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Estimation of Waste Component-Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data

FLORENTINO B. DE LA CRUZ AND MORTON A. BARLAZ*

Department of Civil, Construction, and Environmental Engineering, Campus Box 7908, North Carolina State University, Raleigh, North Carolina 27695-7908

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The current methane generation model used by the U.S. EPA (Landfill Gas Emissions Model) treats municipal solid waste (MSW) as a homogeneous waste with one decay rate. However, component-specific decay rates are required to evaluate the effects of changes in waste composition on methane generation. Laboratory-scale rate constants, k_{lab}, for the major biodegradable MSW components were used to derive field-scale decay rates (k_{field}) for each waste component using the assumption that the average of the field-scale decay rates for each waste component, weighted by its composition, is equal to the bulk MSW decay rate. For an assumed bulk MSW decay rate of 0.04 yr^{-1}, k_{field} was estimated to be 0.298, 0.171, 0.015, 0.144, 0.033, 0.02, 0.122, and 0.029 yr^{-1}, for grass, leaves, branches, food waste, newsprint, corrugated containers, coated paper, and office paper, respectively. The effect of landfill waste diversion programs on methane production was explored to illustrate the use of component-specific decay rates. One hundred percent diversion of yard waste and food waste reduced the year 20 methane production rate by 45%. When a landfill gas collection schedule was introduced, collectable methane was most influenced by food waste diversion at years 10 and 20 and paper diversion at year 40.

Introduction

Landfills represent the dominant disposal practice for municipal solid waste (MSW) in the United States as well as in many other countries. For example, in the United States, it is estimated that 54% of MSW is buried in landfills (*1*) and the corresponding values for Canada (*2*), Australia and the European Union (*3*) are 77, 54, and 45%, respectively. The anaerobic decomposition of waste in landfills results in methane generation and landfills are estimated to be the second largest source of anthropogenic methane emissions in the United States and on a global level (*4, 5*).

In commonly used predictive models, the quantity of methane produced and its rate of production are governed by two factors, the ultimate methane yield (L_0) and a decay rate (k). These factors appear in different forms in different models. The most common landfill gas model in the United States is the U.S. EPA's Landfill Gas Emissions Model (LandGEM) as given in eq 1 (*6*):

$$Q_n = k \cdot L_0 \cdot \sum_{i=0}^{n} \sum_{j=0}^{0.9} \frac{M_i}{10} \cdot e^{-k \cdot t_{i,j}} \quad (1)$$

where Q_n is the CH_4 generation rate ($m^3\ yr^{-1}$) in year n, k is the waste decay rate (yr^{-1}), L_0 is the CH_4 generation potential (m^3 of CH_4 Mg^{-1} wet waste) (Mg = metric ton), M_i is waste mass placement in year i (Mg), j is the deciyear time increment, and t is time (yr). The form of the model that is used in other countries such as The Netherlands and the United Kingdom is similar (*7, 8*). However, in these countries, the model is referred to as a multiphase model in which total methane production is calculated as the sum of individual implementations of eq 1 for waste components that are classified as slowly, moderately, and rapidly degradable. This contrasts with the approach used in LandGEM where MSW is treated as a single substrate.

The rate at which methane production occurs, which is governed by k, has implications for the fraction of the generated methane that is captured. This is because the fraction captured increases with time after burial as a landfill's gas collection system is installed and then expanded. Estimates of the temporally weighted landfill methane collection efficiency for multiple gas collection scenarios and decay rates have been described (*9*). In general, the fraction of gas that is collected decreases as the decay rate increases.

Over the past several years, there has been increasing interest in the diversion of biodegradable waste from landfills. Diversion programs are most prominent in Europe where the European landfill directive prohibits the landfill disposal of biodegradable waste. Programs to divert food and yard waste, primarily to aerobic composting, are increasing in the United States. The implementation of diversion programs has implications for both the rate and quantity of methane produced from landfills and requires information on both L_0 and k for individual waste components. Data on L_0 for individual waste components have been published but data on k are lacking (*10*).

The objective of this paper is to present a method to estimate a field-scale decay constant for each of the major biodegradable components of MSW using laboratory-scale methane generation data. These decay rates are then used to explore the effect of waste diversion programs and their resulting changes in the mass and composition of landfilled MSW, on methane generation and collection using the LandGEM formulation applied to waste components individually.

Gas Production Modeling and Data Analysis

This study emphasizes the LandGEM formulation because of its pervasive use in both engineering and regulatory practice. The derivation of LandGEM and its relationship to MSW biodegradation is given in the Supporting Information. Critical aspects of eq 1 as used for this study are that it assumes no lag time and its derivation is based on the reactive mass of carbon as opposed to the total mass. As illustrated by eq 1, k is the only parameter that can be adjusted to consider factors such as pH, moisture content, and temperature, all of which will influence the methane production rate.

Previously published methane production data for newsprint (ONP), office paper (OFF), old corrugated containers (OCC), old magazines (OMG), food waste (FW), grass (G), leaves (L), and branches (B) were used to calculate laboratory-scale decay rates ($k_{lab,i}$) as described here (*10*). Waste decomposition can be described by the first-order decay rate in eq 2 in terms of the reactive mass of carbon.

