

8. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 8-1). Landfills accounted for approximately 23 percent of total U.S. anthropogenic methane (CH₄) emissions in 2006,¹ the second largest contribution of any CH₄ source in the United States. Additionally, wastewater treatment and composting of organic waste accounted for approximately 4 percent and less than 1 percent of U.S. CH₄ emissions, respectively. Nitrous oxide (N₂O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N₂O emissions from the treatment process itself. N₂O emissions from composting were also estimated. Together, these waste activities account for less than 3 percent of total U.S. N₂O emissions. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-CH₄ volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 8-1 and Table 8-2.

Overall, in 2006, waste activities generated emissions of 161.0 Tg CO₂ Eq., or just over 2 percent of total U.S. greenhouse gas emissions.

Figure 8-1

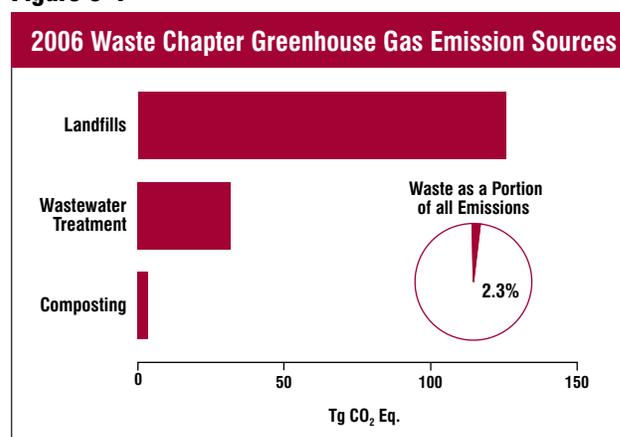


Table 8-1: Emissions from Waste (Tg CO₂ Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH₄	172.9	169.1	146.7	143.0	145.5	151.0	148.1	149.0	151.1
Landfills	149.6	144.0	120.8	117.6	120.1	125.6	122.6	123.7	125.7
Wastewater Treatment	23.0	24.3	24.6	24.2	24.1	23.9	24.0	23.8	23.9
Composting	0.3	0.7	1.3	1.3	1.3	1.5	1.6	1.6	1.6
N₂O	6.6	7.7	8.9	9.2	9.0	9.3	9.6	9.7	9.9
Domestic Wastewater Treatment	6.3	6.9	7.6	7.8	7.6	7.7	7.8	8.0	8.1
Composting	0.4	0.8	1.4	1.4	1.4	1.6	1.7	1.7	1.8
Total	179.6	176.8	155.6	152.1	154.5	160.3	157.7	158.7	161.0

Note: Totals may not sum due to independent rounding.

¹ Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land Use, Land-Use Change, and Forestry chapter.

Table 8-2: Emissions from Waste (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH₄	8,235	8,052	6,983	6,808	6,928	7,190	7,053	7,096	7,197
Landfills	7,124	6,859	5,751	5,598	5,720	5,981	5,838	5,890	5,985
Wastewater Treatment	1,096	1,158	1,173	1,150	1,148	1,140	1,141	1,131	1,136
Composting	15	35	60	60	61	69	74	75	75
N₂O	21	25	29	30	29	30	31	31	32
Domestic Wastewater Treatment	20	22	24	25	25	25	25	26	26
Composting	1	3	4	5	5	5	6	6	6

Note: Totals may not sum due to independent rounding.

8.1. Landfills (IPCC Source Category 6A1)

In 2006, landfill CH₄ emissions were approximately 125.7 Tg CO₂ Eq. (5,985 Gg of CH₄), representing the second largest source of CH₄ emissions in the United States, behind enteric fermentation. Emissions from municipal solid waste (MSW) landfills, which received about 64 percent of the total solid waste generated in the United States, accounted for about 88 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 1,800 operational landfills exist in the United States, with the largest landfills receiving most of the waste and generating the majority of the CH₄ (BioCycle 2006, adjusted to include missing data from five states).

After being placed in a landfill, waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These CH₄-producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO₂) and 50 percent CH₄, by volume.² Significant CH₄ production typically begins one or two years after waste disposal in a landfill and continues for 10 to 60 years or longer.

²The percentage of CO₂ in biogas released from a landfill may be smaller because some CO₂ dissolves in landfill water (Bingemer and Crutzen 1987). Additionally, less than 1 percent of landfill gas is typically composed of non-CH₄ volatile organic compounds (NMVOCs).

From 1990 to 2006, net CH₄ emissions from landfills decreased by approximately 16 percent (see Table 8-3 and Table 8-4), with small increases occurring in some interim years. This downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted,³ which has more than offset the additional CH₄ generation resulting from an increase in the amount of municipal solid waste landfilled.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of waste in MSW landfills, which is related to total waste landfilled annually; (2) the characteristics of landfills receiving waste (i.e., composition of waste-in-place, size, climate); (3) the amount of CH₄ that is recovered and either flared or used for energy purposes; and (4) the amount of CH₄ oxidized in landfills instead of being released into the atmosphere. The estimated annual quantity of waste placed in MSW landfills increased from about 209 Tg in 1990 to 307 Tg in 2006, an increase of 47 percent (see Annex 3.14). During this period, the estimated CH₄ recovered and combusted from MSW landfills increased as well. In 1990, for example, approximately 888 Gg of CH₄ were recovered and combusted (i.e., used for energy or flared) from landfills, while in 2006, 5,958 Gg CH₄ was combusted. In 2006, an estimated 26 new landfill gas-to-energy (LFGTE) projects and 41 new flares began operation, resulting in a 4.4 percent increase in the quantity of CH₄ recovered and combusted from 2005 levels.

Over the next several years, the total amount of municipal solid waste generated is expected to increase as the U.S. population continues to grow. The percentage of waste

³The CO₂ produced from combusted landfill CH₄ at landfills is not counted in national inventories as it is considered part of the natural C cycle of decomposition.

Table 8-3: CH₄ Emissions from Landfills (Tg CO₂ Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
MSW Landfills	172.6	191.8	206.9	211.4	225.8	225.8	233.7	241.2	248.6
Industrial Landfills	12.3	13.6	15.2	15.5	15.8	15.8	16.0	16.1	16.2
Recovered									
Gas-to-Energy	(13.6)	(23.4)	(51.3)	(56.1)	(57.2)	(57.2)	(60.6)	(62.2)	(65.3)
Flared	(5.1)	(22.0)	(36.7)	(40.3)	(44.9)	(44.9)	(52.7)	(57.7)	(59.8)
Oxidized ^a	(16.6)	(16.0)	(13.4)	(13.1)	(14.0)	(14.0)	(13.6)	(13.7)	(14.0)
Total	149.6	144.0	120.8	117.6	120.1	125.6	122.6	123.7	125.7

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

^a Includes oxidation at both municipal and industrial landfills.

