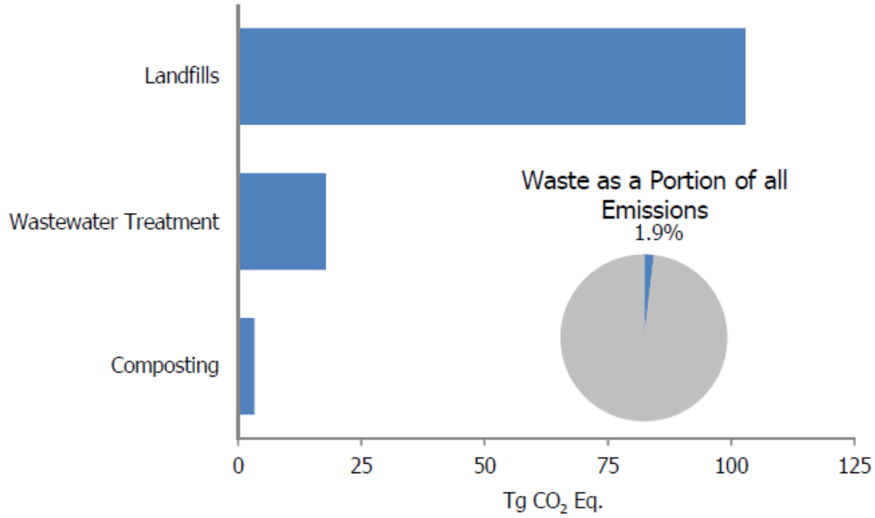
8. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 8-1). Landfills accounted for approximately 18.1 percent of total U.S. anthropogenic methane (CH_4) emissions in 2012, the third largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and composting of organic waste accounted for approximately 2.2 percent and less than 1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N_2O emissions from the treatment process itself. N_2O emissions from composting were also estimated. Together, these waste activities account for less than 2 percent of total U.S. N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 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.

Figure 8-1: 2012 Waste Chapter Greenhouse Gas Sources



Box 8-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report and this chapter, are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on

Climate Change (IPCC).[243] Additionally, the calculated emissions and sinks in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[244] The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this inventory report are comparable to emissions and sinks reported by other countries. Emissions and sinks provided in this inventory do not preclude alternative examinations,[245] but rather this inventory presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

Overall, in 2012, waste activities generated emissions of 124.0 Tg CO_2 Eq., or just under 2 percent of total U.S. greenhouse gas emissions.

Table 8-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	2005	2008	2009	2010	2011	2012
CH_4	**161.2**	**127.0**	**129.3**	**130.0**	**124.5**	**121.8**	**117.2**
Landfills	147.8	112.1	114.3	115.3	109.9	107.4	102.8
Wastewater Treatment	13.2	13.3	13.3	13.1	13.0	12.8	12.8
Composting	0.3	1.6	1.7	1.6	1.5	1.6	1.6
N_2O	**3.8**	**6.2**	**6.6**	**6.6**	**6.6**	**6.7**	**6.8**
Domestic Wastewater Treatment	3.5	4.5	4.8	4.8	4.9	5.0	5.0
Composting	0.4	1.7	1.9	1.8	1.7	1.7	1.8
Total	**165.0**	**133.2**	**136.0**	**136.5**	**131.1**	**128.5**	**124.0**

Note: Totals may not sum due to independent rounding.

Table 8-2: Emissions from Waste (Gg)

Gas/Source	1990	2005	2008	2009	2010	2011	2012
CH_4	**7,678**	**6,048**	**6,159**	**6,190**	**5,926**	**5,798**	**5,580**
Landfills	7,036	5,339	5,444	5,492	5,234	5,112	4,897
Wastewater Treatment	626	635	635	623	619	611	608
Composting	15	75	80	75	73	75	76
N_2O	**12**	**20**	**21**	**21**	**21**	**22**	**22**
Domestic Wastewater Treatment	11	14	15	16	16	16	16
Composting	1	6	6	6	5	6	6

Note: Totals may not sum due to independent rounding.

Carbon dioxide, CH_4, and N_2O emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States

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[243] See <http://www.ipcc-nggip.iges.or.jp/public/index.html>.

[244] See <http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/5270.php>.

[245] For example, see <http://www.epa.gov/aboutepa/oswer.html>.

in 2012 resulted in 12.6 Tg CO_2 Eq. emissions, more than half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 3.3.

Methodological guidance for this chapter was taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. This latest guidance from the IPCC best represents the understanding of emissions profiles from activities in the waste sector. The use of the most recently published calculation methodologies by the IPCC, as contained in the 2006 IPCC Guidelines for waste source categories, is fully in line with the *IPCC Good Practice Guidance* for methodological choice to improve rigor and accuracy. In addition, the improvements in using the latest methodological guidance from the IPCC has been recognized by the UNFCCC's Subsidiary Body for Scientific and Technological Advice in the conclusions of its 30th Session.[246] Numerous U.S. inventory experts were involved in the development of the 2006 IPCC Guidelines, and their expertise has provided this latest guidance from the IPCC with the most appropriate calculation methods that are then used in this chapter.

Box 8-2: Waste Data from the Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. EPA published a rule for the mandatory reporting of greenhouse gases from large GHG emissions sources in the United States. Implementation of 40 CFR Part 98 is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP). 40 CFR part 98 applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by 41 industrial categories. Reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year.

EPA's GHGRP dataset and the data presented in this inventory report are complementary and, as indicated in the respective planned improvements sections for source categories in this chapter, EPA is analyzing how to use facility-level GHGRP data to improve the national estimates presented in this inventory. Most methodologies used in EPA's GHGRP are consistent with IPCC, though for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards. This may differ with the more aggregated data collected for the inventory to estimate total, national U.S. emissions. It should be noted that the definitions for source categories in the GHGRP may differ from those used in this inventory in meeting the UNFCCC reporting guidelines. In line with the UNFCCC reporting guidelines, the inventory report is a comprehensive accounting of all emissions from source categories identified in the IPCC guidelines. Further information on the reporting categorizations in EPA's GHGRP and specific data caveats associated with monitoring methods in EPA's GHGRP has been provided on the EPA's GHGRP website.[247]

EPA presents the data collected by EPA's GHGRP through a data publication tool[248] that allows data to be viewed in several formats including maps, tables, charts and graphs for individual facilities or groups of facilities.

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[246] These Subsidiary Body for Scientific and Technological Advice (SBSTA) conclusions state, "The SBSTA acknowledged that the 2006 IPCC Guidelines contain the most recent scientific methodologies available to estimate emissions by sources and removals by sinks of greenhouse gases (GHGs) not controlled by the Montreal Protocol, and recognized that Parties have gained experience with the 2006 IPCC Guidelines. The SBSTA also acknowledged that the information contained in the 2006 IPCC Guidelines enables Parties to further improve the quality of their GHG inventories." See <http://unfccc.int/resource/docs/2009/sbsta/eng/03.pdf>

[247] See <http://www.ccdsupport.com/confluence/display/ghgp/Detailed+Description+of+Data+for+Certain+Sources+and+Processes>.

[248] See <http://ghgdata.epa.gov>.

8.1 Landfills (IPCC Source Category 6A1)

In the United States, solid waste is managed by landfilling, recovery through recycling or composting, and combustion through waste-to-energy facilities. Disposing of solid waste in modern, managed landfills is the most commonly used waste management technique in the United States. More information on how solid waste data are collected and managed in the United States is provided in Box 8-1 and Box 8-2. The municipal solid waste (MSW) and industrial waste landfills referred to in this section are all modern landfills that must comply with a variety of regulations as discussed in Box 8-3. Disposing of waste in illegal dumping sites is not considered to have occurred in years later than 1980 and these sites are not considered to contribute to net emissions in this section for the inventory time frame of 1990 to 2012. MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil; many have environmental monitoring systems to track performance, collect leachate, and collect landfill gas. Industrial waste landfills are constructed in a similar way as MSW landfills, but accept waste produced by industrial activity, such as factories, mills, and mines.

After being placed in a landfill, organic 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 methane (CH_4) producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO_2) and 50 percent CH_4, by volume. Landfill biogas also contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition by-products or volatilization of biodegradable wastes (EPA 2008).

Methane and CO_2 are the primary constituents of landfill gas generation and emissions. However, the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines set an international convention to not report biogenic CO_2 released due to landfill decomposition in the Waste sector (IPCC 2006). Carbon dioxide emissions from landfills are estimated and reported for under the Land Use/Land Use Change and Forestry (LULUCF) sector (see Box 8-4). Additionally, emissions of NMOC and VOC are not estimated because they are considered to be emitted in trace amounts. Nitrous oxide (N_2O) emissions from the disposal and application of sewage sludge on landfills are also not explicitly modeled as part of greenhouse gas emissions from landfills. N_2O emissions from sewage sludge applied to landfills as a daily cover or for disposal are expected to be relatively small because the microbial environment in an anaerobic landfill is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the 2006 IPCC Guidelines (IPCC 2006) did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, only CH_4 generation and emissions are estimated for landfills under the Waste sector.

Methane generation and emissions from landfills are a function of several factors, including: (1) the total amount of waste-in-place, which is the total waste landfilled annually over the operational lifetime of a landfill; (2) the characteristics of the landfill receiving waste (e.g., composition of waste-in-place, size, climate, cover material); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized as the landfill gas passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills practice similar operating practices, including the application of a daily and intermediate cover material over the waste being disposed of in the landfill to prevent odor and reduce risks to public health. Based on recent literature, the specific type of cover material used can affect the rate of oxidation of landfill gas (RTI 2011). The most commonly used cover materials are soil, clay, and sand. Some states also permit the use of green waste, tarps, waste derived materials, sewage sludge or biosolids, and contaminated soil as a daily cover. Methane production typically begins one or two years after waste is disposed of in a landfill and will continue for 10 to 60 years or longer as the degradable waste decomposes over time.

In 2012, landfill CH_4 emissions were approximately 102.8 Tg CO_2 Eq. (4,897 Gg), representing the third largest source of CH_4 emissions in the United States, behind natural gas systems and enteric fermentation. Emissions from MSW landfills, which received about 69 percent of the total solid waste generated in the United States, accounted for about 95 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 1,900 to 2,000 operational MSW landfills exist in the United States, with the largest landfills receiving most of the waste and generating the majority of the CH_4 emitted (EPA 2010; *BioCycle* 2010; WBJ 2010). Conversely, there are approximately 3,200 MSW landfills in the United States that have been closed since 1980 (for which a closure data is known, WBJ 2010). While the number of active MSW landfills has decreased significantly over the past 20 years, from approximately 6,326 in 1990 to approximately 2,000 in 2010, the average landfill size has increased (EPA 2010; *BioCycle* 2010; WBJ 2010). The exact number of active and closed dedicated industrial waste landfills is not known at this time, but the Waste Business Journal total for landfills accepting industrial and construction and demolition debris for 2010 is 1,305 (WBJ 2010). Conversely, only 176 facilities with industrial waste landfills reported under subpart TT (Industrial Waste Landfills) of EPA's GHGRP in 2011 and 2012, indicating that there may be several hundreds of industrial waste landfills that are not required to report under EPA's GHGRP, or that the actual number of industrial waste landfills in the United States is relatively low compared to MSW landfills.