* Corresponding author phone: (919)515-7676; fax: (919)515-7908; e-mail: barlaz@eos.ncsu.edu.

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$$\frac{dm}{dt} = -km \quad (2)$$

where m is the reactive mass of C in the refuse present at time t (kg), k is the first-order decay rate (yr^{-1}), and t is time (yr). Integration of eq 2 yields an expression for the amount of refuse remaining in a reactor at time t during decomposition.

$$\ln\left(\frac{m}{m_0}\right) = -kt \quad (3)$$

where m_0 is the initial reactive mass of C in the refuse. Given that the dominant mass loss process is anaerobic decomposition, the mass loss of reactive C at any time can be calculated from the methane yield at that time (m_{CH_4}). The initial reactive mass of carbon, m_0, was calculated from the measured cumulative methane yield. The mass of reactive C remaining at any time is given by eq 4:

$$m = m_0 - (m_{CH_4} + m_{CO_2}) \quad (4)$$

Substituting eq 4 into eq 3 and rearranging results in a linear form of the first-order decay equation:

$$\ln(m_0 - (m_{CH_4} + m_{CO_2})) = -kt + \ln(m_0) \quad (5)$$

Methane production data from 2-L reactors filled with the aforementioned waste components were fit to eq 5 to estimate a first-order decay constant, $k_{lab,i}$, by linear regression. In each case, the decay rate was estimated using the linear part of the curve and lag times were not considered as LandGEM does not consider lag times.

To relate $k_{lab,i}$ to a decay rate that is applicable at field scale, $k_{field,i}$, it was assumed that the weighted average decay rate for a waste mixture is equal to the bulk MSW decay rate ($k_{field,MSW}$). This is illustrated by eq 6. To force the left side of eq 6 to be equal to a constant, a correction factor, f, was introduced. Once f is determined, the field-relevant decay rate for each waste component (i), $k_{field,i}$, can be calculated from eq 7.

$$f \times \sum_{i=1}^{n} k_{lab,i} \times (\text{wt.fraction})_i = k_{field,MSW} \quad (6)$$

$$k_{field,i} = f \times k_{lab,i} \quad (7)$$

where i is the ith waste component.

Initially, eqs 6 and 7 were used with a decay rate of 0.04 and the composition of waste as discarded in 1990 (*11*). This decay rate is the default value given in the U.S. EPA's database (AP-42) for regions that receive greater than 63 cm of precipitation annually (*12*). The 1990 waste composition was selected because it corresponds approximately to the time when the landfill gas data used to develop the AP-42 default values were collected. In the Results and Discussion section, eqs 6 and 7 are applied to a number of alternate waste compositions to develop an estimate of the range of appropriate values for $k_{field,i}$ for an assumed $k_{field,\ MSW}$. In addition, this method was used at bulk MSW decay rates of 0.02 and 0.12 yr^{-1}. The lower value represents landfills in arid regions (<63 cm precipitation per year as defined in AP-42), whereas the higher value is representative of recent estimates for bioreactor landfills (*13*–*15*). For any set of assumptions for waste composition and $k_{field,MSW}$, f, and then $k_{field,i}$ can be calculated.

Results and Discussion

The linearized methane production data for office paper are presented in Figure 1 and the data for other components are presented in Figures S1–S7 in the Supporting Information. The computed decay rates ($k_{lab,i}$) for individual waste components based on laboratory data are presented in Table 1. As expected, food waste and grass have the highest decay rates. The relatively high decay rate for leaves is less intuitive and is a function of the relatively short duration of methane production (Figure S6). Field values estimated using eqs 6 and 7 and 1990 waste composition are presented in Table 2 for assumed overall decay rates of 0.04 and 0.12 yr^{-1}.

To evaluate one source of variability in $k_{field,i}$, it was calculated for a range of waste composition data including both the national average composition of waste at different times and statewide waste composition data that were

