THESIS

LANDFILL GAS ANALYSIS TO SUPPORT AN ASSESSMENT OF ORGANIC WASTE STABILITY

Submitted by

Steven C. Mantell

Department of Civil & Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2016

Masters Committee:

Advisor: Christopher A. Bareither

Joe C. von Fischer
Sybil E. Sharvelle

ABSTRACT

LANDFILL GAS ANALAYSIS TO SUPPORT AN ASSESSMENT OF ORGANIC WASTE STABILITY

Organic stability is defined as the state of near complete decomposition of organic waste constituents such that human health, environmental, and financial risks associated with undecomposed waste are reduced. An assessment of organic stability was completed based on comparison between collected and predicted landfill gas. There were two main objectives of the study: (i) assess landfill organic stability for an entire site and specific landfill phases to evaluate how operational practices influence organic stability and (ii) develop recommendations for conducting organic stability assessments based on gas collection and modeling. Landfill gas generation is frequently assessed on a site-wide basis; however, the process of waste disposal and subsequent gas generation varies temporally and spatially within a landfill. In this study, landfill gas modeling was conducted on a site-wide and phase-specific basis (i.e., multiple phases constitute the entire landfill site) for a non-hazardous solid waste landfill in the U.S. The U.S. EPA's LandGEM model for methane generation was used for the gas model simulations. LandGEM calculates the rate of methane generation based on the mass of solid waste, methane generation potential of the waste, and first-order rate coefficient (*k*). Models were completed that considered the following factors: (i) constant methane generation potential; (ii) methane flow rates representative of monthly and annual averages; (iii) collection efficiency of the landfill gas collection system; and (iv) optimization of *k* to reduce the sum of squared residuals between measured and predicted methane flow rates. Collection efficiency of the landfill gas collection system was accounted for in the models via assuming a constant collection efficiency of 85% and assuming a temporally varying collection efficiency. The temporally varying collection efficiency was used to represent temporal installation of a gas collection system and placement of interim and final cover. Site-wide decay rates varied from 0.068 to 0.070 1/yr while phase-specific rates varied from 0.021 to 0.12 1/yr. Observations reinforce previous studies showing that moisture enhancement has potential to create favorable landfill conditions that may lead to higher rates of methane generation and shorter durations to achieve organic stability.

ACKNOWLEDGEMENTS

I am using this opportunity to express my sincere gratitude to all those who have aided and guided me during my time at Colorado State University.

First, I would like to thank my advisor, Dr. Christopher Bareither, who provided constant support and guidance throughout my Master's program. His of knowledge of municipal solid waste and enthusiasm for engineering was inspiring. His challenges and guidance helped drive me throughout the research and writing processes necessary for this thesis. I also appreciate his patience and flexibility with my schedule. I would also like to extend my thanks to Dr. Joe von Fischer and Dr. Sybil Sharvelle for serving on my graduate committee.

Second, I am grateful to my fellow graduate students, particularly Kelechi Nwaokorie, for providing a water balance analysis for the landfill examined in this study. I also greatly appreciate the feedback from other graduate students who observed presentations and provided assistance for the development of figures herein.

Last, but not least, I wish to thank my family and friends for their continuous support throughout my entire academic career. My parents have been nothing but encouraging throughout the research and writing process. My friends have provided incredible support during my time as a graduate student, keeping me focused and pretending to be excited when I talk about "garbage juice".

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Organic stability is viewed as a state of near complete decomposition of organic waste constituents such that human health, environmental, and financial risks associated with undecomposed waste are reduced (Bareither et al. 2014). Short-term and long-term risks of landfilled waste arise from gaseous emissions, organic or inorganic contaminants in leachate that have potential to be released to the environment, and settlement of the waste mass to the extent that settlement results in damage to the final cover and/or gas collection and control system. Organic waste stability can be interpreted as a condition of the waste where there is limited need for subsequent engineering and maintenance efforts, which reduces the potential for unanticipated future financial costs. Degradation of the municipal solid waste (MSW) organic fraction can mitigate some risks and reduce others. Practices to enhance decomposition will exhaust gas generation potential of the waste, treat leachate contaminants in-situ, and reduce the magnitude of future settlement.

In the state of Wisconsin, an organic stability rule (OSR) was implemented by the Wisconsin Department of Natural Resources (WDNR) in 2007 to promote enhanced waste decomposition and progression towards organic stability to reduce risks following landfill closure (section NR 514.07(9), Wis. Adm. Code). A motivating factor for waste stabilization and the implementation of WDNR's OSR was to reduce long-term risks and liabilities associated with Subtitle D landfills (RCRA 1976). The objective of the organic stability plan is outlined by WDNR as meeting all of the following goals within 40 yr following landfill closure (WDNR 2006): (i) monthly average methane and carbon dioxide gas (CH_4 + CO_2) production rate ≤ 5% of average maximum monthly gas production rate observed during the life of the facility, or ≤ 278 L-gas/m^3-waste/yr (7.5 ft^3-gas/yd^3/yr); (ii) steady downward trend in the rate of total gas production (CH_4 +

CO_2); and (iii) cumulative gas (CH_4 + CO_2) yield ≥ 75% of projected total gas production from landfilled waste (WDNR 2006).

Strategies for supervision of closed Subtitle D landfills require management of risks to human health and the environment (HHE). Landfill owners are required to monitor and maintain a closed landfill for an amount of time referred to as the post-closure care (PCC) period. Regulated PCC activities during this period include leachate management, groundwater monitoring, inspection and maintenance of the final cover, and control and monitoring of off-site methane migration (ITRC 2006; Morris and Barlaz 2011; Laner et al. 2012). Currently the duration for PCC is at least 30 yr following landfill closure (USEPA 1993). However, the length of required monitoring and aftercare can potentially be reduced with waste stabilization strategies that are known to enhance decomposition (e.g., liquid addition).

The addition of liquid waste represents a source of revenue for landfills via tipping fees making the acceptance of liquids from outside sources advantageous from a financial perspective. Liquids addition is further beneficial to landfill operators because it increases moisture content of in-place waste. Studies have shown that an increase in moisture content can enhance waste decomposition and biogas generation (Barlaz et al., 1990; Chan et al., 2002; Mehta et al., 2002; Wreford et al., 2000; Alvarez and Martinez-Viturtia, 1986; Barlaz et al. 2010). Furthermore, liquid addition offers a form of leachate management and treatment as well as a means of disposing unwanted liquid wastes from nearby waste generators.

Practicing controlled liquid addition and while also measuring elements such as leachate production and gas generation allows landfill owners to obtain an accurate understanding of the waste decomposition process. Gas modeling is used to approximate gas production due to waste decomposition, ensure energy recovery, and evaluate a landfill’s proximity to becoming organically stable. Landfills are heterogeneous ecosystems in which waste composition, temperature, and water content vary spatially and temporally; making the creation of accurate gas models challenging. Zero, first and second-order kinetics empirical models have been used to estimate landfill gas (LFG) generation as a function of time, waste disposal quantities, and waste characteristics. A simple, accurate, and reliable technique to predict gas generation at landfills is not currently available for landfill owners and operators. A universal method for this process would allow for practical comparisons between landfills. Enhanced waste decomposition practices could then be forecasted, allowing owners and operators to optimize and conserve resources.

1.2 Research Objectives and Tasks

This study was conducted to evaluate the efficacy of employing current gas modeling techniques used in practice to assess organic stability for a full-scale MSW landfill. The end goals of this project were to (i) assess the viability of developing more accurate methods for assessing organic stability via gas collection data and (ii) develop a gas modeling methodology that landfill owners and operators can use in their practice to evaluate organic stability. The specific objectives achieved in this study included the following: (i) assess landfill gas modeling and organic stability for an entire landfill site and specific landfill phases to evaluate how operational practices affect organic stability and (ii) develop recommendations for conducting organic stability assessments based on gas collection and modeling.

The following research tasks were completed as part of this study:

1. Developed a procedure for analyzing landfill gas generation data to be used for gas modeling;
2. Applied methane generation models using a constant and temporally varying gas collection efficiency; and
3. Evaluated landfill organic stability using optimized landfill gas generation models in conjunction with organic stability goals.

Landfill operations and gas collection were evaluated on a landfill phase-specific level using current modeling techniques to provide a more focused assessment of the effectiveness of operation on gas generation rates and organic stability. Preliminary recommendations were developed for using landfill gas modeling techniques to assess organic waste stability. These recommendations are linked to operational conditions of the landfill. N Future work related to this project will be to (i) apply to recommended gas modeling procedure developed herein to additional landfills and (ii) evaluate the presence of common operational practices that successfully lead to enhanced organic waste stability.

CHAPTER 2: LANDFILL OPERATIONS AND DATA REDUCTION

2.1 Landfill Overview

A non-hazardous solid waste landfill was used in this study to implement gas modeling and evaluate organic waste decomposition (i.e., organic stability). The landfill, referred to herein as Landfill T, is located in Wisconsin and has been in operation since 1995. A site map of Landfill T is shown in Figure 2.1. The landfill includes seven existing phases that contain solid waste (Phases 1, 2, 3, 4, 5, 6, and 7) in which different landfill operations (e.g., moisture enhancement strategies) have been employed. The permitted landfill is approximately 26.2 ha (313,000 yd^2) in areal extent with a design capacity of 7.4-million m^3 (9.6-million yd^3). An original plan of operations in 1994 permitted 10.7 ha (128,000 yd^2) with a capacity of 2.24-million m^3 (2.93-million yd^3). In June 2002, the landfill was expanded to add an additional 16.5 ha (197,000 yd^2) and 5.13-million m^3 (6.71 million yd^3) of storage capacity.

Landfill gas modeling was conducted based on a (i) site-wide analysis and (ii) phase-specific analysis. The site-wide analysis considered total gas collection from all seven existing phases that contain waste, whereas phase-specific analyses were conducted for the following: Phases 1A & 2A, Phases 1B & 2B, Phases 3 & 4, Phase 5, Phase 6, and Phase 7. This separation for the phase-specific gas analyses was based on waste disposal and gas collection data provided by the landfill engineer. An additional site-wide analysis was conducted for the grouping of Phases 3 through 7, which was due to uncertainties regarding the gas modeling and analysis for Phases 1 and 2 (described subsequently).

2.2 Waste Composition and Landfilling

A summary of size, start and end of waste filling operations, rate of waste disposal, and estimated total waste disposal for each phase is in Table 2.1. The phases at Landfill T were filled with waste sequentially in order from Phase 1 to Phase 7; i.e., Phase 1 contains the oldest waste and Phase 7 contains the youngest waste. Total waste volume was estimated for each phase based on mass of waste placed and a single total unit weight. An assumed total unit weight of 11 kN/m^3 was obtained from Zekkos et al. (2006) for an MSW landfill with "typical" compaction effort and soil cover, and an average waste depth 22 meters (Table 2.1). Solid waste volumes were used in the landfill organic stability analysis to compute an approximate gas production rate to compare with the ≤ 5% of average maximum monthly gas production rate observed during the life of the facility, or ≤ 278 L-gas/m^3-waste/yr.

A temporal relationship of the average daily filling rate of MSW at Landfill T is shown in Figure 2.2. The rate of MSW disposal initially increased and then remained constant between 1998 and 2007 at approximately 460 Mg/d. From 2008 to 2010 the disposal rate of MSW decreased and subsequently remained at approximately 180 Mg/d for the last 4 yr. This decrease in MSW tonnage was attributed to economic recession and a decrease in the amount of waste entering Landfill T from neighboring states. The reported MSW fraction of the total waste disposed at Landfill T ranged between 41% and 95%, and was 75% on average from 2001 to the present. The MSW fraction of the incoming waste for years 1995 to 2001 was not available. Thus, the MSW fraction for these years was assumed to be 70% based on observations from subsequent years of operation and conservative assumptions.

The common practice observed at Landfill T based on waste filling logs was to fill one phase at a time before moving on to another phase. However, some data records (e.g., a few months) of operation at Landfill T indicated waste placement in more than one phase at a given time. During these periods, waste was assumed to be placed equally in all phases noted to receive waste. As filling progressed in time, waste composition information and data pertaining to waste disposal were recorded more frequently and with greater accuracy.

2.3 Liquids Management

A summary of leachate recirculation and liquid addition conducted under a U.S. EPA Research, Development, and Demonstration (RD&D) permit is in Table 2.2. An RD&D permit provides landfill engineers to use additional means other than leachate recirculation to increase the moisture content of the landfilled waste. The primary RD&D action at Landfill T was disposal of commercial liquid waste directly in the landfill. Thus, leachate recirculation and liquid waste disposal under the RD&D permit were the primary methods of liquid addition.

Leachate recirculation was initiated at Landfill T in 2001 in Phases 1B & 2B via horizontal trenches. Addition of liquid waste began in 2003 via solidifying liquids with high moisture retention capacity wastes. After receiving an RD&D permit in 2010, liquid wastes were directly disposed without solidification. Typical liquid wastes disposed at Landfill T included scrubber waste, boiler wash water, herbicide rinse water, sump sludge, and special liquids. The method of applying leachate and liquid waste to the landfill eventually transitioned to surface application via spraying liquids transferred to the working face via a force main or within a rapid infiltration trench. Infiltration methods involved discharging liquids into a trench excavated near or within the working face. Common trenches were 1.5 meters (5 feet) deep and received approximately 20,000 L of liquid (i.e., ~ one 5000 gallon tanker truck).

Since the commencement of leachate recirculation in May 2001, 99,948 m^3 (26,400,000 gal) of leachate has been recirculated at Landfill T. Phase 1A & 2A received no liquid addition of any kind and Phase 1B & 2B received relatively minor leachate recirculation (Table 2.2). These phases were operated prior to beginning a site-wide initiative to recirculate leachate and decrease off-site leachate treatment.

Phase 3 & 4 were the first phases to receive off-site liquids. Waste placement was completed in Phases 3 & 4 in November 2000, and the majority of recirculated leachate and liquid waste was added after filling was complete. Approximately 70% of the leachate recirculated within Phase 3 & 4 occurred within a 16 month starting May 2001. Three additional rounds of focused leachate recirculation occurred in 2005, 2007, and 2008, but recirculation was not as aggressive as in earlier years. Liquid waste disposal in Phases 3 & 4 accounted for 14% of the total liquids added (Table 2.2).

The amount of liquid waste addition increased in Phase 5 to approximately 20% of the total liquid added (Table 2.2.). Overall leachate recirculation and liquid waste addition in Phase 5 was considerably larger relative to Phases 3 & 4. Recirculation occurred within a three-year period starting approximately one year after final waste placement, from September 2003 to September 2006. Leachate recirculation in Phase 5 accounted for 25% of the total leachate recirculated at Landfill T.

The amount of leachate recirculated in Phase 6 was the largest at Landfill T, and combined with the liquid waste, total liquids added to Phase 6 accounted for approximately 55% of all liquids added to the waste mass at Landfill T (Table 2.2). Leachate recirculation occurred concurrent with solid waste placement. Only 4 months after waste placement began in Phase 6, leachate began to be recirculated as well. An aggressive recirculation strategy was implemented from February 2003 to November 2009. Although the total amount of leachate and liquid waste added to Phase 6 was considerably larger than Phase 5, when normalized to the waste mass (Table 2.2), the aggressiveness of waste wetting was approximately the same in both phases. The mass of total liquid added to mass of total waste placed in these phases was equal to 70%, which was higher than all other phases at Landfill T.

Liquid waste addition under the RD&D permit has not occurred in Phase 7, and all liquid added to this phase has been via leachate recirculation (Table 2.2). Leachate primarily was recirculated in Phase 7 from November 2006 to November 2008 and accounted for only 7,072 m^3 (1,868,228 gal.). At the time of this study (2015), waste placement was still active in Phase 7; however, liquids data provided to the researchers indicate no liquid has been added to Phase 7 since 2008.

2.4 Landfill Gas collection

A summary of phase-specific gas collection information, gas flow rates, and methane (CH_4) fraction of the collected gas is in Table 2.4. Details on the gas collection systems (GCS) include the start date for gas collection, lag time between date of initial waste placement and start of gas collection, and number of gas wells in a given phase. The lag time between initiation of waste placement and start of gas collection ranged between 2.2 and 5.8 yr, with a notable decrease in elapsed time as operations evolved from Phase 5 to Phase 7. This shift to early gas well installation can be attributed to the aggressive liquid addition strategy to stimulate gas generation and the installation of gas engines in 2006 and 2007 that required a consistent gas flow for operation. The number of gas wells installed per landfill area ranged between 2.0 and 3.7 gas wells per hectare (Table 2.4). The highest average gas flow rate was for Phase 6, which coincides with the largest waste mass (Table 2.1). The average CH_4 composition ranged between 53% and 56% and suggests that anaerobic decomposition was occurring in all phases.

A compilation of temporal trends of daily gas flow rates recorded at individual gas wells in Phase 1A & 2A and average monthly and annual flow rates for all of Phase 1A & 2A are shown in Figure 2.3. The plots in Fig. 2.3 exemplify the data processing required to transform actual measurements at individual gas wells into monthly and annual average flow rates for a given phase that were subsequently used for landfill gas modeling. Monthly average flow rates were computed as the average flow rate among the active gas wells in a given month, and then multiplied by the number of gas wells to represent gas collection for the entire phase. Annual average gas flow rates were computed as averages of the monthly flow rates for a given year.