The estimated annual quantity of waste placed in MSW landfills increased 26 percent from approximately 205 Tg in 1990 to 284 Tg in 2012 (see Annex 3.14). The annual amount of waste generated and subsequently disposed in MSW landfills varies annually and depends on several factors (e.g., the economy, consumer patterns, recycling and composting programs, inclusion in a garbage collection service). The total amount of MSW generated is expected to increase as the U.S. population continues to grow. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices.

Net CH_4 emissions have fluctuated from year to year, but a slowly decreasing trend has been observed over the past decade despite increased waste disposal amounts. For example, from 1990 to 2012, net CH_4 emissions from landfills decreased by approximately 30 percent (see Table 8-3 and Table 8-4). This decreasing trend can be attributed to a 21 percent reduction in the amount of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time series (EPA 2010) and an increase in the amount of landfill gas collected and combusted (i.e., used for energy or flared) at MSW landfills, resulting in lower net CH_4 emissions from MSW landfills.[249] For instance, in 1990, approximately 954 Gg of CH_4 were recovered and combusted from landfills, while in 2012, approximately 8,648 Gg of CH_4 were combusted, representing an average annual increase in the quantity of CH_4 recovered and combusted at MSW landfills from 1990 to 2012 of 11 percent (see Annex 3.14). Landfill gas collection and control is not accounted for at industrial waste landfills in the solid waste emissions inventory (see the Methodology discussion for more information).

The quantity of recovered CH_4 that is either flared or used for energy purposes at MSW landfills has continually increased as a result of 1996 federal regulations that require large MSW 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 that encourage CH_4 recovery and beneficial reuse, 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), have also contributed to increased interest in landfill gas collection and control. In 2012, an estimated 67 new landfill gas-to-energy (LFGTE) projects and 3 new flares began operation (EPA 2012). While the amount of landfill gas collected and combusted continues to increase every year, the rate of increase in collection and combustion no longer exceeds the rate of additional CH_4 generation from the amount of organic MSW landfilled as the U.S. population grows.

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[249] Due to a lack of data specific to industrial waste landfills, landfill gas recovery is only estimated for MSW landfills.

Table 8-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	1990	2005	2008	2009	2010	2011	2012
MSW Landfills	172.6	240.8	260.0	265.1	270.1	275.1	280.0
Industrial Landfills	11.6	15.4	15.7	15.8	15.9	15.9	15.9
Recovered							
Gas-to-Energy	(13.3)	(55.9)	(67.2)	(74.2)	(82.5)	(88.0)	(96.8)
Flared	(6.7)	(75.7)	(81.5)	(78.6)	(81.4)	(83.7)	(84.8)
Oxidized	(16.4)	(12.5)	(12.7)	(12.8)	(12.2)	(11.9)	(11.4)
Total	**147.8**	**112.1**	**114.3**	**115.3**	**109.9**	**107.4**	**102.8**

Table 8-4: CH_4 Emissions from Landfills (Gg)

Activity	1990	2005	2008	2009	2010	2011	2012
MSW Landfills	8,219	11,466	12,380	12,623	12,863	13,099	13,331
Industrial Landfills	553	732	748	753	756	758	758
Recovered							
Gas-to-Energy	(634)	(2,660)	(3,198)	(3,532)	(3,927)	(4,190)	(4,608)
Flared	(321)	(3,606)	(3,880)	(3,743)	(3,876)	(3,986)	(4,040)
Oxidized	(782)	(593)	(605)	(610)	(582)	(568)	(544)
Total	**7,036**	**5,339**	**5,444**	**5,492**	**5,234**	**5,112**	**4,897**

Methodology

CH_4 emissions from landfills were estimated as the CH_4 produced from MSW landfills, plus the CH_4 produced by industrial waste landfills, minus the CH_4 recovered and combusted from MSW landfills, minus the CH_4 oxidized before being released into the atmosphere:

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

where,

$CH_{4,\text{Solid Waste}}$ = CH_4 emissions from solid waste
$CH_{4,\text{MSW}}$ = CH_4 generation from MSW landfills,
$CH_{4,\text{Ind}}$ = CH_4 generation from industrial landfills,
R = CH_4 recovered and combusted (only for MSW landfills), and
Ox = CH_4 oxidized from MSW and industrial waste landfills before release to the atmosphere.

The methodology for estimating CH_4 emissions from landfills is based on the first order decay model described by the IPCC (IPCC 2006). Methane generation is based on nationwide waste disposal data; it is not landfill-specific. The amount of CH_4 recovered, however, is landfill-specific, but only for MSW landfills due to a lack of data specific to industrial waste landfills. Values for the CH_4 generation potential (L_0) and decay rate constant (k) used in the first order decay model were obtained from an analysis of CH_4 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 decay rate constant was found to increase with average annual rainfall; consequently, values of k were developed for 3 ranges of rainfall, or climate types (wet, arid, and temperate). 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. Historical census data were used to account for the shift in population to more arid areas over time. An overview of the data sources and methodology used to calculate CH_4 generation and recovery is provided below, while a more detailed description of the methodology used to estimate CH_4 emissions from landfills can be found in Annex 3.14.

States and local municipalities across the United States do not consistently track and report quantities of collected waste or their end-of-life disposal methods to a centralized system. Therefore, national MSW landfill waste generation and disposal data are obtained from the *BioCycle* State of Garbage surveys, published approximately every two years, with the most recent publication date of 2010. The State of Garbage (SOG) survey is the only continually updated nationwide survey of waste disposed in landfills in the United States and is the primary data source with which to estimate CH_4 emissions from MSW landfills. The SOG surveys use the principles of mass balance where all MSW generated is equal to the amount of MSW landfilled, combusted in waste-to-energy plants, composted, and/or recycled (*BioCycle* 2010). This approach assumes that all waste management methods are tracked and reported to state agencies. Survey respondents are asked to provide a breakdown of MSW generated and managed by landfilling, recycling, composting, and combustion (in waste-to-energy facilities) in actual tonnages as opposed to reporting a percent generated under each waste disposal option. The data reported through the survey are adjusted to exclude non-MSW materials (e.g., industrial and agricultural wastes, construction and demolition debris, automobile scrap, and sludge from wastewater treatment plants) that may be included in survey responses. All state disposal data are adjusted for imports and exports where imported waste is included in a particular state's total while exported waste is not. Methodological changes have occurred over the time that the SOG survey has been published, and this has affected the fluctuating trends observed in the data (RTI 2013).

The SOG survey is voluntary and not all states provide data for each survey year. Where no waste generation data are provided by a state in the SOG survey, the amount generated is estimated using one of the following methods: the waste per capita from a previous SOG survey is multiplied by that particular state's population, or the average nationwide waste per capita rate is multiplied by that particular state's population. The quantities of waste generated across all states are summed and that value is then used as the nationwide quantity of waste generated in a given reporting year.

State-specific landfill waste generation data and a national average disposal factor for 1989 through 2008 were obtained from the SOG survey for every two years (i.e., 2002, 2004, 2006, and 2008 as published in BioCycle 2006, 2008, and 2010). State-specific landfill waste generation data for the years in-between the SOG surveys (e.g., 2001, 2003, 2005, 2007, 2009, 2010, 2011, and 2012) were extrapolated based on the SOG data and the U.S. Census population data. The most recent SOG survey was published in 2010 for the 2008 year; therefore, the annual quantities of waste generated for the years through 2012 were determined based on the 2010 data and population growth. Waste generation data will be updated as new reports are published. Because the SOG survey 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 (2009, 2013) and national per capita solid waste generation from the SOG survey (2010).

Estimates of the quantity of waste landfilled from 1989 to the current inventory year are determined by applying a waste disposal factor to the total amount of waste generated (i.e., the SOG data). A waste disposal factor is determined for each year an SOG survey is published and equals the ratio of the total amount of waste landfilled to the total amount of waste generated. The waste disposal factor is interpolated for the years in-between the SOG surveys, as is done for the amount of waste generated for a given survey year.

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 (Methane Conversion Factor, MCF, of 1) and those disposed in dumps (MCF of 0.6). All calculations after 1980 assume waste is disposed in managed, modern landfills. Please see Annex 3.14 for more details.

Methane recovery is currently only accounted for at MSW landfills. Data collected through EPA's GHGRP for industrial waste landfills (subpart TT) show that only 2 of the 176 facilities, or 1 percent of facilities, reporting in the 2012 reporting year have active gas collection systems. EPA's GHGRP is not a national database and no comprehensive data regarding gas collection systems have been published for industrial waste landfills. Assumptions regarding a percentage of landfill gas collection systems, or a total annual amount of landfill gas collected for the non-reporting industrial waste landfills, have not been made for the inventory methodology.

The estimated landfill gas recovered per year at MSW landfills was based on a combination of three databases: the flare vendor database (contains updated sales data collected from vendors of flaring equipment), a database of landfill gas-to-energy (LFGTE) projects compiled by LMOP (EPA 2012), and a database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007). Based on the information provided by the EIA and flare vendor databases, the CH_4 combusted by flares in operation from 1990 to the current inventory year was estimated. Information provided by the EIA and LMOP databases were used to estimate methane combusted in LFGTE projects over the time series. The three databases were carefully compared to identify landfills that were in two or all three of the databases to avoid double or triple counting CH_4 reductions.

The flare vendor database estimates CH_4 combusted by flares using the midpoint of a flare's reported capacity while the EIA database uses landfill-specific measured gas flow. As the EIA database only includes data through 2006, the amount of CH_4 recovered from 2007 to the current inventory year for projects included in the EIA database were assumed to be the same as in 2006. This quantity likely underestimates flaring because these databases do not have information on all flares in operation. The EIA database is no longer being updated and it is expected that data obtained from the EPA's GHGRP will serve as a supplemental data source for facility-reported recovery data in future inventories. 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 provide 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 emission reductions associated with LFGTE projects for which a flare had not been identified from the emission reductions associated with flares (referred to as the flare correction factor). A further explanation of the methodology used to estimate the landfill gas recovered can be found in Annex 3.14.