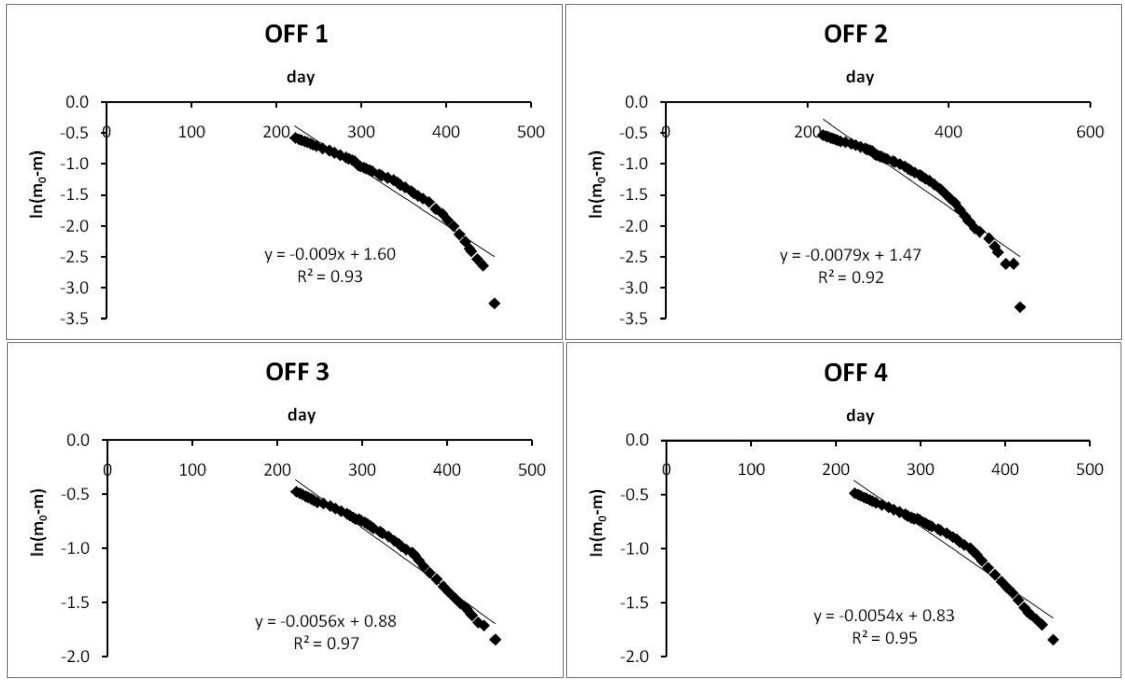

FIGURE 1. Linearized first-order decomposition of office paper (OFF).

TABLE 1. Laboratory-Scale Decay Rates, Methane Yields, and Moisture Contents for MSW Constituents

component	average (yr^{-1})[a]	L_0 (m^3/dry Mg)[b]	moisture (wet wt %)[c]
office paper	3.08(1.03)	217.3	6
grass	31.13(9.32)	144.4	60
branches	1.56(0.30)	62.6	30
newspaper	3.45(0.47)	74.3	6
corrugated containers	2.05(0.07)	152.3	5
food	15.02(0.30)	300.7	70
leaves	17.82(4.28)	30.6	30
coated paper	12.68(4.13)	84.4	6

[a] Data are the average of four replicates except in the cases of leaves and branches where one reactor leaked and was excluded from the data set. The correlation coefficient varied from 0.91 to 0.99 across all regressions. The standard deviation is given parenthetically. [b] L_0 data adopted from ref (*10*). [c] Moisture data adopted from ref (*21*).

recently summarized (*16*). All waste composition data are summarized in Table S1 (*16*). Estimates of $k_{field,i}$ for a range of waste composition data at bulk MSW decay rates of 0.04, 0.02, and 0.12 yr^{-1} are presented in Tables 3 and 4. Only average data are presented in Table 4 as $k_{field,i}$ for each waste composition is directly proportional to the assumed bulk MSW decay rate.

There are several assumptions required to implement the method presented here including (1) knowledge of the initial value of $k_{field,MSW}$, (2) a representative waste composition for use in eq 6, and (3) the absence of interactions between waste components. There is significant uncertainty in the $k_{field,MSW}$ as documented in recent estimates (*13*−*15*) as well as in AP-42. When the AP-42 default parameters for k and L_0 were applied to the data sets used to estimate these parameters, predicted methane collection ranged from 38% to 492% of that measured. The method described here does not reduce the uncertainty in $k_{field,MSW}$, which is the subject of other studies (*13*−*15*). Although the waste component-specific estimates vary with the assumed composition, as illustrated in Tables 3 and 4, the coefficients of variation (std. dev./mean) of the estimated values for $k_{field,i}$ were about 27%.

In the experiments conducted to measure $k_{lab,i}$, waste components were decomposed individually, which leads to questions about whether interactions between waste components are important. However, two aspects of the experimental design mitigate this issue: (1) each component was seeded with decomposed refuse and (2) ammonia and phosphate concentrations were maintained to ensure that methane production was not nutrient-limited. Nonetheless, the values of $k_{field,i}$ are not applicable at the extremes; e.g., a landfill containing 100% newsprint would likely be nutrient-limited.

The values of $k_{field,i}$ derived in this manuscript are compared to values recommended by the Intergovernmental Panel on Climate Change (IPCC) in Figure 2. The $k_{field,i}$ values were calculated at a $k_{field,MSW}$ of 0.05 yr^{-1} to correspond to a value where the IPCC has a published estimate for both bulk MSW and individual waste components (*17*). With the exception of food waste, the component categories used by the IPCC differ somewhat from the categories used in this work. Thus, direct comparisons are imperfect and the waste categories given in Figure 2 are based on the most related waste components. All IPCC default decay rates are given in Table S2 (*17*).

The decay rates for leaves, grass, and branches are 327%, 645%, and −63% of the IPCC value for the garden and park category. The weighted average decay rate for yard waste assuming 30.3% grass, 40.1% leaves, and 29.6% branches (*18*) is 0.20 yr^{-1}, which is a factor of 4 greater than the IPCC value of 0.05 yr^{-1}. The decay rates for textiles, ONP, OFF, and mixed paper calculated in this study are all within 10% of the IPCC value for the paper and textiles category. In contrast, the decay rates for OCC and glossy paper are 280% and 39% greater than the IPCC value, respectively. The decay rate for food waste calculated in this study (0.180 yr^{-1}) is about 200% greater than the IPCC value but comparable to the decay rates of 0.116 and 0.187 yr^{-1} to 0.231 yr^{-1} for rapidly degradable waste that are used in Dutch and British multiphase models (*19*).

