ISSN 1047-3289 *J. Air & Waste Manage. Assoc.* **52**:1000-1011

The Impact of Municipal Solid Waste Management on Greenhouse Gas Emissions in the United States

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ABSTRACT

Technological advancements, environmental regulations, and emphasis on resource conservation and recovery have greatly reduced the environmental impacts of municipal solid waste (MSW) management, including emissions of greenhouse gases (GHGs). This study was conducted using a life-cycle methodology to track changes in GHG emissions during the past 25 years from the management of MSW in the United States. For the baseline year of 1974, MSW management consisted of limited recycling, combustion without energy recovery, and landfilling without gas collection or control. This was compared with data for 1980, 1990, and 1997, accounting for changes in MSW quantity, composition, management practices, and technology. Over time, the United States has moved toward increased recycling, composting, combustion (with energy recovery) and landfilling with gas recovery, control, and utilization. These changes were accounted for with historical data on MSW composition, quantities, management practices, and technological changes. Included in the analysis were the benefits of materials recycling and energy recovery to the extent that these displace virgin raw materials and fossil fuel electricity production, respectively. Carbon sinks associated with MSW management also were addressed. The results indicate that the MSW management actions taken by U.S. communities have significantly reduced potential GHG emissions despite an almost 2-fold increase in waste generation. GHG emissions from MSW management were estimated to be 36 million metric tons carbon equivalents (MMTCE) in 1974 and 8 MMTCE in 1997. If MSW were being managed today as it was in 1974, GHG emissions would be ~60 MMTCE.

IMPLICATIONS

Technology advancements and the movement toward integrated strategies for MSW management have resulted in reduced GHG emissions. GHG emissions from MSW management would be 52 MMTCE higher today if old strategies and technologies were still in use. Integrated strategies involving recycling, composting, waste-to-energy combustion, and landfills with gas collection and energy recovery play a significant role in reducing GHG emissions by recovering materials and energy from the MSW stream.

INTRODUCTION

Solid waste management deals with the way resources are used as well as with end-of-life deposition of materials in the waste stream.[1] Often complex decisions are made regarding ways to collect, recycle, transport, and dispose of municipal solid waste (MSW) that affect cost and environmental releases. Prior to 1970, sanitary landfills were very rare. Wastes were "dumped" and organic materials in the dumps were burned to reduce volume. Waste incinerators with no pollution controls were common.[1] Today, solid waste management involves technologies that are more energy efficient and protective of human health and the environment. These technological changes and improvements are the result of decisions made by local communities and can impact residents directly. Selection of collection, transportation, recycling, treatment, and disposal systems can determine the number of recycling bins needed, the day people must place their garbage at the curb, the truck routes through residential streets, and the cost of waste services to households. Thus, MSW management can be a significant issue for municipalities.

MSW management is also an issue of global significance. The MSW management decisions made by mayors, county executives, and city and county councils and boards can impact the release of greenhouse gas (GHG) emissions that contribute to global climate change. GHG emissions can trap heat in the atmosphere and lead to warming the planet and changing its weather. According to the latest U.S. Environmental Protection Agency (EPA) inventory of GHG emissions, the waste management sector represents ~4% of total U.S. anthropogenic GHG emissions (i.e., 260 out of 6750 teragrams of CO_2 equivalents).[2] Landfills are the largest anthropogenic source of CH_4 in the United States and represented ~90% of GHGs from the waste sector in 1999.[2] Emissions of CH_4 result from the decomposition of biodegradable components in the waste stream such as paper, food scraps, and yard trimmings. The potential for global climate change caused by the release of GHGs is being debated both nationally and internationally. Options for reducing GHG emissions are being evaluated. MSW management presents potential options for GHG reductions and has links to other sectors (e.g., energy, industrial processes, forestry, and transportation) with further GHG reduction opportunities.

This study was conducted for the U.S. Conference of Mayors through funding provided by the Integrated Waste Services Association. It examined the effect of local MSW management decisions on GHG emissions during the past 25 years. The scope of the study included all activities that play a role in MSW management, from the point at which the waste is collected to its ultimate disposition. These activities include MSW collection, transport, recycling, composting, combustion (with and without energy recovery), and landfilling (with and without gas collection and energy recovery). The life-cycle environmental aspects of fuel and electricity consumption were also included, as well as the displacement of virgin raw materials through recycling and the displacement of fossil fuel-based electrical energy through energy recovery from MSW. The GHG emissions studied in this analysis were CO_2 and CH_4. Other GHG emissions such as perfluorocarbons (PFCs) and N_2O were not included, primarily because of limitations in available data. Carbon sinks associated with MSW management were evaluated, and results were presented with and without carbon sinks included.

The life cycle of waste is often referred to as a journey from cradle to grave (i.e., from when an item is put on the curb or placed in a dumpster to when value is restored by creating usable material or energy, or the waste is transformed into emissions to water or air or into inert material placed in a landfill).[3] Methodologies that provide for a more holistic approach toward evaluating the operations within waste management systems that are interconnected began to be introduced in 1995.[4] The methodology used in this study tracks the material and energy flows from cradle to grave. Figure 1 provides an overview of the life-cycle flow diagram of materials in MSW from cradle to grave that were included in this study.[5]

The boundaries for this study include unit processes associated with waste management, including production and consumption of energy, extraction of raw materials, transport, collection, recycling/composting, combustion, and landfilling. The waste to be managed is dictated by the quantity and composition generated in the United States in the years studied. The net energy consumption and environmental releases associated with managing MSW are calculated, including offsets for (1) energy produced from waste combustion and landfill gas utilization and (2) energy and virgin resources that are conserved as a result of recycling programs. The offsets and environmental releases are specific to the different types of materials within the waste stream, which includes the different types of aluminum, glass, paper, plastics, and steel in MSW.[6]

The technical analysis for this study was conducted by RTI International under the direction of EPA's Office of Research and Development (ORD) using data and a computer-based decision support tool (referred to hereafter as the MSW DST) developed through a cooperative agreement between EPA/ORD and RTI.[7,8] Representatives from EPA, RTI, Integrated Waste Services Association, U.S. Conference of Mayors, Solid Waste Association of North America, Environmental Industry Associations, Waste Management Inc., and ICF Consulting worked cooperatively to review this analysis.

