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Characterization of Uncertainty in Estimation of Methane Collection from Select U.S. Landfills

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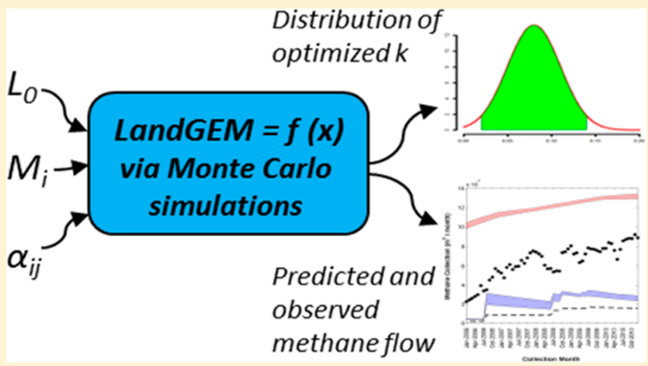
S *Supporting Information*

ABSTRACT: Methane is a potent greenhouse gas generated from the anaerobic decomposition of waste in landfills. If captured, methane can be beneficially used to generate electricity. To inventory emissions and assist the landfill industry with energy recovery projects, the U.S. EPA developed the Landfill Gas Emissions Model (LandGEM) that includes two key parameters: the first-order decay rate (k) and methane production potential (L_0). By using data from 11 U.S. landfills, Monte Carlo simulations were performed to quantify the effect of uncertainty in gas collection efficiency and municipal solid waste fraction on optimal k values and collectable methane. A dual-phase model and associated parameters were also developed to evaluate its performance relative to a single-phase model (SPM) similar to LandGEM. The SPM is shown to give lower error in estimating methane collection, with site-specific best-fit k values. Most of the optimal k values are notably greater than the U.S. EPA's default of 0.04 yr^{-1}, which implies that the gas generation decreases more rapidly than predicted at the current default. We translated the uncertainty in collectable methane into uncertainty in engine requirements and potential economic losses to demonstrate the practical significance to landfill operators. The results indicate that landfill operators could overpay for engine capacity by \$30,000−780,000 based on overestimates of collectable methane.



■ INTRODUCTION

There were 1908 municipal solid waste (MSW) landfills in the U.S. in 2011, and these landfills were estimated to receive between 53 and 69% of disposed MSW.[1,2] Landfill gas (LFG) contains approximately equal volumes of methane and carbon dioxide and is produced when MSW decomposes. LFG fate is dependent on landfill practice. Ideally, all generated methane would be captured for beneficial use. There are currently an estimated 621 LFG beneficial use projects in the U.S., some of which are associated with closed landfills.[3] Even at modern landfills, some methane is released prior to installation of gas collection systems, and some methane is not captured by collection systems. The fraction of the uncollected methane that is not oxidized in the landfill cover is ultimately released as fugitive emissions.[4] Landfills are estimated to account for 16.2% of anthropogenic methane emissions in the U.S.[5]

The U.S. EPA's LFG Emissions Model (LandGEM) is a first-order decay equation for predicting methane production. Its strength is in its simplicity, as evidenced by its application at levels ranging from site-specific to global. In LandGEM, methane production is described by two parameters: L_0, which represents the methane production potential (m^3 Mg^{-1} wet waste [Mg = metric ton]) and k, which represents the first-order decay rate associated with methane generation (yr^{-1}).[6] In developing the current LandGEM default parameters, the U.S. EPA relied on data that were collected over 15 years ago and reflect landfill management practices (e.g., waste composition, cover, gas collection efficiency) that are representative of the early 1990s. More recently, information on waste composition has improved as landfill owners categorize waste into that containing biodegradable (e.g., residential and commercial MSW, biosolids) and inert (e.g., auto shredder waste, contaminated soil, foundry sand) fractions. Similarly, better data are available on component-specific methane yields.[7−9] Because methane is both a potent greenhouse gas and a valuable low carbon fuel, improved predictability of landfill methane production is desirable. A reliable methane production model is central to any effort to improve methane emissions estimates and to ensure that energy recovery from landfills is pursued to the fullest extent. Central to any production model is an estimate of k, which describes the rate at which LFG is produced.

