in addition to the baseline scenario of 541 cubic feet in 2030, as shown in Exhibit 3-4) is only 0.5 percent. This amount is less than the likely statistical error in measuring 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.

[28] 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.



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.

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

(a) Material	(b) Recycling, Recovering One Incremental Ton of Paper (MTCE)	(c) Source Reduction, Assuming Displacement of One 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)
Newspaper	0.73	0.73	65%	0.48
Office Paper	0.73	0.73	76%	0.56
Corrugated Cardboard	0.73	0.73	60%	0.44

3.7 LIMITATIONS OF THE ANALYSIS

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 and other forest products (and the actual choices made by owners of private forest lands) 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. However, some limitations could result in unequal bias in the estimates, 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.

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 US GHG emissions, the actual effects would occur not only in the US but in Canada and other countries.

- The Forest Service models treat forest product markets in the US 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 US 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, the effects would actually be shared by U.S. and Canadian forests.

- 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; however, forests in these countries 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 US forests).[29]

- NAPAP does not account for any effects of lower pulpwood prices (due to higher paper recycling rates) on net exports of US pulpwood to non-Canadian markets. Lower pulpwood prices would be expected to result in increased exports, and possibly changes in foreign timber inventories. Though US pulpwood exports are currently less than one percent of US 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 New Zealand, Australia, Brazil, Chile, and South Africa, and Indonesia. The effect of additional world sources of paper fiber from developed countries on these forest plantation programs is difficult to estimate.

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[29] A comprehensive description of the world paper industry, its fiber sources, and environmental concerns is in IIED. 1996. *Towards a Sustainable Paper Cycle*. International Institute for Environment and Development. London. 258 p. 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.

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. They are as follows:

- The modeling system does not account for any conversion of US forest land to farmland or rangeland that might occur in response to lower prices for pulpwood due to higher paper recycling rates. The NAPAP model did not account for potential changes in timber inventory in the near term (due to lower harvests associated with higher paper recovery), nor potential changes in forest acreage in the longer term (if higher paper recovery depresses pulpwood prices enough to induce landowners to convert forested acreage to other uses). The TAMM and ATLAS models likewise did not allow for long-term changes in forested acreage due to increased paper recovery. These effects, however, may be small. Converting forest land 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 sequestration 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.

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 - and 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 newspapers 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.

- Future harvests from public forest lands may be different from those projected.

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.

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4. SOURCE REDUCTION AND RECYCLING

This chapter presents estimates of GHG emission reductions and carbon sequestration resulting from source reduction and recycling of ten materials: newspaper, office paper, corrugated boxes, mixed paper, aluminum cans, steel cans, glass containers, and three types of plastic containers (LDPE, HDPE, and PET).

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 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.[1] Using this measurement convention, it follows that source reduction[2] 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 estimates of the GHG implications of recycling, which are developed in this chapter, show 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 greenhouse gas emissions associated with making the material and managing the post-consumer waste are avoided. In addition, when paper products are source reduced, trees that would otherwise be harvested are left standing and continue to grow, so that additional carbon is sequestered in forests. The modeled estimates of forest carbon sequestration benefits are discussed in detail in Chapter 3. The additional carbon sequestered due to source reduction is counted in the same way as a reduction in GHG emissions.

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.

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[1] There are no raw materials acquisition and manufacturing emissions attributable to food scraps and yard trimmings in this analysis.

[2] 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

Greenhouse Gas Emissions for Source Reduction
(MTCE/Ton of Material Source Reduced)

Material	Avoided GHG Emissions from Raw Materials Acquistion and Manufacturing		Post-Consumer	Change in Forest Carbon Storage (Minus sign indicates incremental carbon storage)		Net Emissions For Current Mix of Inputs	Net Emissions For 100% Virgin Inputs
	For Current Mix of Inputs	For 100% Virgin Inputs		For Current Mix of Inputs	For 100% Virgin Inputs		
Newspaper	-0.48	-0.55	0.00	-0.43	-0.73	-0.91	-1.28
Office Paper	-0.52	-0.56	0.00	-0.50	-0.73	-1.03	-1.29
Corrugated Cardboar	-0.41	-0.38	0.00	-0.38	-0.73	-0.78	-1.11
Mixed Paper							
Broad Definition	NA	NA	NA	NA	NA	NA	NA
Residential Definitio	NA	NA	NA	NA	NA	NA	NA
Office Paper Definiti	NA	NA	NA	NA	NA	NA	NA
Aluminum Cans	-2.98	-5.39	0.00	0.00	0.00	-2.98	-5.39
Steel Cans	-0.84	-1.12	0.00	0.00	0.00	-0.84	-1.12
Glass	-0.14	-0.16	0.00	0.00	0.00	-0.14	-0.16
HDPE	-0.61	-0.70	0.00	0.00	0.00	-0.61	-0.70
LDPE	-0.89	-0.89	0.00	0.00	0.00	-0.89	-0.89
PET	-0.98	-1.16	0.00	0.00	0.00	-0.98	-1.16
Food Waste	NA	NA	NA	NA	NA	NA	NA
Yard Waste	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.

In order to compare source reduction to other solid waste management options, one compares the GHG reductions from source reduction to the life cycle GHG emissions of the other solid waste management option (e.g., landfilling). With this approach, policy makers can evaluate, on a per ton basis, the overall difference in GHG emissions between (1) source reducing one ton of material and (2) manufacturing and then managing (post-consumer) one ton of the same material. Such comparisons are made in the executive summary chapter and in Chapter 8 of this report. Overall, source reduction has lower GHG emissions than the other waste management options.

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.[3] As with source reduction of paper products, recycling of paper also results in forest carbon sequestration.

Although most of the materials considered are modeled as being recycled in a "closed loop" (e.g., newspapers are recycled into new newspapers), two of the specific products considered - office paper and corrugated boxes - are often recycled in an "open loop" (i.e., they are recycled into more than one product). We modeled office paper as being recycled into either office paper or tissue paper, in proportions of 45 percent and 55 percent, respectively. Corrugated boxes are modeled as being recycled into either corrugated boxes (70 percent) or folding boxes (30 percent).[4]

In addition, several paper types are recycled under the general heading of "mixed paper."[5] Mixed paper is included in this analysis because it is recycled in large quantities, and is an important class of scrap material in many recycling programs. However, it is difficult to present a single definition of mixed paper because each mill using recovered paper defines its own supply which varies with the availability and price of different grades of paper. Therefore, for the purpose of this report, we identified three different definitions for mixed paper — broad, office, and residential. 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 copy 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.

Although our modeling approach addresses some of the most important open loops, it does not fully reflect the prevalence and diversity of open loop recycling. For example, (1) office paper, corrugated cardboard, and mixed paper are recycled into a variety of manufactured products, not just the

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[3] 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 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., methane emissions minus carbon sequestration) were close to zero. Because the emissions are small and highly uncertain, no quantitative estimate is included in this report.

[4] These percentages were provided by Franklin Associates, Ltd. in working papers, October 1995.

[5] This report also includes estimates for "mixed recyclables," i.e., a mixture of the principal paper, metal, and plastic materials that are recycled. Mixed recyclables are discussed in Chapter 8.

two products we selected for each, and (2) most of the other materials are also recycled to some degree in open loops, which are typical outcomes of recycling. Resource limitations prevent an exhaustive analysis of all the recycling possibilities for each of the materials analyzed.

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%
Newsprint	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 newspapers, old corrugated containers, tissue produce, paper plates and cups, converting and special industrial papers, nonpackaging paperboard such as album covers and posterboard, and paper labels.
(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.

For both open and closed loops, 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.

When any material is recovered for recycling, some portion of the recovered materials is unsuitable for use as recycled inputs (these materials are discarded either in the recovery stage or in the remanufacturing stage). Consequently, less than one ton of material is generally made from one ton of recovered inputs. These losses may be expressed as "loss rates." Franklin Associates, Ltd. and the Tellus

Institute provided estimates of loss rates for each material; the averages of these values are shown in Exhibit 4-3.

The avoided GHG emissions from remanufacture using recycled inputs is thus 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.

Exhibit 4-3
Loss Rates For Recovered Materials

(a) Material	(b) Percent of Recovered Materials Retained in the Recovery Stage	(c) Tons of Product Made Per Ton of Recycled Inputs in the Manufacturing Stage	(d) (d = b * c) Tons of Product Made Per Ton of Recovered Materials
Newspaper	90	0.85	0.77
Office Paper	88	0.75	0.66
Corrugated Cardboard	92	0.84	0.77
Aluminum Cans	95	0.87	0.83
Steel Cans	98	1.00	0.97
Glass	90	0.98	0.88
HDPE	87	1.00	0.87
LDPE	87	1.00	0.87
PET	87	1.00	0.87

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."

Exhibit 4-4 shows the greenhouse gas implications of recycling each material. It sums, for each material, the differences between manufacture from virgin and recycled inputs for (1) energy-related greenhouse gas emissions (both in manufacturing processes and transportation), (2) process non-energy-related greenhouse gas 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[6]:

$T_{recyc} = T_{prod}*(RC_p-RC_i)/L$, 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, one compares the total GHG emissions from recycling the material to the GHG emissions from managing the disposal of the same material under the other 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. However, where both the original material and the substitute material are addressed in this report, 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.

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[6] 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).

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 OF THE ANALYSIS

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. Four 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),[7] and (2) professional judgment on the methane generation rates for cellulose, etc. The screening analysis indicated that net GHG emissions (methane emissions minus carbon sequestration) 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.

- We used a simple representation of recycling as mostly closed loop. We considered open loop processes for only three products, and even there our open loop model was simplified – we considered only two products that might be made from each original product.

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

Exhibit 4-4
Greenhouse Gas 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
Newspaper	-0.14	0.01	0.00	-0.73	-0.86
Office Paper	-0.07	-0.01	0.00	-0.73	-0.82
Corrugated Cardboard	0.03	0.00	0.00	-0.73	-0.70
Mixed Paper					
Broad Definition	0.09	-0.02	0.00	-0.73	-0.67
Residential Definition	0.09	-0.02	0.00	-0.73	-0.67
Office Paper Definition	-0.09	-0.02	0.00	-0.73	-0.84
Aluminum Cans	-2.49	-0.07	-1.32	0.00	-3.88
Steel Cans	-0.57	-0.01	0.00	0.00	-0.57
Glass	-0.04	0.00	-0.04	0.00	-0.08
HDPE	-0.30	-0.02	-0.05	0.00	-0.37
LDPE	-0.44	-0.01	-0.05	0.00	-0.49
PET	-0.58	-0.02	-0.03	0.00	-0.62

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.

*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. It accounts for loss rates in collection, processing, and remanufacturing. Recycling credit is based on weighted average of closed and open loop recycling for office paper, corrugated cardboard, and 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-

Explanatory notes continued: related GHG emissions between making one ton of the material from 100% virgin inputs and from 100% recycled inputs, multiplied by (2) the estimated tons of material manufactured from one 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 Franklin Associates, Ltd. (FAL), as shown in Exhibits 2-2 through 2-5. Then we estimated the same values based on data provided by the Tellus Institute, as shown in Exhibits 2-6 through 2-9. Finally, we averaged the two sets of estimates to obtain the values shown in columns "b" and "c." Note that for corrugated cardboard and 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 is because the manufacture of corrugated cardboard and boxboard (the product of open loop recycling of these types of mixed paper) from virgin inputs uses a high proportion of biomass fuels -- whose biogenic CO_2 emissions 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 corrugated cardboard and mixed paper are lower than the net GHG emissions from the manufacture of corrugated cardboard from virgin inputs.