METHODOLOGY

To calculate GHG emissions from MSW management, data were collected on the breakdown of MSW by material for 1974, 1980, 1990, and 1997. The most recent year for which comprehensive information is available is 1997.[9] The oldest available data for MSW management practices were from 1974.[10] A review of technological changes and management practices was conducted. Since 1974, MSW management in the United States is much more complex than simply hauling the waste to a "dump." Advances in technology, in addition to federal and state regulations, have resulted in substantial investments in residential and nonresidential infrastructure for collecting, transporting, and processing of recycling and composting, and for disposal techniques.[1] In a 1995 study of U.S. communities, substantial diversity in system complexity was found, reflecting differences in geographical locations, types and quantities of solid waste managed, operational and ownership structures, energy use, and environmental safety regulations and guidelines.[11] This is quite different from how waste was being managed in the 1970s.

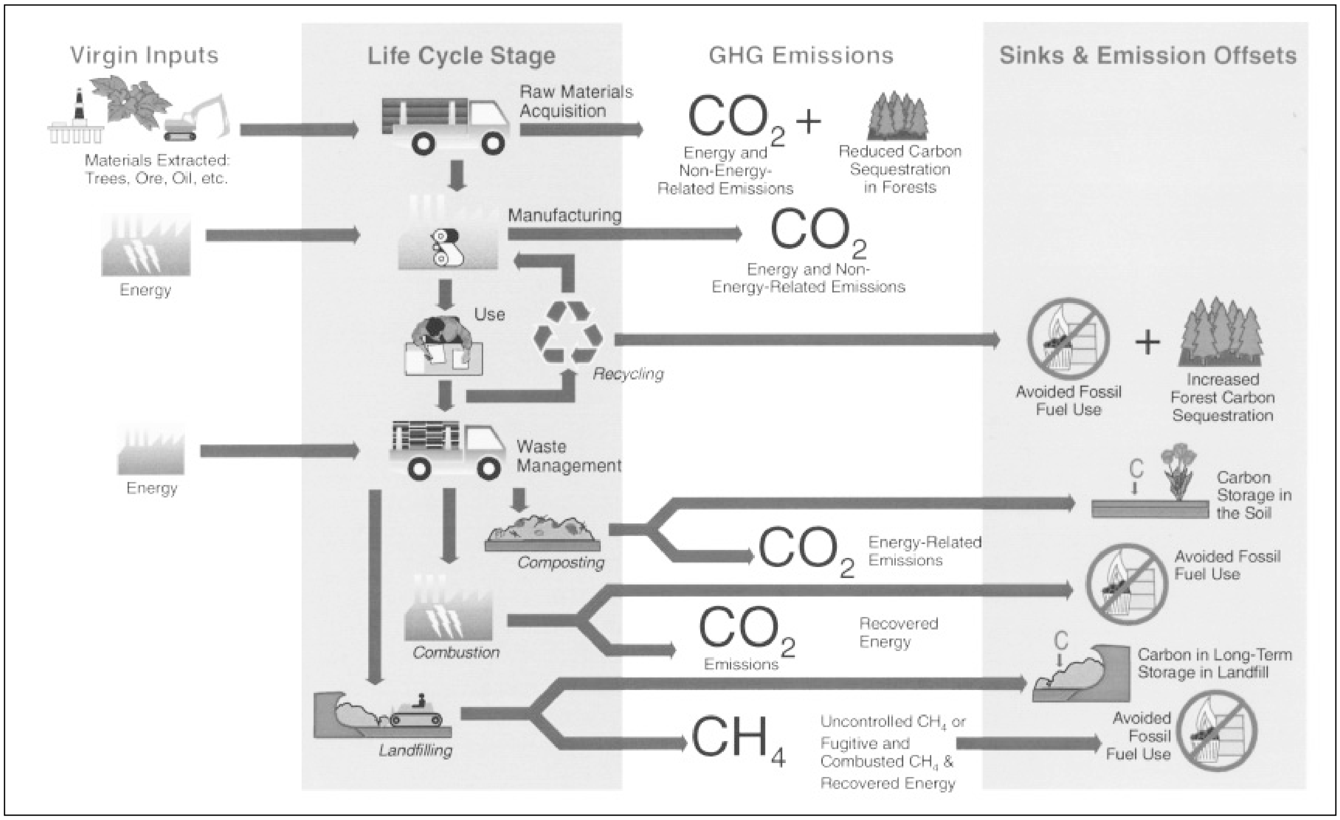

Figure 1. Diagram of material and energy life-cycle flows and the associated GHG sources and sinks.[5]

The following is a description of four U.S. communities using information from the report published in 1995 to illustrate the diversity and complexity that exists.[11]

Complexity of MSW Management Systems in the United States

The Minnesota Waste Management Act was passed in 1980. Since then, substantial changes have occurred throughout the United States. In Minnesota during the study, system components included collection and transport of curbside/alley residential and commercial waste, recyclables, yard waste collection services, drop-off sites, and transfer stations. There is also a mass-burn MSW combustion facility (with energy recovery), three refuse-derived fuel (RDF) waste processing facilities, and a private processing facility for recyclables. Of the MSW being processed, 15% is recycled and 11% (i.e., yard waste) is composted. Regional and out-of-state landfills are used for the disposal of residues, non-processible waste, and ash.[12]

In Palm Beach County, FL, system components include collection and transport of curbside MSW, recyclables, and yard waste. There are also drop-off sites and transfer stations. The system also includes four transfer stations, MSW combustion (with energy recovery), an RDF processing facility, a ferrous processing facility that produces a marketable product from recovered ferrous, a materials recovery facility (MRF) that processes recyclables, and a co-composting facility that processes sewage sludge mixed with source-separated yard waste. About 19% of the MSW is recovered for recycling programs. Compost is processed in an enclosed building using an aerated, agitated bay technology. Only residual waste and ash are sent to landfills.[13]