Table 8-4: CH₄ Emissions from Landfills (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
MSW Landfills	8,219	9,132	9,854	10,068	10,367	10,754	11,127	11,486	11,838
Industrial Landfills	585	649	725	739	746	754	760	760	770
Recovered									
Gas-to-Energy	(646)	(1,113)	(2,441)	(2,670)	(2,721)	(2,723)	(2,888)	(2,961)	(3,110)
Flared	(242)	(1,047)	(1,747)	(1,917)	(2,037)	(2,140)	(2,512)	(2,748)	(2,848)
Oxidized ^a	(792)	(762)	(639)	(622)	(636)	(665)	(649)	(654)	(665)
Total	7,124	6,859	5,751	5,598	5,720	5,981	5,838	5,890	5,985

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

^a Includes oxidation at both municipal and industrial landfills.

landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of CH₄ that is recovered and either flared or used for energy purposes is expected to continue to increase as a result of 1996 federal regulations that require large municipal solid waste landfills to collect and combust landfill gas (see 40 CFR Part 60, Subpart Cc 2005 and 40 CFR Part 60, Subpart WWW 2005), voluntary programs encouraging CH₄ recovery and use such as EPA's Landfill Methane Outreach Program (LMOP), and federal and state incentives that promote renewable energy (e.g. tax credits, low interest loans, and Renewable Portfolio Standards).

Methodology

A detailed description of the methodology used to estimate CH₄ emissions from landfills can be found in Annex 3.14.

CH₄ emissions from landfills were estimated to equal the CH₄ produced from municipal solid waste landfills, plus the CH₄ produced by industrial landfills, minus the CH₄

recovered and combusted, minus the CH₄ oxidized before being released into the atmosphere:

$$CH_{4,Solid\ Waste} = [CH_{4,MSW} + CH_{4,ind} - R] - Ox$$

where,

$CH_{4,Solid\ Waste}$ = CH₄ emissions from solid waste

$CH_{4,MSW}$ = CH₄ generation from municipal solid waste landfills,

$CH_{4,ind}$ = CH₄ generation from industrial landfills,

R = CH₄ recovered and combusted, and

Ox = CH₄ oxidized from MSW and industrial landfills before release to the atmosphere.

The methodology for estimating CH₄ emissions from municipal solid waste landfills is based on the first order decay model described by the Intergovernmental Panel on Climate Change (IPCC 2006). Values for the CH₄ generation potential (L₀) and rate constant (k) were obtained from an analysis of CH₄ recovery rates for a database of 52 landfills and from published studies of other landfills (RTI 2004;

EPA 1998; SWANA 1998; Peer, Thorneloe, and Epperson 1993). The rate constant was found to increase with average annual rainfall; consequently, values of k were developed for 3 ranges of rainfall. The annual quantity of waste placed in landfills was apportioned to the 3 ranges of rainfall based on the percent of the U.S. population in each of the 3 ranges, and historical census data were used to account for the shift in population to more arid areas over time. For further information, see Annex 3.14.

National landfill waste generation and disposal data for 1989 through 2006 were obtained from *BioCycle* (2006). Because *BioCycle* does not account for waste generated in U.S. territories, waste generation for the territories was estimated using population data obtained from the U.S. Census Bureau (2007) and national per capita solid waste generation from *BioCycle* (2006). Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993) and an extensive landfill survey by the EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the first order decay model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For calculations in this Inventory, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in landfills (MCF of 1) and those disposed in dumps (MCF of 0.6). Please see the Recalculations Discussion section and Annex 3.14 for more details.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment, a database of landfill gas-to-energy (LFGTE) projects compiled by LMOP (EPA 2007), and a database maintained by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007). The three databases were carefully compared to identify landfills that were in two or all three of the databases to avoid double-counting reductions. Based on the information provided by the EIA and flare vendor databases, the CH_4 combusted by flares in operation from 1990 to 2006 was estimated. This quantity likely underestimates flaring because these databases do not

have information on all flares in operation. Additionally, the EIA and LMOP databases provided data on landfill gas flow and energy generation for landfills with LFGTE projects. If a landfill in the EIA database was also in the LMOP and/or the flare vendor database, the emissions avoided were based on the EIA data because landfill owners or operators reported the amount recovered based on measurements of gas flow and concentration, and the reporting accounted for changes over time. If both flare data and LMOP recovery data were available for any of the remaining landfills (i.e., not in the EIA database), then the emissions recovery was based on the LMOP data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The flare data, on the other hand, only provided a range of landfill gas flow for a given flare size. Given that each LFGTE project is likely to also have a flare, double counting reductions from flares and LFGTE projects in the LMOP database was avoided by subtracting emissions reductions associated with LFGTE projects for which a flare had not been identified from the emissions reductions associated with flares.

A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided. The value for efficiency was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in EPA's *AP-42 Compilation of Air Pollutant Emission Factors, Chapter 2.4* (EPA 1998) efficiencies used to establish new source performance standards (NSPS) for landfills, and in recommendations for closed flares used in LMOP.

Emissions from industrial landfills were estimated from activity data for industrial production, waste disposal factors, and the first order decay model. As over 99 percent of the organic waste placed in industrial landfills originated from the food processing (meat, vegetables, fruits) and pulp and paper industries, estimates of industrial landfill emissions focused on these two sectors (EPA 1993). The amount of CH_4 oxidized by the landfill cover at both municipal and industrial landfills was assumed to be ten percent of the CH_4 generated that is not recovered (IPCC 2006, Mancinelli and McKay 1985, Czepiel et al. 1996). To calculate net CH_4 emissions, both CH_4 recovered and CH_4 oxidized were subtracted from CH_4 generated at municipal and industrial landfills.

Uncertainty

Several types of uncertainty are associated with the estimates of CH₄ emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is not available on two fundamental factors affecting CH₄ production: the amount and composition of waste placed in every landfill for each year of its operation. The approach used here assumes that the CH₄ generation potential and the rate of decay that produces CH₄, as determined from several studies of CH₄ recovery at landfills, are representative of U.S. landfills.

Additionally, the approach used to estimate the contribution of industrial wastes to total CH₄ generation introduces uncertainty. Aside from uncertainty in estimating CH₄ generation potential, uncertainty exists in the estimates of oxidation by cover soils. There is also uncertainty in the estimates of methane that is recovered by flaring and energy projects. The IPCC default value of 10 percent for uncertainty in recovery estimates was used in the uncertainty analysis when metering was in place (for about 64 percent of the methane estimated to be recovered). For flaring without metered recovery data (approximately 34 percent of the methane estimated to be recovered), a much higher uncertainty of approximately 50 percent was used (e.g., when recovery was estimated as 50 percent of the flare’s design capacity).

N₂O emissions from the application of sewage sludge on landfills are not explicitly modeled as part of greenhouse gas emissions from landfills. N₂O emissions from sewage sludge applied to landfills would be relatively small because the microbial environment in landfills is not very conducive to the nitrification and denitrification processes that result in N₂O emissions. Furthermore, the 2006 IPCC Guidelines (IPCC 2006) did not include a methodology for estimating N₂O emissions from solid waste disposal sites “because they are not significant.” Therefore, any uncertainty or bias caused

by not including N₂O emissions from landfills is expected to be minimal.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-5. Landfill CH₄ emissions in 2006 were estimated to be between 74.7 and 168.5 Tg CO₂ Eq., which indicates a range of 41 percent below to 34 percent above the 2006 emission estimate of 125.7 Tg CO₂ Eq.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. A primary focus of the QA/QC checks was to ensure that methane recovery estimates were not double-counted. Both manual and electronic checks were made to ensure that emission avoidance from each landfill was calculated only in one of the three databases. The primary calculation spreadsheet is tailored from the IPCC waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values were verified by secondary QA/QC review.