TABLE 2. Field-Scale Decay Rates Based on 1990 Waste Composition at Bulk MSW Decay Rates of 0.04 and 0.12 yr^{-1}

MSW component	discarded composition[a] (wet wt %)	k_{lab} (yr^{-1})	comments	$k = 0.04$ $k_{field} = k_{lab} \times f$ (yr^{-1})	$k = 0.12$ $k_{field} = k_{lab} \times f$ (yr^{-1})
textiles (cotton)[b]	0.71	3.08	equal to office paper	0.020	0.059
wood (non-C&D)	7.02	1.56	equal to branches	0.010	0.030
food waste	12.10	15.02		0.096	0.289
leaves	7.18	17.82		0.114	0.343
grass	5.43	31.13		0.200	0.600
branches	5.30	1.56		0.010	0.030
miscellaneous organics	1.40	13.68[b]	equal to average of food, wood, grass, leaves, and branches	0.088	0.263
newspaper	5.17	3.45		0.022	0.066
office paper	4.97	3.08		0.020	0.059
coated paper	1.47	12.68		0.081	0.244
corrugated containers/ Kraft bags	7.26	2.05		0.013	0.040
mixed paper	11.66	3.27	equal to average of office paper and newsprint	0.021	0.063
total biodegradable fraction	69.66[c]				
assumed bulk MSW decay rate				0.040	0.120
correction factor, f				0.0064	0.0192

[a] The composition of the waste discarded was calculated from the difference in waste generation and recovery as given in ref (*11*). [b] Roughly ~23.7% of textiles consumed in the United States from 2001 to 2005 were made of cotton ref (*22*). [c] Other components are inert (e.g., plastic and glass) and therefore the total does not sum 100%.

TABLE 3. Summary of Field-Scale Decay Rates Estimated for Traditional Landfill Scenario (k = 0.04 yr^{-1})[a]

	national						states						
component	1990	1995	2000	2005	CA	DE	GA	MN	OR	PA	WI	avg.	std. dev.
textiles (cotton)	0.020	0.022	0.025	0.024	0.027	0.035	0.034	0.034	0.028	0.030	0.047	0.029	0.008
wood (non-C&D)	0.010	0.011	0.012	0.012	0.014	0.018	0.017	0.017	0.014	0.015	0.024	0.015	0.004
food waste	0.096	0.105	0.120	0.118	0.133	0.170	0.165	0.167	0.135	0.145	0.229	0.144	0.038
yard trimmings, leaves	0.114	0.125	0.143	0.140	0.157	0.202	0.196	0.198	0.160	0.172	0.272	0.171	0.045
yard trimmings, grass	0.200	0.218	0.249	0.244	0.275	0.353	0.342	0.345	0.280	0.300	0.475	0.298	0.078
yard trimmings, branches	0.010	0.011	0.012	0.012	0.014	0.018	0.017	0.017	0.014	0.015	0.024	0.015	0.004
misc. organics	0.088	0.096	0.110	0.107	0.121	0.155	0.150	0.152	0.123	0.132	0.209	0.131	0.034
newspaper	0.022	0.024	0.028	0.027	0.031	0.039	0.038	0.038	0.031	0.033	0.053	0.033	0.009
office paper	0.020	0.022	0.025	0.024	0.027	0.035	0.034	0.034	0.028	0.030	0.047	0.029	0.008
coated paper	0.081	0.089	0.102	0.100	0.112	0.144	0.139	0.141	0.114	0.122	0.194	0.122	0.032
OCC/Kraft bags	0.013	0.014	0.016	0.016	0.018	0.023	0.023	0.023	0.018	0.020	0.031	0.020	0.005
mixed paper	0.021	0.023	0.026	0.026	0.029	0.037	0.036	0.036	0.029	0.031	0.050	0.031	0.008

[a] Waste composition data used to derive the decay rates presented here are given in Table S1.

TABLE 4. Summary of Field-Scale Decay Rates Estimated for Dry (k = 0.02) and Bioreactor (k = 0.12) Landfill Scenarios[a]

	k = 0.02 yr^{-1}			k = 0.12 yr^{-1}		
component	avg.	std. dev.	range	avg.	std. dev.	range
textiles (cotton)	0.015	0.004	0.01−0.023	0.088	0.023	0.059−0.141
wood (non-C&D)	0.007	0.002	0.005−0.012	0.045	0.012	0.030−0.071
food waste	0.072	0.019	0.048−0.115	0.432	0.113	0.289−0.688
yard trimmings, leaves	0.085	0.022	0.057−0.136	0.512	0.134	0.343−0.816
yard trimmings, grass	0.149	0.039	0.100−0.238	0.895	0.234	0.599−1.426
yard trimmings, branches	0.007	0.002	0.005−0.012	0.045	0.012	0.030−0.071
misc. organics	0.066	0.017	0.044−0.105	0.393	0.103	0.263−0.627
newspaper	0.017	0.004	0.011−0.026	0.099	0.026	0.066−0.158
office paper	0.015	0.004	0.010−0.023	0.088	0.023	0.059−0.141
coated paper	0.061	0.016	0.004−0.097	0.365	0.095	0.244−0.581
OCC/Kraft bags	0.010	0.003	0.007−0.016	0.059	0.015	0.039−0.094
mixed paper	0.016	0.004	0.010−0.025	0.094	0.025	0.063−0.150

[a] Waste composition data used to derive the decay rates presented here are given in Table S1.