In 1992, Scottsdale, AZ, system components included collection and transport of curbside MSW and on-call collection of corrugated moving boxes. There were also drop-off sites for MSW and recyclables. Less than 1% of the MSW was recovered for recycling. More than 92% of the MSW was transported to three unlined landfills.[14]

In Seattle, WA, the system components included collection and transport of curbside MSW, yard waste, and recyclables. There were also two transfer stations, two MRFs, and a source-separated yard waste compost facility. The compost facility is in a rural area and is an open-air facility. It uses large windrow piles that are turned and aerated by a windrow turner to process the compost. Residual waste is hauled by rail to a lined landfill. At the time of the study, 13% of yard waste was composted, and 15% of MSW was recycled.[15] Because of the closing of two city-operated landfills in the late 1980s, the city decided to pursue an aggressive waste reduction program and set a recycling goal of 60% of the waste stream by 1998. In 1996, Seattle was approaching this goal, diverting 49% of its residential waste stream, 48% of its commercial waste stream, and 18% of materials delivered to drop-off sites. The recyclable materials were collected and processed at two private facilities using conveyors, trommel and disc screens, magnetic separation, air classification, balers, and hand-sorting to separate materials.[16]

Across the United States, technological advancements in collection, transport, recycling/composting, combustion, and landfilling are helping to minimize potential impacts to human health and the environment. For example, federal and state requirements are in place under the Resource Conservation and Recovery Act of 1976 and the Clean Air Act. For the baseline year of this study, waste was typically hauled to dumps with nuisances associated with odor, airborn litter, occurrence of disease vectors such as rats, mice, and flies, as well the generation of landfill gas emissions and leachate resulting from the decomposition of biodegradable waste and rainwater filtering through the landfilled waste.[17,18] Today's landfills are modern "sanitary landfills in response to state and federal requirements for liners, leachate collection and treatment, and prevention of landfill gas explosions."[19,20] In 1996, New Source Performance Standards and Emission Guidelines were promulgated requiring that landfill gas be collected and controlled at large landfills (>2.5 million tons of waste).[21] The first landfill gas-to-energy recovery project began operating in 1981.[22] Now there are 300 landfill gas-to-energy projects producing electricity or steam.[23]

MSW combustion has also gone through substantial changes. In the 1970s, MSW was directly combusted without energy recovery and with little or no pollution control. Currently, there are 102 facilities in the United States that combust waste to generate steam or electricity. In these communities, the average recycling rate is 33%, which is 5% greater than the national average.[24] These facilities also have heat recovery, electricity production, and the highest levels of pollution control. Results from a recent EPA inventory of these facilities has shown that emissions are well below emission limits established by the Clean Air Act.[25]

Recycling also has greatly increased, growing from 8% in the 1970s to 27% in 1997. Many communities now have state-of-the art material recovery facilities, and there is a dramatic increase in the amounts of food and yard waste being composted. Technological innovations have occurred, making these operations more efficient and cost effective.[15]

The changes in technology and management practices were taken into account for the different years included in the study. The percentages of MSW being recycled (which includes composting), landfilled, and combusted are provided in Figure 2 for each of the years included in this study. Each of these contributes to the production of GHG emissions, as well as to the potential for avoiding GHG emissions and offsetting fossil fuel consumption. Table 1 provides a list of GHG emission sources and sinks associated with the waste management. All these emission sources and sinks were accounted for in each of the years that were included in this study. Although waste management strategies and technologies changed from 1974 to 1997, other aspects, such as transportation distances, were kept constant because their overall contribution to the results were minimal.[26] Data were not available across all waste management practices for PFCs and N_2O. Consequently, they were not included in the study. As additional data become available, they can be included in future analyses.

The methodology used for this study is intended to illustrate GHG emissions and reduction potentials for the integrated waste management system (i.e., all aspects from collection, transportation, remanufacturing into a new product, or disposal are accounted for). This study was not designed to compare GHG reduction potential between specific MSW management technologies (e.g., recycling vs. combustion). The MSW DST was used to calculate the net GHG emissions resulting from waste collection, transport, recycling, composting, combustion, and land disposal option (i.e., offsets for displacement of fossil fuel). Both direct GHG emissions from each waste management activity and the GHG emissions associated with the production and consumption of fuels were included.

For some of the lower quantity materials in MSW, data from the MSW DST were not available. This represented 1.5% of the total waste generated in 1974 and 4% of that in 1997. For these waste streams, data were obtained from EPA's Office of Solid Waste. These items include durable goods, wood waste, rubber tires, textiles, and lead-acid batteries.

The energy consumed and environmental releases associated with production of new products, as well as those saved by using recycled instead of virgin materials, were included in the analysis. GHG emission savings also were calculated for MSW management strategies (namely, MSW combustion and landfill) where energy was recovered. In calculating the GHG emission savings associated with energy recovery, the "saved" energy was assumed to result from offsetting the national electric grid. For every kilowatt-hour of electricity produced from MSW, the analysis assumed that a kilowatt-hour of electricity produced from fossil fuels was not generated. Wherever energy is consumed (or produced), the analysis includes environmental releases (or savings) associated with both the use and production (e.g., the production of a gallon of diesel fuel) of that energy.