In our previous work,[10] gas collection data from 11 landfills were analyzed to estimate a best fit k while considering waste deposition, the fraction of deposition that was MSW, and the schedule of gas collection well and interim/final cover

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installation. Consideration of these latter two factors led to the implementation of a modified version of LandGEM in which the gas collection efficiency varied with both waste age and the time and location of waste disposal. Introduction of a collection efficiency term into LandGEM transformed it into a methane collection model, which enabled direct comparison between observed and calculated methane collection rates. Decay rates were estimated to be between 0.04 and 0.17 yr^{-1} with a recommended range of 0.09–0.12 yr^{-1} based on weighted average calculations. Others have reported k values between 0.03 and 0.3 yr^{-1} for traditional and bioreactor landfills.[11−15] While allowing temporal variation in the LFG collection efficiency is mechanistically correct, judgment is required to estimate this parameter, and it is uncertain. Thus, one objective of this study was to incorporate uncertainty in the temporally varying LFG collection efficiency into estimates of the best fit k. In addition, we included uncertainty in the fraction of disposed waste that is MSW.

The major focus of this research was on the LandGEM formulation, given its dominant use in engineering practice. In addition, an alternate model was explored to evaluate the potential for improved predictability. LandGEM is a single-phase model (SPM) in which all waste is treated as one material with a single decay rate. De la Cruz and Barlaz[16] described the limitations of a SPM and showed that changing respective masses of a rapid or slowly degrading waste component had different effects on methane production. In the alternate dual-phase model (DPM), the waste is divided into fast and slowly degrading fractions. Thus, a second objective of this study was to evaluate the use of a DPM.

LFG collection data from nine operating and two closed landfills were used along with schedules for waste disposal and cover and gas collection system installation. The data were employed in an inverse model that minimized the sum of squared errors (SSEs) between calculated and observed methane collection by optimizing the decay rate (k) at a fixed L_0. Data development, model formulation and parametrization, and the inverse modeling procedure are described in the following sections. This is followed by the results for the SPM and DPM with uncertainty in collection efficiency only and with uncertainty in both the collection efficiency and the fraction of waste that is MSW.

■ METHODS

Landfill Description and Data Collection. The general characteristics of the 11 studied landfills and the criteria by which they were selected were described previously.[10] Briefly, landfills considered in this study are located in nonarid regions of the U.S. (>635 mm annual precipitation) and accept primarily MSW, which includes commercial and institutional waste but excludes construction and demolition (C&D) waste and inert waste (e.g., auto shredder residue and contaminated soil). Data and information collected from each landfill include the waste mass and category, LFG collection rate and methane content, and the schedule for the installation and operation of the gas collection and control system (GCCS) as well as the placement of interim and final covers.

Single- and Dual-Phase Model Formulation. As described previously,[10] a gas collection efficiency term was introduced into LandGEM to convert it from a methane generation model to a methane collection model, since only the collected methane can be measured and compared with model predictions. The collection efficiency term describes the fraction of total methane generation that is captured by the GCCS.

In the methane collection model (eq 1), monthly methane collection is modeled using a first-order decay equation in which all waste components are treated as a mixed waste with a single decay rate.[10] This model is similar to the U.S. EPA's LandGEM with two variations: (a) the inclusion of a term for collection efficiency and (b) the time increment of a month rather than the tenth of a year used in LandGEM:[6]

$$Q_j = \frac{kL_0}{12}\sum_{i=1}^{j}\alpha_{ji}M_i e^{-k\left(\frac{j-i}{12}\right)} \tag{1}$$

where Q_j is the monthly CH_4 collection rate (m^3 $month^{-1}$) in month j; k is the first-order methane generation rate (yr^{-1}); L_0 is the CH_4 generation potential (m^3 Mg^{-1} wet waste); α_{ji} is the monthly gas collection efficiency associated with mass deposited in month i and collected in month j; and M_i is MSW deposition in month i (Mg).

In the proposed DPM (eq 2), biodegradable waste components (e.g., paper, food, yard, and wood wastes) in MSW are grouped into fast and slow degradable fractions based on their respective laboratory-scale decay rates measured under optimal temperature, pH, nutrient, and moisture levels. The fast and slow degradable waste fractions are modeled separately based on first-order decay equations using specific k and L_0 values for each fraction:

$$Q_j = \frac{k_s L_{0(s)}}{12}\sum_{i=1}^{j}\alpha_{ji}M_i F_{(s)} e^{-k_s\left(\frac{j-i}{12}\right)} + \frac{k_f L_{0(f)}}{12}\sum_{i=1}^{j}\alpha_{ji}M_i F_{(f)} e^{-k_f\left(\frac{j-i}{12}\right)} \tag{2}$$

where k_s and k_f are first-order methane generation rates (yr^{-1}) for the slow and fast degradable waste fractions, respectively; $L_{0(s)}$ *and* $L_{0(f)}$ are the CH_4 generation potential (m^3 Mg^{-1} wet waste) for the slow and fast degradable waste fractions, respectively; and $F_{(s)}$ *and* $F_{(f)}$ are the fractions of MSW that biodegrade slow and fast, respectively.