For column "d," which presents the process non-energy GHG emissions from recycling, we used (1) data provided by FAL showing the difference in process non-energy GHG emissions between making one 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 one ton of material recovered, after accounting for loss rates in the recovery and remanufacturing steps.

Next, in column "e," the exhibit 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 presents estimates of greenhouse gas (GHG) emissions and carbon sequestration from composting of yard trimmings and food scraps.[1]

Composting consists of the aerobic decomposition of organic materials. In controlled composting operations, organic materials are typically placed in piles that have sufficient moisture and aeration for aerobic microorganisms (e.g., bacteria) to decompose the materials. Aeration may be provided by turning the piles; this prevents the development of low-oxygen conditions in the piles which could lead to anaerobic decomposition, with its associated noxious odors and methane generation. Nitrogen may be added to a compost pile to achieve a carbon/nitrogen ratio that is optimal for rapid composting.

As organic materials are composted, they are converted into a form of organic matter known as humus. When the compost is added to soil, the humus decomposes further. At both stages of decomposition, much of the carbon in the original material is released in the form of carbon dioxide. Because this carbon dioxide is biogenic in origin, it is not counted as a greenhouse gas (as explained in Section 1.7). However, it is conceivable that composting could result in (1) methane emissions from anaerobic decomposition, or (2) long-term carbon sequestration in the form of undecomposed carbon compounds. In addition, with centralized composting there are 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] Therefore, we investigated the extent to which composting might result in (1) methane emissions, (2) carbon sequestration in soils to which compost is applied (for yard trimmings, we considered the incremental carbon sequestration from composting, beyond the carbon sequestration expected when yard trimmings are left in place on the ground) and (3) CO_2 emissions from transportation of compostable materials, and turning of the compost piles.

Our analysis suggests that composting, when properly done, does not result in methane generation, and results in minimal carbon sequestration for yard trimmings. For centralized composting, slight GHG emissions result from transportation of material to be composted and mechanical turning of the compost. Overall, centralized composting of yard trimmings probably has no net GHG emissions (measured as GHG emissions minus carbon sequestration). Similarly, backyard composting of food scraps is estimated to have no net GHG emissions.

5.1 POTENTIAL GREENHOUSE GAS EMISSIONS

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

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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 (1) compost is a marketable product and (2) CO_2 emissions from transportation of other marketable, finished goods to consumers have not been counted in other parts of this analysis.

Methane. To research the methane issue, we first conducted a literature search for articles on methane generation from composting. We identified no relevant articles published between 1991 and early 1995, and thus decided not to continue searching for earlier articles. Because the literature search was unproductive, we contacted several researchers from universities and the US Department of Agriculture to discuss the potential for methane generation, based on the nature of carbon flows during composting. Our methane analysis was based on their expert opinions.

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

For backyard composting, the compost pile is rarely large enough to permit anaerobic conditions to develop, even in the center of the pile (i.e., all parts of the pile are close enough to the surface to remain oxygenated).

We concluded from the available information that methane generation from backyard and centralized compost piles is negligible.

Carbon Dioxide from Transportation of Materials and Turning of Compost. Next, we estimated the indirect carbon dioxide emissions associated with collecting and transporting yard trimmings to centralized compost facilities, and turning the compost piles. We began with estimates developed by Franklin Associates, Ltd. for the amount of diesel fuel required, for one ton of yard trimmings,[3] to (1) collect and transport the yard trimmings to a central composting facility (363,000 BTUs), and (2) turn the compost piles (221,000 BTUs).[4] We converted these estimates to units of metric tons of carbon equivalent (MTCE) per ton of yard trimmings, based on a carbon coefficient of 0.0208 MTCE per million BTUs 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. There are no indirect CO_2 emissions from backyard composting, because there is no significant use of machinery to transport materials or to turn the compost pile.

5.2 POTENTIAL CARBON SEQUESTRATION

We also evaluated the effect on soil carbon storage of composting yard trimmings and food scraps. A number of long-term field experiments which directly controlled carbon inputs (through crop removal and the readdition of specific amounts of organic matter) have generally shown a linear relationship between carbon inputs and soil carbon levels. This relationship varies depending upon climatic and soil

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

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

factors which affect decomposition rates in a particular location, as well as the length of the experiment.[5] The relationship also depends on the chemical form of the carbon inputs. Our approach focuses on the effect of composting on the persistence of carbon applied to soil.

Yard Trimmings. For yard trimmings, our analysis compared the amount of long-term soil carbon storage when yard trimmings are composted (and subsequently applied to soil) to the amount of soil carbon storage when the trimmings are left directly on the ground to decompose. Because we were unable to find data allowing us to quantify incremental carbon storage, we used a bounding analysis to estimate the upper and lower limits of the magnitude of this phenomenon.

During the process of decomposition, organic materials typically go through a series of steps before finally being converted to CO_2 (as well as water and other reaction products). The intermediate compounds that are formed, and the lifetime of these compounds, can vary widely depending on the chemical composition of the parent compound; the availability of oxygen and nutrients; the population of microorganisms capable of degrading the compounds; temperature and moisture conditions; and many other factors. To evaluate the potential of composting to enhance carbon storage, a useful simplification is to view decomposition as a process consisting of two phases:

- a rapid degradation phase, lasting for a few months to a few years, where the readily degradable materials are converted mostly to CO_2, and to a much lesser extent to humic materials, and
- a slow degradation phase, lasting much longer, where the humic materials are slowly degraded to CO_2.

Composting is designed to accelerate the pace of the first phase. It promotes rapid decomposition of organics, thus reducing their volume. Some evidence suggests that composting produces a greater proportion of humus than that typically formed when yard trimmings 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 than do bacteria that predominate at ambient surface temperatures. These long-chain carbon compounds include lignin and humic materials (humic acids, fulvic acids, and humin).

For our analysis, we assumed that in soils where trimmings (i.e., grass clippings, leaves, and branches) are left in place, there is no net accumulation of carbon in the soil. This assumption is consistent with the observation that the quantity of carbon emitted from soils as carbon dioxide each year is typically in equilibrium with the quantity of additional carbon introduced into the soil each year by roots, leaf litter, and branches.[6] We used this scenario as our baseline against which to measure incremental carbon storage attributable to composting.

The incremental storage is a function of three principal factors:

(1) The amount of carbon in each material (grass, leaves, branches),

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[5] Paustian, K., H.P.Collins,; and E.A. Paul, "Management Controls on Soil Carbon", *Soil Organic Matter in Temperate Agroecosystems*, (CRC Press: Boca Raton, FL), 1997, pp. 15-49.

[6] Alexander, Martin, *Introduction to Soil Microbiology, Second Edition* (Malabar, Florida: Krieger Publishing Company) 1991, p. 133.

(2) The additional proportion of carbon converted into humus when trimmings are composted, rather than left in place, and

(3) The rate at which humus is degraded to CO_2.

We obtained point estimates for the first factor from a series of experiments by Dr. Morton Barlaz, which are described later in Chapter 7. As in other parts of the analysis, we assumed that yard trimmings comprise 50 percent grass clippings, 25 percent leaves, and 25 percent branches, by weight.[7] We used professional judgment to develop lower and upper bound estimates for the second and third factors, and then combined the estimates in a bounding analysis.

As an upper bound on the incremental humus formation, we assumed that composting can result in conversion of up to 25 percent more of the carbon to humus than the "baseline" conversion rate (i.e., if residues were left on the ground).[8] (This upper bound implies, for example, that if 10 percent of the carbon is in a relatively stable form following decomposition at ambient temperatures, then 35 percent of the carbon would be relatively stable after composting.) For a lower bound, we used a value of 5 percent as the incremental portion of carbon that is converted to stable carbon compounds.

We also developed a range for the half-life of stable carbon compounds in soil. Radiocarbon dating of soils has shown that the long-chain carbon compounds in some soil samples can be hundreds or thousands of years old.[9] As noted above, the decay rate of individual compounds is highly site- and compound-specific; to account for this heterogeneity, we used wide bounds - from a half-life of 20 years to a half-life of 2,000 years. We assumed that humus decomposition is a first-order decay process (i.e., the proportional decrease in concentration is constant over time).

Combining the two bounds for incremental humus formation (5 percent and 25 percent) and the two bounds for half-lives (20 years and 2,000 years) resulted in four scenarios for the bounding analysis. We estimated the incremental carbon storage implied by each scenario over a period of 100 years.

The results of our bounding analysis are shown graphically in Exhibit 5-1. The upper bound on the incremental carbon storage from composting is about 0.05 MTCE per ton of yard trimmings (shown in the top left of the graph); the lower bound is about 0.001 (shown in the bottom right of the graph). With the rapid decomposition (20 year half-life) assumption, incremental storage is quite sensitive to the time period over which carbon storage is considered - values at 20 years are sixteen times as high as values at 100 years. Under the slow decomposition assumption, there is little difference in incremental storage for all periods up to 100 years.

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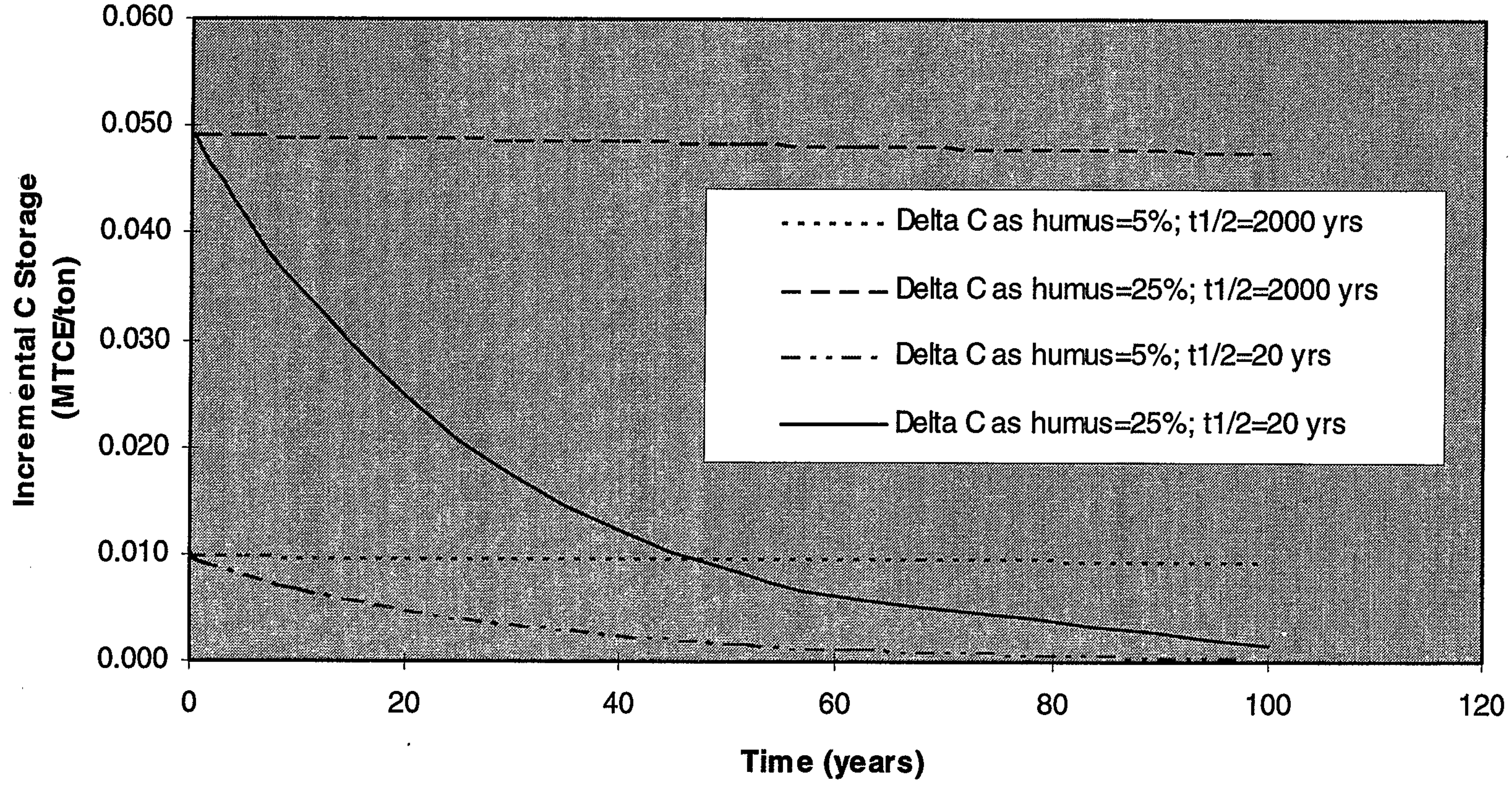
[7] This professional judgment estimate for the percentage composition of yard trimmings (as a national average) was provided by Franklin Associates, Ltd. (FAL) in a telephone conversation with ICF Incorporated, November 14, 1995. Subsequently, FAL obtained and provided data showing a wide range of percentage breakdowns for yard waste composition in different states; the percentage composition used here is within that range.

