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A COMPARISON OF METHODS FOR ESTIMATING GLOBAL METHANE EMISSIONS FROM LANDFILLS

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ABSTRACT

Landfills are a significant source of methane, ranking third in anthropogenic sources after rice paddies and ruminants. Estimating the contribution of landfills to global methane flux is hampered by a lack of accurate refuse and landfill data, and therefore depends heavily on the assumptions used in the calculations. This paper describes research efforts to improve methodologies for estimating landfill emissions. Two key variables are discussed (1) the amount of refuse landfilled, and (2) the methane-generating potential of that refuse. Estimates of annual U.S. municipal solid waste production are compared, and the limitations of each method are reviewed. The implications for global data development are discussed. The estimated amount of methane emitted due to anaerobic decomposition of refuse in landfills can be based on theoretical models, laboratory studies, or measurements. Data from methane recovery systems at selected U.S. landfills were used to evaluate the effect of climate, age of refuse, and physical characteristics of the site on methane recovery. Methodologies for using methane recovery data to estimate methane produced by refuse are described, and resulting methane potentials are compared to other values in the literature. This paper discusses the factors that influence these two key variables and the sensitivity of global methane emissions estimates to assumptions about these factors.

1. INTRODUCTION

The recent rise in atmospheric methane is attributed largely to anthropogenic sources, including ruminants, rice paddies, landfills, biomass burning, coal mining operations, and leakage of natural gas during transmission. Anthropogenic methane emissions from organic material occur mostly because of bacterial anaerobic decomposition, but are also the result of incomplete combustion. Several adjustments to the estimated sinks and sources have been made to reconcile them with observed atmospheric concentrations (Khalil and Rasmussen, 1990; Crutzen, 1991). Considerable uncertainty remains, however, pertaining to the relative contribution of many sources.

Because of its high organic content, municipal solid waste (MSW) disposed of in landfills is thought to be a significant source of methane. The most widely cited estimate of global landfill methane emissions is 30-70 Tg*/year (Bingemer and Crutzen, 1987). Using a different set of assumptions, Richards (1989) estimated global landfill gas emissions to be 39.2 x 10^9 m^3. Assuming 50 percent methane by volume and at a standard temperature and pressure (STP) of 20°C and 0.1 MPa (68°F, 1 atm), this estimate yields 14 Tg/year, which is 53 to 80 percent less than the Bingemer and Crutzen estimate.

Landfills are one of the largest sources of methane in the various global budgets that have been published (Khalil and Rasmussen, 1990). Landfills, however, offer better opportunities for mitigation via gas recovery and energy production, waste minimization, or recycling than many of the other sources. Because of the opportunities that exist for mitigation, further study to improve the reliability of emissions estimates for landfills is warranted.

Obtaining the data needed to estimate emissions for landfills is difficult (Thorneloe and Peer, 1991). Data for many countries are not available; therefore, the information needed to model emissions is frequently estimated by using theoretical arguments or surrogate variables. Even where data are available, they are generally statistical representations of the true values. For these reasons, emission inventories should be treated as model output and should be validated in the same manner as models.

The uncertainty associated with emissions estimates has three general causes: data variability, data errors, and model uncertainty. Data variability can be known with great precision; however, it becomes a source of uncertainty when it is not known, or when parameters are expressed as a single value without any error bounds as for deterministic models or methods.

Data errors include measurement errors that can occur from limitations of equipment or methods. For example, this is a problem when trying to estimate refuse density and composition. Even where refuse acceptance is quantified at a landfill, it is often measured by counting the number of trucks and assuming a density per truckload. Random errors, which can occur in any type of sampling process, can also contribute to uncertainty.

Model uncertainty can be equal to or more important than data errors in its contribution to the uncertainty of an emissions estimate. Models often use surrogate variables because they are easier to measure or model. Surrogates rarely behave exactly as the modeled variable. Models are simplifications of the actual world and, therefore, some variables are excluded. The modeler tries to ensure that no critical variables are left out, but striking the correct balance between simplification and thoroughness is difficult.