Eqs 1 and 2 were formulated to (a) estimate methane collection on a monthly basis and (b) include a collection efficiency term (α_{ji}) to enable direct comparison between calculated and observed methane collection. The estimates of model parameters are presented in the following sections. A lag time was not considered in either model because we tested a 6-month lag time in previous work[10] and showed that with the exception of one of 11 landfills, a time lag produced negligible improvement in fit between calculated and observed data.

Model Parameterization. In our previous work,[10] we made expert judgments of LFG collection efficiency point values (α_{ji}) for each increment of waste disposal based on the location of waste disposal within each landfill and the schedule of cover and gas collection system installation. For instance, waste under daily cover only was assigned a collection efficiency of 20–75% depending on the well density, soil cover type where known, and waste depth.

In the current study, we estimated a range of collection efficiencies instead of a single value to perform uncertainty analysis. The estimates of monthly gas collection efficiency and the site-specific information used to make those estimates, including the timing of waste disposal, cover, and gas collection installation, are presented in Figures S1–S11 and Tables S1–

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Table 1. Estimates of Monthly Collection Efficiency (α_{ji}) from 2006–2010 for Gas Generated at Landfill H (%)[a]

	years of waste burial											
gas recovery period	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
01/06 – 07/06	45–75	45–75	0	0	0	0	0	0	0	0	0	0
08/06 – 06/08	80–95	75–90	30–50	30–50	30–50	0–25	0–25	0	0	0	0	0
07/08 – 09/08	80–95	75–90	75–90	45–75	45–75	0–25	0–25	0	0	0	0	0
10/08 – 04/09	80–95	75–90	75–90	75–85	75–85	10–30	10–30	0	0	0	0	0
05/09 – 06/09	80–95	75–90	75–90	75–85	75–85	10–30	10–30	5–15	0	0	0	0
07/09 – 06/10	80–95	75–90	75–90	75–85	75–85	10–30	10–30	5–15	0–10	0–10	0–10	0
07/10 – 12/10	80–95	75–90	75–90	75–85	75–85	10–30	10–30	5–15	0–10	0–10	0–10	0–10

[a]Collection efficiency was estimated using expert judgment based on cover type and the schedule of waste placement, cover, and GCCS installation. The installation of final cover occurred in multiple years as shown in Figure S3. The effective date for cover installation was assumed to be July of the installation year since the explicit dates of cover installations were not available.

S10 of the Supporting Information. As an example, the ranges in collection efficiency for landfill H are presented in Table 1.

MSW placement (M_i) was estimated from the fraction of the total disposed mass composed of MSW as provided by landfill owners/operators. Other waste types disposed in landfills, such as C&D waste and inert waste, were excluded because of their negligible methane generation potential. We recognized that the MSW fraction included some variability and therefore varied this fraction by 10% to conduct uncertainty analysis (i.e., if the point value used in previous work was 85% MSW, then the possible range would be 75–95%). The point estimates and ranges of the MSW fraction for each landfill are given in Table S11.

Determination of Methane Yield and Decay Rate for Single-Phase Model (SPM). Our previous work showed that L_0, fixed at the EPA default value of 100 m^3 Mg^{-1} wet waste, provided the best fit compared to field measurement at 10 of 11 landfills.[10] In addition, De la Cruz and Barlaz have shown that no clear correlation exists between k and L_0 for individual waste components.[16] Therefore, L_0 was fixed at 100 m^3 Mg^{-1} wet waste in the SPM, and k was either fixed at the EPA default value of 0.04 yr^{-1} to reflect current regulatory practice, or optimized to produce the minimum SSEs between measured and calculated methane collection across all months in each landfill's collection record. The SSEs were minimized in MATLAB using the Trust-Region-Reflective algorithm available through the lsqcurvefit function.[17]

Determination of Methane Yields, Decay Rates, and Fractions of Fast and Slowly Degradable Waste for Dual-Phase Model (DPM). In the DPM, we derived specific model parameters for fast and slow degradable fractions. This was done to ensure that the weighted average L_0 of MSW (including fast, slow, and nondegradable fractions) is equal to 100 m^3 Mg^{-1} wet waste and to retain only one independent variable by establishing a quantitative relationship between k_s and k_f. One independent variable was retained to maintain consistency with the SPM. Clearly, if two independent variables were employed, then a better predictive model would be expected.