[8] Memorandum from Michael Cole, University of Illinois at Urbana-Champaign, U.S. EPA Office of Solid Waste, February 1, 1996.

[9] Allison, F.E., *Soil Organic Matter and Its Role in Crop Production* (Elsevier Scientific Publishing Co.) 1973, pp. 157-8.

Exhibit 5-1. Incremental Carbon Storage: Composting Yard Trimmings MTCE/wet ton vs time



Food Scraps. We also estimated the carbon storage from backyard composting of food scraps. Data were not available on the amount of carbon sequestered in humus when food scraps are composted. We assumed that backyard composting of food scraps converts all of the carbon in food scraps to CO_2, and that none of the carbon is sequestered in humus. To the extent that backyard composting of food scraps may sequester carbon, our results would understate the net carbon sequestration resulting from composting this material.

5.3 NET GHG EMISSIONS FROM COMPOSTING

Exhibit 5-2 presents the estimated net greenhouse gas emissions from composting. Our analysis indicated that composting is a process that produces virtually no greenhouse gas emissions, and is not likely to represent a significant carbon sink. For centralized yard trimmings composting, the transportation emissions are probably balanced (and could well be exceeded) by additional carbon storage. Given the large tonnage of yard trimmings composted annually, and the remaining uncertainties in this analysis, this is an area that would benefit from further study. For backyard food waste composting, we estimated no net GHG emissions.

Exhibit 5-2
Net Greenhouse Gas Emissions from Composting
(In Metric Tons of Carbon Equivalent Per Short Ton of Material Composted)

Material	Centralized Composting				Backyard Composting			
	CH_4	Transport CO_2	C seq	Net C	CH_4	Transport CO_2	C seq	Net C
Yard Trimmings	0	0.01	-0.001 to -0.05	0.009 to -0.04	NA	NA	NA	NA
Food Scraps	NA	NA	NA	NA	0	0	0	0

5.4 LIMITATIONS OF THE ANALYSIS

The analyses in this chapter are limited by the lack of data on methane generation and carbon sequestration that result from composting. Because of inadequate data, we relied on a theoretical approach to estimate the values (and in the case of carbon sequestration from composting of food scraps, we assumed zero carbon sequestration).

Our analysis did not consider the GHG emissions that might be avoided if compost displaces some chemical fertilizers (or peat moss, fungicides, pesticides, and other products applied to soil and plants). The manufacture of chemical fertilizers requires energy, and thus is associated with some level of energy-related GHG emissions. We also did not analyze the extent to which compost may reduce the need for pesticides.[10] For the most part, compost is applied for its soil amendment properties, rather than for purposes of fertilization or pest control.

Moreover, we did not consider other environmental benefits of composting, and of using compost as a soil amendment. For example, adding compost to soil increases the soil's capability to retain moisture and nutrients. This helps to reduce storm runoff, thus preserving topsoil and reducing siltation of streams and rivers. In the future, this may allow continued farming in areas that might have more frequent droughts due to climate change. Adding compost to soil also improves soil tilth and reduces soil density, i.e., it makes the soil easier to till, allows plant roots to go deeper, increases the likelihood that new plantings become established, and helps plants to grow larger. Finally, we did not consider the value of composting in reducing the amount of waste landfilled, and extending the useful lifetime of landfills.

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

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6. COMBUSTION

This chapter presents estimates of the net GHG emissions from combustion of each of the materials considered in this analysis 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 1.7).

Combustion of MSW with energy recovery in a waste-to-energy (WTE) plant also results in avoided CO_2 emissions in two other industrial sectors. 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 US is combusted in WTEs that recover ferrous metals (e.g., steel) and non-ferrous materials (e.g., non-ferrous metals and glass).[1] The ferrous metals and non-ferrous materials that are recovered are then recycled.[2] As discussed in Chapter 4, processes using recycled inputs require less energy than processes using virgin inputs. Thus, in measuring GHG implications of combustion, one must also 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 US, there are approximately 90 mass burn facilities that process approximately 24 million tons of MSW annually.[3] Modular WTE plants are similar to mass burn plants, but the modular units are generally smaller plants prefabricated off-site and more quickly assembled 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 which has undergone varying degrees of processing, from simple removal of bulky and noncombustible items to more complex processes (shredding and material recovery), resulting in a finely divided fuel. Processing MSW into RDF yields a more uniform fuel that has a higher

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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, approximately 775,000 tons of ferrous metal and 135,000 tons of non-ferrous material were recovered in 1996. Of the non-ferrous material, approximately 34,000 tons consisted of non-ferrous metals. Letter received from Maria Zannes, Integrated Waste Services Association, Washington, DC, August 25, 1997.

[3] Integrated Waste Services Association, *The 1997-1998 IWSA Waste-To-Energy Directory of United States Facilities*, Table 1.

heating value.[4] In the US, approximately 20 facilities process and combust RDF, 2 facilities combust RDF using off-site processing, and 8 facilities process RDF for combustion off-site. These 30 facilities process approximately 9 million tons of MSW annually.[5]

We analyzed the net GHG emissions from combustion of mixed MSW, and the following individual materials at mass burn and RDF facilities:

- newspaper,
- office paper,
- corrugated cardboard,
- mixed paper,
- aluminum cans,
- steel cans,
- glass,
- HDPE plastic,
- LDPE plastic,
- PET plastic,
- food scraps, 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; however, we did not count CO_2 absorbed because we estimated the quantity absorbed to be less than 0.01 MTCE per ton of MSW combusted.[6] Similarly, the residual waste from processing MSW into RDF is typically landfilled, and there is some potential for the organic fraction of this residual waste to yield GHG emissions when landfilled; however, we did not count these emissions because we estimate the quantity emitted to be less than 0.01 MTCE per ton of MSW processed into RDF.[7]

Our results showed that combustion of mixed MSW has small negative net GHG emissions (in absolute terms). Combustion of paper products, food scraps, 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

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

[5] Integrated Waste Services Association, *The 1997-1998 IWSA Waste-To-Energy Directory of United States Facilities*, Table 1.

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

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

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.[8]

6.1 METHODOLOGY

Our 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 utilizing recycled inputs.[9] 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.

Estimating Direct CO_2 Emissions from MSW Combustion

The carbon in MSW has two distinct origins. Some of the carbon in MSW 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.

We did not count the biogenic CO_2 emissions from combustion of biomass, for reasons described in Section 1.7. 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 was 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[10] was composed almost entirely of rubber. Based on these assumptions, we estimated that there are 0.11 pounds of non-biogenic carbon in the plastic, textiles, rubber, and leather contained in one pound of mixed MSW.[11] We assumed that 98 percent of this carbon would be converted to CO_2 when the waste was 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 metric tons of carbon equivalent (MTCE) per ton of mixed

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[8] 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.

[9] A comprehensive evaluation would also 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 sequestered. 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.

[10] US EPA, Office of Solid Waste and Emergency Response, *Characterization of Municipal Solid Waste in the United States: 1997 Update*, May 1998.

[11] ICF Incorporated, "Work Assignment 239, Task 2: Carbon Sequestration in Landfills," memorandum to EPA, April 28, 1995, Exhibit 2-A, column "o."

MSW combusted. The resulting value for mixed MSW is 0.10 MTCE per ton of mixed MSW combusted,[12] as shown in Exhibit 6-1.

We estimated that HDPE and LDPE are 84 percent carbon, while PET is 57 percent carbon (accounting for 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.

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 (nitrous oxide), a greenhouse gas with a high global warming potential (GWP).[13] The IPCC compiled reported ranges of N_2O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. We 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 and steel cans.[14]

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

Next, we 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).[15] 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 one 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.

Estimating Gross Greenhouse Gas 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 emissions estimates, for mixed MSW and for each individual material, are shown in column "e" of Exhibit 6-1.

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

[13] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual, Volume 3,* (undated) p. 6-33. The GWP of N_2O is 270 times that of CO_2.

[14] 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.

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

Exhibit 6-1
Gross Emissions of Greenhouse Gases 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
Newspaper	0.00	0.01	0.01	0.02
Office Paper	0.00	0.01	0.01	0.02
Corrugated Cardboard	0.00	0.01	0.01	0.02
Coated paper	0.00	0.01	0.01	0.02
Aluminum Cans	0.00	0.01	0.01	0.02
Steel Cans	0.00	0.01	0.01	0.02
Glass	0.00	0.01	0.01	0.02
HDPE	0.75	0.01	0.01	0.76
LDPE	0.75	0.01	0.01	0.76
PET	0.51	0.01	0.01	0.52
Food Scraps	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

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.

Estimating Utility CO_2 Emissions Avoided

Most WTE plants in the US produce electricity. Only a few produce steam, and few cogenerate electricity and steam. Thus, in our analysis, we assumed that the energy recovered with MSW combustion would be in the form of electricity. Our 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 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 BTUs per pound of mixed MSW combusted, which is a value commonly used in the WTE industry.[16] This estimate is within the range of values (4,500 to 6,500 BTUs per pound) reported by FAL,[17] and is slightly higher than the 4,800 BTUs per pound value reported in EPA's MSW Fact Book.[18] For the energy content of RDF, we used a value of 5,700 BTUs per pound of RDF combusted.[19] This estimate is within the range of values (4,800 to 6,400 BTUs per pound) reported by the US Department of Energy's National Renewable Energy Laboratory (NREL).[20] 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,[21] and (3) a report by Argonne National Laboratories.[22] 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.

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

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

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

[19] 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, October 1997.

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

[21] Procter and Redfern, Ltd. and ORTECH International, *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), September 1993.