The frequency of individual gas well measurements varied throughout the period in which data were made available for this project. For most gas wells, measurements were recorded one to two times per month before 2007 and more frequently thereafter (e.g., up to 15 measurements per month). An initial examination of data trends within each phase was used to determine questionable flow rate measurements. Outlying measurements that did not agree with general trends were excluded from calculating averages. Overall, less than 15% of flow rate measurements were excluded, and in general, individual gas well flow measurements recorded after 2003 appeared more accurate and required less exclusion of individual measurements during data processing.

CHAPTER 3: LANDFILL GAS MODELING

Gas modeling is a technique to estimate gas generation and potential emissions from a landfill. A reliable landfill gas model can be used to assess organic waste stability and minimize or eliminate resources required to monitor a landfill post closure. Progress is being made such that landfill owners and operators can use gas generation models to forecast (i.e., predict) gas generation trends post-closure. Size and heterogeneity of landfills makes accurate gas collection measurements and gas modeling difficult. Landfill gas generation models range in complexity to incorporate different variables known to influence methane production (e.g., Karanjekar et al. 2005, Kim and Townsend 2012). Although there is merit to complex gas modeling options, including additional variables within a model increases complexity and may transition gas analysis to curve fitting of gas collection data. The application of a straightforward gas generation model with controlled or bounded input parameters can be used to more accurately assess the effects of landfill operational procedures on gas production and on enhanced waste decomposition.

3.1 U.S. EPA LandGEM

The U.S. EPA developed the Landfill Gas Emissions Model (LandGEM) to inventory landfill emissions and assist the landfill industry with energy recovery projects (US EPA 2005). LandGEM is a first-order decay equation commonly used in practice to predict gas generation form landfilled waste. The version of LandGEM applied in this study is,

$$Q_j = \frac{k \cdot L_0}{12} \sum_{i=1}^{j} \alpha \cdot M_i \cdot e^{\left[-k\left(\frac{j-i}{12}\right)\right]} \tag{1}$$

where Q_j is the CH_4 generation rate (m^3/month) in month j, k is the first-order decay rate (1/yr), L_0 is the CH_4 generation potential (m^3-CH_4/Mg-wet waste), α is the gas collection efficiency, and M_i is MSW deposition in month i (Mg). This version of LandGEM has been used by Wang et al.

(2013, 2015) to simulate CH_4 generation on a monthly basis as opposed to the deci-year equivalent used in the conventional LandGEM model and also incorporate α to account for collection efficiency. Predicting CH_4 flow rates on a monthly basis is conducive to direct comparison with landfill monitoring data. The Q_j predicted with Eq. 1 can be modified to total gas generation via factoring in the percent CH_4 contribution and assuming the remaining balance during anaerobic biodegradation is CO_2.

Numerous factors are known to have an effect on the methane generation rate. The first-order decay rate can be influenced by moisture content, waste and recirculated liquid composition, waste density, waste depth, pH, collection efficiency of the GCS, and other environmental conditions (Amini et al. 2011). Specific interactions between all of these influences are difficult to calculate or model, but general relationships between select factors have been explored (Bareither et al. 2012). Identifying specific factors affecting k was determined beyond the scope of the analysis for this study as the focus was on practical application of LandGEM to evaluate gas generation and organic stability.

3.3 Gas Collection Efficiency

Gas collection efficiency was incorporated in LandGEM to account for the fact that not all landfill gas generated during anaerobic biodegradation will be collected in the GCS. The efficiency of GCSs depend on many factors, including design and operation of the GCS, surrounding environment or climate, and composition, thickness, and integrity of the landfill cover (Spokas et al. 2006; SCS Engineers 2008; SWANA 2007; Amini et al. 2013). The fraction of LFG that is not collected by the GCS may move through the landfill cover soil where methane can undergo partial oxidation, or escape through preferential pathways within the landfill (e.g., cover imperfections, GCS leaks, leachate collection system, etc.).

A variety of methods and range of values to estimate gas collection efficiency in full-scale landfills has been evaluated in numerous studies (Spokas et al. 2006; SCS Engineers 2008;

SWANA 2007; Amini and Reinhart 2011, Amini et al. 2013). However, accurately measuring the fraction of LFG that is not collected via the GCS is difficult and costly (Abichou et al. 2011a, b). Several studies have shown the U.S. EPA default collection efficiency value of 75% is conservative, and underestimates the effectiveness of a GCS. An upper-bound α = 90-99% has been recommended for use with landfills containing geomembrane covers (Spokas et al. 2006; SWANA 2007; SCS Engineers 2008). Additional recommendations have been developed to account for factors such as operating conditions, GCS, and cover systems (Spokas et al. 2006; SWANA 2007; SCS Engineers 2008; US EPA 2008; Amini et al. 2013).

Gas collection efficiencies used in the landfill gas models completed for this study were estimated with a (i) constant α = 85% and (ii) temporally varying α [$\alpha = f(t)$] based on site-specific conditions. A constant, site-wide α = 85% was used as a straight-forward technique and was selected based on current conditions of the GCS at Landfill T and recommendations in literature (e.g., Spokas et al. 2006; SWANA 2007; SCS Engineers 2008; US EPA 2008). A temporally varying α was used to account for temporal and spatial variability in the deployment and operation of a GCS. Although allowing temporal variation in the LFG collection efficiency is mechanistically correct, judgment is required to estimate this parameter, and even still, the parameter is uncertain (Wang et al. 2015).

A summary of the range of α values used to determine the temporally varying α is in Table 3.1. The α values were identified as a function of gas well density, fraction of the landfill area that had a GCS in-place, and fraction of the landfill area that had final cover in-place. The range of α and associated ranges of the three operational variables in Table 3.1 were based on observations from relevant literature on gas collection efficiency and LFG modeling (e.g., Spokas et al. 2006; SWANA 2007; SCS Engineers 2008; US EPA 2008). An increase in any of the three variables identified in Table 3.1 contributed to an increase in the estimated α. The temporally varying α method was applied to monthly averaged gas collection flow rates for a given phase at Landfill.

Temporal relationships of site-wide measured monthly CH_4 collection flow rates, and modified monthly CH_4 flow rates for methods using α = 85% and $\alpha = f(t)$, are shown in Figure 3.1. Collection efficiencies were applied to data for measured CH_4 to increase flow rates and approximate actual CH_4 generation. Trends for α = 85% and $\alpha = f(t)$ shown in Fig. 3.1 are representative of all individual phases and indicate that as time progressed, collection efficiency based on the $\alpha = f(t)$ method increases and yields modified CH_4 flow rates more comparable to actual observed flow rates. Alternatively, α can be applied to the predicted CH_4 flow rate, as in Eq. 1, to reduce CH_4 predictions and compare directly to measured collection flow rates (e.g., Wang et al. 2013, 2015). In both α applications (i.e., to reduce generation predictions or increase actual collection) the same uncertainties in α are accounted for and will lead to the same end-state analysis between modeled and measured CH_4 flow rates. Karanjekar et al. (2005) similarly modified observed gas flow rate data using a collection efficiency parameter. Their reasoning was that a model reflects ideal conditions compared to imperfect field measurements. Thus, the collection efficiency should modify the imperfect observations to better reflect modeled flow rates. There was found to be very little difference between varying and generic collection efficiencies.

3.4 Decay Rate Optimizations

Landfill gas modeling was conducted for the site-wide analysis at Landfill T, which accounted for all gas well measurements throughout the entire site, and phase-specific analyses, which only incorporated gas wells within a particular phase. The LandGEM model in Eq. 1 was applied based on the following conditions: (i) assumed constant L_0 = 100 m^3-CH_4/Mg-waste; (ii) α = 100%, since the two α methods [α = 85% and $\alpha = f(t)$] described previously were applied to modify gas well flow rate data; (iii) mass of CH_4 generating waste consisted of MSW; and (iv) optimized k to minimize the sum of square residuals between gas well flow rate data and a given model simulation. These conditions were applied to monthly average CH_4 flow rate measurements and annual average CH_4 flow rate measurements to assess if there was any difference in k based on the number of data points used.

The value of L_0 reported in literature varies considerably, ranging from 6 to 270 m^3-CH_4/Mg-waste depending on composition of the waste stream (US EPA, 2008; US EPA AP-42, 1998; Oonk, 2010). The actual L_0 most likely varies between landfills and within a given landfill. Staley and Barlaz (2009) reported that L_0 ranges from 59 to 64 m^3-CH_4/Mg based on U.S. EPA and U.S. state-specific waste characterization data. However, recent analyses of full-scale landfill gas data suggest that L_0 = 100 m^3-CH_4/Mg provides a best fit between LandGEM predictions and gas collection measurements (Wang et al. 2013, US EPA 2008; US EPA AP-42 1998). Thus, a constant L_0 = 100 m^3-CH_4/Mg-waste was assumed for all gas model simulations conducted for this study.

All gas model simulations were conducted to minimize the sum of squared residuals (SSR) between modified CH_4 collection data and predicted CH_4 generation via Eq. 1. Optimizations were completed in Excel using the Solver function to search for k that yielded a minimum SSR. The squared difference between each measured methane flow rate and averaged measured flow rate were summed to compute the SSR. Additionally, a coefficient of determination (R^2) was computed as 1 minus the ratio of SSR to total sum of squares. An initial k = 0.04 1/yr was used for all simulations to control the starting value for subsequent optimization. For comparison, common decay rates used for gas modeling are k = 0.04 1/yr, which is the AP-42 default, and k = 0.08 1/yr, which is a recommended rate based on assessment of gas generation in wet landfills (Reinhart et al. 2005).

3.5 Organic Stability Evaluation

Organic stability evaluations were conducted with respect to total gas generation (CH_4 + CO_2) as well as only CH_4 generation. The WDNR specifies that the following two gas metrics shall be met within 40 yr of post closure to support that current landfill operations are meeting the goal of organic stability (WDNR 2006): (i) monthly average $CH_4 + CO_2$ production rate ≤ 5% of average maximum monthly production rate, or ≤ 278 L-gas/m^3-waste/yr; and (ii) cumulative $CH_4 + CO_2$ yield ≥ 75% of projected total gas production. Alternatively, CH_4 yield and flow rates were evaluated since (i) CH_4 is directly predicted via LandGEM, (ii) CH_4 production may decrease prior to CO_2 at the end of decomposition cycle, and (iii) CH_4 is a more potent greenhouse gas. Thus, total gas flow measurements from Landfill T were adjusted via measured CH_4 composition (Table 2.4) to compare CH_4 yield and flow rates directly with LandGEM predictions. In addition, LandGEM predictions were increased with a respective balance of CO_2 to facilitate organic stability evaluations based on total gas yield and flow rate. These two organic stability evaluations were used to assess if different elapsed times to reach the gas yield and gas flow rate goals were achieved via total gas and CH_4 only.

Waste filling in Phases 1 through 6 was completed prior to this study and the end dates for waste filling (Table 2.1) were used as the start of the 40-yr post closure care period. In actuality, there would be some elapsed time prior to the placement of final cover and transition to post-closure care. However, the end date of waste filling was adopted herein as a conservative data for closure. Forecasts of CH_4 generation and total LFG generation for Phase 7 were completed assuming waste placement stopped in December 2014, the last year MSW disposal data were recorded. All gas model simulations were carried out to approximately 100 yr from the date of initial waste placement. These predictions of gas generation were compared to the organic stability goals stipulated by WDNR to assess organic stability.

A summary of maximum monthly flow rates used for the organic stability analyses is presented in Table 3.2. Maximum flow rates were normalized with respect to the amount of waste placed in the modeled area. The flow rates for organic stability criteria presented in Table 3.2 are based on both maximum observed and modeled flow rates. The maximum monthly flow was estimated via two methods: (1) recorded observations from Landfill T using total gas data and assuming a gas composition of 55% methane and (2) observed data of both gas composition and flow rates at Landfill T. Modeled flow rates were estimated using a *k* optimized with for the monthly data analysis with an average α = 85% (supported subsequently). The projected amount of total gas was estimated using optimized *k* values for specific areas at Landfill T. To achieve organic stability requirements, gas production was required to be under 5% of the maximum monthly total flow rate, and greater 75% of projected total gas yield.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Summary of Model Simulations

Predicted CH_4 flow rates and adjusted CH_4 flow rate measurements versus time for Landfill T based on α = 85% and $\alpha = f(t)$ are shown in Figures 4.1 through 4.8 for site-wide and phase-specific analyses. Optimized first-order decay rates corresponding to site-wide and phase-specific analyses are presented in Table 4.1. Optimized k values ranged from 0.021 to 0.12 1/yr with an average of 0.071 1/yr. Decay rates found using the optimization techniques in this study are comparable to decay rates for leachate recirculation and bioreactor landfills where waste biodegradation has been enhanced anaerobically (e.g., k = 0.08 1/yr is recommended for gas generation in wet landfills; Reinhart et al. 2005).

The site-wide evaluation, including all phases at Landfill T, yielded k ranging from 0.068 to 0.077 1/yr depending on gas flow averaging and the assumption for gas collection efficiency (Table 4.1). These k values are all greater than the AP-42 default for conventional landfills of 0.04 1/yr, and support the conclusion that waste decomposition and biogas generation rates were increased at Landfill T relative to a conventional landfill. Optimized models for Phase 3 & 4 and Phase 5 indicate a more pronounced increase in methane generation rate, suggesting that the waste wetting methods implemented to enhance waste decomposition in these phases were successful. Although an aggressive liquid addition strategy was implemented in Phase 6, optimized methane generation rates were lower and close to the AP-42 value of 0.04 1/yr. The k values optimized for Phase 1A & 2A and Phase 1B & 2B were unrealistically high; and due to observed deviations between the gas models and data, these phases were excluded in a second site-wide analysis.

4.2 Site-Wide Analysis

The site-wide optimized *k* determined in this study, including Phases 1A & 2A and Phase 1B & 2B (0.068 1/yr), was nearly identical to the *k* determined in a site-wide modeling analysis conducted by engineers at Landfill T (*k* = 0.067 1/yr). This *k* value determined via engineers at Landfill T was optimized in LandGEM assuming 50% CH_4 content and a constant α = 85%. The similarity in *k* between the analysis conducted herein and the analysis conducted by Landfill T confirms that similar data were used and supports the gas modeling methods adopted herein.

A second site-wide gas analysis (Site-Wide 2) was performed excluding data from Phase 1A & 2A and Phase 1B & 2B. Temporal trends of adjusted CH_4 collection flow rates and gas model simulations completed for Site-Wide 2 are shown in Fig. 4.2. The goals of this second site-wide analysis were to (i) exclude questionable data and (ii) assess the influence of more recent and aggressive liquid addition / leachate recirculation strategies on waste decomposition and gas generation. However, the best-fit optimized decay rate in this scenario was approximately 0.04 1/yr. This lower *k* relative to the site-wide analysis that included all solid waste disposal and gas collection data for the entire site (i.e., *k* ≈ 0.07 1/yr) suggests that even with an active leachate recirculation / liquid addition plan, on average, waste decomposition and gas generation at Landfill T is representative of a conventional landfill. An important consideration in the Site-Wide 2 analysis is that compiling all site-wide data into a single analysis provides an averaged analysis, whereas the phase-specific analyses (described subsequently) indicate that the moisture enhancement strategies at Landfill T were effective in promoting organic waste decomposition and increasing gas generation.

In the Site-Wide 2 analysis, a lag time between the initial placement of solid waste and onset of gas generation may have been beneficial to improve gas model simulations. Waste placement began in Phase 3 & 4 in 1996 (Table 2.1), but gas collection was not initiated until 2002 (Table 2.3). This lag time is observed in Fig. 4.2, whereby the onset of gas generation via LandGEM does not coincide with initial gas collection measurements. Including a lag time in

LandGEM will shift the entire model to later times (i.e., to the right in Fig. 4.2), and is based on the assumption that gas generation does not start immediately with placement of solid waste. The implication of including a lag time in the LandGEM model (Eq. 1) is discussed subsequently with examples from select phases.

4.3 Phase-Specific Analysis

Moisture enhancement practices implemented for Phase 3 & 4 at Landfill T successfully increased the moisture content in the solid waste and enhanced waste decomposition. Monthly and annual gas model simulations for Phase 3 & 4 are shown in Figure 4.5. Optimized *k* values ranged between 0.06 and 0.10 1/yr (Table 4.1), or approximately equivalent to the recommended *k* value for a “wet landfill” by Reinhart et al. (2005). Phase 3 & 4 was the first phase at Landfill T where operations were implemented to recirculate leachate and add liquid wastes to enhance waste decomposition (Table 2.2). The success of practices in Phases 3 & 4 likely influenced subsequent aggressive liquid addition and leachate recirculation practices at Landfill T to try and further enhance waste decomposition.

Monthly and annual gas model simulations for Phase 5 are shown in Figure 4.6. Model simulations for Phase 5 yielded the largest rates of methane generation and highest *k* of approximately 0.12 1/yr (Table 4.1). The leachate recirculation and liquid addition strategy in Phase 5 was more aggressive compared to Phase 3 & 4 based on both the total liquid added per mass of waste and average wet weight water content (Table 2.2). The gas model simulations shown in Fig. 4.6 effectively capture the declining rate of CH_4 generation, which supports both the validity of the LandGEM model to represent landfill gas generation and the gas modeling methodologies adopted in this study.