The uncertainty associated with the models and assumptions used to estimate emissions can be reduced. For landfill emissions, uncertainty will be reduced as data on country-specific refuse production and refuse management are gathered, and as measurement methods for individual landfills are developed. In the short term, the available data and methods can be reviewed, and the uncertainty associated with key variables and models assessed.

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* Tg = teragram = 10^{12} grams.

Two key variables are the amount of refuse annually placed in landfills and the amount of methane emitted from a given mass of refuse. The first variable is a function of the proportion of total refuse generated within a country that is placed in landfills. The second variable is more complicated, and requires an estimate of the methane potential of the refuse and the amount of methane that actually diffuses through the landfill cover to the atmosphere. The methane potential is a function of the amount of degradable organic carbon in the refuse and the conditions under which it is degraded. When oxygen is present, carbon dioxide is produced. Under anaerobic conditions, methane and carbon dioxide are produced; the efficiency of this process is affected by moisture, temperature, nutrients, and pH, to name only a few factors.

This paper compares alternative methods for estimating total refuse generated and methane potential for the United States only. Data for the United States are more readily available than for most other countries and are sufficient to address some of the uncertainty issues quantitatively. The implications of this analysis of U.S. data for global estimates are discussed.

2. ESTIMATING ANNUAL LANDFILL REFUSE GENERATION

Accurate estimates of refuse production, the proportion placed in landfills, and the composition of that refuse for each country are needed to reduce a lot of the uncertainty associated with landfill methane emissions. For many developing countries and the countries of eastern Europe and the former Soviet Union, these data are incomplete and are often of unknown quality. Data for U.S. landfills, however, should provide a benchmark for global country-specific data. Landfills and MSW have been the subjects of intensive scrutiny in the United States in recent years because of strong regulatory pressure to reduce air and water pollution.

Table 1 presents alternative estimates of the amount of MSW generated in the United States. These estimates were developed using different methods. The per capita waste generation factor of 1.8 kg per person per day used by Bingemer and Crutzen (1987) is an estimate that was developed for New York City in 1979 (Cointreau, 1984). They applied this estimate only to urban populations and assumed that 91 percent was landfilled. The first U.S. EPA estimate (Kaldjian, 1990) was developed using a materials flow methodology. Published domestic production data were compiled and adjusted for scrap conversion, imports and exports, product lifetime, and diversion from waste stream (e.g., products consumed by use) to estimate annual MSW generation (1.6 kg per person per day). The amount landfilled was estimated to be 73 percent (Kaldjian, 1990). The second U.S. EPA estimate (Westat, 1988) was based on a national survey of MSW landfill facilities. A stratified sample of landfills yielded waste collection data from 1,102 facilities (approximately 17 percent of the total active landfills). The upper and lower 95 percent confidence interval of the estimate was 167-212 Tg/yr. The last estimate (Glenn and Riggle, 1991) was developed by surveying individual states to determine the total waste generated and methods of disposal employed. They estimated that 77 percent of the waste generated was landfilled. The authors did not discuss the sample design and methodology used.

Table 1. Estimated U.S. MSW Generation and Amounts Landfilled

Total MSW Generated (Tg/yr)	Year of Estimate	Proportion Landfilled	Estimated Amount Landfilled (Tg/yr)	Reference
119	1979	0.91	108[a]	Bingemer and Crutzen, 1987
163	1988	0.73	119	Kaldjian, 1990 (U.S. EPA)
NA	1986	NA[b]	190 (167-212)	Westat, 1988 (U.S. EPA)
266	1990	0.77	205	Glenn and Riggle, 1991

[a]Calculated assuming urban population of 181 million; see text.

[b]Not available.