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

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

(a) Material Combusted	(b) Energy Content (BTUs per pound)	(c) Energy Content (Million BTUs per ton)	(d) Mass Burn Combustion System Efficiency (Percent)	(e) RDF Combustion System Efficiency (Percent)	(f) Emission Factor for Utility-Generated Electricity (MTCE/ Million BTUs 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)
Newspaper	7,950 a	15.9	17.8%	16.3%	0.083	0.24	0.22
Office paper	6,800 a,b	13.6	17.8%	16.3%	0.083	0.20	0.18
Corrugated cardboar	7,043 a	14.1	17.8%	16.3%	0.083	0.21	0.19
Coated paper	5,258 c	10.5	17.8%	16.3%	0.083	0.16	0.14
Aluminum cans	-335 d	-0.7	17.8%	16.3%	0.083	-0.01 *	-0.01 *
Steel cans	-210 d	-0.4	17.8%	16.3%	0.083	-0.01 *	-0.01 *
Glass	-235 d	-0.5	17.8%	16.3%	0.083	-0.01 *	-0.01 *
HDPE	18,687 a	37.4	17.8%	16.3%	0.083	0.56	0.51
LDPE	18,687 a	37.4	17.8%	16.3%	0.083	0.56	0.51
PET	9,702 e,f	19.4	17.8%	16.3%	0.083	0.29	0.26
Yard trimmings	2,800 g	5.6	17.8%	16.3%	0.083	0.08	0.08
Food scraps	2,370 a	4.7	17.8%	16.3%	0.083	0.07	0.06
Mixed MSW**	5,000 h	10.0	17.8%	16.3%	0.083	0.15	0.14

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

* The amount of energy absorbed by one ton of steel, aluminum cans, or glass in an MSW combustor would, if not absorbed, result in less than 0.01 MTCE of avoided utility CO2.

** Mixed MSW represents the entire waste stream as disposed.

a MSW Fact Book.

b We used the MSW Fact Book's value for mixed paper as a proxy for the value for office paper.

c We used Franklin Associates' value for magazines as a proxy for the value for coated paper.

d 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.

e Gaines and Stodolsky.

f For PET plastic, we converted the value of 9,900 BTUs/pound dry weight, to 9,702 BTUs/pound wet weight, to account for a moisture content of 2 percent.

g Procter and Redfern, Ltd. and ORTECH International.

h Telephone conversation among IWSA, American Ref-Fuel, and ICF Inc., October 28, 1997.

Combustion system efficiency. To estimate the combustion system efficiency of mass burn plants, we used with a net value of 550 kWh generated by mass burn plants per ton of mixed MSW combusted.[23] 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: 1997-1998*, and (3) DOE's 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.[24] First, this value is within the range of values reported by the other sources. Second, the Newport Processing Facility provided a complete set of data from which to evaluate the overall system efficiency of RDF plants.[25]

Next, we considered losses in transmission and distribution of electricity. Using a transmission and distribution loss rate of 5 percent,[26] 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 BTUs of MSW needed to deliver one kWh of electricity. We divided the BTUs per ton of waste by the delivered kWh per ton of waste to obtain the BTUs of waste per delivered kWh. The result is 19,200 BTUs per kWh for mass burn, and 21,000 BTUs per kWh for RDF. Next we divided the physical constant for the energy in one kWh (3,412 BTUs) by the BTUs of MSW and RDF needed to deliver one 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").[27]

Electric utility carbon emissions avoided. 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 0.083 MTCE emitted per million BTUs of utility-generated electricity (delivered), based on the national average fossil fuel mix used by utilities[28] 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

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

[24] 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.

[25] 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.

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

[27] 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.

[28] Value estimated using data from the Energy Information Administration, *Annual Energy Review 1996* (Washington, DC: US Government Printing Office, DOE/EIA-0384(96).) July, 1997.

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 BTUs)	17.91		DOE, EIA, "Annual Energy Review: 1996," July 1997, Table 8.5.
Natural Gas (Quadrillion BTUs)	2.80		DOE, EIA, "Annual Energy Review: 1996," July 1997, Table 8.5.
Petroleum (Quadrillion BTUs)	0.73		DOE, EIA, "Annual Energy Review: 1996," July 1997, Table 8.5.
Total (Quadrillion BTUs)	21.44		The sum of Coal, Natural Gas, and Petroleum.
Energy Value of one Quadrillion BTUs (measured in Kilowatt-hours)	2.9E+11		DOE, EIA, "Form EIA 1605 (1997)," Appendix E.
Total (Billion kWh)	6,279		(21.44 Quad BTUs) x (2.92875x10^{11} kWh/Quad BTUs) / (10^{9} kWh/Billion kWh)
Net Generation: Before Transmission and Distribution Losses (Fossil Fuels Only)			
Coal (Billion kWh)	1,736		DOE, EIA, "Annual Energy Review: 1996," July 1997, Table 8.3.
Natural Gas (Billion kWh)	263		DOE, EIA, "Annual Energy Review: 1996," July 1997, Table 8.3.
Petroleum (Billion kWh)	68		DOE, EIA, "Annual Energy Review: 1996," July 1997, Table 8.3.
Total (Billion kWh)	2,067		The sum of Coal, Natural Gas, and Petroleum.
Generation Efficiency (Fossil Fuels Only)			
Generation Output (Billion kWh)	2,067		Calculated above.
Consumption (Billion kWh)	6,279		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: 1996," July 1997, "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)			
	All Fuels	**Fossil Fuels Only**	
Weighted Average Emission Factor of the US mix of fuels used to generate electricity (kilograms of Carbon in CO_2 per million BTU consumed)	16.80	25.01	Exhibit 6-4 of this report.
Weighted Average Emission Factor (MTCE/million BTU)	0.01680	0.02501	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)	**0.05607**	**0.08349**	Weighted Average Emission Factor (MTCE/million BTU) / Conversion Efficiency.

Exhibit 6-4

Estimating the Weighted Average Carbon Coefficient of the US 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 C in CO_2 per Million BTU Consumed)**
Coal	1,736	56.4%	84%	26.63
Natural Gas	263	8.5%	13%	15.17
Petroleum***	68	2.2%	3%	21.70
Nuclear	675	21.9%		0
Hydroelectric	329	10.7%		0
Other	7	0.2%		0
Total	3,078	100:0%	100%	NA
Weighted Average - All Fuels				16.80
Weighted Average - Fossil Fuels				25.01

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

* Source: EIA's *Annual Energy Review: 1996,* "Table 8.3 Electricity Utility Net Generation of Electricity by Energy Source for 1996."

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

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

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.[29] 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 column "g" and "h" of Exhibit 6-2.

Approach to Estimating CO_2 Emissions Avoided Due to Increased Steel Recycling

We next 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 a lack of data on the proportions of those materials being recovered. This 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 US, and (2) the amount of steel recovered, post-combustion. Ferrous metals are recovered at approximately 79 WTE facilities in the US and at eight RDF processing facilities that do not generate power on-site. These facilities account for approximately 90 percent of the 32 million tons of MSW combusted per year, and recovered a total of about 775,000 tons per year of ferrous metals in 1997.[30] By dividing 775,000 tons (total U.S. steel recovery at combustors) by 32 million tons (total U.S. MSW combustion), we estimated that 0.02 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. Thus, we estimated avoided CO_2 emissions of approximately 0.51 MTCE per ton for steel cans, and 0.01 MTCE per ton for mixed MSW, as shown in column "d" of Exhibit 6-5.

6.2 RESULTS

The results of our 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 net GHG emissions estimates are expressed for combustion in absolute terms;

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[29] 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.

[30] Integrated Waste Services Association, *The 1997-1998 IWSA Waste-To-Energy Directory Of United States Facilities.*

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)
Newspaper	NA	NA	NA
Office paper	NA	NA	NA
Corrugated cardboard	NA	NA	NA
Coated paper	NA	NA	NA
Aluminum cans	NA	NA	NA
Steel cans	0.88	0.57	0.51
Glass	NA	NA	NA
HDPE	NA	NA	NA
LDPE	NA	NA	NA
PET	NA	NA	NA
Yard trimmings	NA	NA	NA
Food scraps	NA	NA	NA
Mixed MSW	0.02	0.57	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.

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)
Newspaper	0.02	0.24	0.22	NA	-0.22	-0.20
Office paper	0.02	0.20	0.18	NA	-0.19	-0.17
Corrugated cardboard	0.02	0.21	0.19	NA	-0.19	-0.17
Coated paper	0.02	0.16	0.14	NA	-0.14	-0.13
Mixed paper						
Broad Definition	0.02	0.21	0.19	NA	-0.19	-0.17
Residential Definition	0.02	0.21	0.19	NA	-0.19	-0.17
Office paper Definition	0.02	0.19	0.18	NA	-0.18	-0.16
Aluminum cans	0.02	-0.01	-0.01	NA	0.03	0.03
Steel cans	0.02	-0.01	-0.01	0.51	-0.48	-0.48
Glass	0.02	-0.01	-0.01	NA	0.02	0.02
HDPE	0.76	0.56	0.51	NA	0.21	0.26
LDPE	0.76	0.56	0.51	NA	0.21	0.26
PET	0.52	0.29	0.26	NA	0.24	0.26
Yard trimmings	0.02	0.08	0.08	NA	-0.07	-0.06
Food scraps	0.02	0.07	0.06	NA	-0.05	-0.05
Mixed MSW	0.12	0.15	0.14	0.01	-0.04	-0.03

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

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. Combustion of food scraps and yard trimmings (two other forms of biomass) also have negative net GHG emissions, 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 0.24 MTCE per ton of material combusted for mass burn facilities, and 0.26 MTCE per ton of material input to RDF facilities. This 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 less than the carbon emissions from the combustion of plastic. This is largely due to the lower system efficiency of WTE plants, compared to electric utility plants. Recovery of ferrous metals at combustors results in negative net GHG emissions, estimated at -0.48 MTCE per ton of steel cans, due to the increased steel recycling made possible by ferrous metal recovery at WTE plants. Combustion of aluminum cans and glass, on the other hand, results in slightly positive net GHG emissions of 0.03 and 0.02 MTCE per ton of material, due to (1) some nitrous oxide emissions during the combustion process (which we allocated to all materials), and (2) the energy used in transporting these materials to the WTE plant.

6.3 LIMITATIONS OF THE ANALYSIS

The reliability 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. A survey of planned WTE plants shows an expected efficiency improvement of 14 percent over current plants.[31] 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 was 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.

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[31] Berenyi and Gould, op cit, p. 46.

- 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, we 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 may also vary from the national average energy content that we 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 our 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 tends to overstate net GHG emissions from combustion.

- We used in this analysis 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 sequestration from landfilling of each of the materials considered in this analysis and for mixed MSW. For this study, we estimated the methane emissions, transportation-related carbon dioxide emissions, and carbon sequestration that will result from landfilling each type of organic waste, and from landfilling mixed MSW.

- When food scraps, yard trimmings, and paper are landfilled, anaerobic bacteria degrade the materials, producing methane and carbon dioxide. The carbon dioxide is not counted as a GHG because it is biogenic, as explained in Section 1.7. Because metals do not contain carbon, they do not generate methane when landfilled. Plastics do not biodegrade, and therefore do not generate any methane.

- Transportation of waste materials to a landfill results in anthropogenic carbon dioxide emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes.

- Because food scraps, yard trimmings, and paper are not completely decomposed by anaerobic bacteria, some of the carbon in these materials is sequestered in the landfill. However, carbon in plastic that remains in the landfill is not counted as sequestered carbon (as explained in Section 1.5).