Estimates of L_0 and k for the fast and slow degradable fractions are from MSW composition data and laboratory measurements of k as presented in Table S12. The fractions of fast and slow degradable waste, $F_{(f)}$ and $F_{(s)}$, were estimated to be 24.5 and 42.9% of MSW based on average waste characterization data from 11 U.S. states;[8] while the balance (32.6%) was nondegradable (plastics, metals, glass, etc.).

The weighted average L_0s for the fast and slow degradable fractions and for the bulk MSW are 76.5, 113.9, and 67.6 m^3 Mg^{-1} wet waste, respectively. To make the weighted average L_0 of MSW (including fast, slow, and nondegradable fractions) equal to 100 m^3 Mg^{-1} wet waste, consistent with the L_0 of MSW used in the SPM, the L_0 values were scaled by a factor of 1.48 to obtain 113.3 and 168.5 for the fast and slow degradable fractions (i.e., $L_{0(f)}$ and $L_{0(s)}$).

The weighted average decay rates for the fast and slowly degradable fractions, based on laboratory measurements, are 15.1 and 3.8 yr^{-1}, respectively (Table S12). Thus, at laboratory scale, $k_f = 4 \times k_s$, and this relationship was assumed to hold at field scale and used in eq 2 so that only k_s was optimized to minimize the SSEs.

Uncertainty Analysis. To determine how uncertainty in the collection efficiency (α_{ji}) and MSW placement (M_i) affects the best fit k, a Monte Carlo simulation was applied to the SPM. Uniform distributions were assumed for these two variables with specified ranges (Tables S1–12) since we did not have sufficient information to assess the relative likelihood of different point values within the specified input ranges. However, three constraints were applied to generate random but plausible values of collection efficiency by considering landfill operational practice: (1) the same collection efficiencies were assigned for collection months when there was no change in both the cover and GCCS installations for a given year of deposited waste; (2) the same collection efficiencies were assigned for waste deposited in consecutive years if the cover and GCCS installations for waste deposited in those consecutive years were similar; and (3) collection efficiencies of deposited waste for subsequent methane collection months were constrained to be greater than or equal to previous months.

The Monte Carlo simulation was performed twice for each landfill by first considering uncertainty in collection efficiency only and second considering uncertainty in both collection efficiency and the monthly amount of MSW disposed. In each of these two simulations, 10^4 model realizations were generated to obtain sufficient data to build accurate distributions of k. With each realization within the Monte Carlo simulation, we obtained a combination of specific model inputs (α_{ji} and M_i) and outputs (best fit k and corresponding monthly methane collection).

■ RESULTS AND DISCUSSION

Comparison of Single- and Dual-Phase Models. Across all studied landfills, the SSEs of the SPM and DPM predictions were compared with the EPA default parametrization (Figure 1). In all cases except landfill T, the SPM exhibits lower error than the DPM. One might expect the DPM to produce lower

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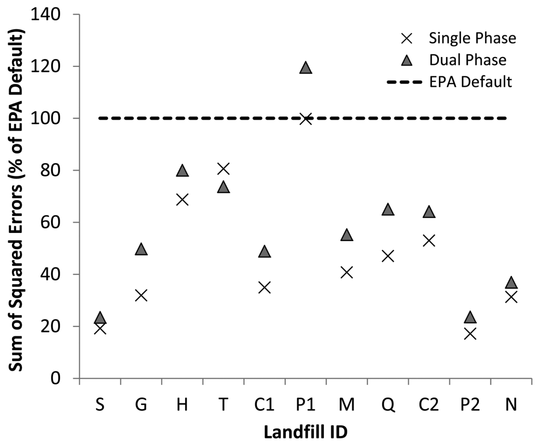

Figure 1. Sum of squared errors observed at each landfill for the SPM and DPM normalized to the sum of squared errors associated with the EPA default parametrization. Point estimates of MSW deposition and methane collection efficiency were used in the optimization.

error because waste is partitioned into fractions that decay at different rates, which ostensibly provides greater accuracy. However, to avoid the bias of introducing more parameters to fit the observed data, only one parameter was optimized in the DPM as described in the Methods section. The higher errors with the DPM at most landfills imply that either the difference in waste decay rates is not a major source of error between predicted and observed methane collection or that the derived ratio between k_f and k_s used in the DPM was not accurately estimated. Oonk et al. described a multiphase model that divided waste into fast, moderate, and slowly degradable fractions and provided a better prediction of methane collection relative to a SPM.[18] However, in the work by Oonk et al., decay rates for the three fractions were independent, so the better predictability can be attributed to the presence of multiple independent variables. Because the DPM does not exhibit better predictability relative to the SPM, all the results and discussion in the subsequent analysis will center on the SPM.