Recalculations Discussion

In developing the 1990 to 2006 Inventory report, the proportion of waste disposed of in managed landfills versus open dumps prior to 1980 was re-evaluated. Based on the historical data presented by Minz et al. (2003), a timeline was developed for the transition from the use of open dumps for solid waste disposed to the use of managed landfills. Based on this timeline, 6 percent of the waste that was land disposed in 1940 was disposed of in managed landfills and 94 percent was managed in open dumps. Between 1940 and 1980, the fraction of waste land disposed transitioned towards managed landfills until 100 percent of the waste was disposed of in managed landfills in 1980. Although this timeline was based primarily on information about MSW disposal, a similar trend in disposal practices was expected

Table 8-5: Tier 2 Quantitative Uncertainty Estimates for CH₄ Emissions from Landfills (Tg CO₂ Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^a			
			(Tg CO ₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Landfills	CH ₄	125.7	74.7	168.5	-41%	+34%

^a Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

for industrial landfills; therefore, this same time line was applied to the industrial landfills. For wastes disposed of in dumps, a methane correction factor (MCF) of 0.6 was used based on the recommended IPCC default value for uncharacterized land disposal (IPCC 2006); this MCF is equivalent to assuming 50 percent of the open dumps are deep and 50 percent are shallow. The recommended IPCC default value for the MCF for managed landfills of 1 was used for the managed landfills (IPCC 2006). This recalculation reduced the MSW landfill CH₄ generation rate for the 1990 to 2005 time series by 5.6 percent, and it reduced the industrial landfill CH₄ generation rate for the 1990 to 2005 time series by 1.8 percent.

Another significant recalculation, which affected estimates of CH₄ recovery, was associated with updating the EIA, LMOP, and flare vendor databases. The estimates of gas recovery by LFGTE projects for 1990 to 2005 increased because more landfills with operational gas recovery projects were identified and included in the LFGTE database. However, many of these LFGTE projects did not have a corresponding flare in the flare vendor database. The gas recovery and combustion estimates from the flare database were adjusted by deducting the recovery and combustion estimates associated with these LFGTE projects with unmatched flares from the flare combustion totals. This results in a decrease in the estimates for flaring. For the 1990 to 2005 time series, the recalculation resulted in an average increase of 1.4 percent in the amount of CH₄ recovered and destroyed by gas-to-energy projects and a net decrease of 0.5 percent in the estimated CH₄ emissions.

Overall, these recalculations resulted in an average decrease of 7.8 percent in emissions across the time series relative to the previous Inventory.

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of the amount of waste placed in MSW landfills. Improvements to the flare database will be investigated, and an effort will be made to identify additional landfills that have flares.

Box 8-1: Biogenic Emissions and Sinks of Carbon

CO₂ emissions from the combustion or decomposition of biogenic materials (e.g., paper, wood products, and yard trimmings) grown on a sustainable basis are considered to mimic the closed loop of the natural carbon cycle—that is, they return to the atmosphere CO₂ that was originally removed by photosynthesis. In contrast, CH₄ emissions from landfilled waste occur due to the man-made anaerobic conditions conducive to CH₄ formation that exist in landfills, and are consequently included in this Inventory.

Depositing wastes of biogenic origin in landfills causes the removal of carbon from its natural cycle between the atmosphere and biogenic materials. As empirical evidence shows, some of these wastes degrade very slowly in landfills, and the carbon they contain is effectively sequestered in landfills over a period of time (Barlaz 1998, 2005). Estimates of carbon removals from landfilling of forest products, yard trimmings, and food scraps are further described in the Land Use, Land-Use Change, and Forestry chapter, based on methods presented in IPCC (2003) and IPCC (2006).

8.2. Wastewater Treatment (IPCC Source Category 6B)

Wastewater treatment processes can produce anthropogenic CH₄ and N₂O emissions. Wastewater from domestic (municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur on site, most commonly through septic systems or package plants,⁴ or off site at centralized treatment systems. Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. In the United States, approximately 21 percent of domestic wastewater is treated in septic systems or other on-site systems, while the rest is collected and treated centrally (U.S. Census Bureau 2007b).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can

⁴Package plants are treatment plants assembled in a factory, skid mounted, and transported to the treatment site.

biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH₄. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. The generation of N₂O may also result from the treatment of domestic wastewater during both nitrification and denitrification of the nitrogen present, usually in the form of urea, ammonia, and proteins. These compounds are converted to nitrate (NO₃) through the aerobic process of nitrification. Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N₂). N₂O can be an intermediate product of both processes, but is more often associated with denitrification.

The principal factor in determining the CH₄ generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH₄ than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH₄ production. The

principal factor in determining the N₂O generation potential of wastewater is the amount of N in the wastewater.

In 2006, CH₄ emissions from domestic wastewater treatment were 16.0 Tg CO₂ Eq. (762 Gg). Emissions gradually increased from 1990 through 1997, but have decreased since 1998 due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems. In 2006, CH₄ emissions from industrial wastewater treatment were estimated to be 7.9 Tg CO₂ Eq. (374 Gg). Industrial emission sources have increased across the time series through 1999 and then fluctuated up and down in keeping with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, and starch-based ethanol production industries.⁵ Table 8-6 and Table 8-7 provide CH₄ and N₂O emission estimates from domestic and industrial wastewater treatment. With respect to N₂O, the United States identifies two distinct sources for N₂O emissions from domestic wastewater: emissions from centralized wastewater treatment processes, and emissions from effluent from centralized treatment systems that has been discharged into aquatic environments. The 2006 emissions of N₂O from centralized wastewater treatment processes and from effluent were estimated to be 0.3 Tg CO₂ Eq. (1 Gg) and 7.8 Tg CO₂ Eq. (25 Gg), respectively. Total N₂O emissions from domestic wastewater were estimated to be 8.1 Tg CO₂ Eq. (26 Gg). N₂O emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.

Table 8-6: CH₄ and N₂O Emissions from Domestic and Industrial Wastewater Treatment (Tg CO₂ Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH₄	23.0	24.3	24.6	24.2	24.1	23.9	24.0	23.8	23.9
Domestic	16.4	16.9	16.8	16.6	16.5	16.4	16.3	16.2	16.0
Industrial*	6.6	7.4	7.8	7.5	7.6	7.6	7.7	7.6	7.9
N₂O	6.3	6.9	7.6	7.8	7.6	7.7	7.8	8.0	8.1
Domestic	6.3	6.9	7.6	7.8	7.6	7.7	7.8	8.0	8.1
Total	29.3	31.2	32.2	32.0	31.7	31.6	31.8	31.8	32.0

* Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, and starch-based ethanol production industries.
 Note: Totals may not sum due to independent rounding.

⁵Other industrial sectors include organic chemicals, starch production, alcohol refining, creameries, and textiles; however, emissions from these sectors are considered to be insignificant.

Table 8-7: CH₄ and N₂O Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH₄	1,096	1,158	1,173	1,150	1,148	1,140	1,141	1,131	1,136
Domestic	782	804	802	792	786	780	775	770	762
Industrial*	314	355	371	358	362	360	366	361	374
N₂O	20	22	24	25	25	25	25	26	26
Domestic	20	22	24	25	25	25	25	26	26

* Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, and starch-based ethanol production industries.
Note: Totals may not sum due to independent rounding.