The estimates of the amount of waste landfilled shown in Table 1 are not strictly comparable. The materials flow method includes a subset of the waste stream components that are counted in the two surveys. Sewage sludge, construction and demolition debris, and nonhazardous industrial wastes are accepted at some MSW landfills. If these materials are subtracted from the EPA/Westat (1988) total, the household and commercial waste landfilled is 156 Tg (154-159 Tg), which remains much higher than the alternative method estimates.

Surveying or sampling of refuse at landfills is the best approach, although some data errors are unavoidable. For example, waste acceptance data are often measured by volume at the landfill. Converting to mass requires that the density of the waste also be known. Refuse density in the industrialized countries has been estimated to range from 100 to 170 kg/m^3 on a wet weight basis (Cointreau, 1984).

Problems also exist with these estimate comparisons because of the different base years used. The Bingemer and Crutzen (1987) estimate in Table 1 was adjusted by using 1990 urban population, but the emission factor from 1987 may no longer be representative. The 1990 survey data (Glenn and Riggle, 1991) fall within the 1986 range; although waste production may have increased since 1986, the amount of waste landfilled has probably not significantly changed. Increased recycling and an increase in alternative waste management methods could potentially result in a steady-state or even a decrease in the amount of wastes going into landfills in the United States.

The upper and lower 95 percent confidence limits suggest that U.S. landfill MSW can be estimated with less than 12 percent error. This level of uncertainty is probably the best that can be achieved for this type of data. Data from other industrialized countries may achieve similar levels of certainty, but data for the less developed countries, eastern Europe, and the former Soviet Union states are not as well quantified

(Bingemer and Crutzen, 1987; Cointreau, 1984). When data are available, the estimation or sampling method needs to be considered.

3. ESTIMATING METHANE YIELD

Global landfill methane has been estimated by two methods: (1) a mass balance approach, and (2) a kinetics-based modeling approach. Both methods have merit, and are both faced with the same problems--the difficulty in estimating the methane potential of refuse, and the difficulty in determining the amount of methane actually emitted to the atmosphere. This analysis focuses on the first problem, but some discussion of the second problem is also included.

Most of the research on the methane potential of refuse has been conducted by those interested in controlling the methane emitted from landfills for a variety of reasons, including energy recovery. The methane potential of refuse can be estimated using theoretical calculations, generation data from laboratory studies, or methane recovery data from landfills. Three commonly used theoretical methods for calculating the methane potential of refuse are based on balanced stoichiometric equations, biodegradability of materials, or total organic content (EMCON, 1982). Table 2 summarizes some of the published methane potential values developed using all of these methods. To facilitate comparisons, the original values were converted to cubic meters of methane per megagram of wet refuse assuming refuse moisture content of 20 percent by weight, and to grams of methane per kilogram of wet refuse (at STP).

The most widely cited reference for global methane production (Bingemer and Crutzen, 1987) was based on methane potentials calculated by the total organic content approach. Assuming a constant landfill temperature of 35°C, a generation rate of 0.5 g methane/g of degradable organic carbon (DOC) was calculated. For the industrialized countries, which have an estimated 14-31 percent of DOC in their MSW (Bingemer and Crutzen, 1987), this results in an emission factor of 70.0 to 154.9 g methane/10^3 g wet refuse (98 to 217 m^3 methane/10^6 g wet refuse).

The optimal conditions for methane production are seldom found throughout a landfill. Actual methane yields for gas recovery operations in U.S. landfills have been estimated as 0.3-54.4 m^3 methane/10^6 g wet refuse (0.2 to 38.8 g methane/10^3 g wet refuse) (Barlaz et al., 1990) and 50-100 m^3 methane/10^6 g wet refuse (0.37.7-71.4 g methane/10^3 g wet refuse) (Augenstein and Pacey, 1990). Gas recovery data have also been used to estimate potential U.S. and global landfill methane production (Richards, 1989; Augenstein, 1990). Augenstein (1990), using a proprietary model developed by EMCON Associates, estimated that U.S. landfills produced 3-8 Tg of methane annually. He assumed upper and lower bound projections of the maximum methane production potentials to be 60 and 110 m^3 methane/10^6 g wet refuse (42.8 and 78.5 g methane/10^3 g wet refuse).