We developed separate estimates of emissions for landfills without gas recovery systems, for landfills that flare methane, for landfills that combust methane for energy recovery, and for the national average mix of these three categories. Our national average emission estimate accounts for the extent to which methane will be flared at some landfills, and will be combusted for energy recovery at others. In both cases, our projected future landfill gas (LFG) recovery rates anticipate a significant increase in the use of LFG recovery systems due to a recent EPA rule that requires gas recovery at large MSW landfills.[1]

From the standpoint of post-consumer GHG emissions, landfilling some materials, including branches, newspaper, and leaves, results in net sequestration (i.e., carbon storage exceeds methane plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present. At the other extreme, food scraps and office paper have net emissions even for landfills with gas recovery and electricity generation. The remaining materials have net post-consumer emissions that are either very low (aluminum cans, steel cans, and plastics have transportation-related emissions of 0.01 MTCE per ton, regardless of whether gas collection is present) or that are 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] The rule 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 nonmethane organic compounds per year, and (3) receive waste on or after November 11, 1987. (Federal Register, Vol. 61, No. 49, p. 9905, March 12, 1996). It is anticipated that by 2000, some 54 percent of landfill methane will be generated at landfills with landfill gas recovery systems subject to these requirements or installed on a voluntary basis.

7.1 EXPERIMENTAL VALUES FOR METHANE GENERATION AND CARBON SEQUESTRATION

To estimate methane emissions and carbon sequestration from landfilling of specific materials, we used data from laboratory experiments conducted by Dr. Morton Barlaz.[2] The experiments provided data on (1) the amount of methane 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., sequestered) at the end of the experiment.

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 methane generation. Dr. Barlaz measured the amount of methane 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 were averaged.[3]

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 scraps, protein) in each material. Cellulose, hemicellulose, and protein partly decompose in a landfill, resulting in methane 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 methane-producing microorganisms (the "seed"), to ensure that methane generation was not limited due to an insufficient population of microorganisms. To promote degradation, water was cycled through each reactor. Nitrogen and phosphorus were then added so that methane 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 were met: (1) no measurable methane was being emitted (i.e., any methane 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 methane generation indicated that the reactor had produced at least 95 percent of the methane that it would produce if allowed to run indefinitely.

Dr. Barlaz measured the amount of methane generated during the experimental period, and subtracted the amount of methane attributable to the seed in order to obtain the amount of methane generated by the material being tested. 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 scraps, 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.

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

[3] Barlaz, op. cit.

The experimental results were then used to estimate the amount of each carbon-containing component remaining that was attributable to the seed,[4] and to estimate the amount of carbon for each material that remained. It was assumed that the experiment reflected actual landfill conditions, and that organic carbon remaining undegraded in the reactors would also remain undegraded over the long term in landfills, i.e., it would be sequestered.

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

- 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.

Dr. Barlaz's experiment did not specifically test mixed paper as defined for recycling purposes, but it did evaluate four specific grades of paper—newsprint, corrugated boxes, office paper, and coated paper. To allow development of estimates of methane emissions and carbon sequestration for the three categories of mixed paper, Franklin Associates started with their detailed characterization of mixed paper (shown in Exhibit 4-2), and 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 the characterization of mixed paper in Exhibit 7-1 and the values obtained from Dr. Barlaz's experiment for newsprint, corrugated boxes, office paper, and coated paper.[5]

Methane Generation: Experimental Data and Adjusted Values

The amount of methane generated by each type of organic material (after deducting the methane 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 methane 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 methane and carbon dioxide (methane-producing microorganisms generate equal amounts, by volume, of methane and carbon dioxide

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[4] Dr. Barlaz tested seed alone to be able to control for the amount of methane generation and carbon sequestration that was attributable to the seed.

[5] Note that Exhibits 7-2 through 7-4 show coated paper but not mixed paper; 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[5]	Mixed Paper from Residential Sources[6]	Mixed Paper from Offices[7]
Newsprint[1]	24	23	21
Corrugated Boxes[2]	48	53	5
Office Paper[3]	20	14	38
Coated Paper[4]	8	10	36
	100	100	100

Explanatory Notes:

[1] Includes newsprint, 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.

[5] Mixed paper characterized by the broad definition can be remanufactured in an open loop system into recycled boxboard.

[6] Mixed paper characterized by the residential definition can be remanufactured in an open loop system into recycled boxboard.

[7] Mixed paper characterized by the office definition is typically used to manufacture paper towels.

gas).[6] Dr. Barlaz referred to this amount as the material's "methane potential." He then calculated the percentage of the methane potential for each material accounted for by the sum of (1) the measured methane generation, and (2) the amount of methane 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.[7] The resulting percentages of the methane potential accounted for are shown in column "c" of Exhibit 7-2. Methane potential not accounted for could be due to either (1) leaks of methane, (2) measurement error, or (3) carbon in the cell mass of microorganisms (which was not measured).

Methane recovery was below 85 percent of the "methane potential" for five materials: office paper, coated paper, food scraps, 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 methane yield based on assumptions that (1) five percent of the carbon in cellulose and hemicellulose (and protein in the case of food scraps) 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 methane and carbon dioxide. The "corrected yields," based on these assumptions, are shown in column "d" of Exhibit 7-2.

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

[7] 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.[8]

The methane 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 methane generation from milliliters per dry gram of waste, to metric tons of carbon equivalent (MTCE) per wet ton of waste.[9] 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).

Carbon Sequestration: Experimental Data and Calculations

Carbon sequestration 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 sequestered if the material were landfilled. Carbon sequestration for each material is presented in Exhibit 7-3.[10]

7.2 FATES OF LANDFILL METHANE: 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 methane to CO_2, and (2) the capture of methane, either for flaring or for combustion with energy recovery (in either case, the captured methane is converted to CO_2).[11] Exhibit 7-4 presents this analysis.

The exhibit begins with the methane 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). The next three sections of the exhibit calculate net GHG emissions from methane generation for each of three categories of landfills: (1) landfills without LFG recovery, (2) landfills with LFG recovery that flare LFG, and (3) landfills with LFG recovery that generate electricity from the LFG. The second to last section of the

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[8] The corrected yield was not available for coated paper. For food scraps, even though the methane potential recovery percentage was lower than 85 percent, we used the measured yield, as shown in column "b." We made this choice for food scraps because the "corrected yield" for food scraps 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 methane yield if all of the cellulose, hemicellulose, and protein in the material: (1) decomposed and (2) were converted to equal parts of methane and carbon dioxide.

[9] 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 methane.

[10] The approach for estimating carbon sequestration 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.

[11] The CO_2 that is emitted is not counted as a GHG because it is biogenic in origin (as described in Section 1.6).

exhibit shows the expected percentage of landfills in each category in 2000. The final column shows the weighted average GHG emissions from methane generation across all types of landfills in 2000.

To estimate MSW methane emissions from each category of landfill, we first needed to estimate the percentage of landfill methane that is oxidized near the surface of the landfill. We estimated that 10 percent of the landfill methane that is generated is either chemically oxidized or converted by bacteria to CO_2,[12] and that the remaining 90 percent is available for atmospheric methane emissions.[13]

To estimate MSW methane emissions from landfills with LFG recovery, we used the assumption that these landfills will have an average LFG recovery efficiency of 75 percent by 2000.[14] Further, to estimate emissions for landfills that recover and then combust LFG to generate electricity, we estimated the avoided utility GHG emissions per unit of methane combusted and then added the avoided emissions to the net GHG emissions from methane generation (our calculations to develop this estimate are shown in Exhibit 7-5).

We also projected the percentage of MSW disposed in each category of landfill in 2000. We estimated that by the year 2000, when large landfills with substantial LFG emissions will be required to recover LFG, 54 percent of all landfill methane will be generated at landfills with recovery systems, and 46 percent will be generated at landfills without LFG recovery.[15] Of the 54 percent of all methane generated at landfills with LFG recovery, 91 percent (or 49 percent of all methane) is expected to be generated at landfills that use LFG to generate electricity, and 9 percent (or 5 percent of all methane) at landfills that flare LFG.[16, 17] By basing our analysis on projected LFG recovery by the year 2000 (and the projected LFG recovery efficiency in 2000), we avoided double-counting of GHG reductions between programs that reduce landfilling and programs that increase recovery of landfill methane.

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[12] 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, Quantifying the effects of oxidation on landfill methane emissions, *Journal of Geophysical Research*, 1996, 101, pp. 16721-16729.

[13] US EPA, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, D.C.: US EPA) April 1993, page 4-20.

[14] Several commenters on the draft version of this report suggested a range of values; 75 percent was most often cited as a best estimate. Comments on the *Draft Municipal Solid Waste Greenhouse Gas Report* from Martin Felker, Senior Environmental Engineer, Waste Management, dated July 28, 1997; Karen Harrington, Principal Planner of the Minnesota Office of Environmental Assistance, dated July 28, 1997; Maria Zannes, President, Integrated Waste Services Association, dated August 25, 1997 and October 15, 1997; and David Sussman, Poubelle Associates, dated June 17, 1997.

[15] Based on data on (1) year 2000 MSW landfill methane generation of 64.5 million MTCE, (2) year 2000 landfill methane recovery of 40.0 million MTCE, and (3) projected year 2000 landfill methane recovery efficiency of 85 percent (all from the memorandum from Cindy Jacobs, of the US EPA Atmospheric Pollution Prevention Division to Michael Podolsky of the US EPA Office of Policy, Planning and Evaluation, July 25, 1995). EPA's current estimates of landfill methane generation and recovery differ from the values in this memo.

[16] Memorandum from Cindy Jacobs, op cit.

[17] The assumption that 91 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.

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

The three sections of the exhibit providing GHG emissions estimates for each category of landfill (in columns "d," "g," and "j") may be used by local MSW planners to estimate GHG emissions from MSW in a given community. For this purpose, one should add to the values in the appropriate column the estimated transportation GHG emissions (the national average used in this study is 0.01 MTCE per ton), and subtract estimated carbon sequestration (as shown for each material in Exhibit 7-3).

Anthropogenic Carbon Dioxide Emissions from Transportation of Wastes to a Landfill

We next estimated the anthropogenic carbon dioxide emissions from transporting waste materials to a landfill. We began with estimates provided by Franklin Associates, Ltd. for the amount of diesel fuel required per ton of waste material for (1) collecting and transporting the material to a landfill (297,000 BTUs), and (2) operating the landfill equipment (231,000 BTUs).[18] We converted these estimates to units of metric tons of carbon equivalent (MTCE) per short ton, based on a carbon coefficient of 0.0208 MTCE per million BTUs of diesel fuel. This resulted in an estimate of 0.01 MTCE of anthropogenic CO_2 emissions per short ton of material landfilled.

7.3 NET GHG EMISSIONS FROM LANDFILLING

To determine the net GHG emissions from landfilling each material, we summed the net GHG emissions from methane generation, carbon sequestration (treated as negative emissions), and transportation CO_2 emissions. The results are shown in Exhibit 7-6.

As the exhibit shows, the post-consumer results for organic materials vary widely. Landfilling some materials, including branches, newspaper, and leaves, results in net sequestration (i.e., carbon storage exceeds methane plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present. At the other extreme, food scraps and office paper have net emissions even for landfills with gas recovery and electricity generation. The remaining materials have net emissions that are either very low (aluminum cans, steel cans, and plastics have transportation-related emissions of 0.01 MTCE per ton, regardless of whether gas collection is present) or that are 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). Based on projected rates of landfill gas recovery in 2000, office paper, food scraps, mixed paper, and corrugated cardboard will, on average, exhibit net emissions, and branches, newspaper, and leaves will exhibit net sequestration.

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[18] Franklin Associates, Ltd., *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful), September 1994, p. I-5.