Methodology

Domestic Wastewater CH₄ Emission Estimates

Domestic wastewater CH₄ emissions originate from both septic systems and from centralized treatment systems, such as publicly owned treatment works (POTWs). Within these centralized systems, CH₄ emissions can arise from aerobic systems that are not well managed, anaerobic systems (anaerobic lagoons and facultative lagoons), and from anaerobic digesters when the captured biogas is not completely combusted. CH₄ emissions from septic systems were estimated by multiplying the total BOD₅ produced in the United States by the percent of wastewater treated in septic systems (21 percent), the maximum CH₄ producing capacity for domestic wastewater (0.60 kg CH₄/kg BOD), and the CH₄ correction factor (MCF) for septic systems (0.5). CH₄ emissions from POTWs were estimated by multiplying the total BOD₅ produced in the United States by the percent of wastewater treated centrally (79 percent), the relative percentage of wastewater treated by aerobic and anaerobic systems, the relative percentage of wastewater facilities with primary treatment, the percentage of BOD₅ treated after primary treatment (67.5 percent), the maximum CH₄-producing capacity of domestic wastewater (0.6), and the relative MCFs for aerobic (zero or 0.3) and anaerobic (0.8) systems. CH₄ emissions from anaerobic digesters were estimated by multiplying the amount of biogas generated by wastewater sludge treated in anaerobic digesters by the proportion of CH₄ in digester biogas (0.65), the density of CH₄ (662 g CH₄/m³ CH₄), and the destruction efficiency

associated with burning the biogas in an energy/thermal device (0.99).⁶ The methodological equations are:

$$\begin{aligned} \text{Emissions from Septic Systems} &= A \\ &= (\% \text{ onsite}) \times (\text{total BOD}_5 \text{ produced}) \times (B_o) \times \\ &\quad (\text{MCF-septic}) \times 1/10^6 \end{aligned}$$

$$\begin{aligned} \text{Emissions from Centrally Treated Aerobic Systems} &= B \\ &= [(\% \text{ collected}) \times (\text{total BOD}_5 \text{ produced}) \times (\% \text{ aerobic}) \times \\ &\quad (\% \text{ aerobic w/out primary}) + (\% \text{ collected}) \times \\ &\quad (\text{total BOD}_5 \text{ produced}) \times (\% \text{ aerobic}) \times \\ &\quad (\% \text{ aerobic w/primary}) \times \\ &\quad (1-\% \text{ BOD removed in prim. treat.})] \times \\ &\quad (\% \text{ operations not well managed}) \times (B_o) \times \\ &\quad (\text{MCF-aerobic_not_well_man.}) \times 1/10^6 \end{aligned}$$

$$\begin{aligned} \text{Emissions from Centrally Treated Anaerobic Systems} &= C \\ &= [(\% \text{ collected}) \times (\text{total BOD}_5 \text{ produced}) \times \\ &\quad (\% \text{ anaerobic}) \times (\% \text{ anaerobic w/out primary}) + \\ &\quad (\% \text{ collected}) \times (\text{total BOD}_5 \text{ produced}) \times \\ &\quad (\% \text{ anaerobic}) \times (\% \text{ anaerobic w/primary}) \times \\ &\quad (1-\% \text{ BOD removed in prim. treat.})] \times (B_o) \times \\ &\quad (\text{MCF-anaerobic}) \times 1/10^6 \end{aligned}$$

$$\begin{aligned} \text{Emissions from Anaerobic Digesters} &= D \\ &= [(\text{POTW_flow_AD}) \times (\text{digester gas}) / (\text{per capita flow})] \times \\ &\quad \text{conversion to m}^3 \times (\text{FRAC_CH}_4) \times (365.25) \times \\ &\quad (\text{density of CH}_4) \times (1-\text{DE}) \times 1/10^9 \end{aligned}$$

$$\text{Total CH}_4 \text{ Emissions (Gg)} = A + B + C + D$$

where,

$$\% \text{ onsite} = \text{Flow to septic systems/total flow}$$

$$\% \text{ collected} = \text{Flow to POTWs/total flow}$$

⁶Anaerobic digesters at wastewater treatment plants generated 798 Gg CH₄ in 2006, 790 Gg of which was combusted in flares or energy devices (assuming a 99% destruction efficiency).

% aerobic	=	Flow to aerobic systems/total flow to POTWs	digester gas	=	Cubic feet of digester gas produced per person per day (1.0 ft ³ /person/day) (Metcalf and Eddy 1991)
% anaerobic	=	Flow to anaerobic systems/total flow to POTWs	per capita flow	=	Wastewater flow to POTW per person per day (100 gal/person/day)
% aerobic w/out primary	=	Percent of aerobic systems that do not employ primary treatment	conversion to m ³	=	Conversion factor, ft ³ to m ³ (0.0283)
% aerobic w/primary	=	Percent of aerobic systems that employ primary treatment	FRAC_CH ₄	=	Proportion CH ₄ in biogas (0.65)
% BOD removed in prim. treat.	=	32.5 %	density of CH ₄	=	662 (g CH ₄ /m ³ CH ₄)
% operations not well managed	=	Percent of aerobic systems that are not well managed and in which Some anaerobic degradation occurs	1/10 ⁹	=	Conversion factor, g to Gg
% anaerobic w/out primary	=	Percent of anaerobic systems that do not employ primary treatment	U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2007a) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. Table 8-8 presents U.S. population and total BOD ₅ produced for 1990 through 2006. The proportions of domestic wastewater treated onsite versus at centralized treatment plants were based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, and 2005 American Housing Surveys conducted by the U.S. Census Bureau (U.S. Census 2007b), with data for intervening years obtained by linear interpolation. The wastewater flow to aerobic systems and anaerobic systems, and the wastewater flow to POTWs that have anaerobic digesters were obtained from the 1992, 1996, 2000, and 2004 Clean Watershed Needs Survey (EPA 1992, 1996, 2000, and 2004a). ⁷ Data for intervening years were obtained by linear interpolation. The BOD ₅ production rate (0.09 kg/capita/day) for domestic wastewater was obtained from Metcalf and Eddy (1991 and 2003). The CH ₄ emission factor (0.6 kg CH ₄ /kg BOD ₅) and the MCFs were taken from IPCC (2006). The CH ₄ destruction efficiency, 99 percent, was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in <i>AP-42 Compilation of Air Pollutant Emission Factors, Chapter 2.4</i> (EPA 1998), efficiencies used to establish new source performance		
% anaerobic w/primary	=	Percent of anaerobic systems that employ primary treatment			
Total BOD ₅ produced	=	kg BOD/capita/day × U.S. population × 365.25 days/yr			
B ₀	=	Maximum CH ₄ -producing capacity for domestic wastewater (0.60 kg CH ₄ /kg BOD)			
MCF-septic	=	CH ₄ correction factor for septic systems (0.5)			
1/10 ⁶	=	Conversion factor, kg to Gg			
MCF-aerobic_not_well_man.	=	CH ₄ correction factor for aerobic systems that are not well managed (0.3)			
MCF-anaerobic	=	CH ₄ correction factor for anaerobic systems (0.8)			
DE	=	CH ₄ destruction efficiency from flaring or burning in engine (0.99 for enclosed flares)			
POTW_flow_AD	=	Wastewater influent flow to POTWs that have anaerobic digesters (gal)			

⁷ Aerobic and anaerobic treatment were determined based on unit processes in use at the facilities. Because the list of unit processes became more extensive in the 2000 and 2004 surveys, the criteria used to identify aerobic and anaerobic treatment differ slightly across the time series. Once facilities were identified as aerobic or anaerobic, they were separated by whether or not they had anaerobic digestion in place. Once these classifications were determined, the flows associated with facilities in each category were summed.