Richards (1989) estimated total landfill gas production of 39.2 x 10^9 m^3 globally, and assumed that 50 percent methane by volume results in methane emissions of 19.6 x 10^9 m^3 (14.0 Tg methane). He assumed that 100 m^3 of landfill gas per metric ton (10^6 g) of refuse was released over a 10-year period.

Table 2. Estimated Methane Potentials of Refuse Developed by Alternative Methods

Calculation Method	Estimated Methane Potential (m^3 $CH_4/10^6$ g wet refuse)	(g $CH_4/10^3$ g wet refuse)	Reference
Balanced stoichiometric equations	230 - 270	164 - 193	EMCON, 1982
Biodegradability of materials	(6 - 230) 47 (average)	(4 - 164) 34 (average)	EMCON, 1982
Biodegradability of materials	104[a]	74	Barlaz et al., 1990
Total organic carbon (TOC)	190 - 270	136 - 193	EMCON, 1982
TOC/Industrialized countries	98 - 217[b]	70 - 155	Bingemer and Crutzen, 1987
TOC/Industrialized countries	120 - 180	86 - 129	Orlich, 1990
TOC/Developing countries	30 - 60	21 - 43	Orlich, 1990
Gas recovery/ Laboratory studies	52 - 122[c]	37 - 87	Barlaz et al., 1989
Gas recovery	0.3 - 54[d]	3 - 39	Barlaz et al., 1990
Gas recovery	50 - 100[e]	38 - 71	Augenstein and Pacey, 1990

[a] Published value was 0.13 m^3 CH_4/dry 10^3 g of refuse; value shown was adjusted to wet refuse assuming 20 percent moisture.

[b] Converted from original units (g $CH_4/10^3$ g wet refuse) to volume assuming 713.8 g CH_4/m^3 at STP.

[c] Published values were 77 to 152 L CH_4/dry 10^3 g refuse; adjusted assuming 20 percent moisture.

[d] Published values were 0.00034 to 0.068 m^3 CH_4/dry 10^3 g refuse; adjusted assuming 20 percent moisture.

[e] Published values were 62 to 125 L $CH_4/10^3$ g dry waste; adjusted assuming 20 percent moisture.

The attributes, uses, and limitations of kinetics-based landfill gas models have been reviewed by several authors (EMCON, 1982; Zison, 1991; Augenstein and Pacey, 1991). In the past, it had been assumed that first-order models were more accurate than zero-order models. However, Zison (1991) has shown that order of kinetics is not very important. This becomes increasingly true for long-term predictions (Augenstein and Pacey, 1991).

The kinetics models have been shown to give reasonably accurate predictions of methane recovery for individual landfills if the parameters are chosen correctly (Augenstein and Pacey, 1991). Model performance is also improved considerably if the input data can be refined using actual recovery data from the landfill. Obtaining accurate data for the decay rate constant, the use of accurate refuse landfilling rates, and the selection of reasonable values for the degradable component are key to the performance of these models (Zison, 1991). The use of these models for global emissions modeling would require more country-specific data than the mass balance approach. As Augenstein (1990) demonstrated, the models can be adapted for generating national estimates; however, the correct parameter values will be difficult to determine for most countries. Furthermore, the inability to refine the estimates using site-specific inputs makes it impossible to achieve the degree of accuracy that is possible for individual sites.