7.4 LIMITATIONS OF THE ANALYSIS

Perhaps the most important caveat to the analysis of GHG emissions and sequestration associated with landfilling is that it is based on a single set of laboratory experiments, those conducted by Dr. Morton Barlaz. While 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 methane potential of mixed MSW are within the range used by landfill gas developers. Nevertheless, given the sensitivity of the landfill results to estimated methane generation and carbon sequestration, we recognize that more research is needed in this area.

Another important caveat relates to our estimate that 54 percent of MSW landfill methane generated in the year 2000 will be generated at landfills with LFG recovery systems. This would be an increase from the estimated 17 percent of landfill methane generated at landfills with LFG recovery in 1995. The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate. Because of the high global warming potential for methane, small changes in the LFG recovery rate by the year 2000 could have a large effect on the net GHG impacts of landfilling each material, and on the ranking of landfilling relative to other MSW management options. The effects of different rates of LFG recovery by the year 2000 are shown in Exhibit 7-7. Column "b" of the exhibit shows net GHG emissions at the 1995 recovery rate of 17 percent. The remaining columns show net GHG emissions at increasing LFG recovery rates, up to a 60 percent recovery rate (exceeding 54 percent, the rate projected for 2000). As the exhibit shows, the net post-consumer GHG emissions for landfilling mixed MSW are positive at lower rates of recovery, and turn negative only when the LFG recovery rate exceeds 40 percent. At the local level, the GHG emissions from landfilling MSW are quite different depending on whether the local landfill has LFG recovery, as shown in Exhibits 7-4 and 7-6.

Because the national average estimate of emissions is based on LFG recovery levels expected by the year 2000, there are several limitations associated with the use of this emission factor. First, landfill methane emissions prior to 2000 will not be recovered at the year 2000 levels, thus, keeping organic materials out of landfills prior to the year 2000 will have GHG benefits in excess of those estimated here. Second, because landfill methane generation occurs over time and has significant timing delays (i.e., methane 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 methane 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. Third, landfills with LFG recovery will 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 nonmethane organic compounds per year.[19] Although the removal of LFG recovery equipment will permit methane from closed landfills to escape into the atmosphere, the amounts of methane emitted should be relatively small, because of the relatively long time period required for LFG collection before LFG recovery equipment is removed.

Methane 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. Commenters on the draft 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

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

efficiency. We investigated the sensitivity of our results to these assumptions; 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).[20] As the exhibit shows, the materials most sensitive to these variables are those with the highest methane generation potential, i.e., office paper, mixed paper, and food scraps. 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. The post-consumer emission factors of several materials—corrugated cardboard, mixed paper, grass, and mixed MSW—change from having net sequestration under the lower bound to having net emissions under the upper bound.

It is also likely that ongoing shifts in the use of landfill cover and liner systems could influence the rate of methane 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, it is possible that this will result in a decrease in methane generation and an increase in carbon sequestration. Moreover, Dr. Barlaz believes that the methane yields from his laboratory experiments are likely to be higher than methane yields in a landfill, because the laboratory experiments were designed to generate the maximum amount of methane possible. If the methane yields used in this analysis are 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 sequestered in a landfill will remain sequestered. For example, if landfilled wastes are later combusted, the carbon that was sequestered in the landfill will be oxidized to CO_2 in the combustor.

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 sequestration 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" methane yields for organic materials in MSW. Because of the high global warming potential of methane, a small difference between estimated and actual methane generation values would have a large effect on the GHG impacts of landfilling, and on the ranking of landfilling relative to other MSW management options.

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

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)
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
Corrugated Boxes	152.3	87.7	NA	279.7	152.3	0.537
Coated Paper	84.4	83.7	NA	NA	84.4	0.294
Food Scraps	300.7	77.4	386.2	357.6	300.7	0.335
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
Yard Trimmings						0.191
Mixed MSW	92.0	97.6	NA	157.6	92.0	0.273

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 Sequestration for Solid Waste Components

(a) Material	(b) Ratio of Carbon Sequestration to Dry Weight (gm C/dry gm)	(c) Ratio of Dry Weight to Wet Weight	(d) (d = b * c) Ratio of Carbon Sequestration to Wet Weight (gm C/wet gm)	(e) Amount of Carbon Sequestered (MTCE per Wet Ton)
Newspaper	0.42	0.94	0.39	0.36
Office Paper	0.05	0.94	0.05	0.04
Corrugated boxes	0.26	0.95	0.25	0.22
Coated Paper	0.34	0.94	0.32	0.29
Food Scraps	0.08	0.30	0.02	0.02
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
Yard Trimmings			0.23	0.21
Mixed MSW	0.22	0.80	0.18	0.16

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 sequestered as a fraction of dry weight to carbon sequestered 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.[21] For grass, leaves, and branches, we used data provided by Dr. Barlaz.
(2) For consistency with the overall analysis, we converted the carbon sequestration values for each material to units of metric tons of carbon equivalent (MTCE) sequestered per short ton of waste material landfilled. The resulting values are shown in column "e" of the exhibit.

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

Exhibit 7-4

Net GHG Emissions from Methane Generation

		Methane from Landfills Without Methane Recovery		Methane from Landfills With LFG Recovery and: Flaring			Electricity Generation			Percentage of Methane From Each Type of Landfill in 2000			TOTAL
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j) (g+i)	(k)	(l)	(m)	(n)
Material	CH4 Generation (MTCE/ Wet Ton)	Percentage Of Methane Not Oxidized to CO2	Net GHG Emissions from CH4 Generation (MTCE/ Wet Ton)	Percentage of Methane Not Recovered (100 % Minus LFG Collection System Efficiency)	Percentage of Methane Not Recovered That is Not Oxidized to CO2	Net GHG Emissions From CH4 Generation (MTCE/ Wet Ton)	Utility CO2 Emissions Avoided Per MTCE CH4 Combusted (MTCE)	Utility CO2 Emissions Avoided (MTCE/ Wet Ton)	Net GHG Emissions From CH4 Generation (MTCE/ Wet Ton)	Percentage of Methane From Landfills Without LFG Recovery in 2000	Percentage of Methane From Landfills With LFG Recovery and Flaring in 2000	Methane From Landfills With LFG Recovery and Electricity Generation in 2000	Net GHG Emissions From CH4 Generation (MTCE/ Wet Ton)
Newspaper	0.259	90%	0.23	25%	90%	0.06	-0.18	-0.04	0.02	46%	5%	49%	0.12
Office Paper	1.207	90%	1.09	25%	90%	0.27	-0.18	-0.16	0.11	46%	5%	49%	0.56
Corr. Boxes	0.537	90%	0.48	25%	90%	0.12	-0.18	-0.07	0.05	46%	5%	49%	0.25
Coated Paper	0.294	90%	0.26	25%	90%	0.07	-0.18	-0.04	0.03	46%	5%	49%	0.14
Food Scraps	0.335	90%	0.30	25%	90%	0.08	-0.18	-0.05	0.03	46%	5%	49%	0.16
Grass	0.214	90%	0.19	25%	90%	0.05	-0.18	-0.03	0.02	46%	5%	49%	0.10
Leaves	0.166	90%	0.15	25%	90%	0.04	-0.18	-0.02	0.01	46%	5%	49%	0.08
Branches	0.170	90%	0.15	25%	90%	0.04	-0.18	-0.02	0.02	46%	5%	49%	0.08
Yard Trimmings	0.191	90%	0.17	25%	90%	0.04	-0.18	-0.03	0.02	46%	5%	49%	0.09
Mixed MSW	0.273	90%	0.25	25%	90%	0.06	-0.18	-0.04	0.02	46%	5%	49%	0.13

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 Methane

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
BTUs/cubic ft. CH_4	1,000	"Opportunity for LF Gas Energy Recovery in Kentucky," USEPA/OAR September 97, p. 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	U.S. DOE, EIA, "Annual Energy Review 1993 (Washington, DC: DOE/EIA) July 1994, p. 252
BTUs/kWh electricity delivered	3,412	Physical constant
Kg. utility C avoided/BTU delivered electricity	8.349E-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) Net Carbon Sequestration (MTCE/Wet Ton)	(d) GHG Emissions from Transportation (MTCE/Wet Ton)	(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	Projected National Average			Landfills Without LFG Recovery	Landfills With LFG Recovery and Flaring	Landfills With LFG Recovery and Electric Generation	Projected National Average
Newspaper	0.23	0.06	0.02	0.12	-0.36	0.01	-0.11	-0.29	-0.32	-0.23
Office Paper	1.09	0.27	0.11	0.56	-0.04	0.01	1.05	0.24	0.08	0.53
Corrugated Cardboard	0.48	0.12	0.05	0.25	-0.22	0.01	0.27	-0.09	-0.17	0.04
Coated Paper	0.26	0.07	0.03	0.14	-0.29	0.01	-0.01	-0.21	-0.25	-0.14
Mixed Paper										
Broad Definition	0.53	0.13	0.05	0.27	-0.23	0.01	0.31	-0.08	-0.16	0.06
Residential Definition	0.49	0.12	0.05	0.25	-0.24	0.01	0.26	-0.10	-0.18	0.03
Office Paper Definition	0.58	0.15	0.06	0.30	-0.21	0.01	0.39	-0.05	-0.14	0.11
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
Food Scraps	0.30	0.08	0.03	0.16	-0.02	0.01	0.29	0.06	0.02	0.15
Grass	0.19	0.05	0.02	0.10	-0.12	0.01	0.09	-0.06	-0.09	-0.01
Leaves	0.15	0.04	0.01	0.08	-0.39	0.01	-0.23	-0.34	-0.37	-0.30
Branches	0.15	0.04	0.02	0.08	-0.21	0.01	-0.04	-0.16	-0.18	-0.12
Yard Trimmings	0.17	0.04	0.02	0.09	-0.21	0.01	-0.02	-0.15	-0.18	-0.11
Mixed MSW	0.25	0.06	0.02	0.13	-0.16	0.01	0.10	-0.09	-0.12	-0.02

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 Landfilling

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) 30% of waste disposed at landfills with LFG recovery	(d) 46% of waste disposed at landfills with LFG recovery	(e) 50% of waste disposed at landfills with LFG recovery	(f) 60% of waste disposed at landfills with LFG recovery
Newspaper	-0.15	-0.18	-0.21	-0.22	-0.24
Office Paper	0.89	0.77	0.61	0.57	0.48
Corrugated Cardbd	0.20	0.14	0.07	0.06	0.01
Coated Paper	-0.05	-0.08	-0.12	-0.13	-0.16
Mixed Paper					
Broad Def'n.	0.23	0.17	0.10	0.08	0.03
Residential Def'n.	0.19	0.13	0.06	0.05	0.00
Office Paper Def'n.	0.30	0.23	0.15	0.13	0.08
Food Scraps	0.25	0.21	0.17	0.16	0.13
Grass	0.06	0.04	0.01	0.00	-0.01
Leaves	-0.25	-0.27	-0.29	-0.30	-0.31
Branches	-0.07	-0.08	-0.11	-0.11	-0.12
Yard Trimmings	-0.05	-0.07	-0.09	-0.10	-0.12
Mixed MSW	0.06	0.03	0.00	-0.01	-0.03

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

Note: Of the methane that is captured, we assumed that 9% is flared and 91% is recovered for energy.

Exhibit 7-8
Net GHG Emissions from Landfilling

Sensitivity Analysis: Varying Oxidation and
Gas Collection Efficiency Rates. Based on projected
national mix of landfill gas recovery systems for 2000.