Table 8-8: U.S. Population (Millions) and Domestic Wastewater BOD₅ Produced (Gg)

Year	Population	BOD ₅
1990	254	8,350
1995	271	8,895
2000	287	9,419
2001	289	9,509
2002	292	9,597
2003	295	9,685
2004	297	9,774
2005	300	9,864
2006	303	9,954

Source: U.S. Census Bureau (2006a); Metcalf & Eddy 1991 and 2003.

standards (NSPS) for landfills, and in recommendations for closed flares used by LMOP. The cubic feet of digester gas produced per person per day (1.0 ft³/person/day) and the proportion of CH₄ in biogas (0.65) come from Metcalf and Eddy (1991). The wastewater flow to a POTW (100 gal/person/day) was taken from the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, “Recommended Standards for Wastewater Facilities (Ten-State Standards)” (2004).

Industrial Wastewater CH₄ Emission Estimates

CH₄ emissions estimates from industrial wastewater were developed according to the methodology described in IPCC (2006). Industry categories that are likely to produce significant CH₄ emissions from wastewater treatment were identified. High volumes of wastewater generated and a high organic wastewater load were the main criteria. The

top four industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; and starch-based ethanol production. Table 8-9 contains production data for these industries.

CH₄ emissions from these categories were estimated by multiplying the annual product output by the average outflow, the organics loading (in COD) in the outflow, the percentage of organic loading assumed to degrade anaerobically, and the emission factor. Ratios of BOD:COD in various industrial wastewaters were obtained from EPA (1997a) and used to estimate COD loadings. The B₀ value used for all industries is the IPCC default value of 0.25 kg CH₄/kg COD (IPCC 2006). The methodological equation is:

$$CH_4 \text{ (industrial wastewater)} = P \times W \times COD \times TA \times B_o \times MCF$$

where,

- CH₄ (industrial wastewater) = Total CH₄ emissions from industrial wastewater (kg/year)
- P = Industry output (metric tons/year)
- W = Wastewater generated (m³/metric ton of product)
- COD = Organics loading in wastewater (kg /m³)
- TA = Percent of wastewater treated anaerobically on site
- B₀ = Maximum CH₄ producing potential of industrial wastewater (default value of 0.25 kg CH₄/kg COD)

Table 8-9: U.S. Pulp and Paper, Meat and Poultry, and Vegetables, Fruits and Juices Production (Tg)

Year	Pulp and Paper	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol
1990	128.9	27.3	14.6	38.7	2.7
1995	140.9	30.8	18.9	46.9	4.2
2000	142.8	32.1	22.2	50.9	4.9
2001	134.3	31.6	22.8	45.0	5.3
2002	132.7	32.7	23.5	47.7	6.4
2003	131.9	32.3	23.7	44.8	8.4
2004	136.4	31.2	24.4	47.8	10.2
2005	131.4	31.4	25.1	43.3	11.7
2006	137.4	32.5	25.5	42.6	14.5

MCF = CH₄ correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically

BOD = BOD concentration in influent (4000 mg/L)

42% = Percent of BOD entering secondary treatment

COD:BOD = COD to BOD ratio (for pulp and paper, COD:BOD = 2)

%TA = estimated percent of wastewater treated anaerobically on site (25%)

B₀ = maximum methane producing capacity (0.25 mg CH₄/mg COD)

MCF = methane conversion factor for anaerobic deep lagoons (0.80)

Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999, Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. In determining the percent that degrades anaerobically, both primary and secondary treatment were considered. In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993b). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993b). However, because the vast majority of primary treatment operations at U.S. pulp and paper mills use mechanical clarifiers, and less than 10 percent of pulp and paper wastewater is managed in primary settling ponds that are not expected to have anaerobic conditions, negligible emissions are assumed to occur during primary treatment.

A time series of CH₄ emissions for 1990 through 2001 was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). Published data from the American Forest and Paper Association, data published by Paper Loop, and other published statistics were used to estimate production for 2002 through 2006 (Pulp and Paper 2005, 2006 and monthly reports from 2003 through 2006; Paper 360° 2007). The overall wastewater outflow was estimated to be 85 m³/metric ton, and the average BOD concentrations in raw wastewater was estimated to be 0.4 g BOD/liter (EPA 1997b, EPA 1993b, World Bank 1999).

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. No anaerobic activity is assumed to occur in activated sludge systems or aerated stabilization basins (note: although IPCC recognizes that some CH₄ can be emitted from anaerobic pockets, they recommend an MCF of zero). However, about 25 percent of the wastewater treatment systems used in the United States are non-aerated stabilization basins. These basins are typically 10 to 25 feet deep. These systems are classified as anaerobic deep lagoons (MCF = 0.8). Therefore, the pulp and paper CH₄ emission calculation is:

The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps and dissolved air flotation when treating wastewater on site. About 33 percent of meat processing operations (EPA 2002) and 25 percent of poultry processing operations (U.S. Poultry 2006) perform on-site treatment in anaerobic lagoons. The IPCC default B₀ of 0.25 kg CH₄/kg COD and default MCF of 0.8 for anaerobic lagoons were used to estimate the CH₄ produced from these on-site treatment systems. Production data, in carcass weight and live weight killed for the meat and poultry industry, were obtained from the USDA Agricultural Statistics Database and the Agricultural Statistics Annual Reports (USDA 2007a). Data collected by EPA's Office of Water provided estimates for wastewater flows into anaerobic lagoons: 5.3 and 12.5 m³/metric ton for meat and poultry production (live weight killed), respectively (EPA 2002). The loadings are 2.8 and 1.5 g BOD/liter for meat and poultry, respectively.

$$\text{Methane} = \text{Production} \times \text{Flow} \times \text{BOD} \times 42\% \times \text{COD:BOD Ratio} \times \%TA \times B_0 \times \text{MCF}$$

where,

Production = metric tons of pulp, paper, and paperboard production

Flow = cubic meters of wastewater generated per ton production

Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling and biological treatment (lagooning). The flows are frequently

seasonal, and robust treatment systems are preferred for on-site treatment. Effluent is suitable for discharge to the sewer. This industry is likely to use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Consequently, 5 percent of these wastewater organics are assumed to degrade anaerobically. The IPCC default B_0 of 0.25 kg CH_4 /kg COD and default MCF of 0.8 for anaerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems. The USDA National Agricultural Statistics Service (USDA 2007a) provided production data for potatoes, other vegetables, citrus fruit, non-citrus fruit, and grapes processed for wine. Outflow and BOD data, presented in Table 8-10, were obtained from EPA (1974) for potato, citrus fruit, and apple processing, and from EPA (1975) for all other sectors.

Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises only about 2 percent of ethanol production, and although the Department of Energy predicts cellulosic ethanol to greatly increase in the coming years, currently it is only in an experimental stage in the United

States. According to the Renewable Fuels Association, 82 percent of ethanol production facilities use corn as the sole feedstock and 7 percent of facilities use a combination of corn and another starch-based feedstock. The fermentation of corn is the principal ethanol production process in the United States and is expected to increase for at least the next 6 years, and potentially more; therefore, emissions associated with wastewater treatment at starch-based ethanol production facilities were estimated (ERG 2006).

Ethanol is produced from corn (or other starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. CH_4 generated in anaerobic digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006).