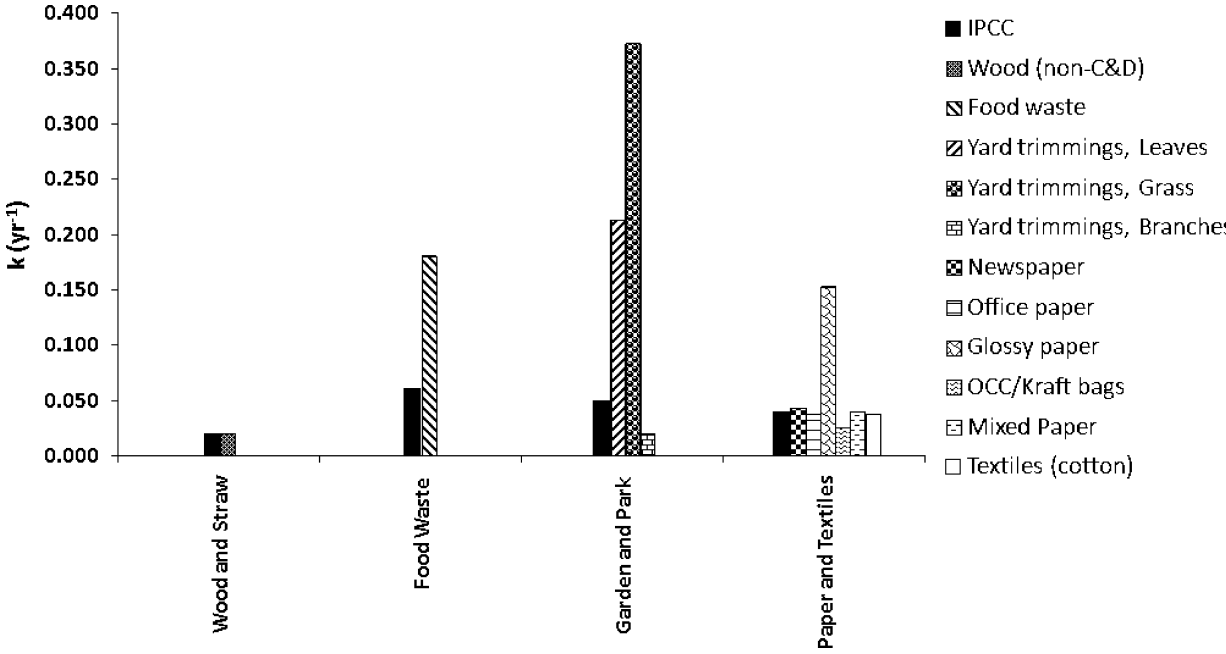

FIGURE 2. Comparison between the IPCC decay rates and the values calculated in this study. The *x*-axis gives the IPCC MSW components categories.

Effect of Changes in Waste Composition on Methane Production

Yard waste is banned from landfills in many states, 60% of the U.S. population has access to curbside recycling programs that are increasingly accepting many types of fiber, and there is increasing interest in the diversion of food waste from landfills (*1*). Five scenarios were analyzed to assess the impact of hypothetical diversion programs