Monthly and annual gas model simulations for Phase 6 and Phase 7 are shown in Figs. 4.7 and 4.8, respectively. Relatively low optimized *k* values were computed for Phase 6 ($k \approx 0.04$ 1/yr) and Phase 7 ($k \approx 0.02$ 1/yr) relative to Phases 3 & 4 and Phase 5. While *k* values for Phase

6 are not as high as expected compared to Phase 5 (which had similar moisture condition), gas generation is enhanced above default conditions (Table 2.2). The moisture enhancement practices implemented in these phases occurred very quickly after waste placement began and may have resulted in conditions past those optimal for enhanced methane generation. For example, liquid addition for Phase 6 and Phase 7 occurred 4 and 5 months respectively after waste placement was initiated (Table 2.2). Whereas in Phase 5, liquid addition did not begin until nearly 3 years after waste placement began. Another possible explanation is that pores within the MSW may have become flooded with liquid. MSW can have highly gas permeability due to the relatively large porous structure within the material (Jain et al. 2005; Powrie et al. 2008). High water content within the waste exerts significant influence on gas permeability and hence a low gas permeability of the waste (Zhan et al., 2015). Thus, if Phase 6 and Phase 7 had too much liquids addition, observations of the methane generation process may not have been possible. Additionally, Phase 7 is a young cell at Landfill T and has limited gas data. Thus, *k* is likely to increase in the future as more gas generation becomes more established.

The gas model simulations for Phase 1A & 2A and Phase 1B & 2B resulted in deceivingly high decay rates (*k* ≈ 0.09 to 0.12 1/yr) for landfill phases that received negligible amounts of liquid to enhance waste moisture content (Table 2.2). These high *k* values were due to the considerably large difference between CH_4 collection flow rates and predicted CH_4 flow rates via LandGEM (Figs. 4.3 and 4.4). Considering that similar *k* values were obtained in this study and by Landfill T for site-wide analyses that included Phases 1 & 2, the gas modeling procedures used for the phase-specific optimizations in Phase 1A & 2A and Phase 1B & 2B can be assumed correct. Thus, there are a couple reasons for the discrepancies observed in Phases 1 & 2: (i) the reported waste mass disposed was lower than the actual waste mass disposed; or (ii) the assumed percent contribution of MSW (i.e., 70%) was too low. Increasing the mass of waste placed or the percent contribution of MSW will lead to a higher predicted CH_4 flow rate (Eq. 1). However, the exact reason for the discrepancy between actual and predicted CH_4 flow rates was not known, and thus, the gas analyses conducted for Phase 1A & 2A and Phase 1B & 2B were not considered in subsequent analyses and discussion herein.

4.4 Gas Model Evaluation

A graphical summary of optimized *k* values from annual and monthly gas model simulations, and completed with constant and temporally varying α for the site-wide and phase-specific analyses, is shown in Fig. 4.9. Most *k* values were within a range between the AP-42 recommended default of 0.04 1/yr and the recommend higher *k* of 0.08 1/yr for “wet” landfills (Reinhart et al. 2005). A higher *k* implies that gas generation is occurring more rapidly and is desirable in regards to organic waste stabilization and more rapid exhaustion of MSW gas potential. Increased rates of gas generation are also desirable for landfill owners and operators as more rapid waste decomposition will lead to increased waste disposal in a given landfill area and more available CH_4 for energy generation. Furthermore, the long-term benefit of elevated gas generation rates will be reduced durations of post-closure care.

A comparison of *k* values between the monthly and annual gas model analyses is shown in Fig. 4.10. Most decay rates for a given phase that were optimized for monthly and annual average gas flow rates were similar (i.e., data plot on or near the 1:1 line). Monthly analyses generally yielded higher decay rates, which was attributed to these analyses having been conducted with more data points relative to the annual analyses. The decay rate optimization method adopted herein (i.e., minimizing SSE) aimed to minimize the difference between observed and predicted CH_4 flow rates. Considering that the monthly averaging technique yielded higher flow rates (i.e., annual averages were lower since this averaging smoothed temporal data fluctuations), higher decay rates were required to more accurately predict higher observed monthly gas flow rates. Although the comparison between *k* values determined via monthly and annual average gas flow rates suggests that the annual analysis is slightly more conservative, the monthly average flow rate analysis is preferred. The monthly average gas flow rate analysis is more straight-forward to implement in LandGEM as waste disposal and gas flow data can easily be computed for a given month, and the higher decay rates can be argued to be more representative of the elevated level of waste decomposition and gas generation that is achieved via waste moisture enhancement.

A comparison of *k* values determined via monthly average gas model simulations that incorporated a constant α = 85% and α = f(t) is shown in Fig. 4.11. The two methods to account for gas collection efficiency yielded similar *k* values (i.e., data plot on or near the 1:1 line); however, *k* values determined with α = f(t) were higher, on average, compared to α = 85%. During the early stages of gas collection (e.g., first few years depending on phase size), gas collection efficiencies are more than likely < 85%, and closer to 50% to reflect a lack of in-place infrastructure to capture landfill gas. Thus, an assumed constant α = 85% underestimates CH_4 generated early in the model simulation, but likely leads to more accurate gas predictions as gas collection systems and final cover evolve during the life of a landfill to more effectively capture gas. The temporally varying α was used to represent a more realistic situation that occurs in landfill operations, which leads to higher CH_4 predictions early in a given analysis, and thus, increased optimized decay rates relative to the constant α approach. However, the α = f(t) method is subjective and difficult to adopt as a universal method that can be generalized across landfills and adopted in practice. In contrast, a single, constant α is straightforward and leads to a more conservative assessment of organic stability. Thus, the constant α approach is recommended for use in practice. Based on simulations conducted herein and in other simulations of full-scale landfill gas data (e.g., Wang et al. 2013, 2015), an α = 85% is an appropriate assumption to use unless landfill operations support the use of a different α.

4.5 Impact of Liquid Addition on Gas Generation

Relationships between first-order decay rate versus liquid addition per waste mass and wet weight water content are shown in Fig. 4.12. First-order decay rates from this study that are plotted in Fig. 4.12 are representative of the monthly average gas flow rate analyses with a constant site-wide collection efficiency of 85%. Optimized decay rates from Barlaz et al. (2010) that are representative of a range of leachate recirculation and bioreactor landfills are also plotted in Fig. 4.12. In general, there was a trend of increasing *k* with increasing liquid addition per mass of solid waste; however, there was no discernable trend between *k* and wet weight water content of the solid waste.

The addition of leachate and other liquids has been shown to increase wastewater content and gas generation rates in landfills (Barlaz et al. 2010, Reinhart et al. 2005). Decay rates, levels of liquid addition, and resulting wet weight water contents from this study are comparable to those reported in Barlaz et al. (2010). The relationship between *k* and total liquid added per mass of waste supports development of a lower-bound threshold (dashed-line in Fig. 4.12a) to identify an approximate level of liquid addition that can be targeted to achieve an elevated *k*. However, the range of *k* for a given level of liquid added per mass of waste (e.g., compare Phase 5 and 6 from this study at approximately 70 L/Mg) cannot be attributed to a single factor, but affected by methane potential of disposed waste, actual gas collection efficiency, or environmental conditions of the waste (e.g., temperature) among other factors. Additional investigation into these factors is needed to shed additional light on the range of *k* for a given amount of added liquid.

Barlaz et al. (2010) attributed the lack of any discernable trend between *k* and wet weight water content (Fig. 4.12b) to considerable variation in physical water content measurements that are reflective of waste composition heterogeneity. Water content measurements will reflect the constituents of the sample. Large amounts of samples would need to be obtained for a specific area in order to gain an accurate understanding of moisture content. Executing this would be impractical and time-consuming.

4.6 Impact of Lag-Time on Gas Modeling

Visual comparisons of phase-specific analyses (Figs. 4.5 - 4.8) suggest that in many cases including a lag time between initial waste placement and onset of gas generation in LandGEM (Eq. 1) would increase model accuracy. A lag time is a natural period of time following waste disposal that is required for microorganisms necessary to carryout methanogenesis (i.e., generate methane) to proliferate. Including a lag time in LandGEM introduces an additional variable that more than likely varies as a function of operational and environmental factors. To assess the inclusion of lag time on the landfill gas model simulations conducted herein, a lag time was introduced into the gas model simulations completed for Phase 3 & 4 and Phase 6.

Temporal trends of monthly average methane flow rates for Phase 3 & 4 and Phase 6 are shown in Fig. 4.13 along with model simulations that included different lag times. All model simulations in Fig. 4.13 were optimized using a constant collection efficiency (i.e., α = 85%) on a monthly basis for lag times of 0 (i.e., baseline LandGEM model in Eq. 1), 1, 2, 3, and 4 yr. Optimized decay rates and coefficients of variation (R^2) are summarized in Table 4.2 for these model simulations. Visual observation of the model simulations for Phase 3 & 4 and Phase 6 suggest that the inclusion of a lag time can lead to an improved fit between the model and observed CH_4 flow rate (Fig. 4.13).

The *k* values determined for Phase 3 & 4 with lag times ranging from 0 to 4 yr are comparable and vary between 0.061 and 0.073 1/yr. Similarly, the *k* values determined for Phase 6 with lag times ranging from 0 to 4 yr are comparable and vary between 0.042 and 0.051 1/yr. However, the R^2 for Phase 3 & 4 increases with increasing lag time (Table 4.2) and the best-fit model was achieved with a lag time of 4 yr. The R^2 for Phase 6 also increases with increasing lag time up to 2 yr, and then subsequently decreases (Table 2.2). In both gas model simulations, the R^2 improved with an inclusion of a lag time between initial waste placement and onset of gas generation. The difference in lag times between the two phases can be attributed to the actual lag time between waste placement and gas collection (i.e., 5.8 yr for Phase 3 & 4 and 2.9 yr for Phase 6, Table 2.3).

Previous studies (Wang et al. 2015) have confirmed that a lag time can potentially enhance the accuracy of a given model optimization similar to the observations made for Phase 3 & 4 and Phase 6. However, the same study reported that for less than 10% of the landfills examined, a time lag produced negligible improvement in concordance between calculated and observed gas flow rates. Furthermore, the actual change in *k* for the optimizations conducted in this study suggest that inclusion of a lag time may have only a minor influence on actual magnitude of the decay rate. The benefit of including a lag time is to improve the model fit and enhance forecasts of gas generation. However, considering that LandGEM does not currently include a lag time, a consistent and direct application of LandGEM for gas modeling efforts to determine a *k* value and assess organic stability should be conducted until additional research can support a recommended lag time that can be readily adopted in LandGEM and is relevant to practicing engineers.

4.7 Assessment of Organic Stability

Summaries of organic stability analyses based on total gas and methane are presented in Table 4.3. The numbers reported in Table 4.3 are the years required following final waste placement to achieve the gas flow rate and gas yield metrics for organic stability stipulated in WDNR (2006). Site-wide and phase-specific evaluations of organic stability that include an assessment of gas flow rate and cumulative gas yield are shown in Figs. 4.14 to Figure 4.19. Phases at Landfill T where waste decomposition practices successfully increased *k* to values greater than the AP-42 recommended *k* of 0.04 1/yr intuitively decreased the duration to achieve organic stability. For the site-wide analysis, the duration to meet organic stability is very short (i.e., about 1 year). This may be because Phases 1 and 2 were included in this analysis and waste placed in these phases began decomposing before waste was placed in other phases. All analyses except for Phase 6 and Phase 7, were either near or less than the required 40 yr duration for post-closure care monitoring. There was a negligible difference in the durations between assessing organic stability in terms of total gas or methane. The amount of time for a given area to reach organic stability based on a cumulative yield gas metric was always shorter than the time to reach organic stability based on gas flow rate. This is likely due to the decay-rate function of LandGEM. The cumulative yield of a modeled area will reach 75% of the total projected yield while flow rates will take longer to decay past required levels.

The maximum monthly total gas and CH_4 determined via adjusted collection rates were consistently larger than the maximum monthly flow rates determined via LandGEM (Table 3.2). Thus, the 5% flow rate goal stipulated in WDNR (2006) can be achieved at a shorter elapsed time when compared to actual adjusted flow rates that represent gas generation versus gas flow rates based on LandGEM. Additionally, the 5% flow rate goals computed from either measured or modeled flow rates were consistently larger relative to the alternative flow rate metric of 278 L-gas/m^3-waste/yr stipulated in WDNR (2006) for all phases except Phase 7. Thus, for all landfill phases evaluated in this study that had $k \geq 0.04$ 1/yr, computing the 5% flow rate goal based on actual data will lead to shorter elapsed times to meet organic stability versus comparing flow rate to the alternative default value of 278 L-gas/m^3-waste/yr.

CHAPTER 5: CONCLUSIONS AND PRACTICAL IMPLICATIONS

An assessment of organic waste stability was completed based on comparison between collected and predicted landfill gas generation. The two main objectives of the study were to (i) assess landfill organic stability for an entire site and specific landfill phases to evaluate how operational practices influence organic stability and (ii) develop recommendations for conducting organic stability assessments based on gas collection and modeling. Gas modeling results were evaluated with regards to organic stability requirements outlined in the Wisconsin Department of Natural Resources organic stability rule (OSR). The following conclusions were drawn from this study.

- Moisture enhancement practices implemented to enhance waste decomposition within a landfill have potential to increase the methane generation rate constant (k), up to and exceeding the 0.08 1/yr rate recommended for "wet landfills." An increase in k leads to more rapid gas generation and reduced time to achieve organic stability.
- Methane generation models optimized for k using a temporally varying collection efficiency [$\alpha = f(t)$] typically yield k values greater than models optimized with a constant collection efficiency (i.e., $\alpha = 85\%$ in this study).
- Methane generation models evaluated on with annual average flow rates yielded higher k values compared to those models evaluated monthly average flow rates.
- The required duration for a given landfill phase to reach organic stability is typically shorter when evaluated based on a cumulative yield gas metric (i.e., ≥ 75% cumulative gas). Thus, evaluating organic stability using rate-specific criteria is recommended as a more conservative assessment. Depending on the goals for landfill owners or regulators, recommendations may be developed to use maximum measured flow rates versus maximum modeled flow rates.

- Adjusted total gas or methane flow rates used to assess the flow rate criterion of the OSR (i.e., ≤ 5% of maximum flow rate) were greater than the default flow rate of 278 L-gas/m^3-waste/yr stipulated in the OSR for all landfill phases with *k* ≥ 0.04 1/yr. Thus, for landfill phases where waste decomposition and gas generation have been enhanced (i.e., *k* ≥ 0.04 1/yr), the default flow rate stipulated in the OSR will lead to longer elapsed times to meet the organic stability flow rate criterion.

Previous studies have shown considerable variability in matching methane generation predictions via LandGEM with actual methane collection data. Landfill gas modeling conducted for this study demonstrated that the effectiveness with which LandGEM can explain temporal fluctuations in measured flow rate is a function of gas collection efficiency as well as the lag time between initial waste placement and assumed onset of gas generation. The following recommendations for landfill gas modeling and assessments of organic waste stability are based on the models and analyses conducted in this study.

- Landfill owners and operators are recommended to use a simple, first-order decay rate gas generation model (e.g., LandGEM) with constant methane generation potential and constant site-wide collection efficiency.
- Optimizations of *k* are recommended to be conducted based on minimizing the sum of squared residuals between monthly average measured flow rates and monthly predicted flow rates from the gas model. The monthly average gas flow rate analysis is more straight-forward to implement in LandGEM as waste disposal and gas flow data can easily be computed for a given month. Higher decay rates can be argued to be more representative of the elevated level of waste decomposition and gas generation that is achieved via waste moisture enhancement.

- The benefit of introducing a lag time into LandGEM is to improve the model fit and enhance forecasts of gas generation. A consistent and direct application of LandGEM with no lag time shall be completed to determine a *k* value and assess organic stability, as this approach can be replicated between phases and sites. Modeling gas generation via LandGEM with a lag time shall include the necessary support and documentation (e.g., delayed liquid addition or installation of gas collection following waste placement) to accompany the model simulations.
- Assessing organic stability at a landfill is recommended to be evaluated on a phase-specific level where applicable. Due to variability in landfill operations (e.g., gas collection, liquid addition, leachate recirculation, etc.), site-wide assessments may not accurately capture enhanced gas generation and improved organic stability. A greater level of detail via a phase-specific analysis will allow specific landfill phases to be deemed organically stable earlier to potentially reduce the duration of required post-closure care.

Table 2.1. Summary of disposal phases at Landfill T, included waste filling dates, landfill dimensions, filling rate, disposed municipal solid waste (MSW), and estimated total waste volume.

Phase	Start Date of Waste Filling	End Date of Waste Filling	Area (ha)	Estimated Depth (m) [a]	Filling Rate (Mg/d) [b]	Mass of Disposed MSW (Mg)	Estimated MSW Volume (m^3) [c]
1A & 2A	Jan. 1995	Jan. 1998	3.16	9	176 (194)	145,127	129,385
1B & 2B	June 1996	Sept. 1998	2.95	15	423 (466)	294,176	262,266
3 & 4	Nov. 1996	Nov. 2000	3.24	34	420 (463)	675,021	601,800
5	Nov. 2000	Oct. 2002	1.58	27	493 (543)	492,443	439,027
6	Oct. 2002	June 2006	1.78	21	512 (564)	978,931	872,745
7	June 2006	Ongoing	2.10	32	230 (253)	1,028,386	916,834
Site-Wide	Jan. 1995	Ongoing	14.8	22	376 (414)	3,614,084	3,222,057

[a] Estimated site-wide depth is average of all phases.

[b] Filling rate in tons/d in parentheses.

[c] Volume of MSW is estimated based on total unit weight for “typical” compaction effort and soil cover for the midpoint of estimated waste depth (11 kN/m^3) via Zekkos et al. (2006).