Available information was compiled from the industry on wastewater generation rates, which ranged from 1.25 gallon per gallon ethanol produced (for dry milling) to 10 gallons per gallon ethanol produced (for wet milling) (Ruocco 2006a,b; Merrick 1998; Donovan 1996; and NRBP 2001). COD concentrations were also found to be about 3 g/L (Ruocco 2006a; Merrick 1998; White and Johnson 2003). The amount of wastewater treated anaerobically was estimated, along with how much of the methane is recovered through the use of biomethanators (ERG 2006). CH_4 emissions were then estimated as follows:

$$\begin{aligned} \text{Methane} = & [\text{Production} \times \text{Flow} \times \text{COD} \times 3.785 \times \\ & \% \text{ TA} \times B_0 \times \text{MCF} \times \% \text{ Not Recovered}] + \\ & [\text{Production} \times \text{Flow} \times 3.785 \times \text{COD} \times \% \text{ TA} \times \\ & B_0 \times \text{MCF} \times (\% \text{ Recovered}) \times (1-DE)] \times 1/10^9 \end{aligned}$$

Table 8-10: Wastewater Flow (m³/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits and Juices Production

Commodity	Wastewater Outflow (m ³ /ton)	BOD (g/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	8.86	0.813
Fruit		
Apples	3.66	1.371
Citrus	10.11	0.317
Non-citrus	12.42	1.204
Grapes (for wine)	2.78	1.831

where,

Production	=	gallons ethanol produced (wet milling or dry milling)
Flow	=	gallons wastewater generated per gallon ethanol produced (1.25 dry milling, 10 wet milling)
COD	=	COD concentration in influent (3 g/l)
3.785	=	conversion, gallons to liters
% TA	=	percent of wastewater treated anaerobically (for dry milling operations, this value is estimated separately for facilities using biomethanators with 100% recovery and facilities using other anaerobic systems)
B ₀	=	maximum methane producing capacity (0.25 g CH ₄ /g COD)
MCF	=	methane conversion factor (0.8 for anaerobic systems)
% Recovered	=	percent of wastewater treated in system with emission recovery
% Not Recovered	=	1 - percent of wastewater treated in system with emission recovery
DE	=	destruction efficiency of recovery system (99%)
1/10 ⁹	=	conversion factor, g to Gg

A time series of CH₄ emissions for 1990 through 2006 was developed based on production data from the Renewable Fuels Association (RFA 2006).

Domestic Wastewater N₂O Emission Estimates

N₂O emissions from domestic wastewater (wastewater treatment) were estimated using the IPCC (2006) methodology, including calculations that take into account N removal with sewage sludge, non-consumption and industrial wastewater N, and emissions from advanced centralized wastewater treatment plants:

- In the United States, a certain amount of N is removed with sewage sludge, which is applied to land, incinerated or landfilled (N_{SLUDGE}). The N disposal into aquatic

environments is reduced to account for the sewage sludge application.⁸

- The IPCC methodology uses annual, per capita protein consumption (kg protein/[person-year]). This number is likely to underestimate the amount of protein entering the sewer or septic system. Food (waste) that is not consumed is often washed down the drain, as a result of the use of garbage disposals. Also, bath and laundry water can be expected to contribute to N loadings. As a result, a factor of 1.4 for non-consumption N is introduced for each year in the Inventory.⁹ Furthermore, a significant quantity of industrial wastewater (N) is co-discharged with domestic wastewater. To account for this, a factor of 1.25 is used.¹⁰
- Small amounts of gaseous nitrogen oxides are formed as byproducts in the conversion of nitrate to N gas in anoxic biological treatment systems. Approximately 7 g N₂O is generated per capita per year if wastewater treatment includes intentional nitrification and denitrification (Scheehle and Doorn 2001) Analysis of the 2000 CWNS shows there are 88 treatment plants in the United States, serving a population of 2.6 million people, with denitrification as one of their unit operations. Based on an emission factor of 7 grams/capita/year, approximately 17.5 metric tons of additional N₂O may have been emitted via denitrification in 2000. Similar analyses were completed for each year in the Inventory using data from CWNS on the amount of wastewater in centralized systems treated in denitrification units. Plants without intentional nitrification/denitrification are assumed to generate 3.2 g N₂O per capita per year.

⁸The methodology for estimating the quantity of sewage sludge N not entering aquatic environments is described in Annex 3.11.

⁹Metcalf & Eddy (1991) provide a typical influent nitrogen concentration of 40 mg/L Total Kjeldahl Nitrogen (TKN) for average wastewater from residences, which includes bathwater, laundry, and the use of garbage disposals. The factor for non-consumptive protein was estimated based on wastewater treated in 1990, the percent of population serviced by centralized treatment systems, and the per capita TKN loading, resulting in a factor of 1.4.

¹⁰The type, composition, and quantity of this co-discharged wastewater vary greatly between municipalities. Metcalf & Eddy (1991) provide a range of influent nitrogen concentrations of 20 to 85 mg/L TKN (average 55) for combined residential and industrial wastewater, while residential wastewater loading was roughly estimated at 40 mg TKN/L (see previous footnote). Until better data become available, the amount of N in wastewater is increased by 10 mg/L to account for industrial co-discharge (factor of 1.25).

With the modifications described above, N₂O emissions from domestic wastewater were estimated using the following methodology:

$$N_2O_{TOTAL} = N_2O_{PLANT} + N_2O_{EFFLUENT}$$

$$N_2O_{PLANT} = N_2O_{NIT/DENIT} + N_2O_{WOUT\ NIT/DENIT}$$

$$N_2O_{NIT/DENIT} = [(US_{POPND}) \times EF_2 \times F_{IND-COM}] \times 1/10^9$$

$$N_2O_{WOUT\ NIT/DENIT} = \{[(US_{POP} \times WWTP) - US_{POPND} \times F_{IND-COM}] \times EF_1\} \times 1/10^9$$

$$N_2O_{EFFLUENT} = \{[(US_{POP} \times Protein \times F_{NPR} \times F_{NON-CON} \times F_{IND-COM}) - N_{SLUDGE}] \times EF_3 \times 44/28\} \times 1/10^6$$

where,

- N₂O_{TOTAL} = Annual emissions of N₂O (kg)
- N₂O_{PLANT} = N₂O emissions from centralized wastewater treatment plants (kg)
- N₂O_{NIT/DENIT} = N₂O emissions from centralized wastewater treatment plants with nitrification/denitrification (kg)
- N₂O_{WOUT NIT/DENIT} = N₂O emissions from centralized wastewater treatment plants without nitrification/denitrification (kg)
- N₂O_{EFFLUENT} = N₂O emissions from wastewater effluent discharged to aquatic environments (kg)
- US_{POP} = U.S. population
- US_{POPND} = U.S. population that is served by biological denitrification (from CWNS)
- WWTP = Fraction of population using WWTP (as opposed to septic systems)
- EF₁ = Emission factor (3.2 g N₂O/person-year)
- EF₂ = Emission factor (7 g N₂O/person-year)
- Protein = Annual per capita protein consumption (kg/person/year)
- F_{NPR} = Fraction of N in protein, default = 0.16 (kg N/kg protein)
- F_{NON-CON} = Factor for non-consumed protein added to wastewater (1.4)

- F_{IND-COM} = Factor for industrial and commercial co-discharged protein into the sewer system (1.25)
- N_{SLUDGE} = N removed with sludge, kg N/yr
- EF₃ = Emission factor (0.005 kg N₂O-N/kg sewage-N produced)
- 44/28 = Molecular weight ratio of N₂O to N₂