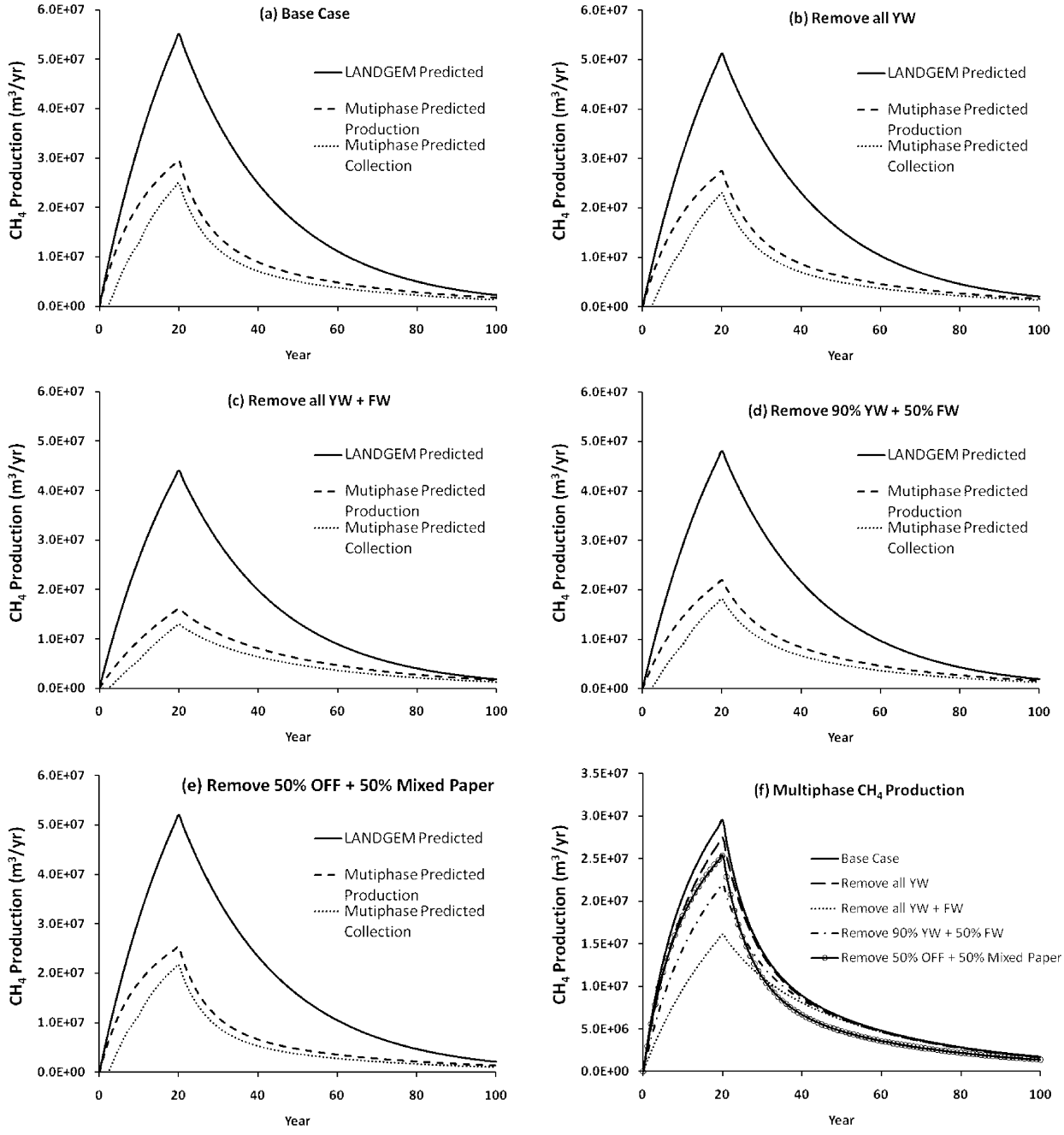

FIGURE 3. Methane production rate for various yard waste (YW), food waste (FW), and paper diversion scenarios. The decay rates for individual waste components are given in Table 3 and assume a bulk MSW decay rate of 0.04. Yard waste includes 30.3% grass, 40.1% leaves, and 29.6% branches based on ref (*18*). The methane collection schedule is given in the text.

and their resulting changes in mass and waste composition on methane production: (1) a base case using the average waste composition from states and EPA (Table S1), (2) all yard waste removed from the discards stream, (3) all yard waste and food waste removed from the discards stream, (4) 90% of yard waste and 50% of food waste removed from the discards stream, and (5) 50% of office paper and 50% of mixed paper removed from the discards stream. In scenario 5, newspaper was not removed from the discards stream because newsprint recycling programs are generally mature and it was assumed that the waste composition data already reflect substantial newsprint recycling. The initial basis was 10^6 Mg of waste buried annually for 20 years. For cases 2, 3, 4, and 5, waste burial was 9.30×10^5, 7.99×10^5, 8.71×10^5, and 9.42×10^5 Mg, annually. Methane production was calculated using a multiphase implementation of eq 1 in which total predicted methane production was the sum of the methane production from individual waste components with unique values of k and L_0. The component-specific L_0's are given in Table 1. For comparison, methane production was also calculated using the LandGEM formulation in which the mass was adjusted for each diversion scenario but the k (0.04 yr^{-1}) and L_0 (100 m^3 of CH_4 Mg^{-1}) remained constant at the AP-42 defaults.

Predicted methane production rates using the LandGEM approach and the multiphase approach with component-specific values of k and L_0 are presented in Figure 3a−e for each scenario. In all cases, the maximum methane production rate is the last year of waste burial as there is no lag time in eq 1. The multiphase approach results in lower methane production rates relative to LandGEM because the LandGEM simulations used an L_0 of 100 m^3 of CH_4 Mg^{-1}, whereas the comparable L_0's for cases 1−5, as calculated using methane