Oxidation Rate:	**40%**	**10%**	**5%**
Collection Efficiency:	**95%**	**75%**	**60%**
Material	**Lower bound emissions**	**Best estimate**	**Upper bound emissions**
Newspaper	-0.29	-0.23	-0.20
Office Paper	0.23	0.53	0.66
Corrugated Cardbd	-0.10	0.04	0.10
Coated Paper	-0.22	-0.14	-0.11
Mixed Paper			
Broad Def'n.	-0.09	0.06	0.12
Residential Def'n.	-0.11	0.03	0.09
Office Paper Def'n.	-0.06	0.11	0.18
Food Scraps	0.06	0.15	0.18
Grass	-0.06	-0.01	0.02
Leaves	-0.35	-0.30	-0.29
Branches	-0.16	-0.12	-0.10
Yard Trimmings	-0.16	-0.11	-0.09
Mixed MSW	-0.09	-0.02	0.01

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

8. ACCOUNTING FOR EMISSION REDUCTIONS

Earlier chapters of this report examined the GHG emissions from (1) raw materials acquisition and manufacturing (and forest carbon sequestration for paper products) and (2) waste management. This chapter combines information from the earlier chapters to present a picture of the life cycle GHG emissions associated with raw materials acquisition, manufacturing, and then managing as waste, each of the materials considered in this analysis.

Management of municipal solid waste presents many opportunities for GHG emission reductions. Source reduction and recycling can reduce GHG emissions at the raw materials acquisition and manufacturing stage, increase forest carbon storage, and avoid landfill methane emissions. When waste is combusted, energy recovery displaces fossil fuel-generated electricity from utilities (thus reducing GHG emissions from the utility sector), and landfill methane emissions are avoided. Landfill methane emissions can be reduced by using gas recovery systems and by diverting organic materials away from the landfill.

In order to support a broad portfolio of climate change mitigation activities covering a broad scope of greenhouse gases, many different emission estimation methodologies will need to be employed. The primary result of this research is the development of material-specific GHG emission factors which can be used to account for the climate change benefits of waste management practices.[1] These emission factors are summarized in the following pages.

In the discussion that follows, we focus on national average conditions. For example, we represent landfills as having the national average landfill gas collection efficiency, and represent combustors based on mass burn units with national average collection efficiency of ferrous metal. As shown in the previous chapters, the GHG emission factors are sensitive to many variables, including several that are site-specific; thus, at specific locations, the emission factors can differ from those described below. A spreadsheet accounting tool, the Waste Reduction Model (WARM), is being developed to allow for customizing of emission factors based on key variables (e.g., landfill gas collection, electric utility fuel mix, transportation distances) which may better reflect local conditions.

8.1 GHG EMISSIONS FOR EACH WASTE MANAGEMENT OPTION

This section presents the life cycle GHG emissions for each waste management option, for each material considered. These emissions are shown in five exhibits that recapitulate the GHG emissions and sinks analyzed in detail in earlier chapters.[2] As mentioned in Chapter 1, we used a waste generation reference point for measuring GHG emissions. That is, one can begin accounting for GHG emissions at the point of waste generation. All subsequent emissions and sinks from waste management practices are

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[1] Note that the exhibits presented in this chapter are intended to present the GHG impacts of the different MSW management options for the specific materials examined and are not intended to compare materials.

[2] We did not provide an exhibit for composting. As described in Chapter 5, we performed a bounding analysis and concluded that net GHG emissions from composting are zero or close to zero.

then 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) impact 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.

Exhibit 8-1 shows the life cycle GHG reductions associated with source reduction. In brief, the exhibit shows that, for all of the manufactured materials evaluated, source reduction results in GHG emission reductions. On a per-ton basis, the metals (aluminum cans and steel cans) have greatest emission reduction potential, due primarily to reductions in energy use in the raw material acquisition and manufacturing step.

Exhibit 8-2 shows the life cycle GHG emissions associated with recycling materials. The third through fifth columns in this exhibit show the GHG reductions associated with using recycled inputs in place of virgin inputs when the material is remanufactured. As the final column in the exhibit indicates, recycling generally results in negative emissions (measured from the point of waste generation). 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.

Exhibit 8-3 presents the life cycle GHG emissions from combusting each of the materials considered. This exhibit shows emissions for mass burn facilities with the national average rate of ferrous recovery; results for RDF facilities are similar. As the exhibit shows, mixed MSW combustion has net emissions of –0.04 MTCE/ton. Net GHG emissions are positive for plastic and negative for paper products, steel cans, food scraps, and yard trimmings.

GHG emissions from landfilling each of the materials is shown in Exhibit 8-4. The values in the final column indicate that net GHG emissions from landfilling mixed MSW, under anticipated national average conditions in 2000, are slightly negative. Among individual materials, emissions are lowest for newspaper and yard trimmings, and highest for office paper and food scraps. For the other materials, the net emissions are close to zero, ranging from 0.01 MTCE/ton for steel, aluminum, glass, and plastics to 0.10 MTCE/ton for mixed paper (from office sources).

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 0.10 MTCE/ton in landfills without landfill gas collection, and -0.12 MTCE/ton in landfills with landfill gas collection and energy recovery. The largest differences attributable to landfill gas recovery are for office paper (range of almost 1 MTCE/ton), corrugated cardboard, and mixed paper. The methane oxidation rate and gas collection system efficiency also have a strong influence on the estimated net emissions for mixed waste and the organic materials.

Exhibit 8-5 displays the net emissions for each of the management options. In addition, it adds a row for "Mixed Recyclables," and provides estimates for recycling, combustion, and landfilling this

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[3] Corrugated cardboard and mixed paper (broad and residential definitions) recycling actually have higher energy GHG emissions, because production with recycled inputs uses fossil fuel-derived energy, while production from virgin inputs uses high proportions of biomass fuel (CO_2 from such fuel is not counted in GHG inventories).

category of materials. We developed the emission factors for mixed recyclables by calculating the average emission factor (weighted by tons recycled in 1996[4]) for newspaper, office paper, corrugated cardboard, aluminum cans, steel cans, HDPE containers, LDPE containers, and PET containers. The exhibit provides a summary of the emission factors, in terms of national average emissions for each management option and each material. 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. 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 8-5 (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 Department of Energy, 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 potential applications include evaluating the progress of voluntary programs aimed at source reduction and recycling, such as EPA's WasteWi$e, Pay-as-You-Throw, and other Climate Change Action Plan programs.

In order to apply the emission factors presented in this report, one must first establish two scenarios: a baseline scenario that represents current management practices (e.g., disposing 10 tons per year of office paper in a landfill without LFG collection); and an alternative scenario that represents the alternative management practice (e.g., recycling the same 10 tons of office paper).[5],[6] The emission factors developed in this report can then be used to calculate emissions under both the baseline and the alternative management practices. Once emissions for the two scenarios have been determined, one calculates 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.

Exhibit 8-6 illustrates 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 represent the *incremental change* in GHG emissions. For example, recycling one ton of office paper, rather than landfilling it, reduces GHG emissions by 1.35 MTCE (this is the second value in the "Recycling" column of the exhibit). 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 * 1.35 MTCE/ton = 13.5 MTCE/yr.

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[4] *Characterization of Municipal Solid Waste in the United States: 1997 Update*, US EPA, Office of Solid Waste and Emergency Response, (May 1998).

[5] In calculating emissions for the scenarios, two different reference points can be used. These reference points are described in detail in Section ES.5. Because the desired information is the difference in emissions between the baseline and alternative scenarios, either reference point yields the same result.

[6] 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 1ton *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.

Exhibit 8-1

Greenhouse Gas Emissions for Source Reduction
(MTCE/Ton of Material Source Reduced)
Emissions Measured from a Waste Generation Reference Point[1]

Material	(a) Raw Materials Acquisition and Manufacturing		(b) Forest Carbon Sequestration		(c)	(d = a + b + c) (d) Net Emissions	
	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
Newspaper	-0.48	-0.55	-0.43	-0.73	0.00	-0.91	-1.28
Office Paper	-0.52	-0.56	-0.50	-0.73	0.00	-1.03	-1.29
Corrugated Cardboard	-0.41	-0.38	-0.38	-0.73	0.00	-0.78	-1.11
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
Aluminum Cans	-2.98	-5.39	0.00	0.00	0.00	-2.98	-5.39
Steel Cans	-0.84	-1.12	0.00	0.00	0.00	-0.84	-1.12
Glass	-0.14	-0.16	0.00	0.00	0.00	-0.14	-0.16
HDPE Containers	-0.61	-0.70	0.00	0.00	0.00	-0.61	-0.70
LDPE Containers	-0.89	-0.89	0.00	0.00	0.00	-0.89	-0.89
PET Containers	-0.98	-1.16	0.00	0.00	0.00	-0.98	-1.16
Food Scraps	NA	NA	NA	NA	NA	NA	NA
Yard Trimmings	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
Recycling
(GHG Emissions in MTCE/Ton)
Emissions Measured from a Waste Generation Reference Point[1]

	Raw Materials Acquisition and Manufacturing		Recycled Input Credit[2]					
Material	(a) RMAM Emissions Not Included in Baseline[3] (current mix of inputs)	(b) Waste Generation Baseline	(c) Process Energy	(d) Transportation Energy	(e) Process Non-Energy	(f) Forest Carbon Sequestration	(g) Waste Management Emissions	(h) (h = b+c+d+e+f+g) Net Emissions
Newspaper	0.48	0.00	-0.14	0.01	0.00	-0.73	0.00	-0.86
Office Paper	0.52	0.00	-0.07	-0.01	0.00	-0.73	0.00	-0.82
Corrugated Cardboard	0.41	0.00	0.03	0.00	0.00	-0.73	0.00	-0.70
Mixed Paper								
Broad Definition	0.38	0.00	0.09	-0.02	0.00	-0.73	0.00	-0.67
Residential Definition	0.38	0.00	0.09	-0.02	0.00	-0.73	0.00	-0.67
Office Paper Definition	0.89	0.00	-0.09	-0.02	0.00	-0.73	0.00	-0.84
Aluminum Cans	2.98	0.00	-2.49	-0.07	-1.32	0.00	0.00	-3.88
Steel Cans	0.84	0.00	-0.57	-0.01	0.00	0.00	0.00	-0.57
Glass	0.14	0.00	-0.04	0.00	-0.04	0.00	0.00	-0.08
HDPE Containers	0.61	0.00	-0.30	-0.02	-0.05	0.00	0.00	-0.37
LDPE Containers	0.89	0.00	-0.44	-0.01	-0.05	0.00	0.00	-0.49
PET Containers	0.98	0.00	-0.58	-0.02	-0.03	0.00	0.00	-0.62
Food Scraps	NA	0.00	NA	NA	NA	NA	0.00	NA
Yard Trimmings	NA	0.00	NA	NA	NA	NA	0.00	NA
Mixed MSW (as disposed)	0.49	0.00	NA	NA	NA	NA	0.00	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 rather than virgin inputs. It accounts for loss rates in collection, processing, and remanufacturing. Recycling credit is based on weighted average of closed and open loop recycling for office paper, corrugated cardboard, and mixed paper. All other estimates are for closed loop recycling.

[3] The value for mixed MSW is the weighted average of the RMAM emissions for those materials we studied.