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2007a) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. The fraction of the U.S. population using wastewater treatment plants is based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, and 2005 American Housing Survey (U.S. Census 2007b). Data for intervening years were obtained by linear interpolation. The emission factor (EF₁) to estimate emissions from wastewater treatment was taken from IPCC (2006). Data on annual per capita protein intake were provided by U.S. Department of Agriculture Economic Research Service (ERS 2006b). Protein consumption data for 2005 and 2006 were extrapolated from data for 1990 through 2004. Table 8-11 presents the data for U.S. population and average protein intake. An emission factor to estimate emissions from effluent (EF₃) has not been specifically estimated for the United States, thus the default IPCC value (0.005 kg N₂O-N/kg sewage-N produced) was applied. The fraction of N in protein (0.16 kg N/kg protein) was also obtained from IPCC (2006). Sludge generation was obtained from

Table 8-11: U.S. Population (Millions) and Average Protein Intake [kg/(person-year)]

Year	Population	Protein
1990	254	38.7
1995	271	39.8
2000	287	41.3
2001	289	42.0
2002	292	40.9
2003	295	40.9
2004	297	41.3
2005	300	41.7
2006	303	41.9

Source: U.S. Census Bureau 2006a, USDA ERS 2006b.

EPA (1999) for 1988, 1996, and 1998 and from Beecher et al. (2007) for 2004. Intervening years were interpolated, and estimates for 2005 and 2006 were forecasted from the rest of the time series. An estimate for the N removed as sludge (N_{SLUDGE}) was obtained by determining the amount of sludge disposed by incineration, by land application (agriculture or other), through surface disposal, in landfills, or through ocean dumping. In 2006, 263 Tg N was removed with sludge.

Uncertainty

The overall uncertainty associated with both the 2006 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the IPCC *Good Practice Guidance Tier 2* methodology (2000). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater, and wastewater from pulp and paper production, meat and poultry processing, fruits and vegetable processing, and ethanol production. Uncertainty associated with the parameters used to estimate N_2O emissions include that of sewage sludge disposal, total U.S. population, average protein consumed per person, fraction of N in protein, non-consumption N factor, emission factors per capita and per mass of sewage-N, and for the percentage of total population using centralized wastewater treatment plants.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 8-12. CH_4 emissions from wastewater treatment were estimated to be between 15.0 and 35.2 Tg CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 37 percent below to 48 percent above the 2006 emissions estimate of 23.9 Tg CO_2 Eq. N_2O emissions from wastewater treatment were estimated to be

between 1.8 and 16.2 Tg CO_2 Eq., which indicates a range of approximately 78 percent below to 100 percent above the actual 2006 emissions estimate of 8.1 Tg CO_2 Eq.

QA/QC and Verification

A QA/QC analysis was performed on activity data, documentation, and emission calculations. This effort included a Tier 1 analysis, including the following checks:

- Checked for transcription errors in data input;
- Ensured references were specified for all activity data used in the calculations;
- Checked a sample of each emission calculation used for the source category;
- Checked that parameter and emission units were correctly recorded and that appropriate conversion factors were used;
- Checked for temporal consistency in time series input data for each portion of the source category;
- Confirmed that estimates were calculated and reported for all portions of the source category and for all years;
- Investigated data gaps that affected emissions estimates trends; and
- Compared estimates to previous estimates to identify significant changes.

All transcription errors identified were corrected. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

Recalculations Discussion

The 2006 estimates for CH_4 emissions from domestic wastewater include one major methodological refinement

Table 8-12: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Wastewater Treatment (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate ^a			
			Lower Bound	Upper Bound	Lower Bound (%)	Upper Bound (%)
Wastewater Treatment	CH_4	23.9	15.0	35.2	-37%	+48%
Domestic	CH_4	16.0	7.9	26.6	-51%	+66%
Industrial	CH_4	7.9	4.5	12.8	-43%	+62%
Domestic Wastewater Treatment	N_2O	8.1	1.8	16.2	-78%	+100%

^a Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

and one major data change. First, for centralized wastewater treatment systems, CH₄ emissions were estimated based on the total BOD₅ available for biological treatment rather than the total BOD₅ entering wastewater treatment plants. Metcalf and Eddy (1991) estimate that 25–40 percent of BOD₅ at aerobic and anaerobic plants is removed through primary sedimentation, meaning that not all of the BOD₅ entering treatment plants has the potential to generate methane during biological treatment. This change resulted in a decrease of methane emissions from centrally treated anaerobic systems of 20 percent, and an overall reduction in methane emissions of 4.5 to 5.5 percent. The major data adjustment for the current Inventory estimates involved the adjustment of the 1995 AHS data (US Census Bureau 2007b) that indicates the percent of wastewater treated onsite versus the percent collected. The previous Inventory indicated a total percent of wastewater treated onsite and collected of 97.6 percent for 1995, while all other years had a total of approximately 99.5 percent. Reevaluation of the 1995 AHS data resulted in an updated total percent of 99.5 percent.

For industrial wastewater, the 2006 estimates include a change in calculation methodology for pulp and paper, and the inclusion of wastewater emissions from U.S. starch-based ethanol production. First, the types of primary treatment in place at pulp and paper operations were evaluated and it was concluded that due to the majority of operations using mechanical clarifiers, negligible emissions of CH₄ occur during primary treatment. The estimate of BOD treated anaerobically during secondary treatment was also updated based on the number of operations expected to have non-aerated stabilization basins. These systems were reclassified as anaerobic deep lagoons, and CH₄ emissions were revised. These changes resulted in a decrease in emissions from pulp and paper wastewater treatment of 18.5 percent across the time series.

Next, emissions associated with ethanol production were estimated, as described earlier. The addition of this industrial sector increased industrial wastewater emission estimates by 0.4 to 0.9 percent across the time series.

Flow and BOD data for fruits and vegetable processing wastewater were updated to reflect commodity-specific data, which had minimal impact on the emissions. Overall, the CH₄ emission estimates for wastewater treatment are on average 6 percent lower than the previous Inventory.

For N₂O emissions from domestic wastewater, one major data source adjustment was made along with two minor changes to account for co-discharged industrial and commercial wastewater and to update the values used for the nitrogen composition of sludge. The current Inventory utilizes protein consumption data from the U.S. Department of Agriculture Economic Research Service (USDA 2006b). The previous Inventory report used UN FAO protein consumption data. The protein data changed on average approximately one percent for each year in the time series. The current Inventory estimates also apply a factor for co-discharged industrial and commercial wastewater to the emission factors for direct N₂O emissions from centralized wastewater treatment plants. This resulted in a N₂O emission factor from centralized treatment plants that have intentional nitrification/denitrification unit operations of 8.75 g N₂O/person-year (7 g N₂O/person-year × 1.25) and a N₂O emission factor from centralized wastewater treatment plants that do not have intentional nitrification/denitrification unit operations of 4 g N₂O/person-year (3.2 g N₂O/person-year × 1.25). In addition, the nitrogen composition of sludge was updated to 3.9 percent, representing an average N composition, rather than the previous value of 3.3 percent which represented a median value. The sludge generation estimates across the time series changed slightly based on the inclusion of a new reference for sludge generation in 2004.

Overall, emissions from wastewater treatment and discharge (CH₄ and N₂O) decreased by an average of approximately 5 percent from the previous Inventory.