To complete this study, information about MSW generation and composition was needed for 1974, 1980, 1990, and 1997. We used three primary data sources to calculate MSW generation and composition: (1) EPA's Municipal

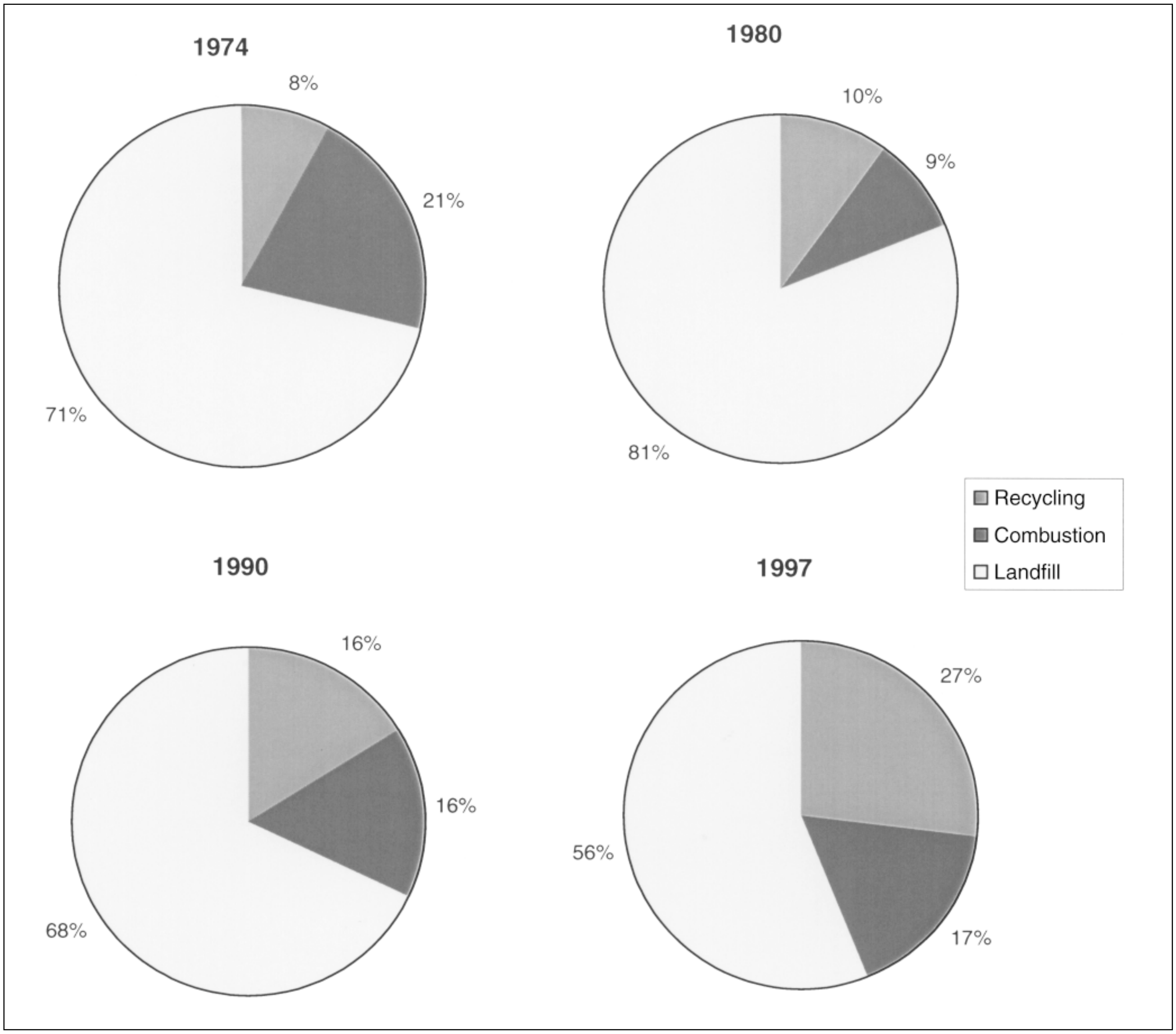

Figure 2. Changes in the management of MSW in the United States from 1974 to 1997.[9,10]

Solid Waste Characterization Report for 1998 (providing information about 1980, 1990, and 1997 waste trends, composition, and generation);[9] (2) unpublished waste characterization data for 1974 from Franklin Associates;[10] and (3) U.S. Bureau of the Census historical housing data.[27] EPA and Franklin Associates waste characterization studies include data for waste generation and composition and MSW management practices in the United States. The amount of MSW generated in the United States for each of the study years is shown in Table 2. Waste composition data are shown in Table 3, and waste management data are shown in Table 4.

U.S. Census data[27] were used to estimate the number of residential, multifamily, and commercial waste generators. This information was used within the MSW DST to generate waste generation rates (in lb/person/day, or lb/location in the commercial sector). The composition and quantities of materials recycled and composted were set at the levels of recycling reported by EPA's and Franklin Associates' national data sets. Recycling and composting rates were based on EPA data.[9] The composition of materials that are recycled and composted is presented in Table 5.

Using the previous data, GHG emissions were calculated for the years 1974, 1980, 1990, and 1997. Figure 2 illustrates the changes to solid waste management for each of these years. In 1974, waste management primarily involved the collection and landfilling of MSW. About 8% of waste was recycled as commingled material and 21% of waste was combusted (without energy recovery). The remaining 71% of waste was landfilled without landfill gas control. During the next 25 years, recycling steadily increased from 8% in 1974 to 10% in 1980, 16% in 1990,

Table 1. Sources and sinks for GHG emissions from MSW management-related technologies included in the analysis.

Waste Management Activity	GHG Emissions (CH_4 and CO_2) Sources and Sinks
Collection (recyclables and mixed waste)	Combustion of diesel in collection vehicles
	Production of diesel and electricity (used in garage)
Material recovery facilities	Combustion of diesel used in rolling stock (front-end loaders, etc.)
	Production of diesel and electricity (used in building and for equipment)
Yard waste composting facility	Combustion of diesel used in rolling stock
	Production of diesel and electricity (used for equipment)
Combustion (also referred to as waste to energy)	Combustion of waste
	Offsets from electricity produced
Landfill	Decomposition of waste
	Combustion of diesel used in rolling stock
	Production of diesel
	Offsets from electricity or steam produced
Transportation	Combustion of diesel used in vehicles
	Production of diesel
Reprocessing of recyclables	Offsets (net gains or decreases) from reprocessing recyclables recovered; offsets include energy- and process-related data

and 27% by 1997. By 1980, waste combustion without energy recovery declined and was replaced by waste-to-energy plants. Data indicate that by 1997, 17% of the MSW generated in the United States was used to produce electricity at 102 waste-to-energy facilities nationwide. Also in 1997, 56% of the waste that was landfilled was going to ~1200 sites with liners, leachate collection, and control. Some of these sites, primarily the larger ones, also have landfill gas control. All of these considerations were taken into account in the calculations.