Consistent with our previous study,[10] Figure 1 also indicates that the SPM produces the same or lower error than the EPA defaults across all landfills with site-specific optimal k values. Note that the normalized SSEs cannot be used to compare the goodness-of-fit of model predictions across landfills because the SSEs associated with the EPA default parametrization vary between landfills.

Relative Frequency Distribution of Optimal Decay Rates in the Single-Phase Model (SPM). Uncertainty in both methane collection efficiency (α_{ji}) and MSW disposal (M_i) can affect the estimated k values. Figure 2 presents the distribution of optimal decay rates based on the Monte Carlo simulation when only uncertainty in collection efficiency is considered and when uncertainty in both collection efficiency and the fraction of MSW are considered simultaneously. Representative decay rates associated with each frequency distribution are presented in Table 2. The optimal k values range from 0.07−0.19 yr^{-1} at nine of the 11 landfills, which is notably greater than the EPA default of 0.04 yr^{-1}. The distribution of k values is nearly identical between the two cases, which suggests that the collection efficiency is the dominant factor contributing to variation in optimal decay rates.

Landfills S and P2 exhibit wide ranges of optimal decay rates. Landfill S is one of the two closed sites (S and P1) that has final

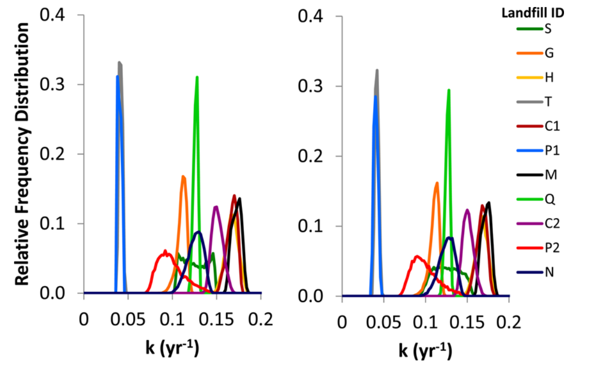

Figure 2. Relative frequency distributions of k in the SPM with uncertainty in collection efficiency only (left) and with uncertainty in both collection efficiency and MSW disposal (right).

Table 2. Estimated Fraction of Methane Collected and Representative k Values Drawn from the Monte Carlo Simulation with the Single-Phase Model

landfill ID	optimized k percentile 10	25	50	75	90	estimated fraction of methane collected[a]
S	0.11	0.11	0.13	0.14	0.14	0.90
G	0.10	0.11	0.11	0.11	0.12	0.54
H	0.16	0.16	0.17	0.17	0.18	0.19
T	0.039	0.040	0.042	0.043	0.044	0.76
C1	0.16	0.16	0.17	0.17	0.17	0.54
P1	0.038	0.039	0.040	0.042	0.044	0.90
M	0.17	0.17	0.17	0.18	0.18	0.30
Q	0.12	0.12	0.13	0.13	0.13	0.24
C2	0.14	0.15	0.15	0.16	0.16	0.36
P2	0.081	0.088	0.10	0.11	0.12	0.28
N	0.11	0.12	0.13	0.13	0.14	0.57

[a]Fraction of total methane collected was calculated by (1) separately estimating the average monthly methane collection and generation using the 10th and 90th percentile k values, (2) taking the average of those monthly values over the observation period, and (3) dividing the average modeled methane generation by average collection.

cover over all of the deposited mass through the entire observation period; however, the distribution of collection efficiencies for landfills S and P1 is similar, and landfill P1 does not exhibit similarly widespread k values. We investigated variations in methane collection efficiency and MSW waste fraction across all studied landfills but failed to identify any factor that explains the wider distribution of optimal k values for landfills S and P2.

Methane Collection and Generation over the Observation Period. The 10th and 90th percentile optimal k values and their corresponding collection efficiencies drawn from the Monte Carlo simulations were adopted to calculate the ranges of monthly methane collection. Likewise, methane generation during the same observation period was calculated using those same k values but assuming 100% collection efficiency. Examples of these results are illustrated in Figure 3 for landfills H and P2, with corresponding figures for the other landfills given in Figures S12−S20.