A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided due to the combusting of CH_4 in destruction devices, i.e., flares. The destruction efficiency value was selected based on the range of efficiencies (86 to 99+ percent) recommended for flares in EPA's AP-42 Compilation of Air Pollutant Emission Factors, Draft Chapter 2.4, Table 2.4-3 (EPA 2008). A typical value of 97.7 percent was presented for the non-methane components (i.e., volatile organic compounds and non-methane organic compounds) in test results (EPA 2008). An arithmetic average of 98.3 percent and a median value of 99 percent are derived from the test results presented in EPA (2008). Thus, a value of 99 percent for the destruction efficiency of flares has been used in Inventory methodology. Other data sources supporting a 99 percent destruction efficiency include those used to establish new source performance standards (NSPS) for landfills and in recommendations for shutdown flares used in the LMOP.

Emissions from industrial waste landfills were estimated from industrial production data (ERG 2013), waste disposal factors, and the first order decay model. As over 99 percent of the organic waste placed in industrial waste 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). There are currently no data sources that track and report the amount and type of waste disposed of in industrial waste landfills in the United States. Therefore, the amount of waste landfilled is assumed to be a fraction of production that is held constant over the time series as explained in Annex 3.14. The composition of waste disposed of in industrial waste landfills is expected to be more consistent in terms of composition and quantity than that disposed of in MSW landfills.

The amount of CH_4 oxidized by the landfill cover at both municipal and industrial waste landfills was assumed to be 10 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 waste landfills.

Uncertainty and Time-Series Consistency

Several types of uncertainty are associated with the estimates of CH_4 emissions from MSW and industrial waste landfills. The primary uncertainty concerns the characterization of landfills. Information is not available on two fundamental factors affecting CH_4 production: the amount and composition of waste placed in every MSW and industrial waste landfill for each year of its operation. The SOG survey is the only nationwide data source that compiles the amount of MSW disposed at the state-level. The surveys do not include information on waste composition and there are no comprehensive data sets that compile quantities of waste disposed or waste composition by landfill. Some MSW landfills have conducted detailed waste composition studies, but landfills in the United States are not required to perform these types of studies. The approach used here assumes that the CH_4 generation potential and the rate of decay that produces CH_4, as determined from several studies of CH_4 recovery at MSW landfills, are representative of conditions at U.S. landfills. When this top-down approach is applied at the nationwide level, the uncertainties are assumed to be less than when applying this approach to individual landfills and then aggregating the results to the national level. In other words, this approach may over- and under-estimate CH_4 generation at some landfills if used at the facility-level, but the end result is expected to balance out because it is being applied nationwide. There is also a high degree of uncertainty and variability associated with the first order decay model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006).

Additionally, there is a lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States. The approach used here assumes that the majority (99 percent) of industrial waste disposed of in industrial waste landfills consists of waste from the pulp and paper and food and beverage industries. However, because waste generation and disposal data are not available in an existing data source for all U.S. industrial waste landfills, we apply a straight disposal factor over the entire time series to the amount of waste generated to determine the amounts disposed.

Aside from the uncertainty in estimating CH_4 generation potential, uncertainty exists in the estimates of the landfill gas oxidized. A constant oxidation factor of 10 percent as recommended by the Intergovernmental Panel on Climate Change (IPCC) for managed landfills is used for both MSW and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system. The number of field studies measuring the rate of oxidation has increased substantially since the IPCC 2006 Guidelines were published and, as discussed in the Potential Improvements section, efforts are being made to review the literature and revise this value based on recent, peer-reviewed studies.

Another significant source of uncertainty lies with the estimates of CH_4 that are recovered by flaring and gas-to-energy projects at MSW landfills. Three separate databases containing recovery information are used to determine the total amount of CH_4 recovered and there are uncertainties associated with each. The LMOP database and the flare vendor databases are updated annually, while the EIA database has not been updated since 2005 and will essentially be replaced by GHGRP data for a portion of landfills (i.e., those meeting the GHGRP thresholds). To avoid double counting and to use the most relevant estimate of CH_4 recovery for a given landfill, a hierarchical approach is used among the three databases. The EIA data are given precedence because CH_4 recovery was directly reported by landfills, the LMOP data are given second priority because CH_4 recovery is estimated from facility-reported LFGTE system characteristics, and the flare data are given third priority because this database contains minimal information about the flare and no site-specific operating characteristics (Bronstein et al., 2012). The IPCC default value of 10 percent for uncertainty in recovery estimates was used in the uncertainty analysis when metering of landfill gas was in place (for about 64 percent of the CH_4 estimated to be recovered). This 10 percent uncertainty factor applies to 2 of the 3 databases (EIA and LMOP). For flaring without metered recovery data (approximately 34 percent of the CH_4 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). The compounding uncertainties associated with the 3 databases leads to the large upper and lower bounds for MSW landfills presented in Table 8-5.

The results of the *IPCC Good Practice Guidance* Tier 2 quantitative uncertainty analysis are summarized in Table 8-5. In 2012, landfill CH_4 emissions were estimated to be between 45.0 and 151.3 Tg CO_2 Eq., which indicates a range of 47 percent below to 56 percent above the 2012 emission estimate of 102.9 Tg CO_2 Eq.

Table 8-5: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2012 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**	**102.9**	**45.0**	**151.3**	**-56%**	**+47%**
MSW	CH_4	88.5	30.9	137.5	-65%	+55%
Industrial	CH_4	14.4	10.5	17.4	-27%	+21%

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

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section, above. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are not performed on the published data used to populate the Inventory data set, including the SOG survey data and the published LMOP database. A primary focus of the QA/QC checks was to ensure that CH_4 recovery estimates were not double-counted and that all LFGTE projects and flares were included in the respective project databases. Both manual and electronic checks were made to ensure that emission avoidance from each landfill was calculated in only 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. A data linking error was identified during the QA/QC review of the summary data spreadsheet. The industrial waste generation data for 2012 was found to be linking to the 2011 industrial waste generation data. This error results in an increase in net methane emissions of 2.2 Gg (0.05 Tg CO2 Eq.) for 2012. This will be corrected in the 1990-2013 Inventory report, and improved initial QA/QC procedures will be implemented to avoid any similar errors.

Recalculations Discussion

When conducted, methodological recalculations are applied to the entire time-series to ensure time-series consistency from 1990 through the current inventory year. Methodological changes were made to the amount of MSW landfill waste generation data for states that did not report an annual amount of waste generated in the SOG surveys for the 2004, 2006, and 2008 data. This change impacted the data for 2003 through 2012. This recalculation was warranted after reviewing the waste generation and disposal trends over the time series, particularly for years after 2004 where a noticeable decrease in the amount of waste generated was calculated. The methodology used by the SOG survey changed (BioCycle 2006) to include only MSW in the values reported in the survey (i.e., other wastes that may be disposed of in an MSW landfill were excluded). This change resulted in the decrease in total waste generation between years before and after 2006. As states got more accustomed to the revised survey questions, they were presumed to be better able to report the MSW portions. Further investigation is warranted for the years after 2006 to better account for the non-MSW portion of waste that is disposed of in MSW landfills.

For states that did not report an amount of waste generated in the surveys, the recalculations made to the 1990 through 2012 inventory used the most recent SOG state-specific waste per capita data from one of the previous SOG surveys. These recalculations resulted in a 3.0 million metric ton decrease in the estimate amount of MSW generated in 2003 and an 8.0 million metric ton decrease in the estimated amount of MSW generated in 2004, reducing landfill methane emissions by 0.05 to 0.4 Tg CO_2 Eq. from 2004 through 2007. An 8.4 million metric ton increase in the MSW generation estimate for 2006 and a 39.2 million metric ton increase in the MSW generation estimate for 2008 increased emissions by under 0.7 to 4.3 Tg CO_2e from 2008 through 2011. The large change in the 2008 data results from the fact that 13 states did not report 2008 data for the 2010 SOG survey. One of these states is California.

Previously, the 2008 nationwide waste per capita rate (1.33 tons per year) was used to estimate the amount of waste generated in California for 2008. This change resulted in using the California-specific waste generation rate from a previous survey (for the year 2004) of 2.17 tons per year, which was more reflective of waste generation in that state than the nationwide waste generation rate.

Planned Improvements

Improvements being examined include incorporating data from the EPA's GHGRP and recent peer-reviewed literature, modifying the default oxidation factor applied to MSW and industrial waste landfills, and either modifying the bulk waste degradable organic carbon (DOC) value or estimating emissions using a waste-specific approach in the first order decay model.

Beginning in 2011, all MSW landfills that accepted waste on or after January 1, 1980 and generate CH_4 in amounts equivalent to 25,000 metric tons or more of carbon dioxide equivalent (CO_2 Eq.) were required to calculate and report their greenhouse gas emissions to EPA through its GHGRP. The MSW landfill source category of EPA's GHGRP consists of the landfill, landfill gas collection systems, and landfill gas destruction devices, including flares. Potential improvements to the inventory methodology may be made using the GHGRP data, specifically for inputs to the first order decay equation. The approach used in the inventory to estimate CH_4 generation assumes a bulk waste-specific DOC value that may not accurately capture the changing waste composition over the time series (e.g., the reduction of organics entering the landfill environment due to increased composting, see Box 8-4). Using data obtained from EPA's GHGRP and any publicly available landfill-specific waste characterization studies in the United States, the methodology may be modified to incorporate a waste composition approach, or revisions may be made to the bulk waste DOC value currently used. Additionally, GHGRP data could be analyzed and a weighted average for the CH_4 correction factor (MCF), fraction of CH_4 (F) in the landfill gas, the destruction efficiency of flares, and the decay rate constant (k) could replace the values currently used in the inventory.

The most significant contribution of GHGRP data to the emission estimates is expected to be the amount of recovered landfill gas and other information related to the gas collection system (Bronstein et al. 2012). Information for landfills with gas collection systems reporting under EPA's GHGRP will be incorporated into the inventory data set and the measured CH_4 recovery data will be used for the reporting landfills in lieu of the EIA, LMOP, and flare vendor data. GHGRP data undergo an extensive series of verification steps, are more reliable and accurate than the data currently used, and will reduce uncertainties surrounding CH_4 recovery when applied to the landfills in the inventory data set (Bronstein et al. 2012).

In addition to MSW landfills, industrial waste landfills at facilities emitting CH_4 in amounts equivalent to 25,000 metric tons or more of CO_2 Eq. were required to report their GHG emissions beginning in September 2012 through EPA's GHGRP. Similar data for industrial waste landfills as is required for the MSW landfills will be reported. Any additions or improvements to the inventory using reported GHGRP data will be made for the industrial waste landfill portion of the inventory. One possible improvement is the addition of industrial sectors other than pulp and paper, and food and beverage (e.g., metal foundries, petroleum refineries, and chemical manufacturing facilities). Of particular interest in the GHGRP data set for industrial waste landfills will be the presence of gas collection systems since recovery is not currently associated with industrial waste landfills in the inventory methodology. It is unlikely that data reported through EPA's GHGRP for industrial waste landfills will yield improved estimates for k and L_o for the industrial sectors. However, EPA is considering an update to the L_o and k values for the pulp and paper sector and will work with stakeholders to gather data and other feedback on potential changes to these values.