3.1 Regression Model of Methane Recovery

The approaches described above yield quite different estimates, but the key factor appears to be the methane potential used. Generally, the estimated emissions based on methane recovery are lower by a factor of 2 or 3 than those based on DOC estimates. Another approach has been developed (Thorneloe and Peer, 1991; Campbell et al., 1991; Peer et al., 1991) which uses landfill gas recovery data to build an empirical model. This method is similar to those of Richards (1989) and Augenstein and Pacey (1990) in that it uses methane recovery data; it differs in that a statistical model is used rather than a theoretical or mechanistic model.

A key assumption of this method is that methane recovery can be used as a surrogate for methane emissions. Data from a field study of U.S. landfills with gas recovery systems were used to develop a regression model of methane recovery as a function of refuse mass. Twenty-one sites were selected that were optimizing (or appeared to be attempting to optimize) gas recovery. In addition, climate data for each site were included in the study. The main conclusion of the study was that the annual methane recovery rate was linearly correlated with the mass of refuse in the landfill, and with landfill depth (Peer et al., 1992). No statistically significant relationships were identified between annual methane recovery and climate variables (precipitation, temperature, and dew point). In this study, the effect of refuse age on gas production was also analyzed. Gas recovery correlated most strongly with refuse between 10 and 20 years old. Although results were not conclusive, they suggest that the generation time for gas production is 20 to 30 years (Peer et al., 1992). This generation time is within the range of generation times assumed by many landfill gas recovery modelers (EMCON, 1982; Augenstein and Pacey, 1990).

From these data, a linear regression model was developed based on methane recovery and refuse mass alone. The data values, regression line, and the 95 percent confidence limits of the regression coefficient are shown in Figure 1. The regression was significant ($P = 0.0003$), but much of the variability in the data is unexplained (adjusted $R^2 = 0.50$). The intercept was not significant, so the final model was forced through the intercept. An EPA report (Peer et al., 1992) provides information on the characteristics of each site that may contribute to the variabilities demonstrated in the data.

The performance of this model was compared to a first order decay model, EPA's Landfill Air Emissions Estimation Model (i.e., "Landfill Model") (Pelt et al., 1990). Like other kinetics models, a generation rate constant (k) and the total methane potential of a refuse (L_o) are required as inputs.