Table 2.2. Landfill phase-specific and site-wide summary data on leachate recirculation, liquid waste addition, and average wet weight water content.

Phase	Duration Between Initial Waste Placement and Initial Liquid Addition (yr)	Leachate Recirculated (m^3)	Off-Site Liquid Addition (m^3) [a]	Percent Leachate Recirculation of Total Liquids Added (%)	Percent Contribution of RD&D Liquid to Maximum Observed Methane Flow Rate (%) [b]	Total Liquid / Total Waste Mass (L/Mg)	Average Wet Weight Water Content (%) [c]
1A & 2A	-	0	0	0	0	0	—
1B & 2B	14	739	0	100	0	3	37 (10)
3 & 4	4.5	11,690	1,943	86	0.0020	29	42 (5.1)
5	2.8	24,726	6,454	79	0.019	70	45 (4.7)
6	0.33	55,721	1,321	98	0.0025	68	47 (4.3)
7	0.42	7,072	0	100	0	7	44 (3.5)
Site-Wide	14	99,948	9,718	91	0.0005	33	43 (6.4)

Note: Phase 5 and Phase 6 have very similar levels of liquid addition relative to total waste mass. Leachate recirculation began much earlier after initial waste placement for Phase 6.

[a] Includes liquids added via solidification and under the U.S. EPA Research, Development, and Demonstration (RD&D) permit

[b] Methane flow rates due to dissolved organic matter degradation from commercial waste water were estimated using an assumed total organic carbon = 260 mg/L for all off-site liquid, ratio for chemical oxygen demand (COD) to TOC (COD/TOC) = 3, and conversion rate of 0.25 g-CH_4/g-COD (El-Fadel and Massoud 2001). Contributions of methane gas from off-site liquid was assumed negligible.

[c] Standard deviation included in parentheses

Table 2.3. Summary of gas collection system installation, lag time between waste placement and gas collection, number of gas wells, gas flow rate, and percent methane composition.

Phase	Start Date for Gas Collection	Lag Time Between Initial Waste Placement and Gas Collection (yr)	Number of Gas Wells	Gas Well Density (wells/ha)	Average Total Gas Flow Rate (m^3/d)	Range of Total Gas Flow Rate (m^3/d)	Average Percent Methane (%)	Range of Percent Methane (%)
1A & 2A	Mar. 2000	5.2	6	1.9	8,312	897 - 26,296	56	44 - 63
1B & 2B	Mar. 2000	3.8	8	3.2	7,467	460 - 17,321	56	46 - 79
3 & 4	Aug. 2002	5.8	7	2.5	8,239	1,237 - 26,990	55	46 - 61
5	Sept. 2005	4.8	6	3.8	7,943	2,297 - 21,162	55	45 - 61
6	Sept. 2005	2.9	16	3.1	10,406	2,047 - 17,470	53	41 - 59
7	Aug. 2009	3.2	6	2.2	3,895	2,201 - 7,666	54	51 - 59

Table 3.1. Range of estimated gas collection efficiencies and factors contributing to a given collection efficiency that were used for computing temporally varying gas collection efficiencies ($\alpha = f(t)$).

Estimated Gas Collection Efficiency, α (%)	Range of Gas Well Density (wells/ha)	Fraction of Phase Area with an Active Gas Collection System	Fraction of Active Waste Area with Final Cover System
50	0.25 - 0.49	0 - 0.50	0.30 - 0.45
70	0.74 - 1.5	0.50 - 0.55	0.45 - 0.55
85	1.5 - 2.2	0.58 - 0.67	0.55 - 0.65
90	2.2 +	0.70	0.70

Table 3.2. Compilation of maximum total gas and methane flow rates used to assess organic stability.

Phase	Duration of Waste Filling (yr)	Estimated Waste Volume (m^3)	Flow Rates Based on LandGEM Model Simulation with α = 85%		Flow Rates based on Adjusted Gas Collection Data with α = 85%	
			Maximum Total Gas Flow Rate (L/m^3-waste/yr)	Maximum Methane Flow Rate (L/m^3-waste/yr)	Maximum Total Gas Flow Rate (L/m^3-waste/yr)	Maximum Methane Flow Rate (L/m^3-waste/yr)
Site-Wide	19.0	3,222,057	6,131 (307)	3,066 (153)	10,687 (534)	5,343 (267)
3 & 4	3.8	601,800	10,128 (506)	5,064 (253)	21,930 (1,096)	10,965 (548)
5	1.8	439,027	17,495 (875)	8,747 (437)	22,033 (1,102)	11,017 (551)
6	3.6	872,745	6,190 (310)	3,095 (155)	9,059 (453)	4,529 (226)
7	8.0	916,834	2,423 (121)	1,211 (61)	3,984 (199)	1,992 (100)

Note: maximum total gas and methane flow rates were based on the maximum monthly average observed for a given landfill phase or for the site-wide data, and units were subsequently adjusted to reflect gas flow rate units used in the Wisconsin Department of Natural Resources organic stability rule (gas volume / waste volume / year). Flow rates corresponding to 5% of total gas or methane flow rate are included in parentheses.

Table 4.1. Optimized decay rates (k) for site-wide and phase-specific analysis using temporally varying and constant collection efficiencies based on annual and monthly methane flow rate assessments.

Analysis	Parameter	Annual Methane, $\alpha = f(t)$	Annual Methane, $\alpha = 85\%$	Monthly Methane, $\alpha = f(t)$	Monthly Methane, $\alpha = 85\%$
Site-Wide	k (1/yr)	0.074	0.068	0.077	0.070
	R^2	0.68	0.76	0.39	0.53
Site-Wide (excluding 1A & 2A, 1B & 2B)	k (1/yr)	0.042	0.041	0.042	0.041
	R^2	0.66	0.67	0.57	0.60
Phase 1A & 2A	k (1/yr)	0.12	0.12	0.11	0.11
	R^2	-2.7	-2.8	-2.3	-2.4
Phase 1B & 2B	k (1/yr)	0.093	0.089	0.10	0.098
	R^2	-2.9	-2.6	-2.8	-2.7
Phase 3 & 4	k (1/yr)	0.099	0.060	0.085	0.073
	R^2	-0.58	-0.03	0.11	0.05
Phase 5	k (1/yr)	0.085	0.087	0.12	0.12
	R^2	0.067	-0.048	0.34	0.28
Phase 6	k (1/yr)	0.040	0.038	0.044	0.042
	R^2	0.18	0.03	0.00	-0.17
Phase 7	k (1/yr)	0.025	0.022	0.023	0.021
	R^2	-1.81	-3.03	-0.68	-0.67

Table 4.2. First-order decay rates (k) and coefficients of determination (R^2) for model simulations conducted for Phase 3 & 4 and Phase 6 that consider lag times between initial placement solid waste and onset of gas generation of 1, 2, 3, and 4 yr.

Phase	Lag Time for Gas Model Simulation (yr) [a]	Decay Rate, k (1/yr)	R^2
Phase 3 & 4	—	0.073	0.051
	1	0.066	0.059
	2	0.061	0.067
	3	0.063	0.19
	4	0.069	0.31
Phase 6	—	0.042	-0.16
	1	0.043	0.071
	2	0.046	0.35
	3	0.049	0.057
	4	0.051	-1.3

[a] All model simulations conducted with monthly averaged methane flow rates and an assumed constant gas collection efficiency (α) of 85%

Table 4.3. Organic stability evaluation for site-wide and phase-specific analyses that includes the years since final waste placement that are required to meet gas flow rate and gas yield metrics stipulated in the organic stability rule based on total gas and methane gas.

Analysis	Duration of Active (yr)	Optimized k for Monthly, α = 85%	Years to Meet Flow Rate and Cumulative Gas Metrics Based on Total Gas ($CO_2 + CH_4$)			Years to Meet Flow Rate and Cumulative Gas Metrics Based on Methane Gas (CH_4)		
			5% of Max Flow Rate from Model	5% of Max Flow Rate from Data	75% Projected Cumulative Gas	5% of Max Flow Rate from Model	5% of Max Flow Rate from Data	75% Projected Cumulative Gas
Site-Wide	Ongoing	0.070	31	33	1	31	33	1
Site-Wide 2 [a]	Ongoing	0.041	63	54	13	63	54	13
Phase 3 & 4	3.75	0.073	42	36	17	42	33	17
Phase 5	1.83	0.123	25	25	10	25	26	10
Phase 6	3.58	0.042	72	68	30	72	67	30
Phase 7	Ongoing	0.021	87	87	37	87	86	37

Note: Years required to meet organic stability requirements was measured from the end of filling to the estimated date when the requirement would be met. The end of filling was thus taken to be the point of closure for the area examined. A typical design life for a landfill is around 30 years. Because was placement for Landfill T began in 1995, a closing date of January 1st, 2025 was assumed for both side-wide and Phase 7 analyses.

[a] Site-Wide 2 analysis excludes Phase 1A & 2A and Phase 1B & 2B

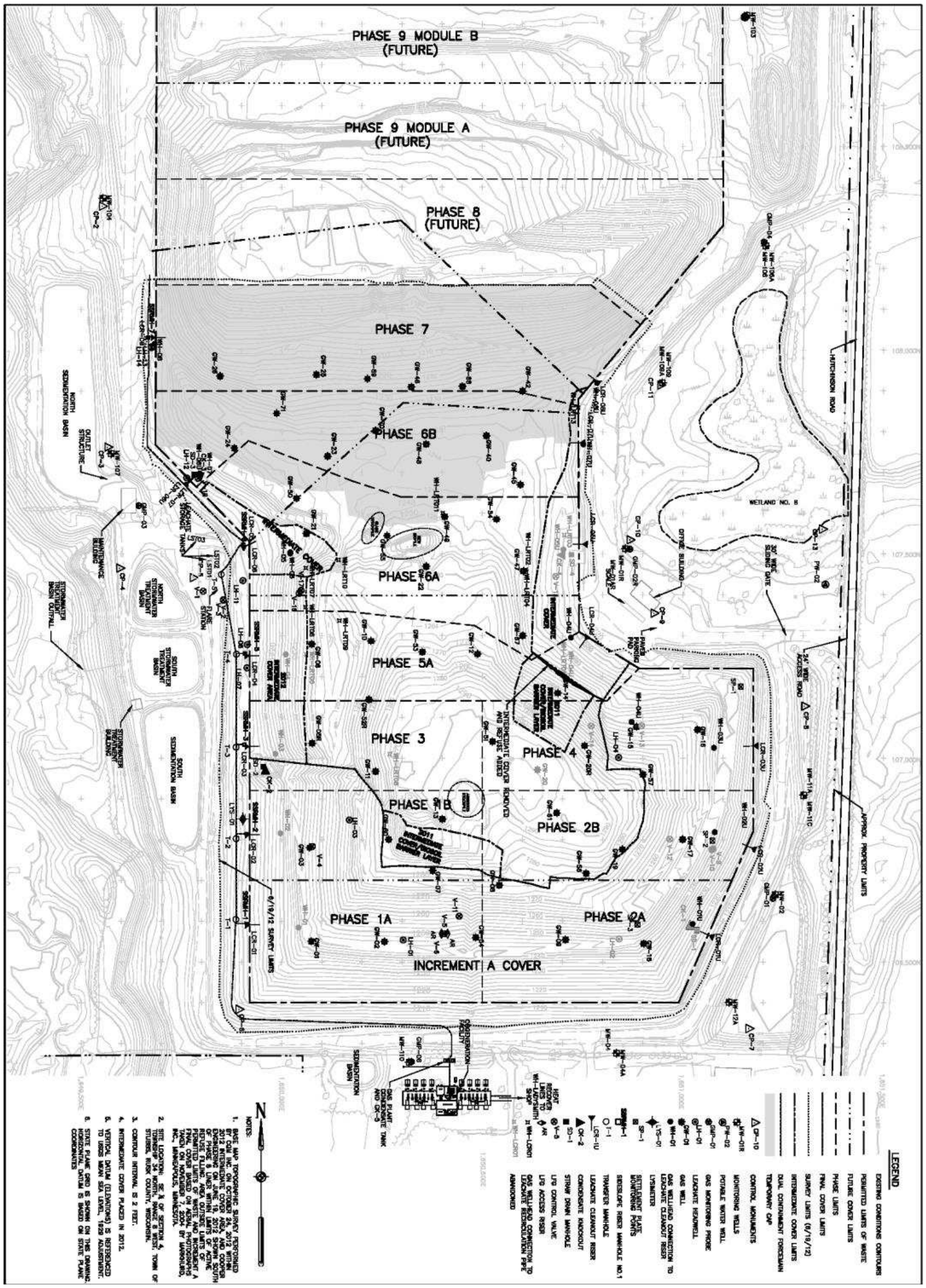

Fig. 2.1. Plan view of Landfill T with delineation of existing phases 1-7.

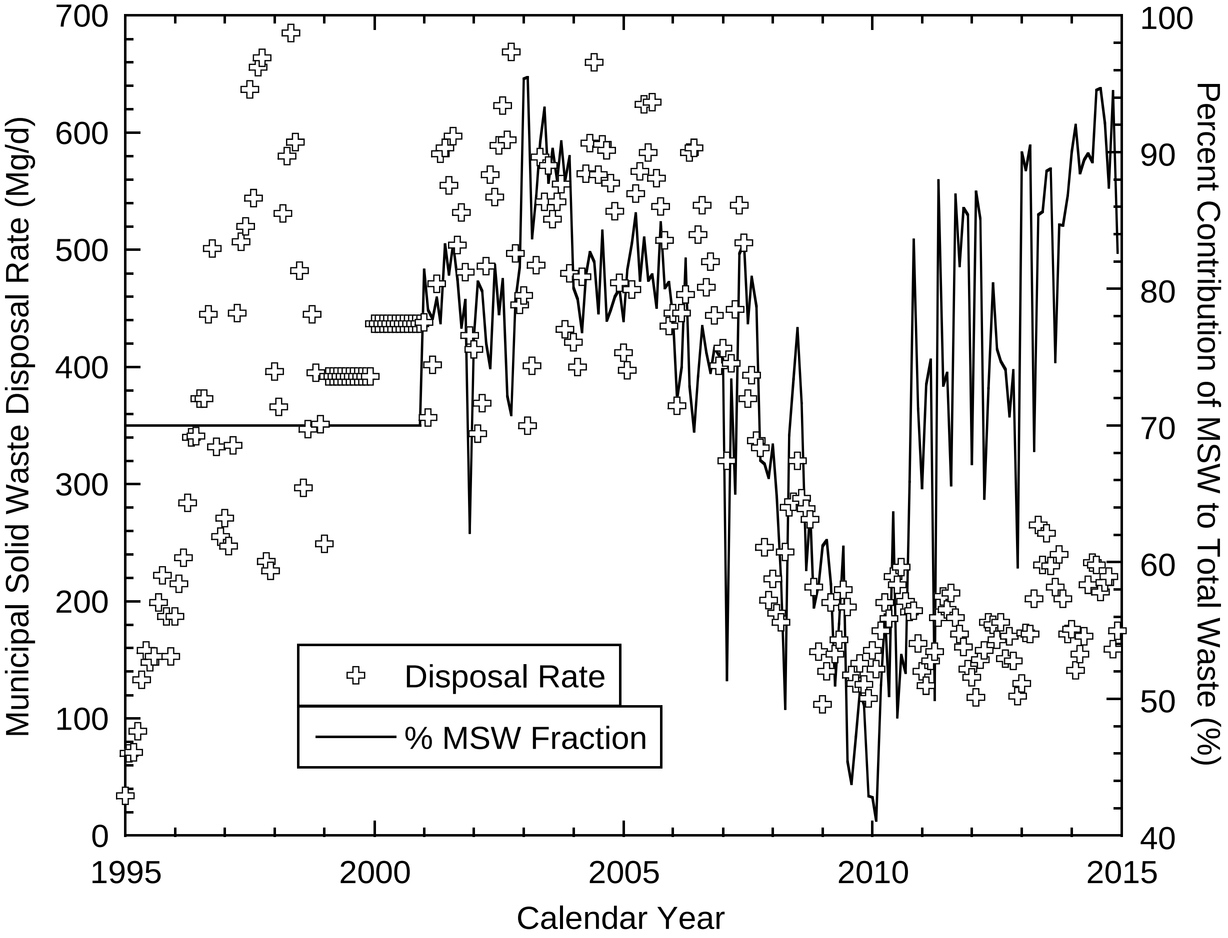

Fig. 2.2. Temporal trend of municipal solid waste (MSW) disposal rate and percent MSW fraction of total waste at Landfill T. Note: The MSW fraction of the incoming waste for years 1995 to 2001 was not available. The MSW fraction for these years was assumed to be 70% based on observations from subsequent years of operation and making conservative assumptions.