The addition of this higher tier data will improve the emission calculations to provide a more accurate representation of greenhouse gas emissions from MSW and industrial waste landfills. It is expected that these potential improvements can occur as early as the 1990 to 2013 inventory year since EPA's GHGRP equation inputs for both MSW and industrial waste landfills will have been reported and verified by that time.[250] Facility-level reporting data

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[250] Due to the large numbers of entities reporting under the GHGRP and the large number of data reporting elements, EPA concluded that case-by-case determinations would not result in a timely release of non-confidential data. EPA determined through a series of rulemaking actions which categories of data elements to protect as confidential business information (CBI). Any data submitted under the Reporting Program that is classified as CBI will be protected under the provisions of 40 CFR part

from EPA's GHGRP are not available for all inventory years as reported in this inventory; therefore, particular attention will be made to ensure time series consistency while incorporating data from EPA's GHGRP that would be useful to improve the emissions estimates for MSW landfills. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[251]

As a first step toward revising the oxidation factor used in the inventory, a literature review was conducted in 2011 (RTI 2011). A standard CH_4 oxidation factor of 10 percent has been used for both industrial and MSW landfills since the inventory began and is currently recommended as the default for well-managed landfills in the latest IPCC guidelines (2006). Recent comments on the inventory methodology indicated that a default oxidation factor of 10 percent may be less than oxidation rates achieved at well-managed landfills with gas collection and control. The impact of different landfill cover types on the rate of oxidation warrants further investigation as well.

Currently, one oxidation factor (10 percent) is applied to the total amount of waste generated nationwide. Changing the oxidation factor and calculating the amount of CH_4 oxidized from landfills with gas collection and control requires the estimation of waste disposed in these types of landfills. The inventory methodology uses waste generation data from the SOG surveys, which report the total amount of waste generated and disposed nationwide by state. In 2010, the State of Garbage survey requested data on the presence of landfill gas collection systems for the first time. Twenty-eight states reported that 260 out of 1,414 (18 percent) operational landfills recovered landfill gas (*BioCycle* 2010). However, the survey did not include closed landfills with gas collection and control systems. In the future, the amount of states collecting and reporting this information is expected to increase. GHGRP data for MSW landfills could be used to fill in the gaps related to the amount of waste disposed in landfills with gas collection systems. Although EPA's GHGRP does not capture every landfill in the United States, larger landfills are expected to meet the reporting thresholds and will be reporting waste disposal information by year beginning in March 2013. After incorporating GHGRP data, it may be possible to calculate the amount of waste disposed of at landfills with and without gas collection systems in the United States, which will allow the inventory waste model to apply different oxidation factors depending on the presence of a gas collection system.

Box 8-3: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

Municipal solid waste generated in the United States can be managed through landfilling, recycling, composting, and combustion with energy recovery. There are two main sources for nationwide solid waste management data in the United States,

- The *BioCycle* and Earth Engineering Center of Columbia University's State of Garbage (SOG) in America surveys and
- The EPA's Municipal Solid Waste in The United States: Facts and Figures reports.

The SOG surveys collect state-reported data on the amount of waste generated and the waste managed via different management options: landfilling, recycling, composting, and combustion. The survey asks for actual tonnages instead of percentages in each waste category (e.g., residential, commercial, industrial, construction and demolition, organics, tires) for each waste management option. If such a breakdown is not available, the survey asks for total tons landfilled. The data are adjusted for imports and exports so that the principles of mass balance are adhered to, whereby the amount of waste managed does not exceed the amount of waste generated. The SOG reports present survey data aggregated to the state level.

The EPA Facts and Figures reports use a materials flow methodology, which relies heavily on a mass balance approach. Data are gathered from industry associations, key businesses, similar industry sources, and government agencies (e.g., the Department of Commerce and the U.S. Census Bureau) and are used to estimate tons of materials and products generated, recycled, or discarded nationwide. The amount of MSW generated is estimated by adjusting

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2, Subpart B. According to Clean Air Act section 114(c), "emission data" cannot be classified as CBI. EPA deferred the reporting requirements for inputs to emission equations until 2013 for some data and 2015 for others to allow EPA to fully evaluate issues regarding the release of these data. Reporting of all inputs for MSW landfills and the majority of inputs for industrial waste landfills were deferred from reporting until 2013.

[251] See: <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

the imports and exports of produced materials. MSW that is not recycled, composted, or combusted is assumed to be landfilled. The data presented in the report are nationwide totals.

The State of Garbage surveys are the preferred data source for estimating waste generation and disposal amounts in the inventory because they are considered a more objective, numbers-based analysis of solid waste management in the United States. However, the EPA Facts and Figures reports are useful when investigating waste management trends at the nationwide level and for typical waste composition data, which the State of Garbage surveys do not request.

In this Inventory, emissions from solid waste management are presented separately by waste management option, except for recycling of waste materials. Emissions from recycling are attributed to the stationary combustion of fossil fuels that may be used to power on-site recycling machinery, and are presented in the stationary combustion chapter in the Energy sector, although the emissions estimates are not called out separately. Emissions from solid waste disposal in landfills and the composting of solid waste materials are presented in the Landfills and Composting chapters in the Waste sector of this report. In the United States, almost all incineration of MSW occurs at waste-to-energy facilities or industrial facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Incineration chapter of the Energy sector of this report.

Box 8-4: Overview of the Waste Sector

As shown in Figure 8-2 and Figure 8-3, landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted would have normally been disposed of in a landfill.

Figure 8-2: Management of Municipal Solid Waste in the United States, 2010 (BioCycle 2010)

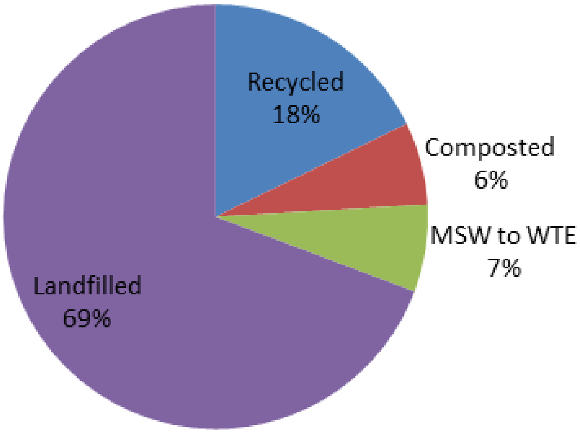


Figure 8-3: MSW Management Trends from 1990 to 2010 (EPA 2011)

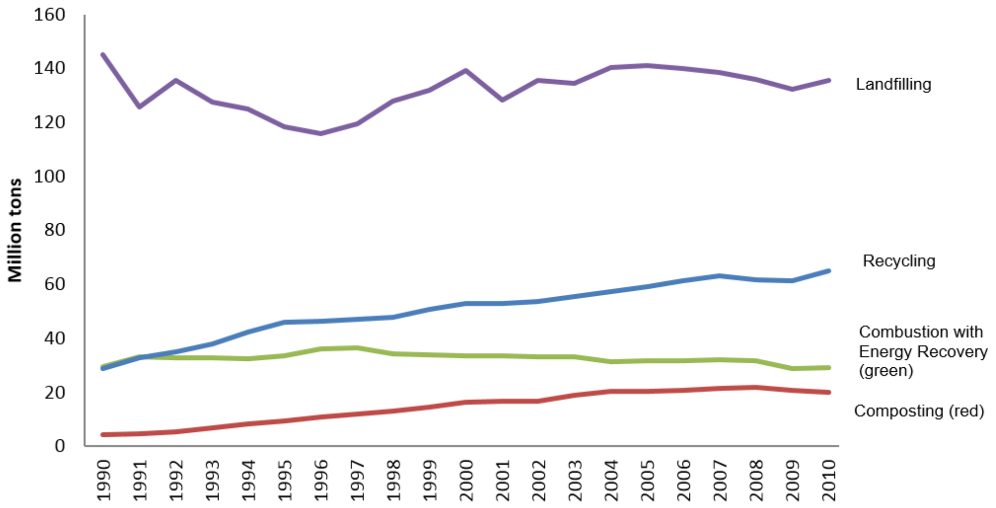


Table 8-6 presents a typical composition of waste disposed of at a typical MSW landfill in the United States over time. It is important to note that the actual composition of waste entering each landfill will vary from that presented in Table 8-6. Understanding how the waste composition changes over time, specifically for the degradable waste types, is important for estimating greenhouse gas emissions. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in recovery (see Table 8-6 and Figure 8-4). Landfill ban legislation affecting yard trimmings resulted in an increase of composting from 1990 to 2008. Table 8-6 and Figure 8-4 do not reflect the impact of backyard composting on yard trimming generation and recovery estimates. The recovery of food trimmings has been consistently low. Increased recovery of degradable materials reduces the CH_4 generation potential and CH_4 emissions from landfills.