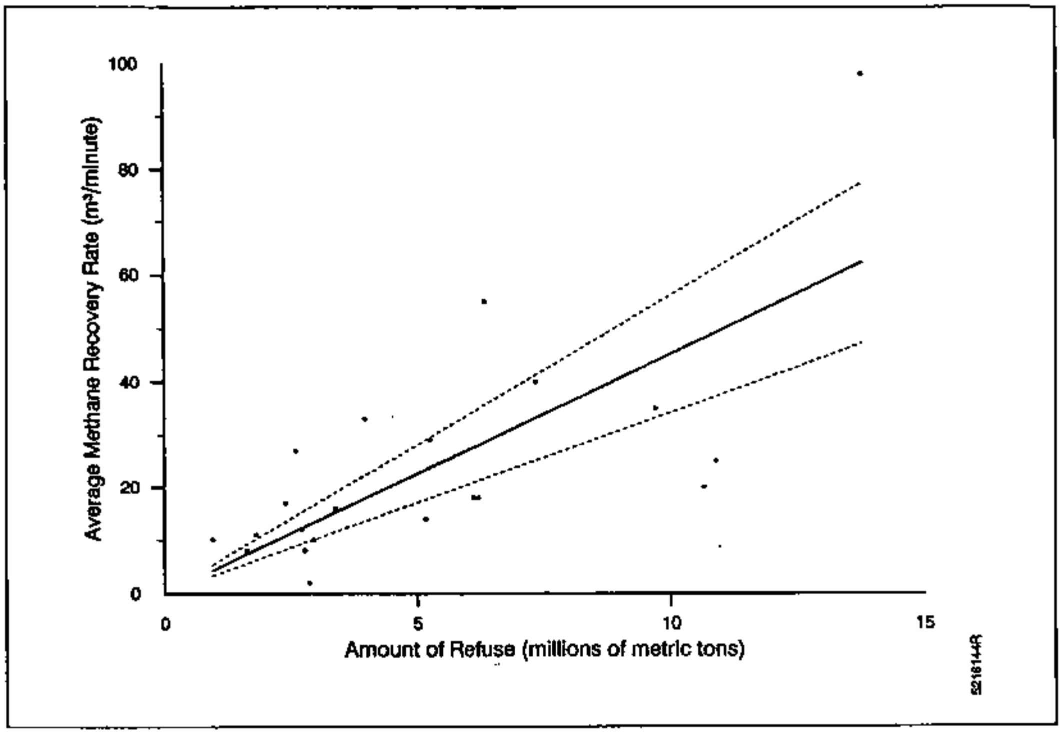

Figure 1. Methane recovery data are shown with regression line and 95 percent confidence intervals of the slope.

Assuming that the refuse has been accepted at the same annual rate over time (i.e., all submasses are of the same size), the model equation is:

$$Q_{CH_4} = L_0 * R * \left(e^{-kc} - e^{-kt}\right)$$

where:

Q_{CH_4}	=	methane generation rate at time t, m^3/yr
L_0	=	potential methane generation capacity of the refuse, m^3 methane/10^6 g wet refuse
R	=	average annual refuse acceptance rate during active life, 10^6 g/yr
k	=	methane generation rate constant, yr^{-1}
c	=	time since landfill closure, year (c = 0 for an active landfill)
t	=	time since initial refuse placement, year

The Landfill Model methodology is based on the Scholl Canyon model (EMCON, 1982) which is a first order decay equation. Because site-specific characteristics are required as model input, the Landfill Model is impractical for use on a global scale.

For the comparison to the regression model, three cases were evaluated. For the first two, the model default value for k was used (0.02 yr^{-1}) with two L_0 values: Case 1 uses 50 m^3 methane/10^6 g refuse (35.7 g methane/10^3 g wet refuse), and Case 2 uses 162 m^3 methane/10^6 g refuse (115.6 g methane/10^3 g wet refuse). The L_0 values are based on the range of published values for U.S. landfills (Ham and Barlaz, 1987; Augenstein and Pacey, 1990). Case 3 uses the same L_0 as Case 2, but assumes $k = 0.04$ yr^{-1}. This k value is suggested as a typical rate for U.S. landfills (Zison, 1991). Data from the 21 U.S. landfills (Peer et al., 1992) were used for this comparison.

The Landfill Model and regression model are compared in Table 3. The relative performance of the models can be assessed using the ratio of the predicted value to the actual methane gas recovery data. As shown by the mean of the ratios, the Landfill Model with L_0 of 50 m^3 methane/10^6 g (45.7 g methane/10^3 g wet refuse) and $k = 0.02$ yr^{-1} tends to underpredict (ratio less than 1). When L_0 is set to 162 m^3 methane/10^6 g (115.6 g methane/10^3 g wet refuse) and $k = 0.02$ yr^{-1}, the model, on average, closely corresponds to the amount of gas being collected and recovered (the mean ratio of 1.07 approximates 1). The regression model's mean ratio of 1.39 falls between those of Cases 2 and 3.

Table 3. Comparison of Estimates from Two Methane Recovery Models for 21 U.S. Landfills

Site Code	Landfill Air Emissions Estimation Model			Regression Model
	Case 1 Predicted[a]/ Actual[b]	Case 2 Predicted/ Actual	Case 3 Predicted/ Actual	Predicted[c]/Actual
Mean	0.43	1.07	1.69	1.39
Maximum	1.74	4.35	8.12	6.32
Minimum	0.15	0.36	0.33	0.47
Standard Deviation	0.34	0.85	1.56	1.24
Coefficient of Variation (CV)[d], %	79.1	79.4	92.3	89.2

[a]Predicted: The amount of methane predicted using a first-order decomposition rate equation.

[b]Actual: The amount of methane being collected and recovered at actual landfill sites.