Role of Carbon Sequestration and Storage

When CO_2 is removed from the atmosphere by photosynthesis or other processes and stored in sinks (like forests or soil), it is sequestered. One of the more controversial issues with accounting for GHG emissions from MSW management is associated with whether carbon sinks should be considered. There is no consensus on a methodology for estimating carbon storage in forests, soils, and landfills. During the series of peer reviews conducted on the methodology developed for the MSW DST, the recommendation from the reviewers was that carbon sequestration should not be considered unless a full product life cycle was being analyzed. However, the MSW DST was developed to include an offline calculator for estimating carbon storage potentials resulting from forests, soils, and landfills. Users can decide whether to calculate and incorporate the carbon storage potentials into their analysis. For this study, results with and without carbon storage included are provided.

Table 2. Total MSW generated in the United States for each study year (metric tons).[9,10]

Year	Waste Generated
1974	116,000,000
1980	137,000,000
1990	186,000,000
1997	197,000,000

The carbon storage values used in this study and included in the MSW DST calculator are from EPA's Office of Solid Waste in a report that was released in 1998[5] to support its voluntary partnership program on climate change and MSW management. This methodology tracks carbon storage related to waste processes and tracks carbon associated with fossil fuel and nonenergy GHGs such as PFCs and N_2O. The principal carbon storage mechanisms addressed are changes in forest carbon stocks related to paper and wood recycling, long-term storage of carbon in landfills, and accumulation of carbon in soils resulting from compost application. Carbon storage from combustion ash residue also was studied and was estimated to be negligible. Although carbon storage in forests, soils, and landfills clearly has a strong influence on net GHG emissions, the exact accounting methods that should be used to quantify them are still a matter of debate, because many scientific and policy questions remain to be resolved. However, EPA currently includes estimates of carbon storage from landfills and forests in its national GHG inventory.[1]

To help illustrate the difference in estimates of GHG emissions when carbon storage is taken into account, EPA's Office of Solid Waste and ICF Consulting provided data and information using the EPA WARM model[28] for making the comparisons. Table 6 shows the potential carbon storage for the years that were evaluated for this study. The negative values in the table indicate that the storage is, in effect, a negative emission. In scenarios where waste is managed according to 1974 technology, substantial carbon storage is associated with landfills. In the 1990s, the balance shifts—the large volume of paper recycling results in substantial benefits in the form of forest carbon storage, and there are also some soil carbon benefits from composting.

Table 3. Waste composition.[9,10]

	Composition (%)[a]							
	1974		1980		1990		1997	
Waste Category	**Residential**	**Commercial**	**Residential**	**Commercial**	**Residential**	**Commercial**	**Residential**	**Commercial**
Yard trimmings, leaves[b]	13		6.7		6.6		5.4	
Yard trimmings, grass[b]	13		13		13		11	
Yard trimmings, branches[b]	11		6.7		6.6		5.4	
Newsprint	12	2.0	10	2.9	9.6	2.5	8.0	1.8
Corrugated cardboard	2.2	19	1.9	27	2.0	27	2.6	29
Office paper	1.1	3.0	1.1	5.3	1.4	5.9	1.5	5.7
Phone books					0.3	0.3	0.2	0.2
Books	3.0		2.9		0.7		0.8	
Magazines					1.6		3.1	
3rd-class mail					2.1	1.6	2.7	1.8
HDPE—translucent[c]			0.2		0.4		0.6	
HDPE—pigmented[c]	2.2		1.0		1.2		1.3	
PET[d]			0.2	0.1	0.3	0.1	0.5	0.2
Steel cans	1.8	5.2	2.6	2.0	1.8	0.9	2.1	0.7
Ferrous metal—other	0.3							
Aluminum—food cans	0.5	0.2	0.8	0.4	1.0	0.4	1.1	0.4
Aluminum—other cans		0	0.4		0.3		0.3	
Aluminum—foil and closures	0.6							
Glass—clear[e]	9.4	1.9	6.8	2.5	4.5	1.5	4.1	1.1
Glass—brown[e]	6.0	1.2	4.3	1.6	2.9	0.9	2.6	0.7
Glass—green[e]	1.7	0.3	1.2	0.4	0.8	0.3	0.7	0.2
Paper—nonrecyclable	10		16		16		20	
Food waste	11		7.0		8.8		9.2	
Other organic materials		27		40		43		40
Plastic—nonrecyclable			1.8		3.1		4.5	
Metals—nonrecyclable	0.3							
Miscellaneous		41	14	17	14	16	13	18

[a]Numbers may not add up to 100% because of rounding; [b]Yard waste split between leaves, grass, and branches was assumed to be 35, 35, and 30%, respectively; [c]HDPE is high-density polyethylene; [d]PET is polyethylene terephthalate; [e]Glass composition split between clear, brown, and green was assumed to be 55, 35, and 10%, respectively.

RESULTS

Figure 3 illustrates the overall trend in GHG emissions from 1974 to 1997. Two technology pathways are shown. One pathway represents GHG emissions from the actual integrated MSW management technologies employed in each study year. The other pathway represents what GHG emissions would be if the same 1974 technologies and MSW management practices were used in all study years (i.e., 1980, 1990, and 1997). As illustrated in this figure, by adopting new technologies and MSW management practices, GHG emissions have decreased from 1974 to 1997, despite an almost 2-fold increase in the quantity of waste generated. Net GHG emissions in 1997 were ~8 million MMTCE versus 36 MMTCE in 1974. If the same technology and MSW management practices were used today as were used in 1974, net GHG emissions would be ~60 MMTCE. Thus, it could be concluded that the employment of new MSW management technologies currently are saving on the order of 52 MMTCE per year. The following sections discuss the net

Table 4. Annual waste input to management options (metric tons).[9,10]

	1974	1980	1990	Today
Collection of Yard Waste	0	0	3,800,000	10,400,000
Collection of Recyclables	6,700,000	10,700,000	20,900,000	35,300,000
Collection of Mixed Waste	108,000,000	124,000,000	157,000,000	144,000,000
Recovery of Recyclables in MRF[a]	8,400,000	13,100,000	25,900,000	43,300,000
Composting (yard waste)	0	0	3,800,000	10,400,000
Combustion	23,900,000	12,400,000	28,800,000	32,900,000
Landfill of Mixed Waste	83,600,000	112,000,000	128,000,000	111,000,000
Landfill of Combustion Ash	62,500	41,700	70,500	89,200

[a]MRF is mixed recovery facility.