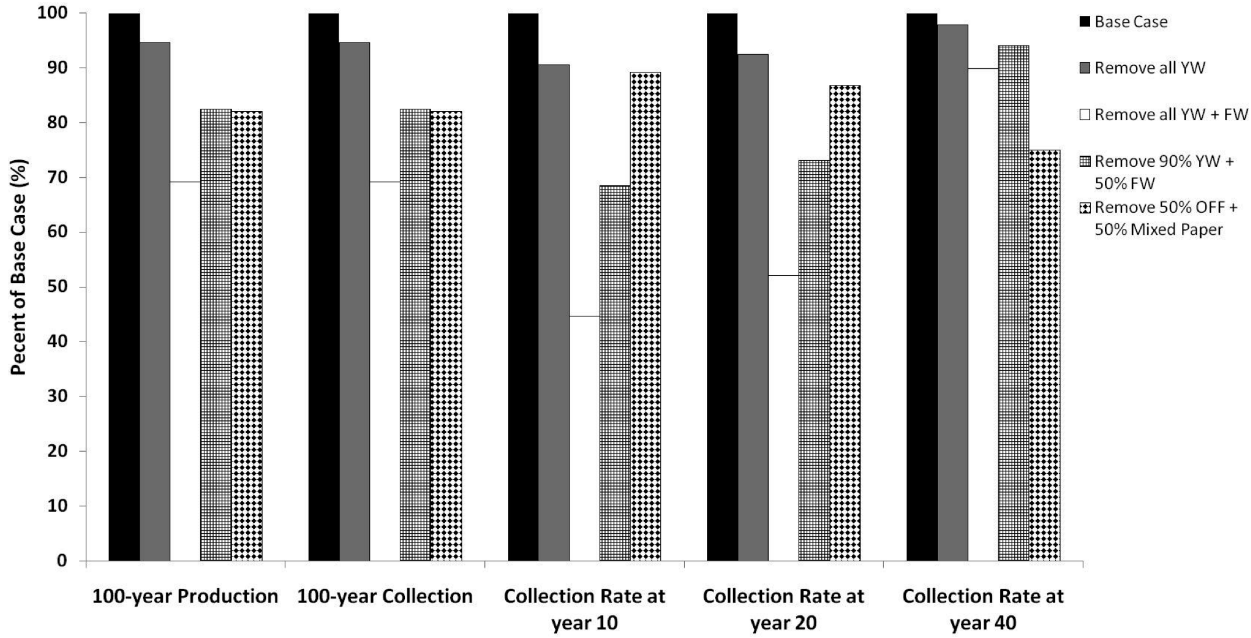

FIGURE 4. Cumulative methane collection and collection rate at different years for various yard waste (YW), food waste (FW), and paper diversion scenarios. All comparisons are based on the multiphase approach.

yields in Table 1, are 50.6, 51.5, 45.1, 48.4, and 44.1 m^3 of CH_4 Mg^{-1}, respectively.

The effect of diversion using the multiphase approach only is presented in Figure 3f. At year 20, the methane production rate is 93%, 55%, 75%, and 86% of the base case for scenarios 2−5, respectively. For cases 3−5, this is well below the mass reductions of 20%, 13%, and 6%, respectively, which emphasizes the need to consider waste composition in estimating methane production. Of course, year 20 is a snapshot and the reduction in methane production changes with time. When the multiphase approach is used, the decreases in cumulative methane over 100 years are 5%, 31%, 18%, and 18% relative to the base case for cases 2−5, respectively. When LandGEM is used, the reductions would be proportional to the mass reductions only and the corresponding reductions in cumulative methane are 7%, 20%, 13%, and 6% for cases 2−5, respectively.

The methane production rates converge at about year 40 for cases 1−4 (Figure 3f). Methane production is affected by both the reduction in tonnage and the removal of degradable materials. Given their relatively high decay rates, food waste, grass, and leaves are the primary substrates for methane production during the early stages of decomposition. Later, paper dominates the methane production curve. The mass of paper does not change among cases 1−4. Thus, the methane production rate curves converge where paper is the dominant contributor to methane production. The opposite trend is observed when paper was removed from the discarded stream (Figure 3f). The significance of removing paper is realized later in the methane curve's life as paper decomposes more slowly and its effects are masked somewhat by rapidly decomposing material in early years of decomposition.

One source of uncertainty is the methane yield attributable to each waste component as the waste component-specific L_0's are based on one set of substrates (*10*). An L_0 of 300.7 m^3 of CH_4·dry Mg of food waste^{-1} was reported initially and used here. However, a second study reported food waste yields of 152.9 and 200.7 m^3 of CH_4·dry Mg^{-1} (*20*). If the average methane yield for food waste is utilized (218.1 m^3 of CH_4·dry Mg^{-1}), then the year 20 methane production rate is 61% and 78% of the base case scenarios for cases 3 and 4, respectively, as opposed to 55% and 75% of the base case at a food waste L_0 of 300.7 m^3 of CH_4·dry Mg^{-1}.

Finally, the effect of various diversion strategies on methane collection is considered. As described previously, the fraction of the generated methane that is collected increases with time as the gas collection system is extended to the youngest waste. A methane collection scenario was adopted from (*9*) in which the collection efficiency was 0% in years 1 and 2, 50% in year 3, 70% in year 4, 75% in years 5−10, and 95% through year 100 based on the assumption that a final cover is placed in year 10. The year refers to waste age as opposed to the landfill's age. This collection schedule results in a 100-year temporally averaged collection efficiency of about 83% (i.e., total collection/total production) for $k = 0.04$ yr^{-1}.

Methane rate curves based on collected gas are presented in Figure 3a−e for cases 1−5, and methane collection is compared in Figure 4. There is a significant reduction in the rate of methane collection relative to base case in years 10 and 20 when the relatively fast degrading food waste is removed (cases 3 and 4). However, in year 40, the reduction in methane collection can be attributed largely to the removal of slowly degrading materials such as paper (case 5). These observations emphasize the need to consider changes in waste mass and composition in landfill gas modeling and have implications for both estimates of fugitive emissions and plans for landfill gas to energy programs. Clearly, LandGEM in its current implementation with one set of parameters to characterize MSW is not useful for exploring the sensitivity of changes in waste composition on methane production; rather, a component-specific approach is required.

Supporting Information Available

The derivation of LandGEM, waste composition data used for this study, IPCC default decay rates, and transformed plots of methane production data. This material is available free of charge via the Internet at http://pubs.acs.org.