Table 8-6: Materials Discarded in the Municipal Waste Stream by Waste Type, Percent

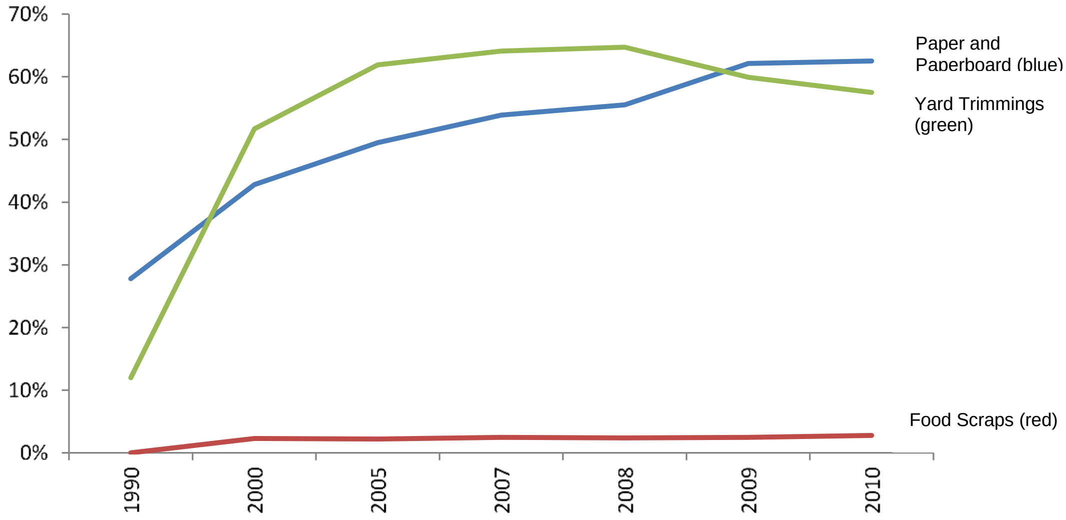
Waste Type	1990	2005	2007	2008	2009	2010
Paper and Paperboard	30.0%	24.5%	21.7%	19.7%	14.8%	15.3%
Glass	6.0%	5.7%	5.5%	5.3%	5.0%	4.8%
Metals	7.2%	7.7%	7.9%	8.0%	8.0%	8.3%
Plastics	9.6%	15.7%	16.4%	16.0%	15.8%	16.3%
Rubber and Leather	3.1%	3.5%	3.6%	3.7%	3.7%	3.8%
Textiles	2.9%	5.5%	5.9%	6.2%	6.3%	6.4%
Wood	6.9%	7.4%	7.5%	7.6%	7.7%	7.8%
Other[a]	1.4%	1.8%	1.9%	1.9%	1.9%	1.9%
Food Scraps[b]	13.6%	17.9%	18.2%	18.6%	19.1%	19.3%
Yard Trimmings[c]	17.6%	7.0%	6.7%	6.6%	7.6%	8.1%
Miscellaneous Inorganic Wastes	1.7%	2.1%	2.1%	2.2%	2.2%	2.2%

[a] Includes electrolytes in batteries and fluff pulp, feces, and urine in disposable diapers. Details may not add to totals due to rounding. Source: EPA 2011.

[b] Data for food scraps were estimated using sampling studies in various parts of the country in combination with demographic data on population, grocery store sales, restaurant sales, number of employees, and number of prisoners, students, and patients in institutions. Source: EPA 2010.

[c] Data for yard trimmings were estimated using sampling studies, population data, and published sources documenting legislation affecting yard trimmings disposal in landfills. Source: EPA 2010.

Figure 8-4: Percent of Recovered Degradable Materials from 1990 to 2010, percent (EPA 2011)



Box 8-5: Description of a Modern, Managed Landfill

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. Municipal solid waste (MSW) landfills must be designed to protect the environment from contaminants which may be present in the solid waste stream. Requirements for affected MSW landfills may include:

- Siting requirements to protect sensitive areas (e.g., airports, floodplains, wetlands, fault areas, seismic impact zones, and unstable areas)
- Design requirements for new landfills to ensure that Maximum Contaminant Levels (MCLs) will not be exceeded in the uppermost aquifer (e.g., composite liners and leachate collection systems)
- Leachate collection and removal systems
- Operating practices (e.g., daily and intermediate cover, receipt of regulated hazardous wastes, use of landfill cover material, access options to prevent illegal dumping, use of a collection system to prevent stormwater run-on/run-off, record-keeping)
- Air monitoring requirements (explosive gases)
- Groundwater monitoring requirements
- Closure and post-closure care requirements (e.g., final cover construction), and
- Corrective action provisions.

Specific federal regulations that affected MSW landfills must comply with include the 40 CFR Part 258 (Subtitle D of RCRA), or equivalent state regulations and the New Source Performance Standards (NSPS) 40 CFR Part 60 Subpart WWW. Additionally, state and tribal requirements may exist.[252]

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[252] For more information regarding federal MSW landfill regulations, see <http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm>.

Box 8-6: Biogenic Wastes in Landfills

Regarding the depositing of wastes of biogenic origin in landfills (i.e., all degradable waste), empirical evidence shows that some of these wastes degrade very slowly in landfills, and the C they contain is effectively sequestered in landfills over a period of time (Barlaz 1998, 2006). Estimates of C 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 CH_4 and N_2O emissions. Wastewater from domestic[253] 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, 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 20 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 2011).

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 biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. 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 N_2O may also result from the treatment of domestic wastewater during both nitrification and denitrification of the N present, usually in the form of urea, ammonia, and proteins. These compounds are converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). N_2O can be an intermediate product of both processes, but has typically been associated with denitrification. Recent research suggests that higher emissions of N_2O may in fact originate from nitrification (Ahn et al. 2010).

The principal factor in determining the CH_4 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 CH_4 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 CH_4 production. The principal factor in determining the N_2O generation potential of wastewater is the amount of N in the wastewater. The variability of N in the influent to the treatment system, as well as the operating conditions of the treatment system itself, also impact the N_2O generation potential.

In 2012, CH_4 emissions from domestic wastewater treatment were 7.8 Tg CO_2 Eq. (373 Gg CH_4). Emissions remained fairly steady from 1990 through 1997, but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic

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[253] Throughout the inventory, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

treatment systems (EPA 1992, 1996, 2000, and 2004, U.S. Census 2011). In 2012, CH_4 emissions from industrial wastewater treatment were estimated to be 4.9 Tg CO_2 Eq. (234 Gg CH_4). Industrial emission sources have generally increased across the time series through 1999 and then fluctuated up and down with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries. Table 8-7 and Table 8-8 provide CH_4 and N_2O emission estimates from domestic and industrial wastewater treatment.

With respect to N_2O, the United States identifies two distinct sources for N_2O 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 2012 emissions of N_2O from centralized wastewater treatment processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (1 Gg N_2O) and 4.7 Tg CO_2 Eq. (15.2 Gg N_2O), respectively. Total N_2O emissions from domestic wastewater were estimated to be 5.0 Tg CO_2 Eq. (16.2 Gg N_2O). N_2O emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.

Table 8-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Activity	1990	2005	2008	2009	2010	2011	2012
CH_4	**13.2**	**13.3**	**13.3**	**13.1**	**13.0**	**12.8**	**12.8**
Domestic	8.8	8.4	8.2	8.2	8.1	7.9	7.8
Industrial[a]	4.3	4.9	5.1	4.9	4.9	4.9	4.9
N_2O	**3.5**	**4.5**	**4.8**	**4.8**	**4.9**	**5.0**	**5.0**
Domestic	3.5	4.5	4.8	4.8	4.9	5.0	5.0
Total	**16.7**	**17.8**	**18.1**	**17.9**	**17.9**	**17.8**	**17.8**

[a] Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.

Note: Totals may not sum due to independent rounding.

Table 8-8: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990	2005	2008	2009	2010	2011	2012
CH_4	**626**	**635**	**635**	**623**	**619**	**611**	**608**
Domestic	421	401	393	392	384	375	373
Industrial*	206	234	242	231	235	235	234
N_2O	**11**	**14**	**15**	**16**	**16**	**16**	**16**
Domestic	11	14	15	16	16	16	16

* Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.

Note: Totals may not sum due to independent rounding.

Methodology

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems, such as publicly owned treatment works (POTWs). Within these centralized systems, CH_4 emissions can arise from aerobic systems that are not well managed or that are designed to have periods of anaerobic activity (e.g., constructed wetlands), anaerobic systems (anaerobic lagoons and facultative lagoons), and from anaerobic digesters when the captured biogas is not completely combusted. CH_4 emissions from septic systems were estimated by multiplying the United States population by the percent of wastewater treated in septic systems (about 20 percent) and an emission factor (10.7 g CH_4/capita/day), and then converting the result to Gg/year. Methane emissions from POTWs were estimated by multiplying the total BOD_5 produced in the United States by the percent of wastewater treated centrally (about 80 percent), the relative percentage of wastewater treated by aerobic and anaerobic systems, the relative percentage of wastewater facilities with primary treatment, the percentage of BOD_5 treated after primary treatment (67.5 percent), the maximum CH_4-producing capacity of domestic wastewater (0.6), and the relative MCFs for well-managed aerobic (zero), not well managed aerobic (0.3), and anaerobic (0.8) systems with all aerobic systems assumed to be well-managed. Methane emissions from anaerobic digesters were estimated by multiplying the amount of biogas generated by wastewater sludge treated in anaerobic digesters by the proportion of CH_4 in digester biogas (0.65), the density of CH_4 (662 g CH_4/m^3 CH_4), and the destruction efficiency associated with burning the biogas in an energy/thermal device (0.99). The methodological equations are:

Emissions from Septic Systems = A
= US_{POP} × (% onsite) × (EF_{SEPTIC}) × 1/10^9 × Days

Emissions from Centrally Treated Aerobic Systems = B
= [(% collected) × (total BOD_5 produced) × (% aerobic) × (% aerobic w/out primary) + (% collected) × (total BOD_5 produced) × (% aerobic) × (% aerobic w/primary) × (1-% BOD removed in prim. treat.)] × (% operations not well managed) × (B_o) × (MCF-aerobic_not_well_man)

Emissions from Centrally Treated Anaerobic Systems = C
= [(% collected) × (total BOD_5 produced) × (% anaerobic) × (% anaerobic w/out primary) + (% collected) × (total BOD_5 produced) × (% anaerobic) × (% anaerobic w/primary) × (1-%BOD removed in prim. treat.)] × (B_o) × (MCF-anaerobic)

Emissions from Anaerobic Digesters = D
= [(POTW_flow_AD) × (digester gas)/ (per capita flow)] × conversion to m^3 × ($FRAC\_CH_4$) × (365.25) × (density of CH_4) × (1-DE) × 1/10^9

Total CH_4 Emissions (Gg) = A + B + C + D

where,

US_{POP} = U.S. population
% onsite = Flow to septic systems / total flow
% collected = Flow to POTWs / total flow
% aerobic = Flow to aerobic systems / total flow to POTWs
% anaerobic = Flow to anaerobic systems / total flow to POTWs
% aerobic w/out primary = Percent of aerobic systems that do not employ primary treatment
% aerobic w/primary = Percent of aerobic systems that employ primary treatment
% BOD removed in prim. treat. = 32.5%
% operations not well managed = Percent of aerobic systems that are not well managed and in which some anaerobic degradation occurs
% anaerobic w/out primary = Percent of anaerobic systems that do not employ primary treatment
% anaerobic w/primary = Percent of anaerobic systems that employ primary treatment
EF_{SEPTIC} = Methane emission factor (10.7 g CH_4/capita/day) – septic systems
Days = days per year (365.25)
Total BOD_5 produced = kg BOD/capita/day × U.S. population × 365.25 days/yr
B_o = Maximum CH_4-producing capacity for domestic wastewater (0.60 kg CH_4/kg BOD)
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 (MGD)
digester gas = Cubic feet of digester gas produced per person per day (1.0 ft^3/person/day) (Metcalf and Eddy 2003)
per capita flow = Wastewater flow to POTW per person per day (100 gal/person/day)
conversion to m^3 = Conversion factor, ft^3 to m^3 (0.0283)