Table 5. Recovery rates of materials.[9,10]

	Recovery of Materials (%)[a]							
	1974		1980		1990		1997	
Waste Category	**Residential**	**Commercial**	**Residential**	**Commercial**	**Residential**	**Commercial**	**Residential**	**Commercial**
Yard trimmings, leaves			0.0		13		46	
Yard trimmings, grass			0.0		13		46	
Yard trimmings, branches			0.0		13		46	
Newsprint	29	1.4	31	5.2	44	7.2	64	11
Corrugated cardboard	3.1	81	4.3	41	5.5	53	7.6	74
Office paper	0.9	14	0.9	29	1.1	35	2.0	67
Phone books					0.0	8.2		19
Books	13		10		28		78	
Magazines					16		48	
3rd-class mail						7.5		28
HDPE—translucent[b]					3.8		31	
HDPE—pigmented[b]					1.4		9.7	
PET[c]			4.3	1.9	37	16	50	22
Steel cans	4.2	2.1	5.6	5.6	25	22	64	50
Ferrous metal—other	0.5		1.3		5.7		13	
Aluminum cans	27	0.4	35	28	64	56	58	50
Aluminum—foil and closures			0		5.4		7.4	
Glass—clear	2.8	0.9	5.2	5.9	22	24	24	28
Glass—brown	2.8	0.6	5.2	5.9	22	24	23	26
Glass—green	2.8	0.2	5.2	5.9	22	24	54	60

[a]Recovery of materials is defined as the percentage of a material generated that is recycled. Where appropriate, materials that were recycled based on EPA data were combined into a similar waste category for which reprocessing data were available. For example, 3rd-class mail and phone books recycled in 1997 were combined into the Books category. This assumption makes some recovery numbers appear high; [b]HDPE is high-density polyethylene; [c]PET is polyethylene terephthalate.

contributions of GHGs from recycling and composting, waste-to-energy combustion, landfills, and collection and transportation practices. In addition, the effects of carbon storage on the net total GHG emissions are discussed.

Recycling and Composting

Recycling contributes to the reduction of GHG emissions by displacing virgin raw materials and thereby avoiding environmental releases associated with raw materials extraction and materials production. In addition, recycling and composting avoids GHG emissions by diverting the disposal of materials from landfills that produce CH_4 and other GHGs. As shown in Figures 2 and 4, increasing recycling and composting from ~8 million metric tons, or 8%, in 1974, to more than 53 million metric tons, or 27%, in 1997, currently is avoiding the release of more than 3.2 MMTCE annually. These results include GHG emissions from materials collection, separation, treatment (in the case of composting), and transportation to a remanufacturing facility. For recycled materials, GHG

Table 6. Carbon storage potentials for waste management strategies (MMTCE/yr).

Scenario	Recycling (includes compost)	Landfill	Total
1974	–5.5	–12.8	–18.3
1980	–8.6	–17.1	–25.6
1980 with 1974 technology	–6.7	–15.4	–22.1
1990	–14.9	–19.2	–34.2
1990 with 1974 technology	–8.9	–20.7	–29.6
Today	–26.4	–14.8	–41.2
Today with 1974 technology	–9.5	–21.0	–30.6

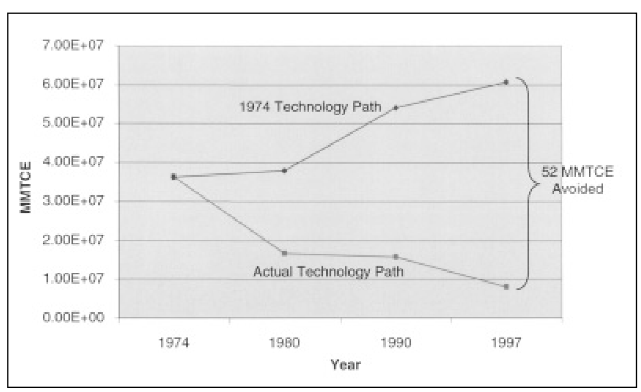

Figure 3. Comparison of net GHG emissions for MSW management reflecting technological changes, landfill diversion, and source reduction.

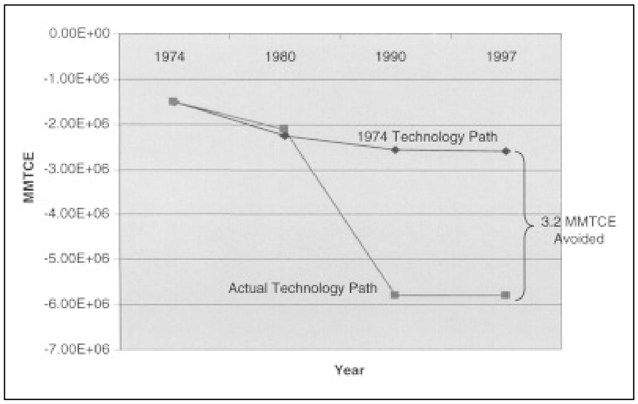

Figure 4. Comparison of net GHG emissions for recycling and composting. Avoided emissions reflect offsets from resource conservation.