The goodness-of-fit of predicted methane collection to field observations can vary widely as illustrated by landfills H and P2 in Figure 3. Across the 11 landfills, the predicted methane collection (average calculated with the 10th and 90th percentile

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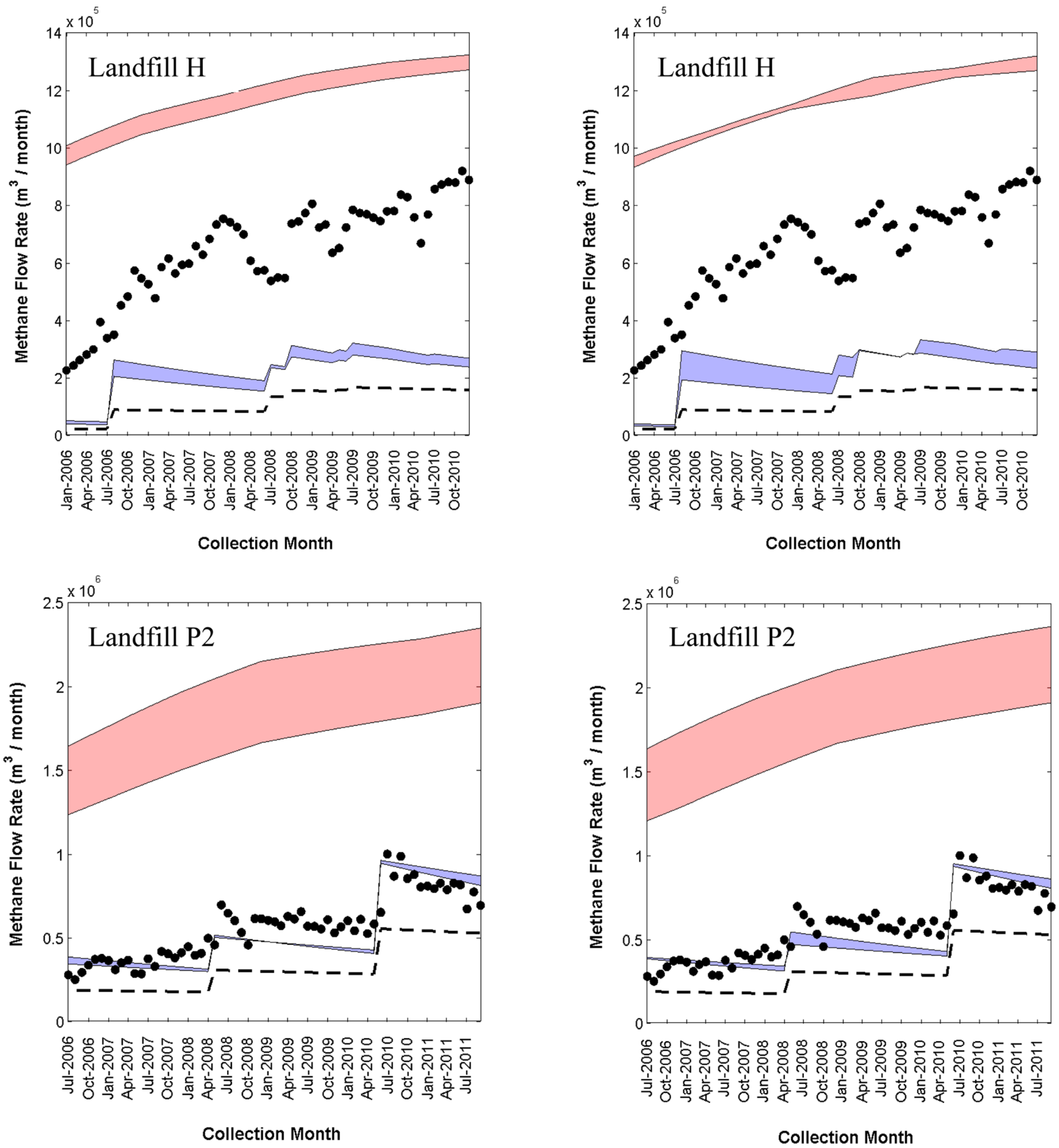

Figure 3. Observed methane collection (dots), estimated methane generation (pink band), and estimated methane collection (blue band) for landfill H (top) and landfill P2 (bottom). The left panel includes only uncertainty in landfill gas collection efficiency, while the right panel includes uncertainty in both collection efficiency and the fraction of waste considered MSW. The dashed line represents methane collection using EPA defaults and point estimates of collection efficiency and MSW fraction. The edges of each band are generated with the 10th and 90th percentile k values and associated collection efficiencies.

k values and corresponding collection efficiencies) ranges from 36−101% of actual measurements on a monthly average basis, which is an improvement over the 38−492% reported in the U.S. EPA's documentation.[19] Landfills H and C2 exhibit the most dramatic under-bias compared with the observed data. We estimate that these two sites accepted the smallest fraction of biodegradable waste, which suggests that the variability of estimates in MSW fraction might contribute to the poor match observed at these two sites.