[c]Predicted: The amount of methane predicted using the regression model.

[d]CV=(mean/s.d.)•100

The regression model performs reasonably well when compared to the Landfill Model. One advantage of using this statistical model is that only one variable is required--refuse mass. Furthermore, it is relatively easy to add new observations and further refine the model, because only average methane recovery and refuse mass are required. The confidence limits of the regression coefficient can be used to bound estimated emissions. The upper and lower 95 percent confidence limits are 6.5 and 2.5 m^3 methane/min/10^6 g wet refuse (4.6-1.8 g methane/min/10^3 g wet refuse), respectively. Assuming an average generation time of 25 years gives an average methane potential of 59.4 m^3 methane/10^6 g wet refuse (42.4 g methane/10^3 g wet refuse) with a range of 32.9 to 85.7 m^3 methane/10^6 g wet refuse (23.5 to 61.2 g methane/10^3 g wet refuse). Since this factor is based on U.S. MSW, which is generally higher in organic content than that of most other countries (Bingemer and Crutzen, 1987), it is likely to overestimate for most other countries.

3.2 Comparison of the Methods

Table 4 compares methane emissions calculated using three methods. For the first estimate, the DOC-based methane potential was used (Bingemer and Crutzen, 1987); the emissions estimate was calculated as the product of their methane production value and a refuse placement rate of 100 Tg/yr. This value for landfilled refuse was used so that results from the three methods would be comparable. Augenstein (1990) used estimated placement rates for each year from 1950 through 1990. The midpoint in his range of landfilled refuse values is approximately 100 Tg/yr. The methane emissions estimate shown for the kinetics model was calculated by Augenstein (1990) using a proprietary kinetics model. Finally, emissions calculated using the emission factors developed from the regression model, and a refuse placement rate of 100 Tg/yr are shown. The first estimate is twice as high as the last two estimates. The kinetics model and regression model approaches used similar methane potential values, and have nearly identical results. This comparison suggests that the actual model used to estimate the emissions may be less important than the assumed methane potential of the refuse.

Table 4. Comparison of Landfill Methane Emissions Calculated by Three Methods

Method Used to Determine Methane Potential	Methane Generation Potential (g CH_4/g wet refuse)	Estimated CH_4 (Tg/yr)
DOC mass balance (Bingemer and Crutzen, 1987)	0.070 to 0.155	7 to 16[a]
Kinetics model (Augenstein, 1990)	0.033 to 0.061	3 to 8[b]
Regression model (This study)	0.023 to 0.061	2 to 6[a]

a Assumes average annual refuse filling rate of 100 Tg per year (see text).

[b] Uses estimated annual placement rates from 1950 to 1990.

The validity of each of these methods is dependent on the validity of the underlying assumptions. The DOC mass balance methodology, as applied by Bingemer and Crutzen (1987), appears to overestimate the actual methane emissions. The methane generation potential calculations, while not assuming optimal conditions, do assume yields that are close to stoichiometric estimates. These yields have not been found even in laboratory studies where conditions can be controlled (e.g., Barlaz et al., 1989). The landfill methane recovery data, even allowing for capture inefficiencies, show that the high yields used by Bingemer and Crutzen (1987) are unlikely. The estimate produced by the DOC method could easily be lowered by assuming a lower percent conversion of DOC. However, it is difficult to justify *a priori* any particular percent conversion; that is, the 80 percent value used by Bingemer and Crutzen is as reasonable a value as any other. Data from gas recovery suggest that it is too high; but, as this analysis has shown, rather than adjust conversion percentages to match the gas recovery data, the data themselves can be used to model emissions.