Acknowledgments

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Literature Cited

(1) Municipal solid waste in the United States 2007 Facts and Figures; EPA530-R-08-010; U.S. Environmental Protection Agency: Washington, D.C., 2008.

(2) Human Activity and the Environment: Annual Statistics 2005; catalogue no. 16-201-XPE; Statistics Canada, Environmental Accounts and Statistics Division, System of National Accounts: Ottawa, Ontario, Canada, 2005; available at http://www.statcan.gc.ca/pub/16-201-x/16-201-x2005000-eng.pdf (accessed January 8, 2010).

(3) Submission to the Productivity Commission Inquiry into Waste Generation and Resource Efficiency; Australian Government Department of the Environment, Water, Heritage and the Arts 2006; available at http://www.environment.gov.au/settlements/publications/waste/pubs/deh-submission.pdf (accessed January 8, 2010).

(4) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990−2007; U.S. Environmental Protection Agency: Washington, D.C., 2009; EPA 430-R-09-004.

(5) Denman, K. L.; Brasseux, G.; Chidthaisong, A.; Ciais, P.; Cox, P. M.; Dickinson, R. E.; Hauglustaine, D.; Heinze, C.; Holland, E.; Jacob, D.; Lohmann, U.; Ramachandran, S.; da Silva Dias, P. L.; Wofsy, S. C.; Zhang, X. Couplings between changes in the climate system and biogeochemistry. In *Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Solomon, S., Qin, D., Manning, M.,Eds.; Cambridge University Press: Cambridge, U.K., 2007.

(6) *Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide*; U.S. Environmental Protection Agency: Washington, D.C., 2005.

(7) Oonk, H.; Weenk, A.; Coops, O.; Luning, L. Validation of landfill gas formation models. 1994, TNO Report94−315.

(8) Gregory, R. G.; Attenborough, G. M.; Hall, D. H.; Deed, C. The Validation and Development of an Integrated Landfill Gas Risk Assessment Model: GasSim. In *Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium, S. Margherita di Pula, Cagliari, Italy*, October 6−10, 2003; CISA, Environmental Sanitary Engineering Centre: Cagliari, Italy, 2003.

(9) Barlaz, M. A.; Chanton, J. P.; Green, R. B. Controls on landfill gas collection efficiency: Instantaneous and lifetime performance. *J. Air Waste Manag. Assoc.* **2009**, *59*, 1399–1404.

(10) Eleazer, W. E.; Odle, W. S.; Wang, Y. S.; Barlaz, M. A. Biodegradability of municipal solid waste components in laboratory-scale landfills. *Environ. Sci. Technol.* **1997**, *31*, 911–917.

(11) Characterization of Municipal Solid Waste in the United States: 1990 Update; EPA 530-SW-90-042; U.S. Environmental Protection Agency: Washington, D.C., 1990.

(12) *AP-42 Emission Factors for Municipal Solid Waste Landfills - Supplement E; November 1998*; U.S. Environmental Protection Agency: Washington, D.C., 1998; available at http://www.epa.gov/ttn/chief/-ap42/ch02/final/-c02s04.pdf.

(13) Tolaymat, T. M.; Green, R. B.; Hater, G. R.; Barlaz, M. A.; Black, P.; Bronston, D.; Powell, J. Evaluation of Landfill Gas Decay Constant for Municipal Solid Waste Landfills Operated as Bioreactors. *J. Air Waste Manag. Assoc.* **2010**, *60*, 91–97.

(14) Barlaz, M. A.; Bareither, C. A.; Hossain, A.; Saquing, J.; Mezzari, I.; Benson, C. H.; Yazdani, R. Performance of North American Bioreactor Landfills: II. Chemical and Biological Characteristics. *J. Environ. Eng.*, in press.

(15) Faour, A.; Reinhart, D. R.; You, H. First-order kinetic gas generation model parameters for wet landfills. *Waste Manage* **2007**, 946–953.

(16) Staley, B. F.; Barlaz, M. A. Composition of Municipal solid waste in the US and implications for carbon sequestration and methane yield. *J. Environ. Eng.* **2009**, 901–909.

(17) IPCC Intergovernmental Panel on Climate Change. *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (Volume 3)*, IPCC National Greenhouse Gas Inventory Program; IPCC, WMO: Geneva, Switzerland, 2006.

(18) Oshins, C.; Block, D. Feedstock composition at composting sites. *Biocycle* **2000**, *41*, 31–34.

(19) Scharff, H.; Jacobs, J. Applying guidance for methane emission estimation for landfills. *Waste Manage.* **2006**, *26*, 417–429.

(20) Staley, B. F.; Xu, F.; Cowie, S. J.; Barlaz, M. A.; Hater, G. R. Release of trace organic compounds during the decomposition of municipal solid waste components. *Environ. Sci. Technol.* **2006**, *40*, 5984–5991.

(21) Tchobanoglous, G.; Theisen, H.; Vigil, S. A. *Integrated Solid Waste Management: Engineering Principles and Management Issues*; McGraw-Hill: New York, 1993; p 978.

(22) Fiber Economics Bureau. U.S. Manufactured Fiber, Cotton and Wool End Use Survey. *Fiber Organon* **2006**, *10*, 187−204.

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