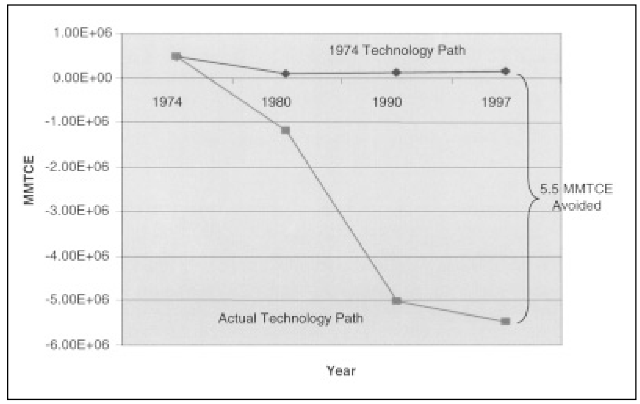

Figure 5. Comparison of net GHG emissions for MSW combustion. Avoided emissions reflect offsets for fossil-fuel conservation from energy that is produced.

emissions avoided by displacing virgin raw materials production are netted out of the results. Additional emissions also are avoided as the result of diversion from landfills and from source reduction.

Combustion

For nearly 100 years, the United States has used combustion as a means of waste disposal. Similar to landfill technology of 25 years ago, the benefit of early combustion technology was solely its disposal ability, as well as its ability to destroy pathogens in waste. Energy recovery through the combustion of waste was not considered seriously in the United States until the 1970s. At that time, waste combustion technology developed from a realization that waste had an inherent energy content and could be harnessed to generate electricity. For the past 20 years, combustion technology has grown to include an added benefit of energy recovery. Combustion facilities have been successful in recovering materials from the waste stream that can be recycled and recovering energy from the residual waste to generate electricity. All MSW combustion facilities in the United States include recycling programs and energy production. Electricity generated from waste combustion has become so reliable that the power is "base load" for utilities that buy it, thereby allowing those utilities to avoid construction of new power plants or the purchase of fossil fuel-generated electricity.

In 1974, ~24 million metric tons of MSW, representing ~21% of U.S. MSW, was managed in combustion units without energy recovery. As shown in Figure 5, this technology was a net generator of GHG emissions. By 1997, ~33 million metric tons of MSW, representing ~17% of U.S. MSW, was managed by MSW combustion. This resulted in avoiding the release of ~5.5 MMTCE of GHG emissions annually, as compared to GHG emissions if 1974 combustion technology was still employed. The GHG emissions from combustion facilities were based on emission test results provided to EPA and state environmental agencies.[29]

Waste combustion is similar to recycling in that it can reduce GHG emissions in two ways. First, combustion diverts MSW from landfills where it would otherwise produce CH_4 as it decomposes. Second, the electrical energy resulting from waste combustion displaces electricity generated by fossil fuel-fired power generators (and associated GHG emissions). Figures 4 and 5 both reflect the net decrease in emissions that are attributed to displacement of virgin resources and fossil fuel. They do not reflect added reductions from CH_4 emissions that would be avoided if waste were landfilled. If the avoided GHG emissions were included in Figure 5, an additional 6 MMTCE would be reduced, increasing the total avoided emissions from 5.5 to 11 MMTCE. If the MSW had been landfilled, 33 million metric tons would have been released. The assumptions for this calculation are presented in Table 7. Half of the MSW being landfilled is located at sites with landfill gas control. Of these sites, half of those with gas control utilize the landfill CH_4 to produce steam or electricity using reciprocating engines, boilers, and turbines. Offsets for this produced energy were included in the calculations. The total emissions were calculated to ensure that a comparable basis was used in calculating the avoided emissions. For combustion, emissions are released immediately. For landfills, the GHG emissions are released over a long period of time, and not all of the potential carbon is re-released. GHG emissions over a 100-year period were used for this study.

Landfills

In 1974, 108 million metric tons of MSW and combustion ash were landfilled in the United States. In 1997, ~129 million metric tons of MSW and combustion ash were landfilled, representing 56% of the MSW generated. As of

Table 7. Key landfill design and operation assumptions.

Parameter (%)	Study Year 1974	1980	1990	1997
Waste managed in landfills with gas control	0	10	30	50
Landfill gas collection efficiency	0	75	75	75
CH_4 oxidation rate	20	20	20	20
Controlled landfill gas utilized for energy recovery projects using boilers, reciprocating engines, and turbines	0	0	31	50

2000, there were 2526 MSW landfills in the United States.[30] Landfills with gas collection systems reduce the release of GHG emissions associated with the decomposition of waste. Figure 6 illustrates the landfill gas-generation rate over a 100-year period. Because GHG emissions are reported for a specific time period, the cumulative CH_4 yield, as opposed to an annual emission rate, is needed to account for the total emissions for the management (i.e., landfilling) of the MSW for each year of the study. Energy can be recovered from the utilization of the CH_4 in landfill gas (which is typically ~50% of the landfill gas) to produce energy. Offsets for fossil fuel conservation were included in the analysis, as was done for recycling and combustion. Because of diversion of waste from landfills, the growth of landfill gas-to-energy projects from 0 in 1974 to nearly 300 in 1997,[23] Clean Air Act requirements, and improvements in landfill design and management, there has been a substantial reduction of GHG emissions associated with MSW landfills.

For the baseline year of 1974, there was no gas control or energy recovery. For 1997, using recent data, GHG emissions were calculated based on 50% of MSW being landfilled at sites with landfill gas collection and control.[23] Of this 50%, half of the gas was flared and half was used for energy recovery using recent statistics of the distribution of energy recovery projects (internal combustion engines, direct gas use, gas turbines, etc.).[23] Specific assumptions for landfill gas parameters in each study year are included in Table 7. These assumptions were verified through communication with national experts. The GHG emissions associated with fossil fuel-based electrical energy that was displaced by the use of landfill gas was also included in the calculations using the national electrical energy grid mix.

