**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:

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

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

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

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

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

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.