$FRAC\_CH_4$ = Proportion CH_4 in biogas (0.65)
density of CH_4 = 662 (g CH_4/m^3 CH_4)
1/10^9 = Conversion factor, g to Gg

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2013) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. Table 8-9 presents U.S. population and total BOD_5 produced for 1990 through 2012, while Table 8-10 presents domestic wastewater CH_4 emissions for both septic and centralized systems in 2012. 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, 2005, 2007, 2009, 2011 American Housing Surveys conducted by the U.S. Census Bureau (U.S. Census 2011), with data for intervening years obtained by linear interpolation and data for 2012 forecasted using 1990-2011 data. The percent of wastewater flow to aerobic and anaerobic systems, the percent of aerobic and anaerobic systems that do and do not employ primary treatment, 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 2004). Data for intervening years were obtained by linear interpolation and the years 2004 through 2012 were forecasted from the rest of the time series. The BOD_5 production rate (0.09 kg/capita/day) and the percent BOD_5 removed by primary treatment for domestic wastewater were obtained from Metcalf and Eddy (2003). The CH_4 emission factor (0.6 kg CH_4/kg BOD_5) and the MCF used for centralized treatment systems were taken from IPCC (2006), while the CH_4 emission factor (10.7 g CH_4/capita/day) used for septic systems were taken from Leverenz et al. (2010). The CH_4 destruction efficiency for methane recovered from sludge digestion operations, 99 percent, was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in 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 by the Landfill Methane Outreach Program (LMOP). The cubic feet of digester gas produced per person per day (1.0 ft^3/person/day) and the proportion of CH_4 in biogas (0.65) come from Metcalf and Eddy (2003). 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).

Table 8-9: U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (Gg)

Year	Population	BOD_5
1990	253	8,333
2005	300	9,853
2008	308	10,132
2009	311	10,220
2010	313	10,303
2011	316	10,377
2012	318	10,450

Source: U.S. Census Bureau (2013); Metcalf & Eddy 2003).

Table 8-10: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2012)

	CH_4 emissions (Tg CO_2 Eq.)	% of Domestic Wastewater CH_4
Septic Systems	5.1	66.2%
Centralized Systems (including anaerobic sludge digestion)	2.8	33.8%
Total	**7.8**	**100%**

Note: Totals may not sum due to independent rounding.

Industrial Wastewater CH_4 Emission Estimates

Methane emission estimates from industrial wastewater were developed according to the methodology described in IPCC (2006). Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified and included in the inventory. The main criteria used to identify these industries are whether they generate high volumes of wastewater, whether there is a high organic wastewater load, and whether the wastewater is treated using methods that result in CH_4 emissions. The top five industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; and petroleum refining. Wastewater treatment emissions for these sectors for 2012 are displayed in Table 8-11 below. Table 8-12 contains production data for these industries.

Table 8-11: Industrial Wastewater CH_4 Emissions by Sector (2012)

	CH_4 emissions (Tg CO_2 Eq.)	% of Industrial Wastewater CH_4
Meat & Poultry	3.7	74%
Pulp & Paper	0.9	19%
Fruit & Vegetables	0.1	2%
Petroleum Refineries	0.1	2%
Ethanol Refineries	0.1	2%
Total	**4.9**	**100%**

Note: Totals may not sum due to independent rounding.

Table 8-12: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, and Petroleum Refining Production (Tg)

Year	Pulp and Paper[a]	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol	Petroleum Refining
1990	128.9	27.3	14.6	38.7	2.5	702.4
2005	138.5	31.4	25.1	42.9	11.7	818.6
2008	133.1	34.4	26.6	45.1	27.8	836.8
2009	120.4	33.8	25.2	46.5	32.7	822.4
2010	128.6	33.7	25.9	43.2	39.7	848.6
2011	128.3	33.8	26.2	44.3	41.7	858.8
2012	132.3	33.8	26.1	44.8	39.7	852.8

[a] Pulp and paper production is the sum of woodpulp production plus paper and paperboard production.

Methane 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 maximum CH_4 producing potential of industrial wastewater (B_o), and the percentage of organic loading assumed to degrade anaerobically in a given treatment system (MCF). Ratios of BOD:COD in various industrial wastewaters were obtained from EPA (1997a) and used to estimate COD loadings. The B_o value used for all industries is the IPCC default value of 0.25 kg CH_4/kg COD (IPCC 2006).

For each industry, the percent of plants in the industry that treat wastewater on site, the percent of plants that have a primary treatment step prior to biological treatment, and the percent of plants that treat wastewater anaerobically were defined. The percent of wastewater treated anaerobically onsite (TA) was estimated for both primary treatment ($\%TA_p$) and secondary treatment ($\%TA_s$). For plants that have primary treatment in place, an estimate of COD that is removed prior to wastewater treatment in the anaerobic treatment units was incorporated.

The methodological equations are:

$$CH_4 \text{ (industrial wastewater)} = [P \times W \times COD \times \%TA_p \times B_o \times MCF] + [P \times W \times COD \times \%TA_s \times B_o \times MCF]$$

$$\%TA_p = [\%Plants_o \times \%WW_{a,p} \times \%COD_p]$$

$$\%TA_s = [\%Plants_a \times \%WW_{a,s} \times \%COD_s] + [\%Plants_t \times \%WW_{a,t} \times \%COD_s]$$

where,

CH_4 (industrial wastewater) = Total CH_4 emissions from industrial wastewater (kg/year)
P = Industry output (metric tons/year)
W = Wastewater generated (m^3/metric ton of product)
COD = Organics loading in wastewater (kg/m^3)
$\%TA_p$ = Percent of wastewater treated anaerobically on site in primary treatment
$\%TA_s$ = Percent of wastewater treated anaerobically on site in secondary treatment
$\%Plants_o$ = Percent of plants with onsite treatment
$\%WW_{a,p}$ = Percent of wastewater treated anaerobically in primary treatment
$\%COD_p$ = Percent of COD entering primary treatment
$\%Plants_a$ = Percent of plants with anaerobic secondary treatment
$\%Plants_t$ = Percent of plants with other secondary treatment
$\%WW_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%WW_{a,t}$ = percent of wastewater treated anaerobically in other secondary treatment
$\%COD_s$ = percent of COD entering secondary treatment
B_o = Maximum CH_4 producing potential of industrial wastewater (default value of 0.25 kg CH_4/kg COD)
MCF = CH_4 correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically

Alternate methodological equations for calculating %TA were used for secondary treatment in the pulp and paper industry to account for aerobic systems with anaerobic portions. These equations are:

$$\%TA_a = [\%Plants_a * \%WW_{as} * \%COD_s] + [\%Plant_{st} * \%WW_{at} * COD_s]$$

$$\%TA_{at} = [\%Plants_{at} * \%WW_{as} * \%COD_s]$$

where,

$\%TA_a$ = Percent of wastewater treated anaerobically on site in secondary treatment
$\%TA_{at}$ = Percent of wastewater treated in aerobic systems with anaerobic portions on site in secondary treatment
$\%Plants_a$ = Percent of plants with anaerobic secondary treatment
$\%Plants_{a,t}$ = Percent of plants with partially anaerobic secondary treatment
$\%WW_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%WW_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment
$\%COD_s$ = Percent of COD entering secondary treatment

As described below, the values presented in Table 8-13 were used in the emission calculations and are described in detail in Aguiar and Bartram (2008), Bicknell et al. (2013), and Aguiar et al. (2013).

Table 8-13: Variables Used to Calculate Percent Wastewater Treated Anaerobically by Industry (%)

Variable	Industry						
	Pulp and Paper	**Meat Processing**	**Poultry Processing**	**Fruit/ Vegetable Processing**	**Ethanol Production – Wet Mill**	**Ethanol Production – Dry Mill**	**Petroleum Refining**
$\%TA_p$	0	0	0	0	0	0	0
$\%TA_s$	0	33	25	4.2	33.3	75	23.6
$\%TA_a$	2.2	0	0	0	0	0	0
$\%TA_{a,t}$	11.8	0	0	0	0	0	0
$\%Plants_o$	0	100	100	11	100	100	100
$\%Plants_a$	5	33	25	5.5	33.3	75	23.6
$\%Plants_{a,t}$	28	0	0	0	0	0	0
$\%Plants_t$	35	67	75	5.5	66.7	25	0

$\%WW_{a,p}$	0	0	0	0	0	0	0
$\%WW_{a,s}$	100	100	100	100	100	100	100
$\%WW_{a,t}$	0	0	0	0	0	0	0
$\%COD_p$	100	100	100	100	100	100	100
$\%COD_s$	42	100	100	77	100	100	100

Sources: Aguiar and Bartram (2008) Planned Revisions of the Industrial Wastewater Inventory Emission Estimates for the 1990-2007 Inventory. August 10, 2008; Bicknell et al. (2013) Revisions to Pulp and Paper Wastewater Inventory. October 2013; and Aguiar et al. (2013) Revisions to the Petroleum Wastewater Inventory. October 2013.

Pulp and Paper. 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 1993). 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 1993). 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.

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Based on EPA's OAQPS Pulp and Paper Sector Survey, 5.3 percent of pulp and paper mills reported using anaerobic secondary treatment for wastewater and/or pulp condensates (Bicknell et al. 2011). Twenty-eight percent (28%) of mills also reported the use of quiescent settling ponds. Using engineering judgment, these systems were determined to be aerobic with possible anaerobic portions. For the truly anaerobic systems, an MCF of 0.8 is used, as these are typically deep stabilization basins. For the partially anaerobic systems, an MCF of 0.2 is used, which is the IPCC suggested MCF for shallow lagoons.

A time series of CH_4 emissions for 1990 through 2001 was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). Data from the Food and Agricultural Organization of the United Nations (FAO) database FAOSTAT were used for 2002 through 2012 (FAO 2013). The overall wastewater outflow varies based on a time series outlined in Bicknell et al. (2013) to reflect historical and current industry wastewater flow, and the average BOD concentrations in raw wastewater was estimated to be 0.4 gram BOD/liter (EPA 1997b, EPA 1993, World Bank 1999). The COD:BOD ratio used to convert the organic loading to COD for pulp and paper mills was 2 (EPA 1997a).

Meat and Poultry Processing. 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 B_o of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic lagoons were used to estimate the CH_4 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 2013). Data collected by EPA's Office of Water provided estimates for wastewater flows into anaerobic lagoons: 5.3 and 12.5 m^3/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. The COD:BOD ratio used to convert the organic loading to COD for both meat and poultry facilities was 3 (EPA 1997a).