The greatest uncertainty is associated with the assumption that all the methane produced is emitted to the atmosphere. All three of the methods compared in this analysis share this assumption. The main argument against this assumption is that landfill methane may be oxidized to CO_2 by methanotrophs before it reaches the surface (Whalen et al., 1990; Senior, 1990); while theoretically probable, it has been difficult to document the degree to which these processes reduce methane emissions from landfills. Laboratory studies of methane consumption by bacteria found in landfill cover showed that the organisms consumed 10 percent of methane gas (Mancinelli and McKay, 1985). Orlich (1990) assumed that 40 to 50 percent of the methane was oxidized before it reached the surface; however, he does not document the basis for using these relatively high values. Clearly, this is an important area for further research.

4. CONCLUSIONS

Improving the emission estimates for global methane from MSW landfills will require the acquisition of country-specific data on refuse quantities and management, and the development of better models for estimating emissions. As this analysis has shown, the underlying assumptions can have a very large effect on the methane emissions estimate. Unfortunately, verifying model results is difficult because the true values of the parameters are either unknown or not known with great certainty. Annual refuse production data, for example, are available for some countries. These values are usually based on surveys of municipal refuse collection for large urban areas, where the results are then extrapolated to the rest of the population. These data are assumed to be the true values in this analysis for purposes of model evaluation, but some error is inherent in the sample process.

Waste generation and management data from other industrialized countries may be of similar quality to that of the United States, but the rest of the world poses greater difficulties. Reliable information from the countries of eastern Europe and the former Soviet Union is nearly nonexistent. Some data are available for large cities in the less-developed countries (e.g., Cointreau, 1984; Holmes, 1984; Thomé-Kozmiensky, 1986). Much of these data are based on surveys at the point of origin of the waste or at collection boxes rather than at the landfills. Scavenging by humans and by animals may reduce the amount of material actually landfilled by as much as 10 percent (Bartone, 1990). Furthermore, volume reduction by burning is still common at landfills in less-developed countries, further reducing the amount of biodegradable materials. Even less is known about the fate of wastes in rural areas, although the assumption that all of it is composted, or otherwise used, is probably reasonable for most of the less-developed countries (Bingemer and Crutzen, 1987). Obtaining better estimates of the fate of refuse in the less-developed countries and of the methane that may be produced by other disposal practices (such as burning) is critical for improving the accuracy of the global methane budget.

This analysis suggests that the initial estimates of global landfill methane are too high. As shown by this analysis, the estimates of landfill waste used by Bingemer and Crutzen (1987) may actually be too low for the United States and, by analogy, also for other industrialized counties. The greatest source of error, however, is in the assumptions used to estimate the methane emissions from a given mass of landfill refuse. The assumed methane potential was shown to affect the emissions estimate by a factor of two or more. Methane recovery data should be used to set an upper limit to the methane potential. Even if the recovery is not completely efficient, it is also likely that some methane is destroyed by microorganisms in the soil or clay cap. The composition of U.S. refuse, however, is higher in degradable carbon compounds than that of most other countries. Using U.S. methane recovery data would overestimate methane production for most of the world. Data from landfill gas recovery operations in other countries could be used to calibrate the U.S. emission factor.

Two issues that could also affect the estimates of landfill methane emissions are the efficiency of gas recovery and the potential for oxidation of methane in the soil. Gas recovery systems do not capture 100 percent of the gas; the recovery efficiency is generally estimated to range from 50 to 90 percent (Augenstein and Pacey, 1990), but no field verification of this assumption has been found by the authors. Therefore, emission factors derived using gas recovery data may have to be adjusted upwards to account for the lost gas. Offsetting the recovery inefficiency, however, is the potential for destruction of methane by methanotrophs in the soil. All models assume that all of the methane produced is eventually emitted. As previously discussed, however, evidence to the contrary exists (Mancinelli and McKay, 1985; Senior, 1990; Whalen et al., 1990). The development of methane budgets based on measured values may help resolve this issue; however, the considerable variability in landfill design, construction, and operation, and in refuse composition is a very large hurdle to this type of research. Until this hurdle has been overcome, models such as the ones described here will have to suffice.

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