In Figure 3, the width of the methane generation bands reflects the difference between the 10th and 90th percentile k values because the collection efficiencies do not impact methane generation. In contrast, the width of the methane collection bands represents variations in both k values and associated collection efficiencies. With the exception of landfill P2, the narrow generation bands observed at most landfills suggest that the middle 80% of the optimal k values are concentrated within a relatively small range. This is consistent with the observation in Figure 2 in which landfill P2 has a wide distribution of k values. At landfills S and N, the upper and lower methane generation rates converge during the observation period (Figures S12 and S20). This is probably because these two landfills were closed during their respective observation periods, and in the absence of additional mass burial, the methane generation curves will intersect.

The quotient of the generation and collection bands at a given time point in Figure 3 indicates the instantaneous overall collection efficiency associated with the buried waste in place at that time, which varies over the observation period as a function of waste tonnage and age, cover type, and the extent of gas collection system coverage. The time-averaged collection efficiency over the observation period ranges from 19−90%

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(Table 2). Note that the calculated efficiencies in Table 2 are not based on actual field measurements.

The lowest collection values correspond to landfills H and Q where wells had not been installed for a 5 year period. The highest values correspond to landfills with a final cover throughout the observation period (P1 and S). These averages are comparable with averages of default collection efficiencies for each landfill as given in Tables 1 and S1−S10. These values serve to illustrate how collection efficiencies vary temporally based on gas well and cover installation.

We observed a somewhat seasonal pattern in methane collection at landfill G (Figure S13). In consecutive years, the methane collection rates peak in late summer and fall as winter approaches. In theory, the annual cycle of climate may influence the progress of waste decay because microbial activity may be restricted by cold temperatures in winter or stimulated by high temperatures in summer. However, landfill H is located in an adjacent geographic area to landfill G with a similar climate. Because we did not observe a similar climate effect at landfill H, climate factors alone are insufficient to explain the observed seasonal pattern at landfill G.

Projected Methane Collection at Year Five beyond Observation Period. Methane production models are often used by landfill practitioners to develop LFG to energy recovery projects. As a result, we formulated a scenario to explore how variation in decay rates would affect the projection of methane collection. We assumed all landfills were closed with final cover at the end of their respective observation periods with a collection efficiency of 95% assumed throughout the entire five-year projection period. The 10th, 25th, 75th, and 90th percentile *k* values and default MSW mass were used to calculate monthly methane collection 5 years beyond the last observation (Figure 4). Methane collected in the last month of the fifth year beyond the last observation was then normalized to the monthly methane collection predicted at the median *k*.

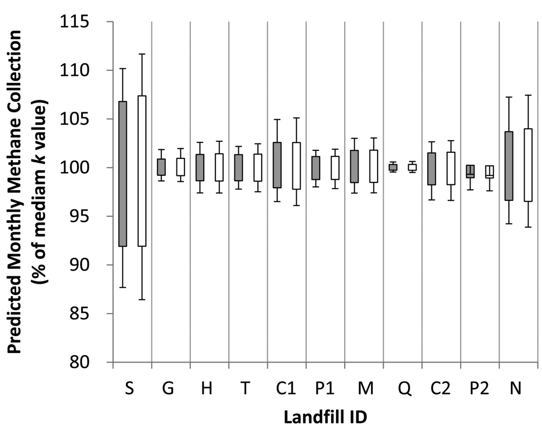

Figure 4. Box and whisker plot of predicted monthly methane collection 5 years after the end of the data observation period as a function of the optimized *k* value. The ends of the whiskers represent the 10th and 90th percentile *k* values, while the edges of the box represent the 25th and 75th percentile *k* values. The point estimates of MSW placement and collection efficiencies of 95% were used to calculate monthly methane collection. For each landfill, the box-and-whiskers to the left (in gray) reflect the *k* values when only uncertainty in collection efficiency is considered; the box-and-whiskers to the right (in white) assume uncertainty in both collection efficiency and MSW fraction. Note the suppressed zero on the *y*-axis.

A second projection was also included in Figure 4, which utilizes the 10th and 90th percentile *k* values calculated while considering uncertainty in both collection efficiency and the total mass of MSW. The distribution of projected monthly methane collection is nearly identical between the two cases at all landfills. The consideration of uncertainty in the MSW fraction does not affect the distribution of best fit *k* values, which is consistent with Figure 2.