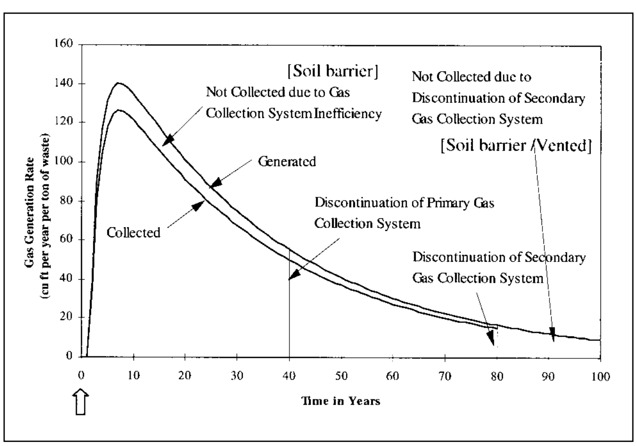

Figure 6. Landfill gas-generation rate during a 100-year period.[32,33]

The results, as illustrated in Figure 7, indicate that modern landfills in 1997 avoided the release of 44 MMTCE of GHG emissions annually. This level of avoided GHG emissions was achieved through the use of gas collection and control systems, as well as the diversion of MSW from landfills by using recycling, composting, and combustion technologies. The key factors in determining GHG emissions produced from landfills are the amount of waste managed, level of gas collection and control, effectiveness and timing of the control, and level and type of energy recovery. Gas that would be oxidized and not emitted as CH_4 was also accounted for. The gas collection efficiency that was used was obtained from EPA's guidance on estimating landfill gas emissions and is considered environmentally conservative.[31]

Collection and Transportation

Collection and transportation of MSW and recyclables accounted for ~0.5 and 1 MMTCE in 1974 and 1997, respectively. More GHG emissions were emitted in 1997 from collection and transportation because of the doubling of the amount of MSW generated and collected since 1974. In addition to increases in GHG emissions from collection and transportation, increases in other local pollutants (such as SO_x, NO_x, CO, O_3, and particulate) should also be considered, particularly in regions that are

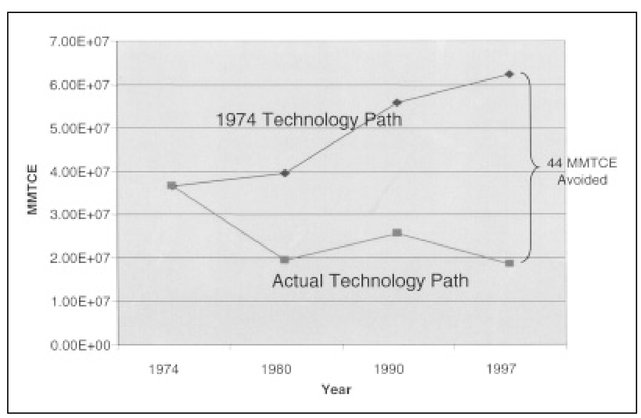

Figure 7. Comparison of net GHG emission reductions from landfills caused by diversion of waste from landfills, increased landfill gas control, and energy recovery of landfill CH_4.

Table 8. Non-GHG pollutant releases from waste collection and transportation (lb/yr).

Scenario	Pollutant			
	SO_x	NO_x	CO	Particulate
1974	166,000	1,530,000	273,000	23,900
1980	167,000	1,580,000	287,000	25,300
1980 with 1974 technology	167,000	1,580,000	285,000	24,900
1990	229,000	2,150,000	403,000	36,300
1990 with 1974 technology	221,000	2,100,000	378,000	32,900
1997	272,000	2,490,000	488,000	45,600
1997 using 1974 technology	245,000	2,310,000	414,000	36,200

Table 9. Net GHG emissions, including the effects of carbon sequestration for waste management strategies (MMTCE/yr).

Scenario	Estimated Amount of Carbon Sequestered (from Table 6)	Estimated GHG Emissions	Total Net GHG Emissions
1974	–18.3	36.2	17.9
1980	–25.6	16.7	–8.9
1980 with 1974 technology	–22.1	38.0	15.9
1990	–34.2	15.6	–18.6
1990 with 1974 technology	–29.6	54.2	24.6
1997	–41.2	8.0	–33.2
1997 using 1974 technology	–30.6	60.5	29.9

classified as nonattainment areas with respect to the National Ambient Air Quality Standards. Table 8 includes estimates of other non-GHG pollutants associated with waste collection and transportation.

Carbon Sequestration and Storage

The magnitude of carbon storage relative to the magnitude of emissions is shown in Table 9. When the consideration of carbon storage is included in the calculations, it dramatically offsets all of the energy and landfill emissions. If carbon sequestration is considered in this analysis, net GHG emissions avoided remain a factor of ~6. Overall, the basic findings remain the same: improvements in management have resulted in dramatically reduced net GHG emissions from the waste sector.

CONCLUSIONS

America's cities are avoiding the annual release of 52 MMTCE of GHG emissions each year through the use of modern MSW management practices. The total quantity of GHG emissions from MSW management was reduced by more than a factor of 6 (from 60 to 8 MMTCE) from what it otherwise would have been, despite an almost doubling in the rate of MSW generation. This reduction is a result of several key factors:

- Increasing recycling and composting efforts from 8 to 27% resulted in savings of 4 MMTCE from avoiding use of virgin materials.
- Producing electricity in waste combustion facilities avoids 5 MMTCE that otherwise would have been produced by fossil fuel electrical energy generation and avoids 6 MMTCE of GHG emissions that would be produced if the MSW were landfilled.
- There has been an increasing diversion of MSW from landfills by using recycling, composting, and waste combustion.
- Increasing landfill gas collection and energy recovery technology avoids 32 MMTCE that would otherwise have been produced by older landfills (without landfill gas control), by displacing fossil fuel consumption for that portion of sites utilizing landfill CH_4 (rather than flaring the gas), and through diversion to other technologies and source reduction.

This study illustrates that there has been a positive impact on GHG emissions as a result of technology advancements in managing MSW and more integrated management strategies. Although there has been a 60% increase in MSW since 1974, more than 52 MMTCE of GHG emissions per year are being avoided based on actions taken in U.S. communities. There are additional opportunities for decreases in GHG emissions as well as improvement in other environmental cobenefits through improved materials and energy recovery from MSW management. From this study, it can be concluded that the greatest reductions in GHG emissions during the past 25 years have come from technology advancements to recover energy and recycle materials. The large reductions in GHG emissions from energy recovery and recycling result from displacing the need to produce energy from fossil sources and to produce new raw materials from virgin sources.

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