Planned Improvements Discussion

The methodology to estimate CH₄ emissions from domestic wastewater treatment currently utilizes estimates for the percentage of centrally treated wastewater that is treated by aerobic systems and anaerobic systems. These data come from the 1992, 1996, 2000, and 2004 CWNS. The designation of systems as aerobic or anaerobic could be further refined to differentiate aerobic systems with the potential to generate small amounts of CH₄ (aerobic lagoons) versus other types of aerobic systems, and to differentiate between anaerobic systems to allow for the use of different MCFs for different types of anaerobic treatment systems. Currently it is assumed that all aerobic systems are well managed and produce no CH₄, and that all anaerobic systems have an MCF of 0.8. Efforts to obtain better data reflecting

emissions from various types of municipal treatment systems are currently being pursued.

Available data on wastewater treatment emissions at petroleum refineries will be reviewed to determine if this is a significant source to be included in future versions of the Inventory.

With respect to estimating N₂O emissions, the default emission factor for N₂O from wastewater effluent has a high uncertainty. The IPCC recently updated this factor; however, future research may identify new studies that include updated data. The factor that accounts for non-sewage nitrogen in wastewater (bath, laundry, kitchen, industrial components) also has a high uncertainty. Obtaining data on the changes in average influent nitrogen concentrations to centralized treatment systems over the time series would improve the estimate of total N entering the system, which would reduce or eliminate the need for other factors for non-consumed protein or industrial flow. In addition there is uncertainty associated with the N₂O emission factors for direct emissions from centralized wastewater treatment facilities. Efforts to gain greater confidence in these emission factors are currently being pursued.

8.3. Composting (IPCC Source Category 6D)

Composting of organic waste, such as food waste, garden (yard) and park waste and sludge, is common in the United States. Advantages of composting include reduced volume in the waste material, stabilization of the waste, and destruction of pathogens in the waste material. The end products of composting, depending on its quality, can be recycled as fertilizer and soil amendment, or be disposed in a landfill.

Composting is an aerobic process and a large fraction of the degradable organic carbon in the waste material is converted into carbon dioxide (CO₂). Methane (CH₄) is formed in anaerobic sections of the compost, but it is oxidized to a large extent in the aerobic sections of the compost. Anaerobic sections are created in composting piles when there is excessive moisture or inadequate aeration (or mixing) of the compost pile. The estimated CH₄ released into the atmosphere ranges from less than 1 percent to a few per cent of the initial carbon content in the material (IPCC 2006). Composting can also produce emissions of nitrous oxide (N₂O). The range of the estimated emissions varies from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006).

From 1990 to 2006, the amount of material composted in the United States has increased from 3,810 Gg to 18,852 Gg, an increase of almost 400 percent. Emissions of CH₄ and N₂O from composting have increased by the same percentage (see Table 8-13 and Table 8-14). In 2006, CH₄ emissions from composting were 1.6 Tg CO₂ Eq. (75 Gg), and N₂O emissions from composting were 1.8 Tg CO₂ Eq. (6 Gg). The wastes that are composted include primarily yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from residences and commercial establishments (such as grocery stores, restaurants, and school and factory cafeterias). The composting waste quantities reported here do not include backyard composting. The growth in composting is attributable primarily to two factors: (1) steady growth in population and residential housing and (2) state and local governments started enacting legislation that discouraged the disposal of yard trimmings in landfills. In 1992, 11 states and the District of Columbia had legislation in effect that banned or discouraged disposal of yard trimmings in landfills. In

Table 8-13: CH₄ and N₂O Emissions from Composting (Tg CO₂ Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH ₄	0.3	0.7	1.3	1.3	1.3	1.5	1.6	1.6	1.6
N ₂ O	0.4	0.8	1.4	1.4	1.4	1.6	1.7	1.7	1.8
Total	0.7	1.5	2.6	2.7	2.7	3.1	3.3	3.3	3.3

Table 8-14: CH₄ and N₂O Emissions from Composting (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH ₄	15	35	60	60	61	69	74	75	75
N ₂ O	1	3	4	5	5	5	6	6	6

2005, 21 states and the District of Columbia, representing about 50 percent of the nation’s population, had enacted such legislation (EPA 2006).

Methodology

CH₄ and N₂O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content and aeration during the process.

The emissions shown in Table 8-13 and Table 8-14 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006), which is the product of an emission factor and the mass of organic waste composted (note: no CH₄ recovery is expected to occur at composting operations):

$$E_i = M \times EF_i$$

where,

- E_i = CH₄ or N₂O emissions from composting, Gg CH₄ or N₂O,
- M = mass of organic waste composted in Gg,
- EF_i = emission factor for composting, 4 g CH₄/kg of waste treated (wet basis) and 0.3 g N₂O/kg of waste treated (wet basis), and
- i = designates either CH₄ or N₂O.

Estimates of the quantity of waste composted (M) are presented in Table 8-15. Estimates of the quantity composted for 1990, 1995, 2001, and 2002 were taken from EPA’s

Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2003 (EPA 2005); estimates of the quantity composted for 2003 through 2005 were taken from EPA’s *Municipal Solid Waste In The United States: 2005 Facts and Figures* (EPA 2006). The quantity composted estimate for 2006 was taken from the “2006 MSW Characterization Data Tables” associated with EPA’s *Municipal Solid Waste In The United States: 2006 Facts and Figures* (EPA 2007).

Uncertainty

The estimated uncertainty from the 2006 IPCC Guidelines is ±50 percent for the Tier 1 methodology. Emissions from composting in 2006 were estimated to be between 1.7 and 5.0 Tg CO₂ Eq., which indicates a range of 50 percent below to 50 percent above the actual 2006 emission estimate of 3.3 Tg CO₂ Eq. (see Table 8-16).

Recalculations Discussion

No recalculations were performed because this is the first year that composting has been included in the Inventory.

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of CH₄ and N₂O emissions from composting. For example, a literature search may be conducted to determine if emission factors specific to various composting systems and composted materials are available.

Table 8-15: U.S. Waste Composted (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Waste Composted	3,810	8,682	14,923	15,014	15,187	17,309	18,570	18,643	18,852

Source: EPA 2005, EPA 2006, and EPA 2007.

Table 8-16: Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (Tg CO₂ Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO ₂ Eq.) (%)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH ₄ , N ₂ O	3.3	1.7	5.0	-50%	+50%

8.4. Waste Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of indirect greenhouse gas emissions. Total emissions of NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2006 are provided in Table 8-17.

Methodology

These emission estimates were obtained from preliminary data (EPA 2008), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. Emission estimates of these gases were provided by sector, using a “top down” estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions.

National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which relate the quantity of emissions to the activity. Emission factors are generally available from the EPA’s Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty

No quantitative estimates of uncertainty were calculated for this source category. Uncertainties in these estimates, however, are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

Table 8-17: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
NO_x	+	1	2						
Landfills	+	1	2	2	2	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+	+	+	+
Miscellaneous ^a	+	1	+	+	+	+	+	+	+
CO	1	2	8	8	7	7	7	7	7
Landfills	1	2	7	7	6	6	6	6	6
Wastewater Treatment	+	+	1	1	+	+	+	+	+
Miscellaneous ^a	+	1	+	+	+	+	+	+	+
NMVOCs	673	731	119	122	115	114	112	111	110
Wastewater Treatment	57	61	23	23	22	22	21	21	21
Miscellaneous ^a	557	602	51	53	50	49	48	48	47
Landfills	58	68	46	46	44	43	43	42	42

^a Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.
 Note: Totals may not sum due to independent rounding.
 + Does not exceed 0.5 Gg.