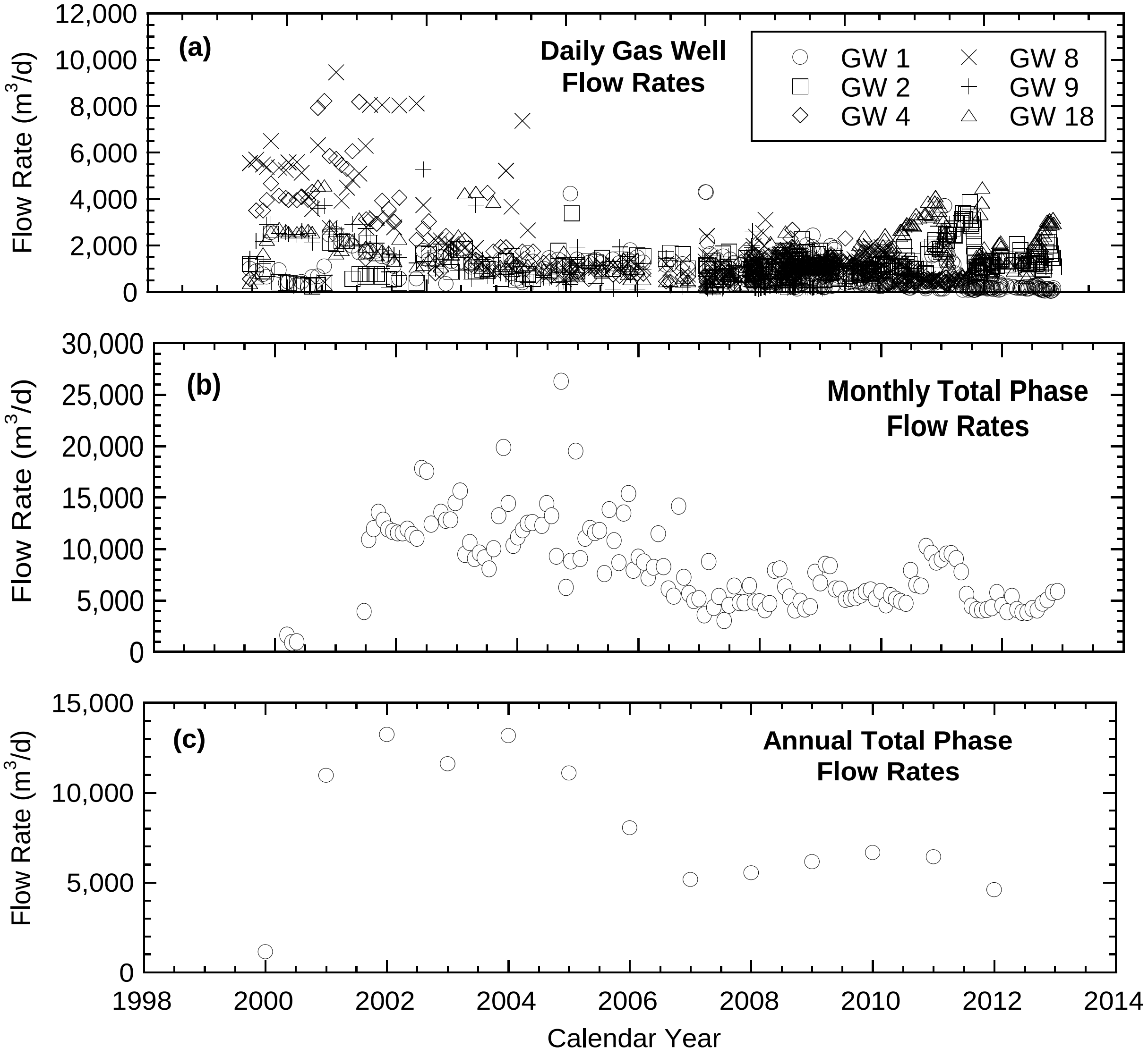

Fig. 2.3. Gas flow rate data for Phase 1A & 2A: (a) individual gas well measurements; (b) monthly gas flow rates for the entire phase; and (c) annual gas flow rates for the entire phase.

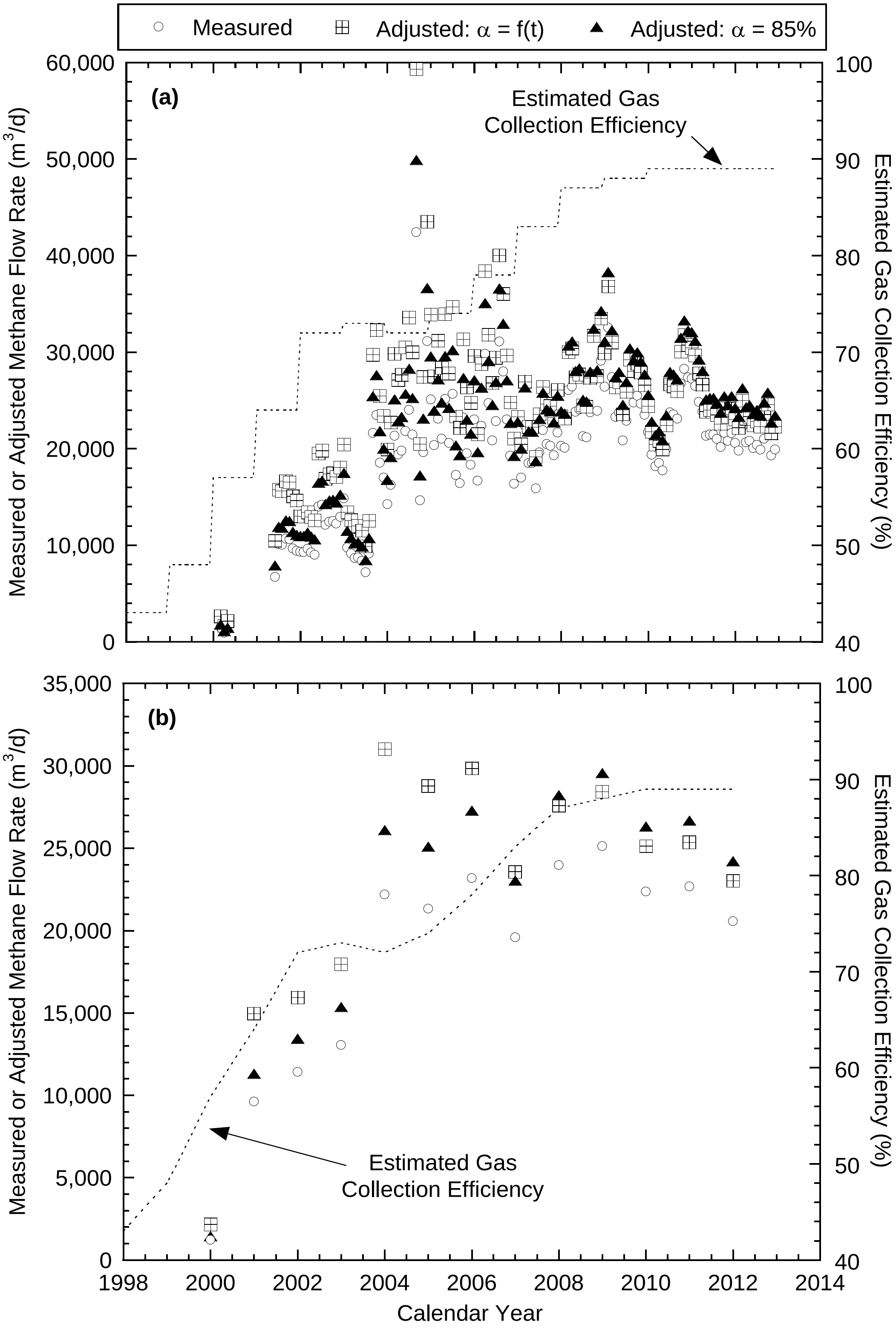

Fig. 3.1. Temporal trends of measured and adjusted methane flows rates and the temporally varying gas collection efficiency for the (a) monthly analysis and (b) annual analysis.

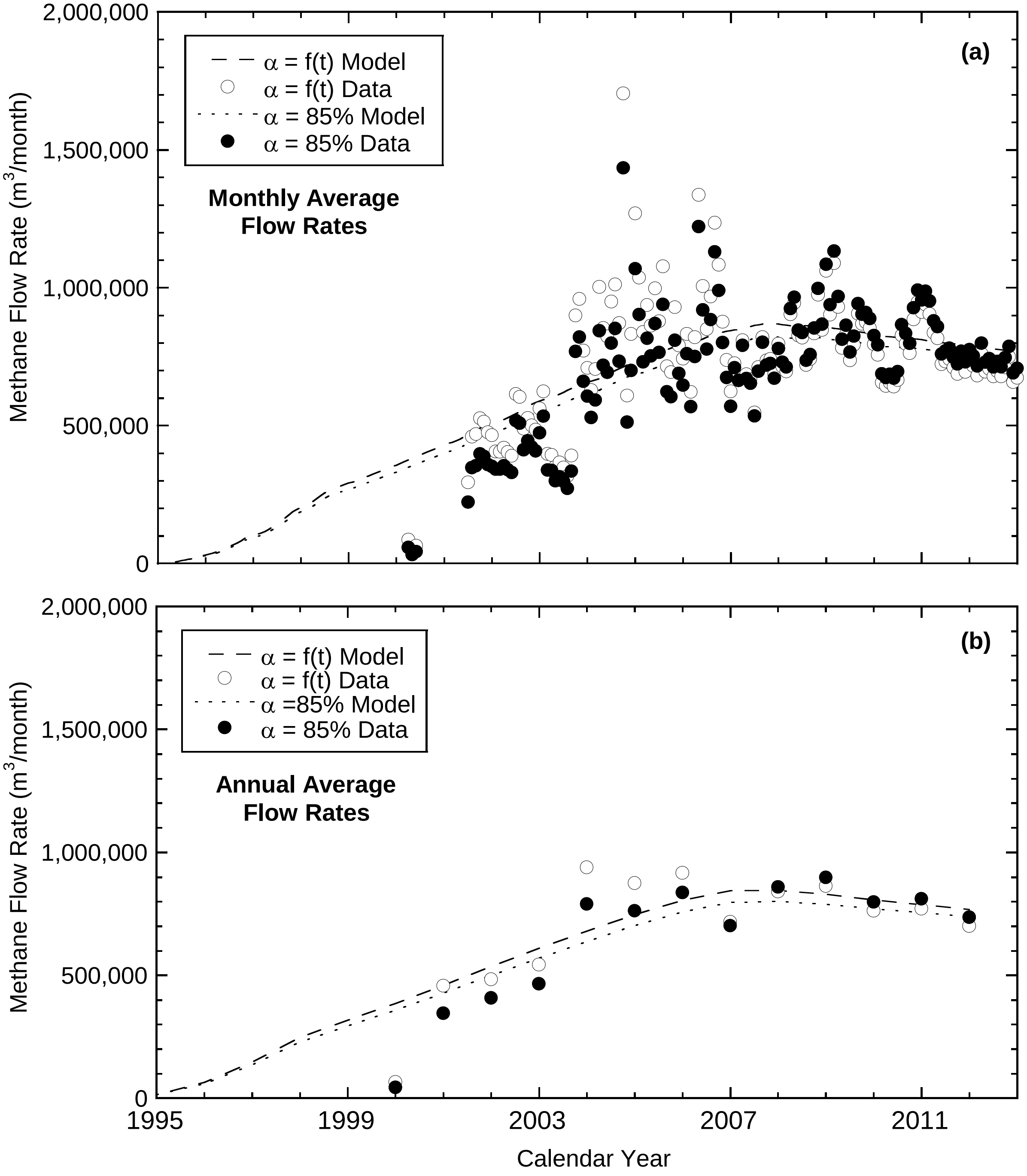

Fig. 4.1. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for the entire landfill (i.e., site-wide analysis). Model simulations completed in LandGEM based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

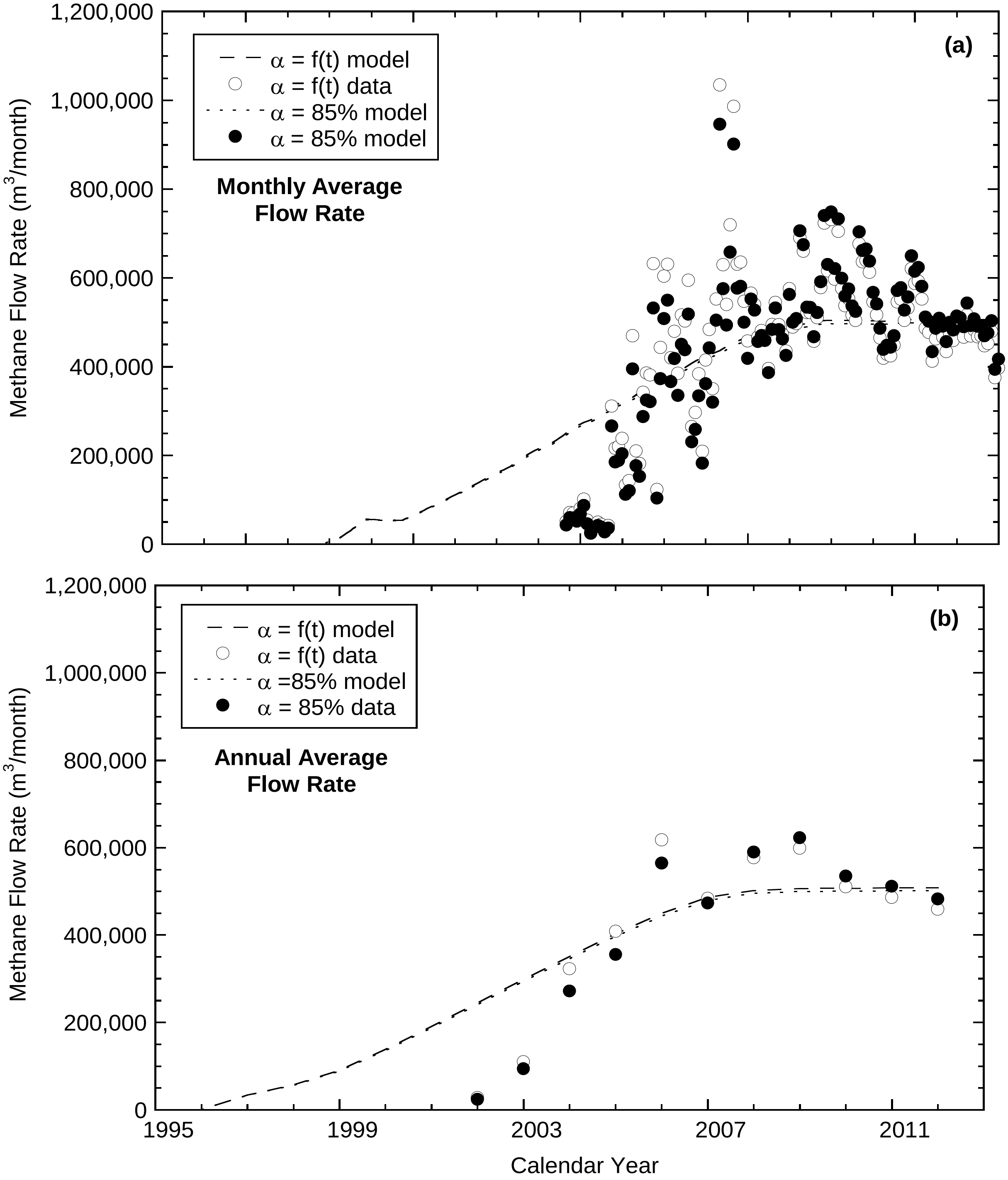

Fig. 4.2. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for a site-wide analysis excluding Phase 1A & 2A and Phase 1B & 2B. Model simulations completed in LandGEM based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

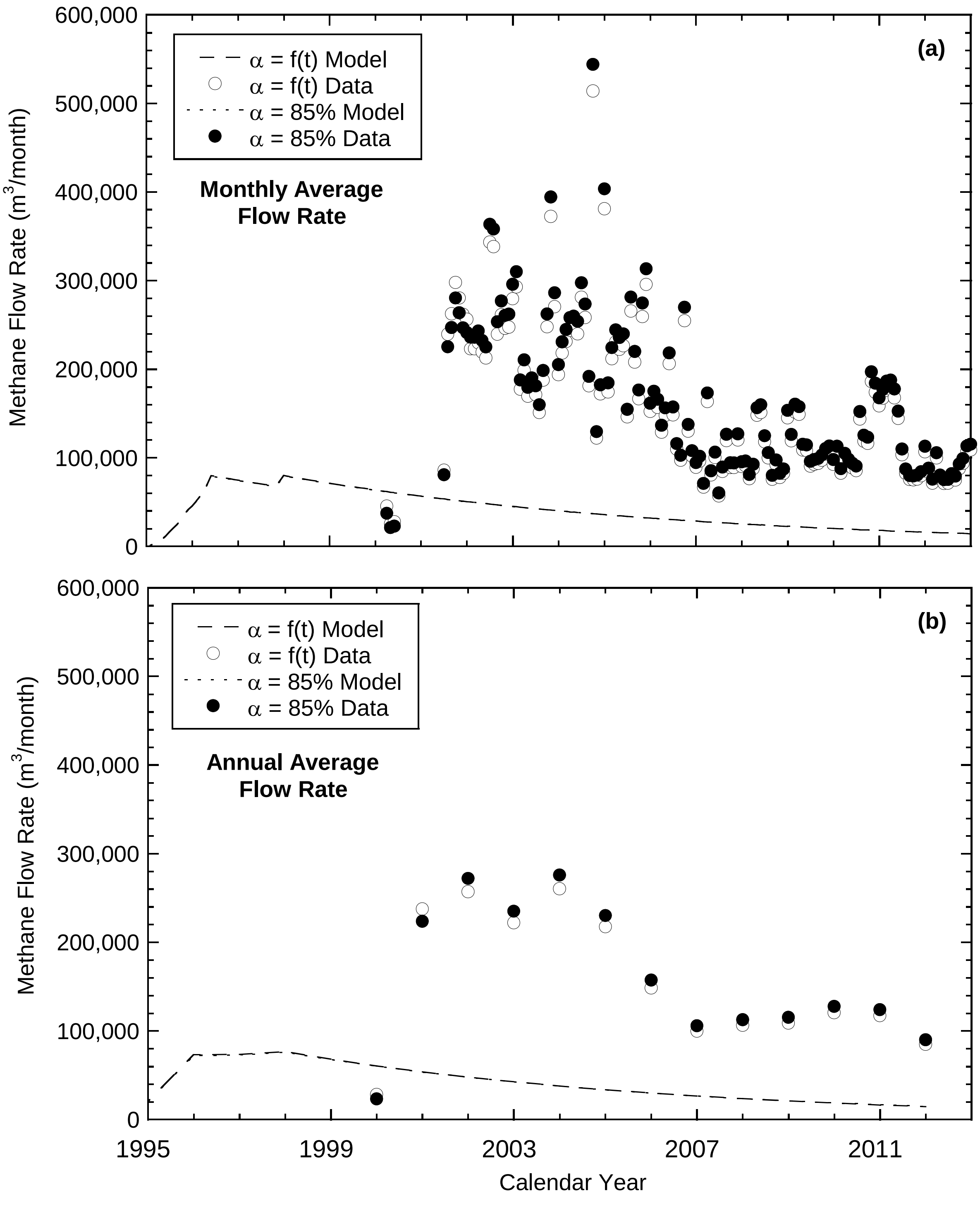

Fig. 4.3. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 1A & 2A. Model simulations completed in LandGEM based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