Vegetables, Fruits, and Juices Processing. 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, 4.2 percent of these wastewater organics are assumed to degrade anaerobically. The IPCC default B_o 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 2013) provided production data for potatoes, other vegetables, citrus fruit, non-citrus fruit, and grapes processed for wine. Outflow and BOD data, presented in Table 8-14, were obtained from EPA (1974) for potato, citrus fruit, and apple processing, and from EPA (1975) for all other sectors. The COD:BOD ratio used to convert the organic loading to COD for all fruit, vegetable, and juice facilities was 1.5 (EPA 1997a).

Table 8-14: Wastewater Flow (m^3/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	8.67	0.791
Fruit		
Apples	3.66	1.371
Citrus	10.11	0.317
Non-citrus	12.42	1.204
Grapes (for wine)	2.78	1.831

Ethanol Production. 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. Currently, ethanol is mostly made from sugar and starch crops, but with advances in technology, cellulosic biomass is increasingly used as ethanol feedstock (US DOE 2013).

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 gallons 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 CH_4 is recovered through the use of biomethanators (ERG 2006). Methane emissions were then estimated as follows:

$$\text{Methane} = [\text{Production} \times \text{Flow} \times \text{COD} \times 3.785 \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times B_o \times \text{MCF} \times \%\ \text{Not Recovered}] + [\text{Production} \times \text{Flow} \times 3.785 \times \text{COD} \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times B_o \times \text{MCF} \times (\%\ \text{Recovered}) \times (1\text{-DE})] \times 1/10\text{^}9$$

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

%Plants$_o$ = percent of plants with onsite treatment (100%)
%WW$_{a,p}$ = percent of wastewater treated anaerobically in primary treatment (0%)
%COD$_p$ = percent of COD entering primary treatment (100%)
%Plants$_a$ = percent of plants with anaerobic secondary treatment (33.3% wet, 75% dry)
%Plants$_t$ = percent of plants with other secondary treatment (66.7% wet, 25% dry)
%WW$_{a,s}$ = percent of wastewater treated anaerobically in anaerobic secondary treatment (100%)
%WW$_{a,t}$ = percent of wastewater treated anaerobically in other secondary treatment (0%)
%COD$_s$ = percent of COD entering secondary treatment (100%)
B$_o$ = 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 CH_4 emissions for 1990 through 2012 was developed based on production data from the Renewable Fuels Association (RFA 2013).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH_4 emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.[254] Of the responding facilities, 23.6 percent reported using non-aerated surface impoundments or other biological treatment units, both of which have the potential to lead to anaerobic conditions (Aguiar et al. 2013). In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product (Aguiar et al. 2013). An average COD value in the wastewater was estimated at 0.45 kg/m^3 (Benyahia et al. 2006).

The equation used to calculate CH_4 generation at petroleum refining wastewater treatment systems is presented below:

$$\text{Methane} = \text{Flow} \times \text{COD} \times \text{TA} \times B_o \times \text{MCF}$$

where,

Flow = Annual flow treated through anaerobic treatment system (m^3/year)
COD = COD loading in wastewater entering anaerobic treatment system (kg/m^3)
TA = Percent of wastewater treated anaerobically on site
B$_o$ = maximum methane producing potential of industrial wastewater (default value of 0.25 kg CH_4 /kg COD)
MCF = methane conversion factor (0.3)

A time series of CH_4 emissions for 1990 through 2012 was developed based on production data from the Energy Information Association (EIA 2013).

Domestic Wastewater N_2O Emission Estimates

N_2O 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/commercial 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.
- The IPCC methodology uses annual, per capita protein consumption (kg protein/person-year). For this inventory, the amount of protein available to be consumed is estimated based on per capita annual food availability data and its protein content, and then adjusts that data using a factor to account for the fraction of protein actually consumed.

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[254] Available online at <https://refineryicr.rti.org/>.

- 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 N_2O is generated per capita per year if wastewater treatment includes intentional nitrification and denitrification (Scheehle and Doorn 2001). Analysis of the 2004 CWNS shows that plants with denitrification as one of their unit operations serve a population of 2.4 million people. Based on an emission factor of 7 g per capita per year, approximately 21.2 metric tons of additional N_2O may have been emitted via denitrification in 2004. 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 N_2O per capita per year.

N_2O emissions from domestic wastewater were estimated using the following methodology:

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

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

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

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

$$N_2O_{EFFLUENT} = \{[(((US_{POP} \times WWTP) - (0.9 \times US_{POPND})) \times Protein \times F_{NPR} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}) - N_{SLUDGE}] \times EF_3 \times 44/28\} \times 1/10^6$$

where,

N_2O_{TOTAL} = Annual emissions of N_2O (Gg)
N_2O_{PLANT} = N_2O emissions from centralized wastewater treatment plants (Gg)
$N_2O_{NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification (Gg)
$N_2O_{WOUT\ NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification (Gg)
$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments (Gg)
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)
EF_1 = Emission factor (3.2 g N_2O/person-year) – plant with no intentional denitrification
EF_2 = Emission factor (7 g N_2O/person-year) – plant with intentional denitrification
Protein = Annual per capita protein consumption (kg/person/year)
F_{NPR} = Fraction of N in protein, default = 0.16 (kg N/kg protein)
$F_{NON\text{-}CON}$ = Factor for non-consumed protein added to wastewater (1.4)
$F_{IND\text{-}COM}$ = Factor for industrial and commercial co-discharged protein into the sewer system (1.25)
N_{SLUDGE} = N removed with sludge, kg N/yr
EF_3 = Emission factor (0.005 kg N_2O -N/kg sewage-N produced) – from effluent
0.9 = Amount of nitrogen removed by denitrification systems (EPA 2008)
44/28 = Molecular weight ratio of N_2O to N_2

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2013) 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, 2005, 2007, 2009, and 2011 American Housing Survey (U.S. Census 2011). Data for intervening years were obtained by linear interpolation and data from 2012 were forecasted using 1990-2011 data. The emission factor (EF_1) used to estimate emissions from wastewater treatment for plants without intentional denitrification was taken from IPCC (2006), while the emission factor (EF_2) used to estimate emissions from wastewater treatment for plants with intentional denitrification was taken from Scheehle and Doorn (2001). Data on annual per capita protein intake were provided by the U.S. Department of Agriculture Economic Research Service (USDA 2012). Protein consumption data for 2007 through 2012 were extrapolated from data for 1990 through 2006. An emission factor to estimate emissions from effluent (EF_3) has not been specifically estimated for the United States, thus the default IPCC value (0.005 kg N_2O-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). The factor for non-consumed protein and the factor for industrial and commercial co-discharged protein were obtained from IPCC (2006). Sludge generation was obtained from EPA (1999) for 1988, 1996, and 1998 and from Beecher et al. (2007) for 2004. Intervening years were interpolated, and estimates for 2005 through 2012 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 2012, 280 Gg N was removed with sludge. Table 8-15 presents the data for U.S. population, population served by biological denitrification, population served by wastewater treatment plants, available protein, protein consumed, and nitrogen removed with sludge.

Table 8-15: U.S. Population (Millions), Population Served by Biological Denitrification (Millions), Fraction of Population Served by Wastewater Treatment (%), Available Protein (kg/person-year), Protein Consumed (kg/person-year), and Nitrogen Removed with Sludge (Gg-N/year)

Year	Population	$Population_{ND}$	WWTP Population	Available Protein	Protein Consumed	N Removed
1990	253	2.0	75.6	38.4	29.3	215.6
2005	300	2.7	78.8	39.8	30.5	260.3
2007	305	2.8	79.4	40.7	31.2	265.9
2008	308	2.9	79.4	40.8	31.3	268.7
2009	311	2.9	79.3	40.9	31.4	271.4
2010	313	3.0	80.0	41.0	31.5	274.2
2011	316	3.0	80.6	41.1	31.6	277.0
2012	318	3.0	80.4	41.2	31.6	279.8

Uncertainty and Time-Series Consistency

The overall uncertainty associated with both the 2012 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 manufacture, meat and poultry processing, fruits and vegetable processing, ethanol production, and petroleum refining. 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 nitrogen 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 8-16. Methane emissions from wastewater treatment were estimated to be between 9.3 and 15.4 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 27 percent below to 21 percent above the 2012 emissions estimate of 12.8 Tg CO_2 Eq. N_2O emissions from wastewater treatment were estimated to be between 1.2 and 10.1 Tg CO_2 Eq., which indicates a range of approximately 75 percent below to 100 percent above the 2012 emissions estimate of 5.03 Tg CO_2 Eq.

Table 8-16: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Wastewater Treatment (Tg CO_2 Eq. and Percent)

Source	Gas	2012 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
Wastewater Treatment	**CH_4**	**12.8**	**9.3**	**15.4**	**-27%**	**+21%**
Domestic	CH_4	7.8	5.8	10.1	-26%	+29%
Industrial	CH_4	4.9	2.4	6.9	-51%	+41%
Wastewater Treatment	**N_2O**	**5.03**	**1.2**	**10.1**	**-75%**	**+100%**

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

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section, above. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section, above.

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

Production data were updated to reflect revised USDA NASS datasets. In addition, a new source of data was identified for pulp and paper production and incorporated this inventory year. These data were used to revise production values of wood pulp and paper and paperboard for 2002 through 2012. In addition, the most recent USDA ERS data were used to update protein values from 1990 through 2006. The updated ERS data also resulted in small changes in forecasted values from 2007.

Using the information summarized in Bicknell et al. (2013) and Aguiar et al. (2013), both pulp and paper and petroleum refining estimates were updated to be consistent with the most current and representative data available for these industries. Primarily due to these new data, overall industry emissions from industrial wastewater treatment decreased by 40% from the 1990-2011 Inventory.

In addition, an improved forecasting methodology for domestic wastewater resulted in small changes to both nitrous oxide and methane emissions beginning in 2005.

Planned Improvements

The methodology to estimate CH_4 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 question of whether activity data for wastewater treatment systems are sufficient across the time series to further differentiate aerobic systems with the potential to generate small amounts of CH_4 (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, continues to be explored. The CWNS data for 2008 were evaluated for incorporation into the inventory, but due to significant changes in format, this dataset is not sufficiently detailed for inventory calculations. However, additional information and other data continue to be evaluated to update future years of the inventory, including anaerobic digester data compiled by the North East Biosolids and Residuals Association (NEBRA) in collaboration with several other entities. These data, available at www.biogasdata.org, are still preliminary, and not yet complete for inclusion in the inventory. EPA will continue to monitor the status of these data as a potential source of digester, sludge, and biogas data from POTWs.