Exhibit 8-3
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]

Material	Raw Materials Acquisition and Manufacturing							
	(a) RMAM Emissions Not Included in Baseline[2]	(b) Waste Generation Baseline	(c) Transportation to Combustion	(d) CO_2 from Combustion	(e) N_2O from Combustion	(f) Avoided Utility Emissions	(g) Ferrous Recovery	(h) (h =b+c+d+e +f+g) Net Emissions (Post-Consumer)
Newspaper	0.48	0.00	0.01	0.00	0.01	-0.24	0.00	-0.22
Office Paper	0.52	0.00	0.01	0.00	0.01	-0.20	0.00	-0.19
Corrugated Cardboard	0.41	0.00	0.01	0.00	0.01	-0.21	0.00	-0.19
Mixed Paper								
Broad Definition	0.38	0.00	0.01	0.00	0.01	-0.21	0.00	-0.19
Residential Definition	0.38	0.00	0.01	0.00	0.01	-0.21	0.00	-0.19
Office Paper Definition	0.89	0.00	0.01	0.00	0.01	-0.19	0.00	-0.18
Aluminum Cans	2.98	0.00	0.01	0.00	0.01	0.01	0.00	0.03
Steel Cans	0.84	0.00	0.01	0.00	0.01	0.01	-0.51	-0.48
Glass	0.14	0.00	0.01	0.00	0.01	0.01	0.00	0.02
HDPE Containers	0.61	0.00	0.01	0.75	0.01	-0.56	0.00	0.21
LDPE Containers	0.89	0.00	0.01	0.75	0.01	-0.56	0.00	0.21
PET Containers	0.98	0.00	0.01	0.51	0.01	-0.29	0.00	0.24
Food Waste	NA	0.00	0.01	0.00	0.01	-0.07	0.00	-0.05
Yard Waste	NA	0.00	0.01	0.00	0.01	-0.08	0.00	-0.07
Mixed MSW (as disposed)	0.49	0.00	0.01	0.10	0.01	-0.15	-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 8-4
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]

Material	Raw Materials Acquisition and Manufacturing					
	(a) RMAM Emissions Not Included in Baseline[2]	(b) Waste Generation Baseline	(c) Transportation to Landfill	(d) Net Landfill CH_4	(e) Landfill Carbon Sequestration	(f) (f=b+c+d+e) Net Emissions
Newspaper	0.48	0.00	0.01	0.12	-0.36	-0.23
Office Paper	0.52	0.00	0.01	0.56	-0.04	0.53
Corrugated Cardboard	0.41	0.00	0.01	0.25	-0.22	0.04
Mixed Paper						
Broad Definition	0.38	0.00	0.01	0.27	-0.23	0.06
Residential Definition	0.38	0.00	0.01	0.25	-0.24	0.03
Office Paper Definition	0.89	0.00	0.01	0.30	-0.21	0.10
Aluminum Cans	2.98	0.00	0.01	0.00	0.00	0.01
Steel Cans	0.84	0.00	0.01	0.00	0.00	0.01
Glass	0.14	0.00	0.01	0.00	0.00	0.01
HDPE Containers	0.61	0.00	0.01	0.00	0.00	0.01
LDPE Containers	0.89	0.00	0.01	0.00	0.00	0.01
PET Containers	0.98	0.00	0.01	0.00	0.00	0.01
Food Scrap	NA	0.00	0.01	0.16	-0.02	0.15
Yard Trimmings	NA	0.00	0.01	0.09	-0.21	-0.11
Mixed MSW (as disposed)	0.49	0.00	0.01	0.13	-0.16	-0.02

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 r 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 8-5
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[3]	Combustion[4]	Landfilling[5]
Newspaper	-0.91	-0.86	NA	-0.22	-0.23
Office Paper	-1.03	-0.82	NA	-0.19	0.53
Corrugated Cardboard	-0.78	-0.70	NA	-0.19	0.04
Mixed Paper					
Broad Definition	NA	-0.67	NA	-0.19	0.06
Residential Definition	NA	-0.67	NA	-0.19	0.03
Office Paper Definition	NA	-0.84	NA	-0.18	0.10
Aluminum Cans	-2.98	-3.88	NA	0.03	0.01
Steel Cans	-0.84	-0.57	NA	-0.48	0.01
Glass	-0.14	-0.08	NA	0.02	0.01
HDPE Containers	-0.61	-0.37	NA	0.21	0.01
LDPE Containers	-0.89	-0.49	NA	0.21	0.01
PET Containers	-0.98	-0.62	NA	0.24	0.01
Food Scraps	NA	NA	0.00	-0.05	0.15
Yard Trimmings	NA	NA	0.00	-0.07	-0.11
Mixed MSW (as disposed)	NA	NA	NA	-0.04	-0.02
Mixed Recyclables	NA	-0.76	NA	-0.18	0.03

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] 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 projected national average methane recovery in year 2000.

Exhibit 8-6

Net GHG Emissions of MSW Management Options Compared to Landfilling[1]

Negative values indicate emission reductions.

(MTCE/Ton)

Material	Source Reduction Net Emissions Minus Landfilling Net Emissions		Recycling Net Emissions Minus Landfilling Net Emissions	Composting[2] Net Emissions Minus Landfilling Net Emissions	Combustion[3] Net Emissions Minus Landfilling Net Emissions
	Current Mix of Inputs	100% Virgin Inputs			
Newspaper	-0.68	-1.05	-0.63	NA	0.01
Office Paper	-1.56	-1.82	-1.35	NA	-0.72
Corrugated Cardboard	-0.82	-1.15	-0.74	NA	-0.23
Mixed Paper					
Broad Definition	NA	NA	-0.73	NA	-0.25
Residential Definition	NA	NA	-0.69	NA	-0.22
Office Paper Definition	NA	NA	-0.95	NA	-0.28
Aluminum Cans	-3.00	-5.40	-3.89	NA	0.02
Steel Cans	-0.85	-1.13	-0.58	NA	-0.49
Glass	-0.15	-0.17	-0.09	NA	0.01
HDPE Containers	-0.62	-0.71	-0.38	NA	0.20
LDPE Containers	-0.90	-0.90	-0.51	NA	0.20
PET Containers	-0.99	-1.17	-0.63	NA	0.22
Food Scrap	NA	NA	NA	-0.15	-0.20
Yard Trimmings	NA	NA	NA	0.11	0.04
Mixed MSW (as disposed)	NA	NA	NA	NA	-0.02
Mixed Recyclables	NA	NA	-0.79	NA	-0.20

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

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

All of the exhibits presented so far in this report have expressed GHG emissions in units of metric tons of carbon equivalent (MTCE), 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 Gases Program, established by the Department of Energy's Energy Information Administration (DOE/EIA), reporters are asked to provide emission reductions for each of the individual gases. DOE/EIA is using this approach because GWPs change as new scientific information becomes available, and at some point in the future, the reported data may be used to develop a baseline of emission reductions. If the GWPs change in the future, and if the weighted contributions of all gases were aggregated in the voluntary reports, it would be difficult (and in many cases impossible) to adjust the estimated emission reductions for the new GWPs.

For purposes of supporting participants in the DOE/EIA's Voluntary Reporting of Greenhouse Gases Program, we developed a set of emission factors, by gas. These provide incremental emissions for a baseline of landfilling, and alternative scenarios of source reduction (Exhibit 8-7) and recycling (Exhibit 8-8). The emission factors for CO_2 and CH_4 are specified in terms of three possible landfilling baselines: no LFG recovery, LFG recovery with energy recovery, and national average landfill. The exhibits are set up such that one obtains the appropriate factor for the material being source reduced or recycled, and multiplies it by the tons that are diverted from landfilling to yield the emission reductions for each gas. DOE/EIA provides detailed reporting instructions and forms, including a step-by-step description of how to use the factors, on their 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. However, the accuracy of the estimates is limited by the use of these assumptions and by 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 effects, from a GHG perspective, 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.

Exhibit 8-7
GHG Emission Reductions, by Gas, of Source Reduction Relative to Landfilling*
(Metric Tons (MT) of Gas Per Short Ton of Product Source Reduced)

	CO_2 Emissions (MT/Ton of Product)			CH_4 Emissions (MT/Ton of Product)				
Waste Component	Relative to (a) Landfills Without LFG Recovery or (b) Landfills With LFG Recovery and Flaring	Relative to Landfills With LFG Recovery and Electricity Generation	Relative to the National Average Landfill	Relative to Landfills Without LFG Recovery	Relative to (a) Landfills With LFG Recovery and Flaring or (b) Landfills With LFG Recovery and Electricity Generation	Relative to the National Average Landfill	CF_4 Emissions (MT/Ton of Product)	C_2F_6 Emissions (MT/Ton of Product)
Newspaper	-1.99	-1.86	-1.93	-0.043	-0.013	-0.027	0.000	0.000
Office Paper	-3.60	-3.00	-3.30	-0.192	-0.050	-0.115	0.000	0.000
Corrugated Cardboard	-2.02	-1.75	-1.89	-0.086	-0.023	-0.052	0.000	0.000
Mixed Paper (Broad)	NA	NA	NA	NA	NA	NA	NA	NA
Aluminum Cans	-8.53	-8.53	-8.53	-0.014	-0.014	-0.014	-0.0003	-0.00003
Steel Cans	-3.05	-3.05	-3.05	-0.002	-0.002	-0.002	0.000	0.000
Glass	-0.54	-0.54	-0.54	-0.001	-0.001	-0.001	0.000	0.000
HDPE Containers	-2.05	-2.05	-2.05	-0.010	-0.010	-0.010	0.000	0.000
LDPE Containers	-3.03	-3.03	-3.03	-0.014	-0.014	-0.014	0.000	0.000
PET Containers	-3.46	-3.46	-3.46	-0.008	-0.008	-0.008	0.000	0.000

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.

*Assuming Source Reduction displaces the current mix of virgin and recycled inputs in the manufacture of the material.

Exhibit 8-8
GHG Emission Reductions, by Gas, of Recycling Relative to Landfilling
(Metric Tons (MT) of Gas Per Short Ton of Product Recycled)

	CO_2 Emissions (MT/Ton of Product)			CH_4 Emissions (MT/Ton of Product)				
Waste Component	Relative to (a) Landfills Without LFG Recovery or (b) Landfills With LFG Recovery and Flaring	Relative to Landfills With LFG Recovery and Electricity Generation	Relative to the National Average Landfill	Relative to Landfills Without LFG Recovery	Relative to (a) Landfills With LFG Recovery and Flaring or (b) Landfills With LFG Recovery and Electricity Generation	Relative to the National Average Landfill	CF_4 Emissions (MT/Ton of Product)	C_2F_6 Emissions (MT/Ton of Product)
Newspaper	-1.86	-1.73	-1.79	-0.041	-0.011	-0.025	0.000	0.000
Office Paper	-2.89	-2.29	-2.59	-0.190	-0.048	-0.113	0.000	0.000
Corrugated Cardboard	-1.80	-1.53	-1.67	-0.084	-0.020	-0.047	0.000	0.000
Mixed Paper (Broad)	-1.67	-1.38	-1.67	-0.091	-0.022	-0.049	0.000	0.000
Aluminum Cans	-10.26	-10.26	-10.26	-0.015	-0.015	-0.015	0.000	0.000
Steel Cans	-2.10	-2.10	-2.10	-0.002	-0.002	-0.002	0.000	0.000
Glass	-0.33	-0.33	-0.33	0.000	0.000	0.000	0.000	0.000
HDPE Containers	-1.18	-1.18	-1.18	-0.010	-0.010	-0.010	0.000	0.000
LDPE Containers	-1.64	-1.64	-1.64	-0.010	-0.010	-0.010	0.000	0.000
PET Containers	-2.18	-2.18	-2.18	-0.007	-0.007	-0.007	0.000	0.000

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