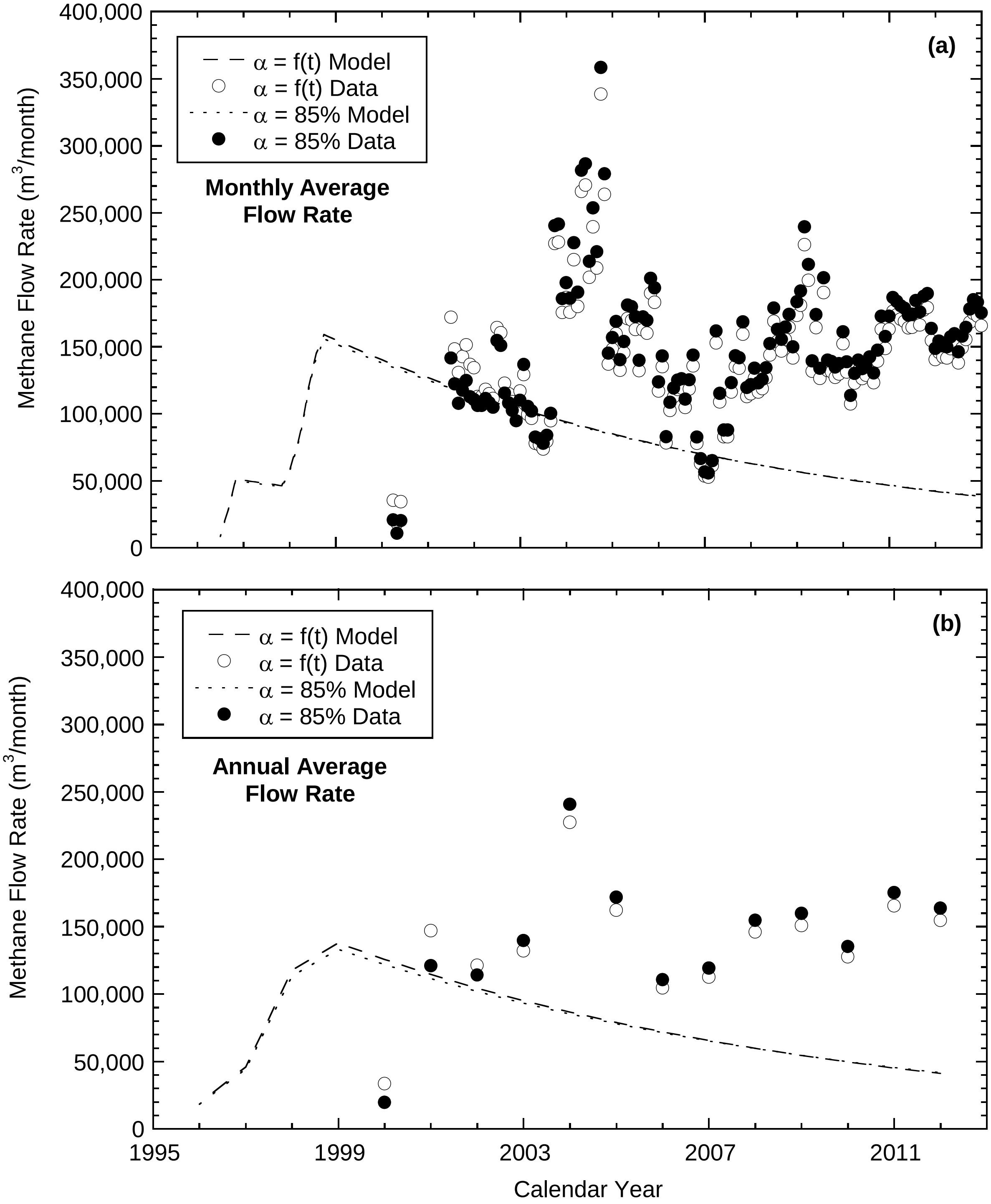

Fig. 4.4. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 1B & 2B. Model simulations completed in LandGEM based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

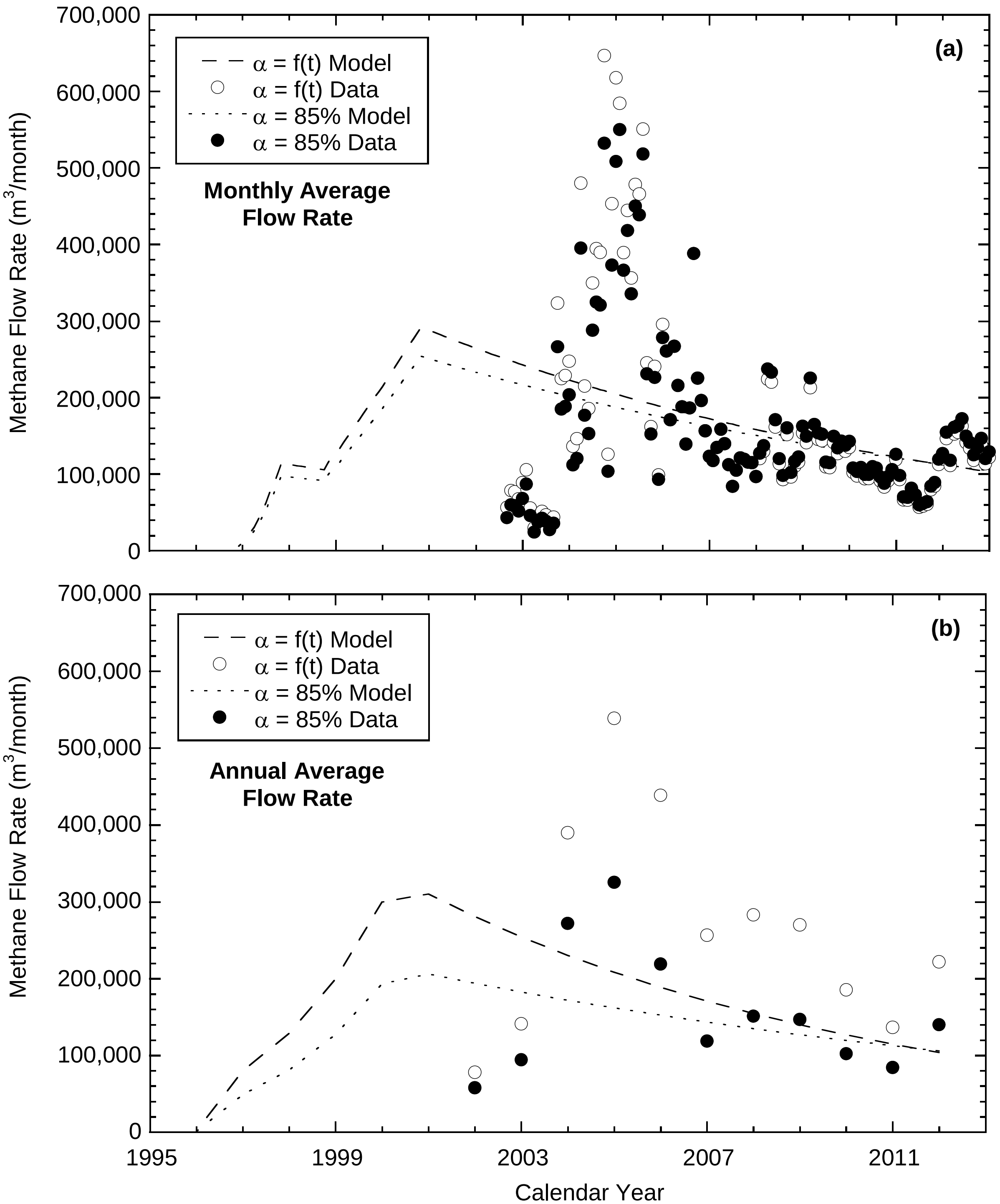

Fig. 4.5. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 3 & 4. Model simulations completed in LandGEM based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

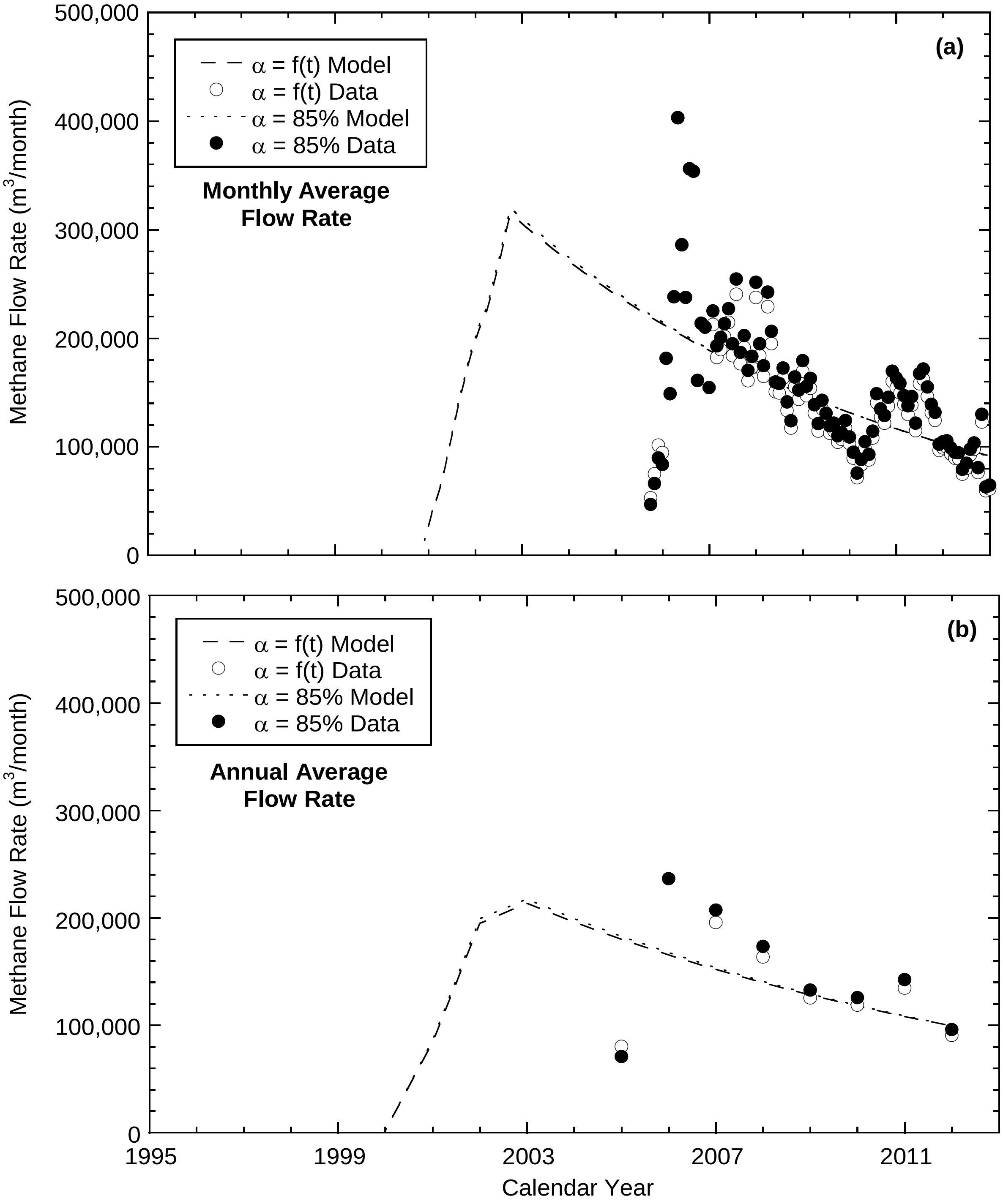

Fig. 4.6. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 5. Model simulations completed in LandGEM based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

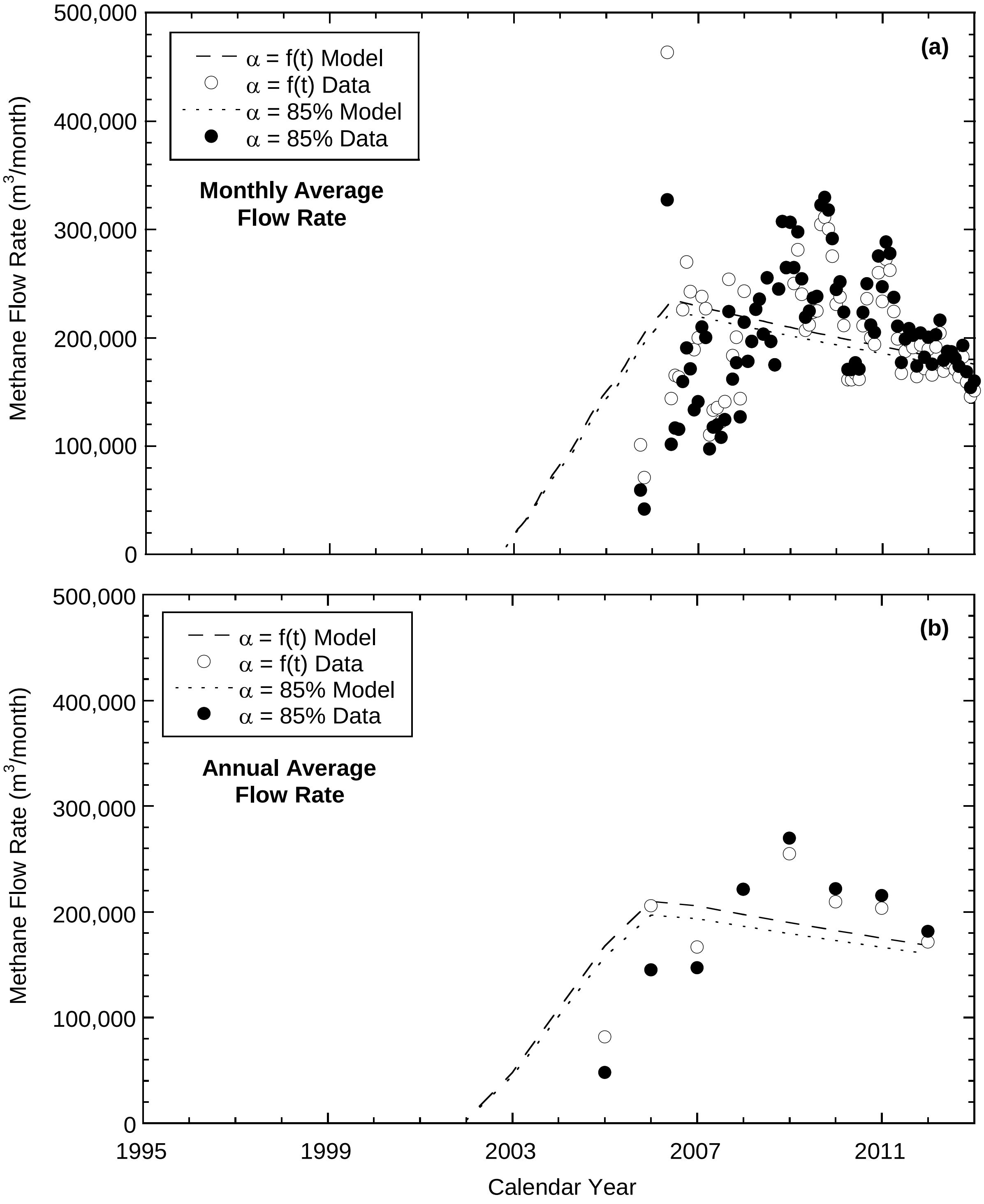

Fig. 4.7. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 6. Model simulations completed in LandGEM based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