Variations in projected methane collection using the 10th and 90th percentile *k* values under the assumed conditions are less than 15% different from the median *k* values for all landfills. This implies that when a studied landfill is closed with final cover installed, the projection of methane collection is not sensitive to the selection of *k* values within the range determined by site-specific conditions. The 10th and 90th percentile *k* values are presented in Table 2 and range from 0.08−0.18 yr^{-1} for nine of the 11 landfills. Landfills T and P1 had the lowest *k* values (approximately 0.04 yr^{-1}).

Implications for Energy Recovery. The uncertainty in collection efficiency affects the economics of landfill gas recovery and beneficial use. Here, we translate the uncertainty in collected methane into the fraction of a typical 1 MW internal combustion (IC) engine operating at an assumed thermal efficiency of 33%.[20] Table 3 summarizes the uncertainty in average monthly collected methane expressed as both the average difference in monthly flow rate and fractional number of engines. Note that uncertainty in collection efficiency alone translates into 3−78% of the capacity of a typical 1MW engine.

Table 3. Uncertainty in Average Monthly Collected Methane Expressed as the Average Difference in Monthly Flow Rate, Fractional Number of Engines, and Total Capital Investment

landfill ID	average difference in methane collection rate (10^4 m^3 CH_4 mo^{-1})[a]	average difference in LFG collection rate (cfm LFG)[b]	percent of a typical IC engine[c]	capital expenditure (million $)[d]
S	2.8	45.8	13.6	0.14
G	7.7	125.8	37.5	0.37
H	3.6	58.8	17.5	0.18
T	5.3	86.6	25.8	0.26
C1	16	261.5	77.8	0.78
P1	0.7	11.4	3.4	0.03
M	7.2	117.7	35.0	0.35
Q	1.7	27.8	8.3	0.08
C2	3.4	55.6	16.5	0.17
P2	2.3	37.6	11.2	0.11
N	5.6	91.5	27.2	0.27

[a]Average difference in methane collection rates over the observation period assuming uncertainty only in collection efficiency, calculated using the 10th and 90th percentile decay rates and associated collection efficiencies. [b]Column 2 converted to cubic feet per minute (cfm) of landfill gas assuming 50% methane. [c]On the basis of a typical IC engine with nominal capacity of 1 MW. The engine is able to handle up to 337 cfm LFG. [d]On the basis of a typical capital cost of $1,000 per kW engine capacity.[20]

To evaluate potential economic implications, we translate the fractional number of engines into potential economic losses assuming an engine capital cost of $1000/kW.[20] Suppose the engine capacity is sized at the top of the collection range shown in Figures 3 and S12−S20 but realized methane collection is at the bottom of the range: landfills operators will have overpaid

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for engine capacity by \$30,000−780,000. On the other hand, if landfill operators size an engine at the bottom of the collected methane range but realized methane collection is near the top of the range, then landfill operators would potentially forgo \$18,000−410,000 of annual revenue assuming an electricity price of \$0.06/kWh.[21] This annual lost revenue maintained over a 20-year engine lifetime at a 5% discount rate amounts to \$220,000−5,100,000. Though these economic calculations are rough, they indicate that it might be better to size an engine on the high end of the methane collection range and risk lower gas production than undersize the engine and forego the lost revenue. Of course, this analysis does not address long-term variability in energy prices.

Although the single phase model presented here does not always produce predictions that match the observed data well, the model with site-specific best-fit k values provides more accurate estimates of methane collection than does LandGEM with the EPA's default parameters. The best-fit k values at most landfills are markedly greater than the EPA default value of 0.04 yr^{-1}, which implies that gas generation will decrease more rapidly than predicted at a decay rate of 0.04 yr^{-1}. This too has implications for the economics of gas recovery projects. While prediction of landfill gas collection rates is complex, the method illustrated here shows that the predicted range is within the size of a typical IC engine.

Further work is required to identify unmodeled parameters that affect methane generation and collection and to expand observational data sets to include both longer time series and additional climate types. All landfills involved in this study are located in nonarid regions of the United States (>635 mm annual precipitation). In the future, arid landfills should be considered for similar analysis.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Schedule of waste disposal, cover, and GCCS installation; estimates of monthly collection efficiency (α_{ji}) and MSW fraction; estimates of model parameters for the dual-phase model; figures that present the results of methane generation; and collection curves that incorporate uncertainty in k values. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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