Data collected under the EPA's GHGRP will be investigated for use in improving the emission estimates for the industrial wastewater category. Particular attention will be made to ensure time series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[255] For all industries, EPA will continue to review new research on industrial wastewater characteristics, utilization of treatment systems, and associated greenhouse gas emissions as it becomes available. Before the incorporation of any new data, EPA will ensure it is representative of industry conditions.

Wastewater inventory submissions from other countries will be reviewed for additional data and methodologies that could be used to inform the US wastewater inventory calculations. Items to be investigated include emission factors, specific methodologies, and additional industries that could be used to improve or supplement the wastewater treatment emissions calculations. In addition to this investigation, EPA will investigate reports from the Global Water Research Coalition to inform potential updates to the inventory based on international research.

Currently, for domestic wastewater, it is assumed that all aerobic wastewater treatment systems are well managed and produce no CH_4 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 by researchers, including the Water Environment Research Federation (WERF). This research includes data on emissions from partially anaerobic treatment systems. In addition, information on flare efficiencies are being reviewed for potential updates to the inventory.

With respect to estimating N_2O emissions, the default emission factors for indirect N_2O from wastewater effluent and direct N_2O from centralized wastewater treatment facilities have a high uncertainty. Research is being conducted by WERF to measure N_2O emissions from municipal treatment systems and is periodically reviewed for its utility for the inventory. In addition, a literature review has been conducted focused on N_2O emissions from wastewater treatment to determine the state of such research and identify data to develop a country-specific N_2O emission factor or alternate emission factor or method. Such data will continue to be reviewed as they are available to determine if a country-specific N_2O emission factor can or should be developed, or if alternate emission factors should be used. EPA will also follow up with the authors of any relevant studies, including those from WERF, to determine if there is additional information available on potential methodological revisions.

Previously, new measurement data from WERF were used to develop U.S.-specific emission factors for CH_4 emissions from septic systems and incorporated it into the inventory emissions calculation. Due to the high uncertainty of the measurements for N_2O from septic systems, estimates of N_2O emissions were not included. Appropriate emission factors for septic system N_2O emissions will continue to be investigated as the data collected by WERF indicate that septic soil systems are a source of N_2O emissions.

In addition, the estimate of N entering municipal treatment systems is under review. The factor that accounts for non-sewage N in wastewater (bath, laundry, kitchen, industrial components) also has a high uncertainty. Obtaining data on the changes in average influent N 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. The dataset previously provided by the National Association of Clean Water Agencies (NACWA) was reviewed to determine if it was representative of the larger population of centralized treatment plants for potential inclusion into the inventory. However, this limited dataset was not representative of the number of systems by state or the service populations served in the United States, and therefore could not be incorporated into the inventory methodology. Additional data sources will continue to be researched with the goal of improving the uncertainty of the estimate of N entering municipal treatment systems.

The value used for N content of sludge continues to be investigated. This value is driving the N_2O emissions for wastewater treatment and is static over the time series. To date, new data have not been identified that would be able to establish a time series for this value. The amount of sludge produced and sludge disposal practices will also be

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[255] See: <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

investigated. In addition, based on UNFCCC review comments, improving the transparency of the fate of sludge produced in wastewater treatment will also be investigated.

A review of other industrial wastewater treatment sources for those industries believed to discharge significant loads of BOD and COD has been ongoing. Food processing industries have the highest potential for CH_4 generation due to the waste characteristics generated, and the greater likelihood to treat the wastes anaerobically. However, in all cases there is dated information available on U.S. treatment operations for these industries. Previously, organic chemicals, the seafood processing industry, and coffee processing were investigated to estimate their potential to generate CH_4. Due to the insignificant amount of CH_4 estimated to be emitted and the lack of reliable, up-to-date activity data, these industries were not selected for inclusion in the inventory. Preliminary analyses of the beer and malt and dairy products industries have been performed. These industries will continue to be investigated for incorporation. Other industries will be reviewed as necessary for inclusion in future years of the inventory using EPA's Permit Compliance System and Toxics Release inventory.

8.3 Waste Incineration (IPCC Source Category 6C)

As stated earlier in this chapter, CO_2, N_2O, and CH_4 emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2012 resulted in 12.6 Tg CO_2 Eq. emissions, over half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste incineration include non-hazardous industrial waste incineration and medical waste incineration. As described in Annex 5 of this report, data are not readily available for these sources and emissions estimates are not provided. Further investigations will be made, including assessing the applicability of state-level data collected for EPA's National Emission Inventory (NEI).[256]

8.4 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 (CO_2). Methane (CH_4) 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 CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial C content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can be produced. The formation of N_2O depends on the initial nitrogen content of the material and is mostly due to nitrogen oxide (NOx) denitrification during the later composting stages. Emissions vary and range from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006). Animal manures are typically expected to generate more N_2O than, for example, yard waste, however data are limited.

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[256] See <http://www.epa.gov/ttn/chief/eiinformation.html>.

From 1990 to 2012, the amount of material composted in the United States has increased from 3,810 Gg to 18,919 Gg, an increase of approximately 397 percent. From 2000 to 2012, the amount of material composted in the United States has increased by approximately 27 percent. Emissions of CH_4 and N_2O from composting have increased by the same percentage. In 2012, CH_4 emissions from composting (see Table 8-17 and Table 8-18) were 1.6 Tg CO_2 Eq. (75.7 Gg), and N_2O emissions from composting were 1.8 Tg CO_2 Eq. (5.7 Gg). The wastes composted primarily include 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 composted waste quantities reported here do not include backyard composting. The growth in composting since the 1990s is attributable to primarily two factors: (1) steady growth in population and residential housing, and (2) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings in landfills. Most bans on disposal of yard trimmings initiated in the early 1990s (U.S. Composting Council 2010). By 2010, 25 states, representing about 50 percent of the nation's population, have enacted such legislation (BioCycle, 2010). Despite these factors, the total amount of waste composted exhibited a downward trend between 2008 and 2009 and then started recovering every year after that, but it is still not at the same level it was in 2008 (see Table 8-17). The percent change between 2008 and 2012 is approximately 6 percent. The same trend is observed in the total waste generated and is consistent with trends in the United States economy, e.g., the beginning of the recession in 2008.

Table 8-17: CH_4 and N_2O Emissions from Composting (Tg CO_2 Eq.)

Activity	1990	2005	2008	2009	2010	2011	2012
CH_4	0.3	1.6	1.7	1.6	1.5	1.6	1.6
N_2O	0.4	1.7	1.9	1.8	1.7	1.7	1.8
Total	**0.7**	**3.3**	**3.5**	**3.3**	**3.2**	**3.3**	**3.3**

Note: Totals may not sum due to independent rounding.

Table 8-18: CH_4 and N_2O Emissions from Composting (Gg)

Activity	1990	2005	2008	2009	2010	2011	2012
CH_4	15.2	74.6	80.2	75.3	73.2	75.1	75.7
N_2O	1.1	5.6	6.0	5.6	5.5	5.6	5.7

Note: Totals may not sum due to independent rounding.

Methodology

Methane and N_2O 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 8-17 and Table 8-18 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 CH_4 recovery is expected to occur at composting operations):

$$E_i = M \times EF_i$$

where,

E_i = CH_4 or N_2O emissions from composting, Gg CH_4 or N_2O,
M = mass of organic waste composted in Gg,
EF_i = emission factor for composting, 4 g CH_4/kg of waste treated (wet basis) and 0.3 g N_2O/kg of waste treated (wet basis) (IPCC 2006), and
i = designates either CH_4 or N_2O.

Estimates of the quantity of waste composted (M) are presented in Table 8-19. Estimates of the quantity composted for 1990, 2005 and 2007 through 2010 were taken from *Municipal Solid Waste in the United States: 2010 Facts and Figures* (EPA 2011); estimates of the quantity composted for 2006 were taken from EPA's *Municipal Solid Waste In The United States: 2006 Facts and Figures* (EPA 2007); estimates of the quantity composted for 2011 were taken from EPA's *Municipal Solid Waste In The United States: 2011 Facts and Figures* (EPA 2013); estimates of the quantity composted for 2012 were calculated using the 2011 quantity composted and a ratio of the U.S. population in 2011 and 2012 (U.S. Census Bureau 2013).

Table 8-19: U.S. Waste Composted (Gg)

Activity	1990	2005	2008	2009	2010	2011	2012
Waste Composted	3,810	18,643	20,049	18,824	18,298	18,779	18,919

Source: EPA 2007, EPA 2011 and EPA 2013.

Uncertainty and Time-Series Consistency

The estimated uncertainty from the 2006 IPCC Guidelines is ±50 percent for the Tier 1 methodology. Emissions from composting in 2012 were estimated to be between 1.7 and 5.0 Tg CO_2 Eq., which indicates a range of 50 percent below to 50 percent above the actual 2012 emission estimate of 3.3 Tg CO_2 Eq. (see Table 8-20).

Table 8-20 : Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (Tg CO_2 Eq. and Percent)

Source	Gas	2012 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_2O	3.3	1.7	5.0	-50%	+50%

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section, above. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section, above.

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 the amount of waste composted annually was correct according to the latest EPA *Municipal Solid Waste In The United States: Facts and Figures* report (EPA 2013).

Recalculations Discussion

The estimated amount of waste composted in 2011 was updated relative to the previous Inventory based on new data contained in EPA's *Municipal Solid Waste In The United States: 2011 Facts and Figures* (EPA 2013). The amounts of CH_4 and N_2O emissions estimates presented in Table 8-17 and Table 8-18 were revised accordingly. No methodological changes were made.

Planned Improvements

In the future, additional efforts will be made to improve the estimates of CH_4 and N_2O 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. Further cooperation with estimating emissions in cooperation with the LULUCF Other section will be made.

8.5 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 2012 are provided in Table 8-21.

Table 8-21: Emissions of NO$_x$, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	2005	2008	2009	2010	2011	2012
NO$_x$	**+**	2	2	1	1	1	1
Landfills	+	2	2	1	1	1	1
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous[a]	+	+	+	+	+	+	+
CO	**1**	**7**	**6**	**5**	**5**	**5**	**5**
Landfills	1	6	5	5	5	4	4
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous[a]	+	+	+	+	+	+	+
NMVOCs	**673**	**114**	**54**	**49**	**44**	**38**	**38**
Wastewater Treatment	57	49	23	21	19	17	17
Miscellaneous[a]	557	43	20	18	17	15	15
Landfills	58	22	10	9	8	7	7

[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.

Methodology

Emission estimates for 1990 through 2012 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2013), and disaggregated based on EPA (2003). Emission estimates for 2012 for non-EGU and non-mobile sources are held constant from 2011 in EPA (2013). 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.

Uncertainty and Time-Series Consistency

No quantitative estimates of uncertainty were calculated for this source category. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section, above. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2012. Details on the emission trends through time are described in more detail in the Methodology section, above.