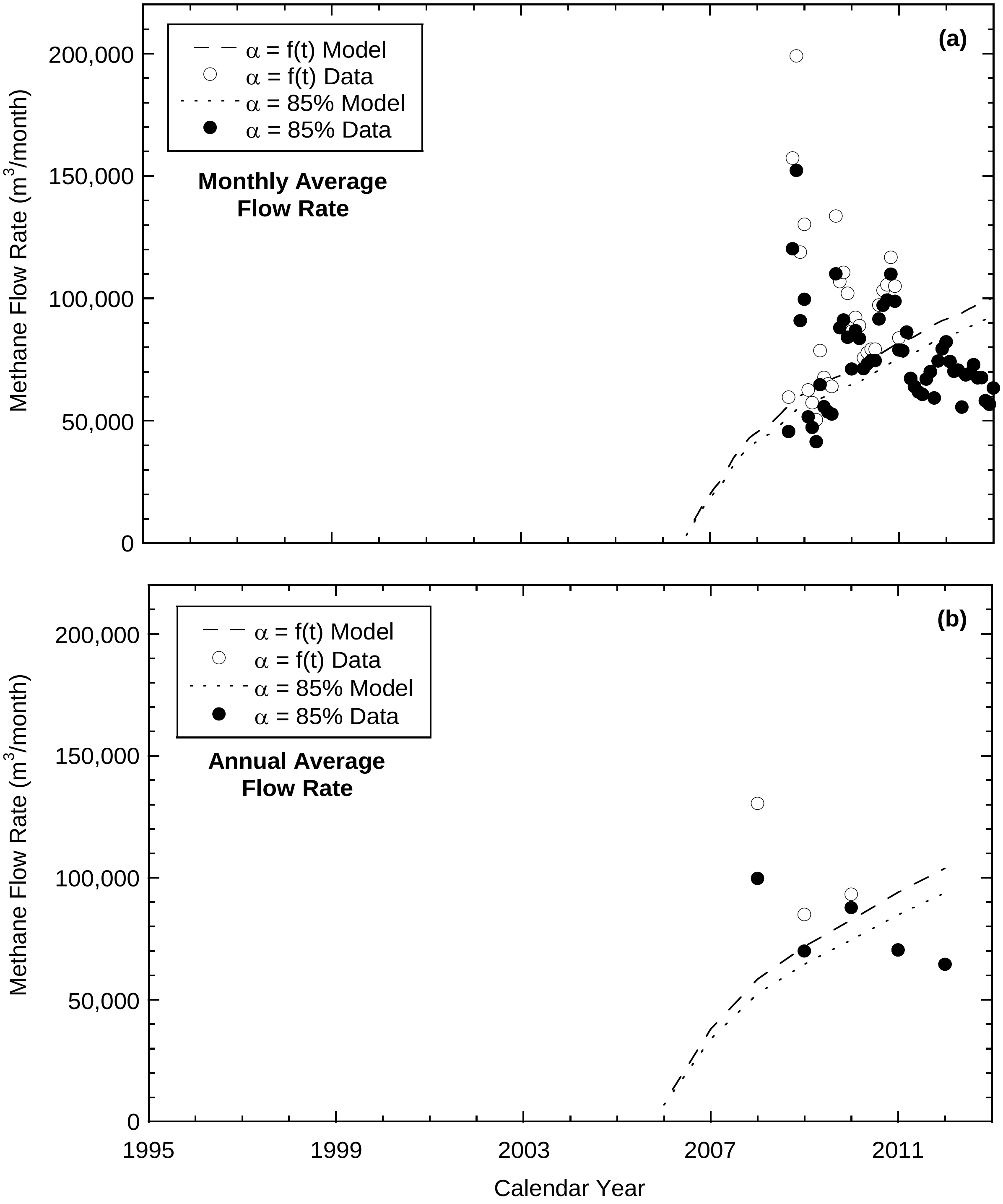

Fig. 4.8. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 7. Model simulations completed in LandGEM based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)]. Note: the last two years of modeling with α = f(t), the estimated α was 85%; thus, data points for gas collection flow rates overlap.

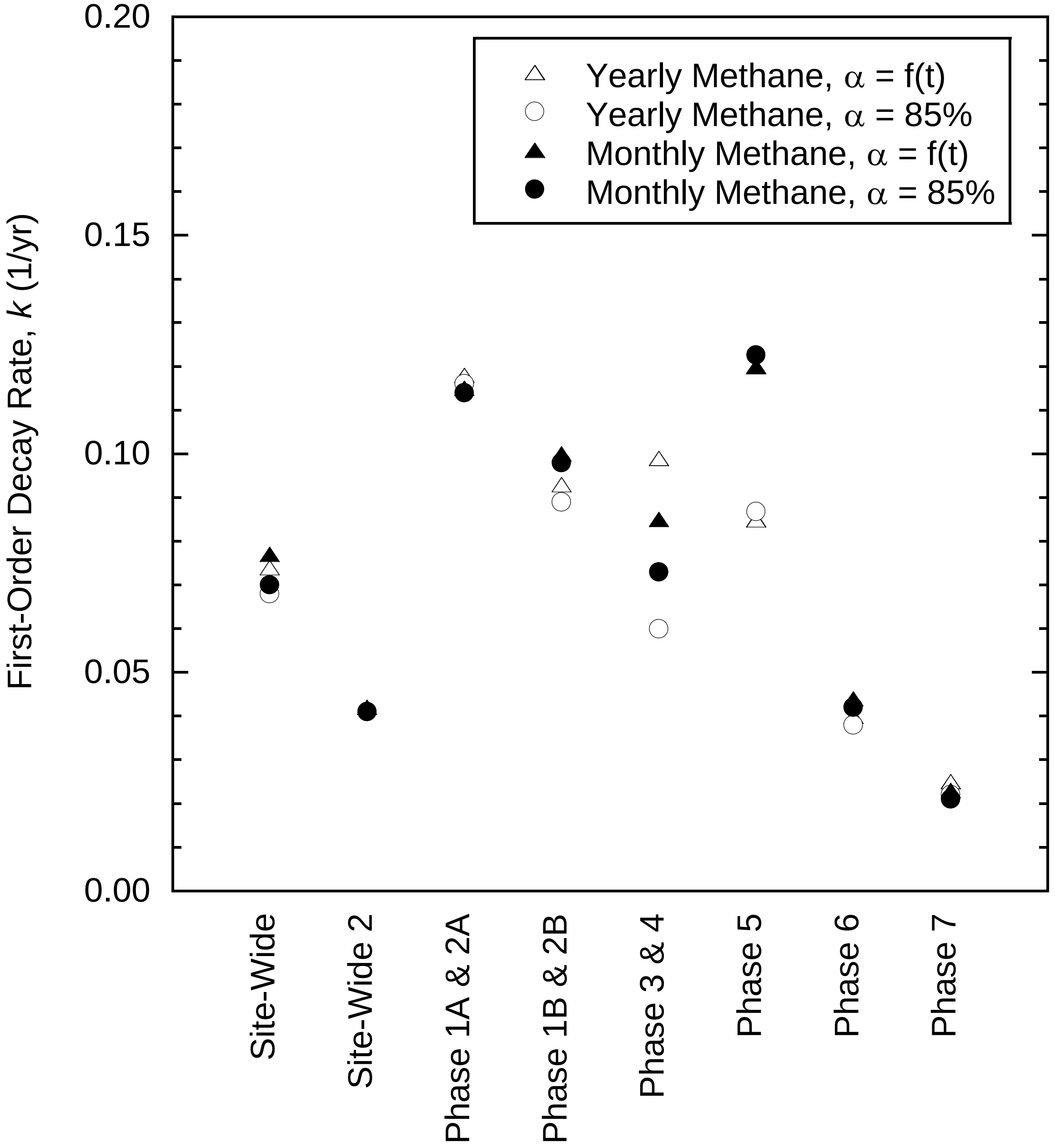

Fig. 4.9. Graphical summary of optimized first-order decay rates for all gas analyses. Note: Site-Wide 2 = site-wide optimization that excluded Phase 1A & 2A and Phase 1B & 2B.

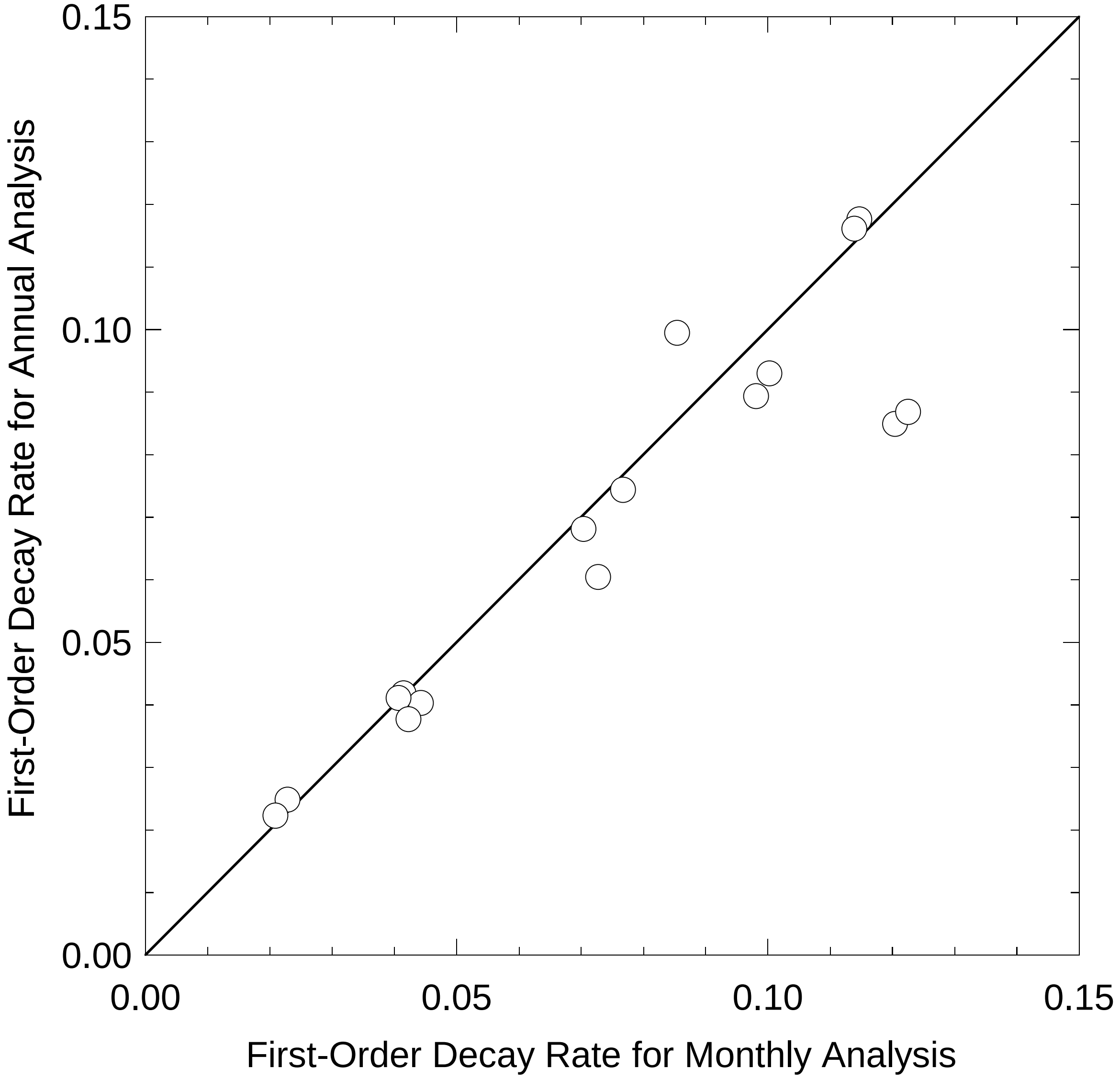

Fig. 4.10. Comparison between first-order decay rates optimized for monthly average methane flow rates using a monthly versus annual level of analysis.

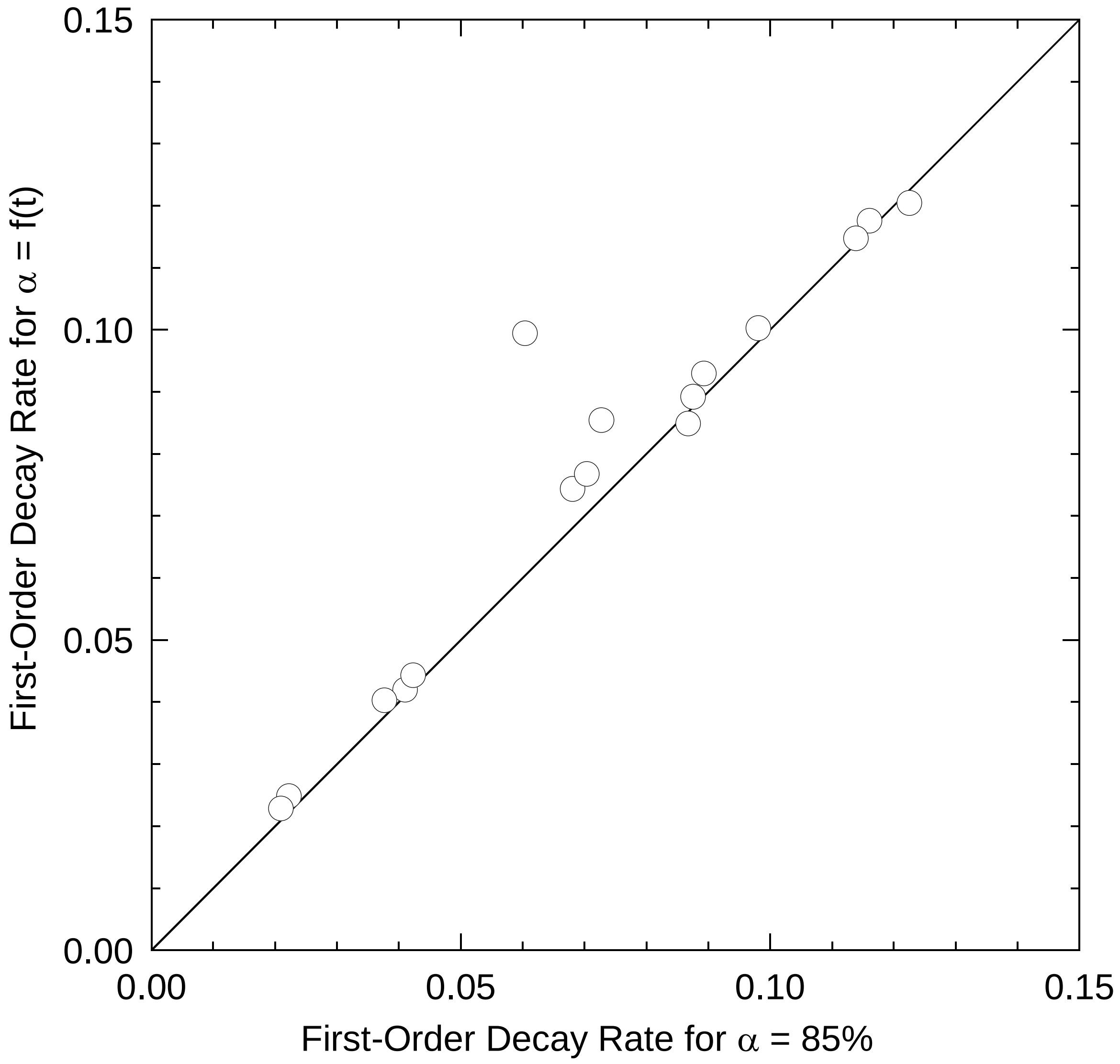

Fig. 4.11. Comparison between first-order decay rates optimized for monthly average methane flow rates using monthly and annual temporally varying collection efficiency [α = f(t)] versus a constant gas collection efficiency of α = 85%.

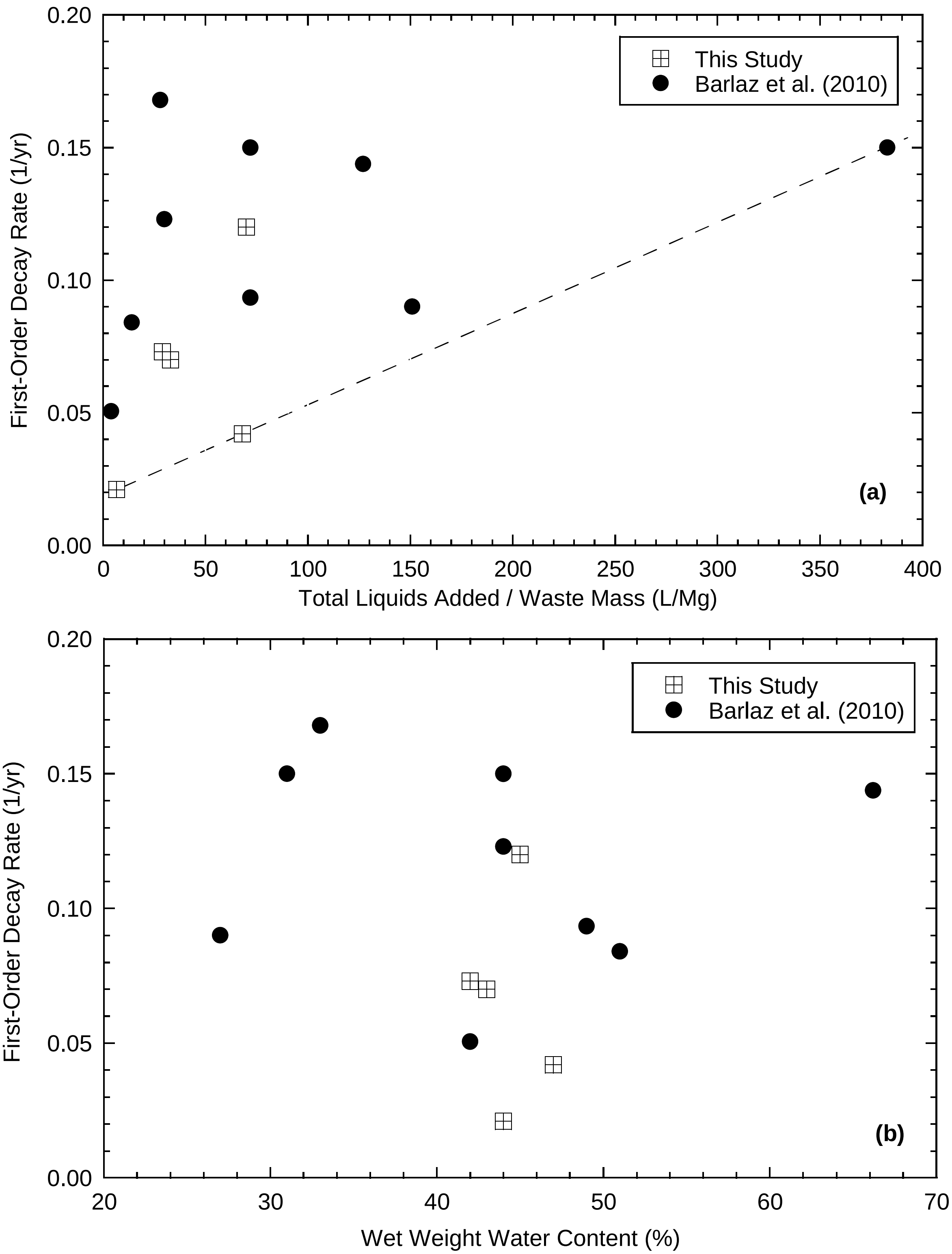

Fig. 4.12. Relationships between first-order decay rates determined for Landfill T in this study and compiled from Barlaz et al. (2010) versus (a) total liquid added per waste mass and (b) wet weight water content of the solid waste.

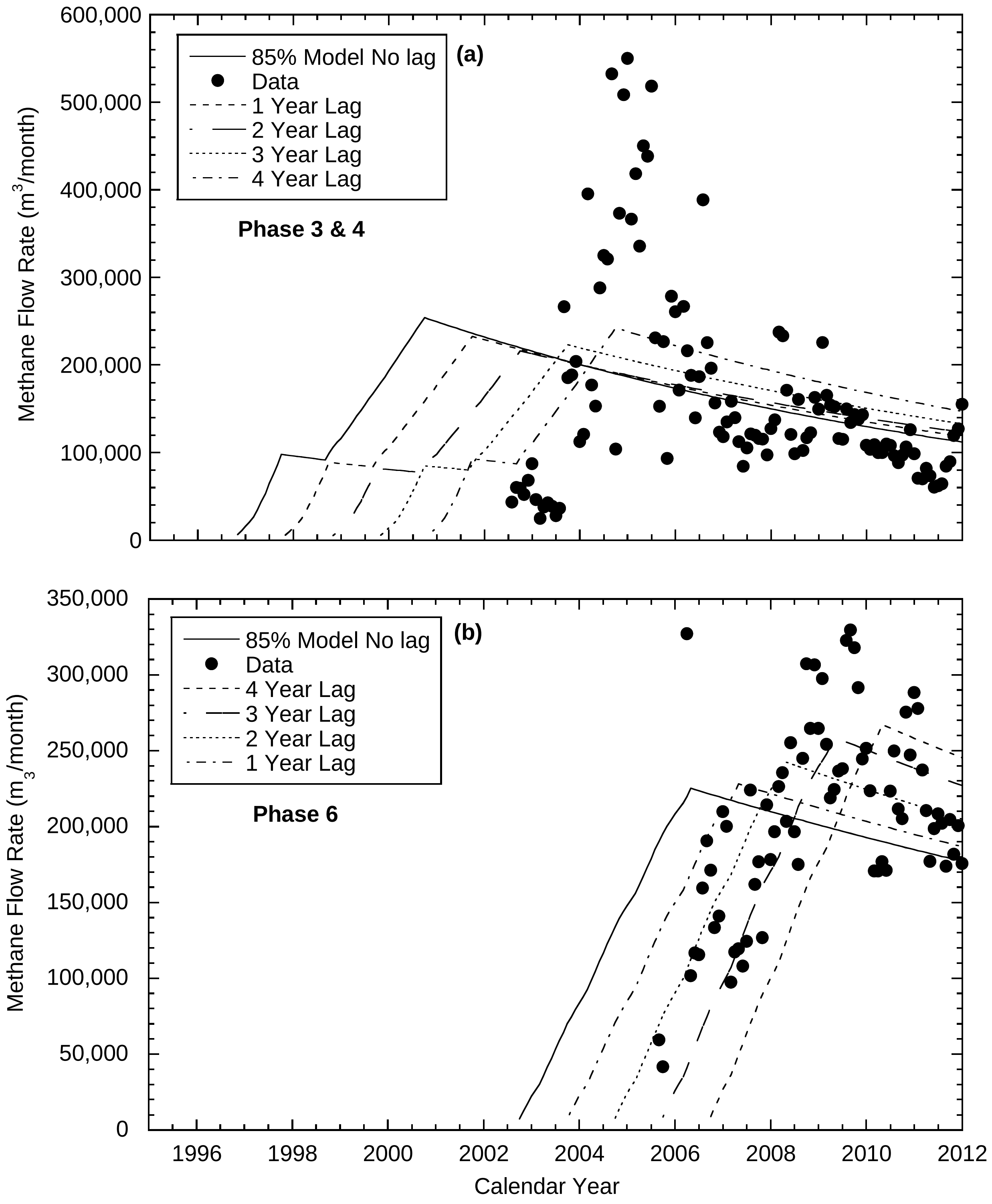

Fig. 4.13. Temporal trends of monthly average methane flow rates for a) Phase 3 & 4 and b) Phase 6 with an assumed constant gas collection efficiency of a = 85%. LandGEM model simulations are shown for the conventional analysis conducted in this study assuming no lag-time between waste placement and gas generation and also with an assumed lag-time of 1, 2, 3, and 4 yr.

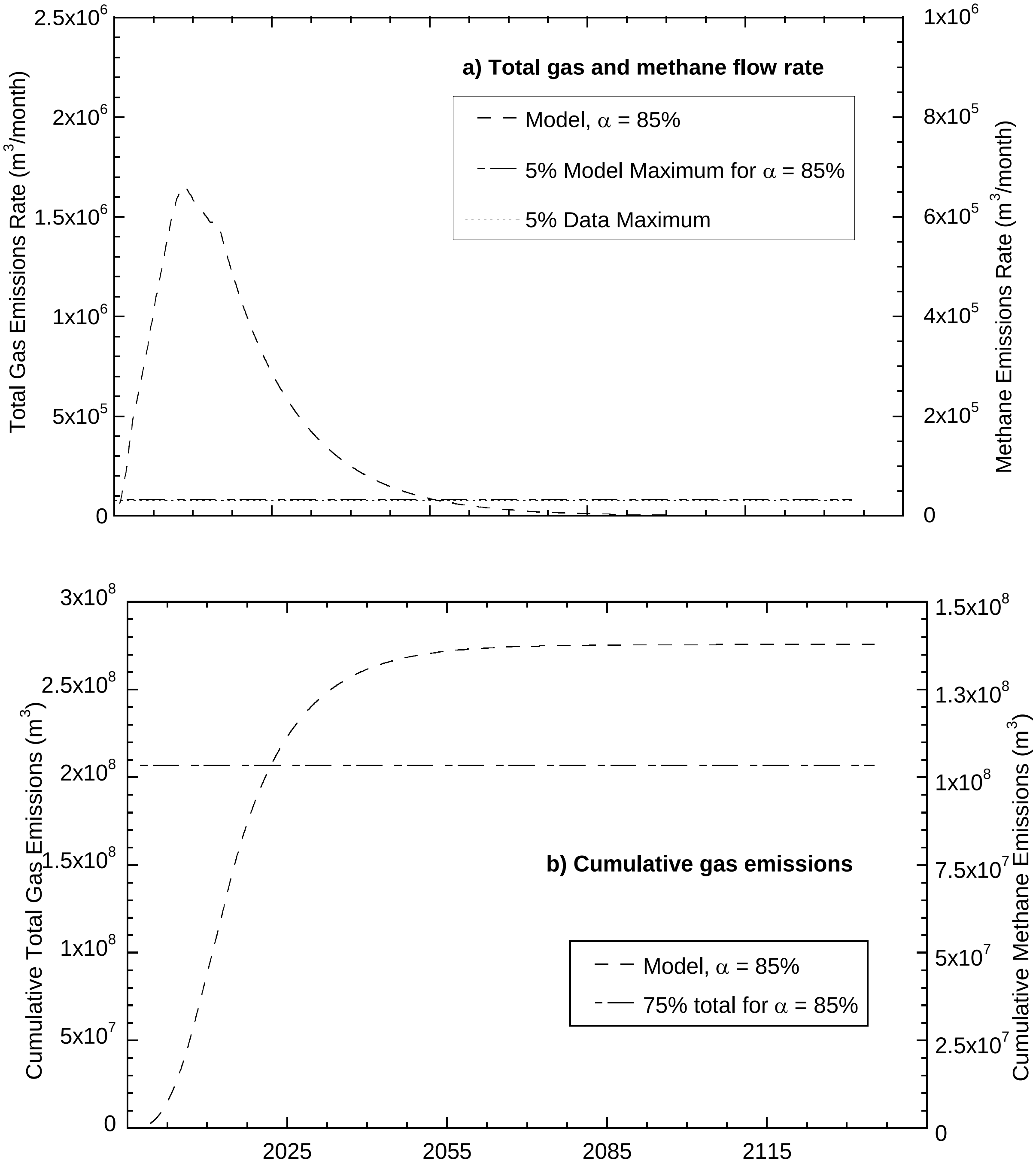

Fig. 4.14. Site-wide organic stability analysis based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

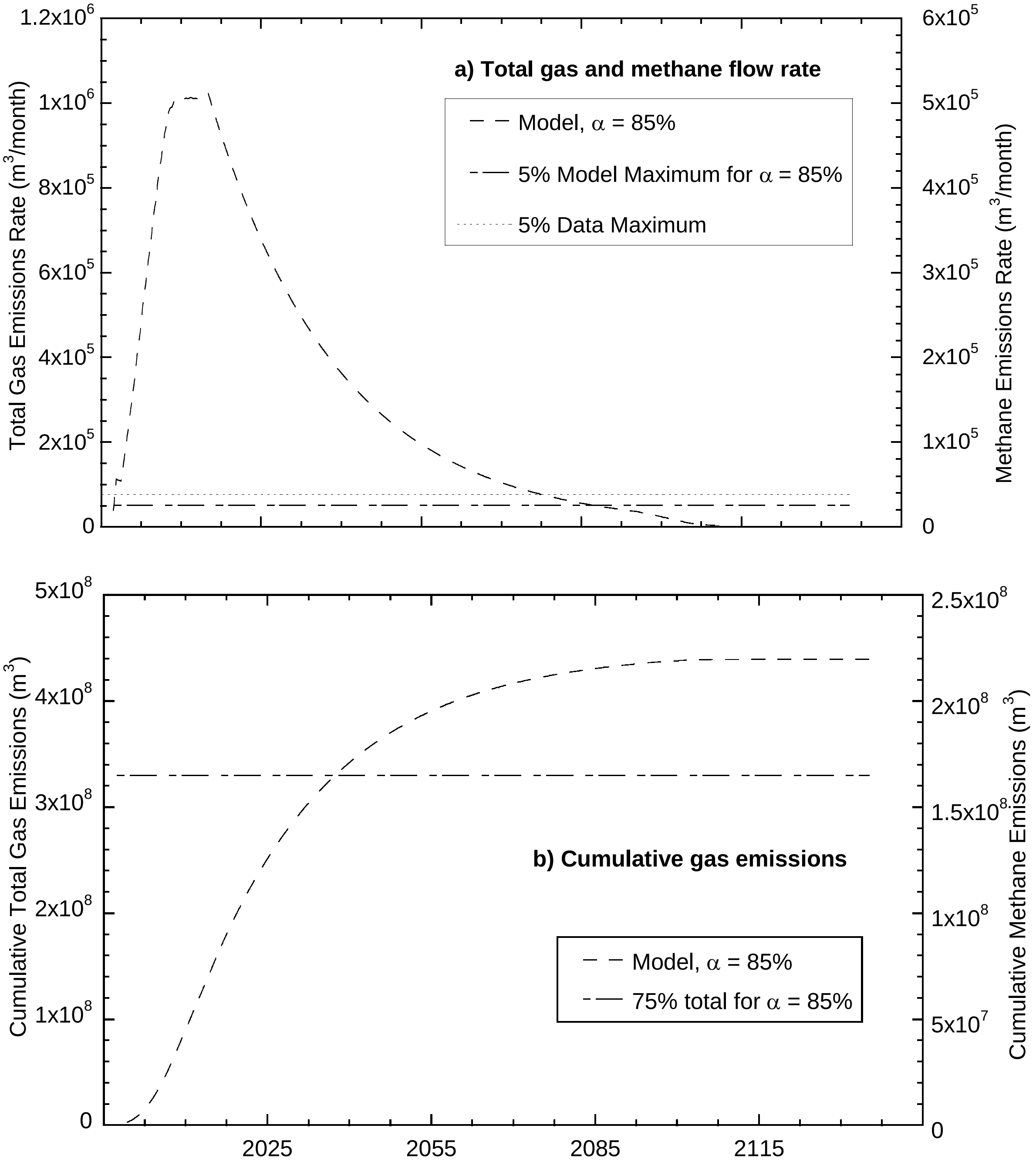

Fig. 4.15. Site-Wide 2 organic stability analysis based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

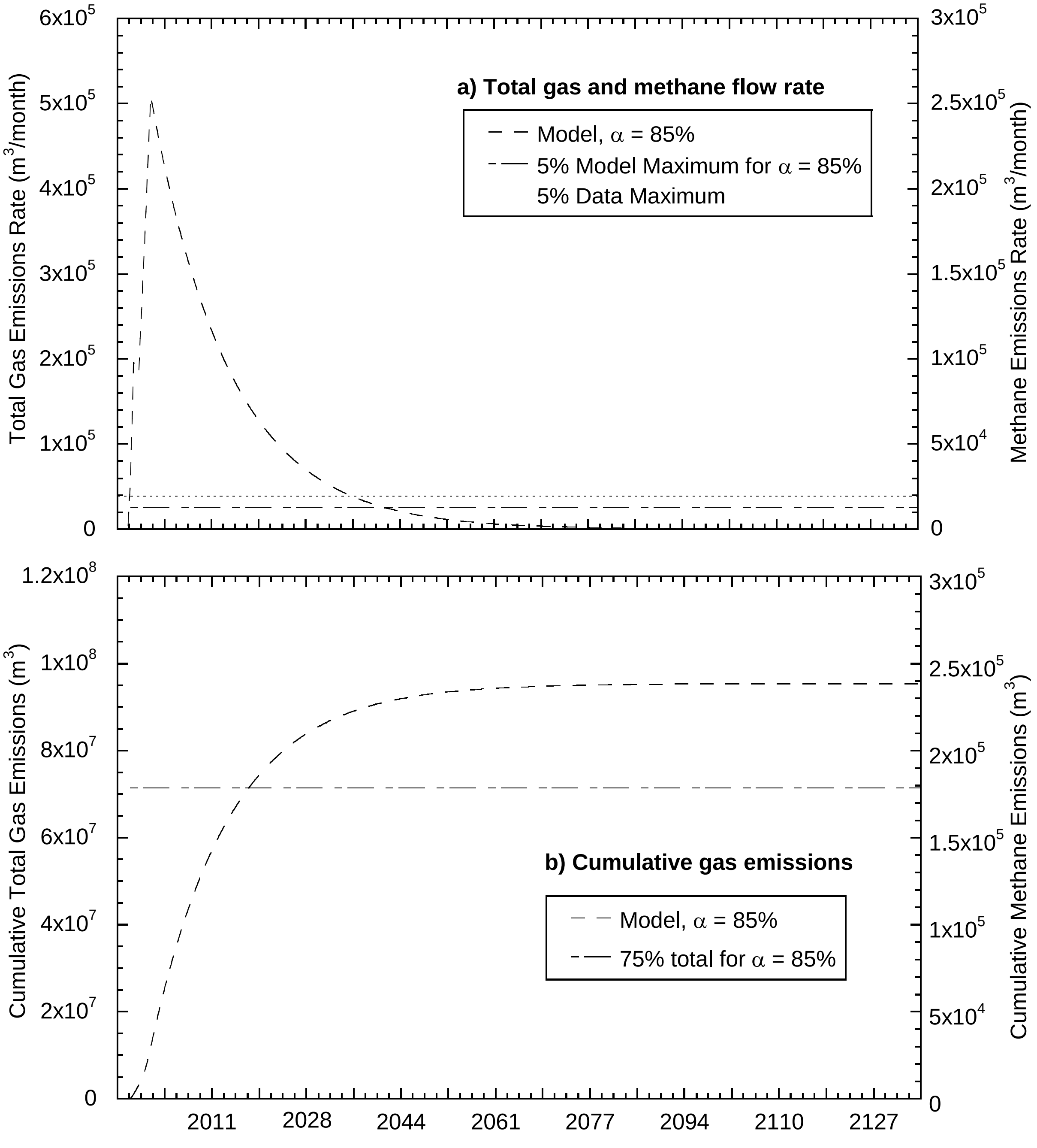

Fig. 4.16. Organic stability analysis for Phase 3 & 4 based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

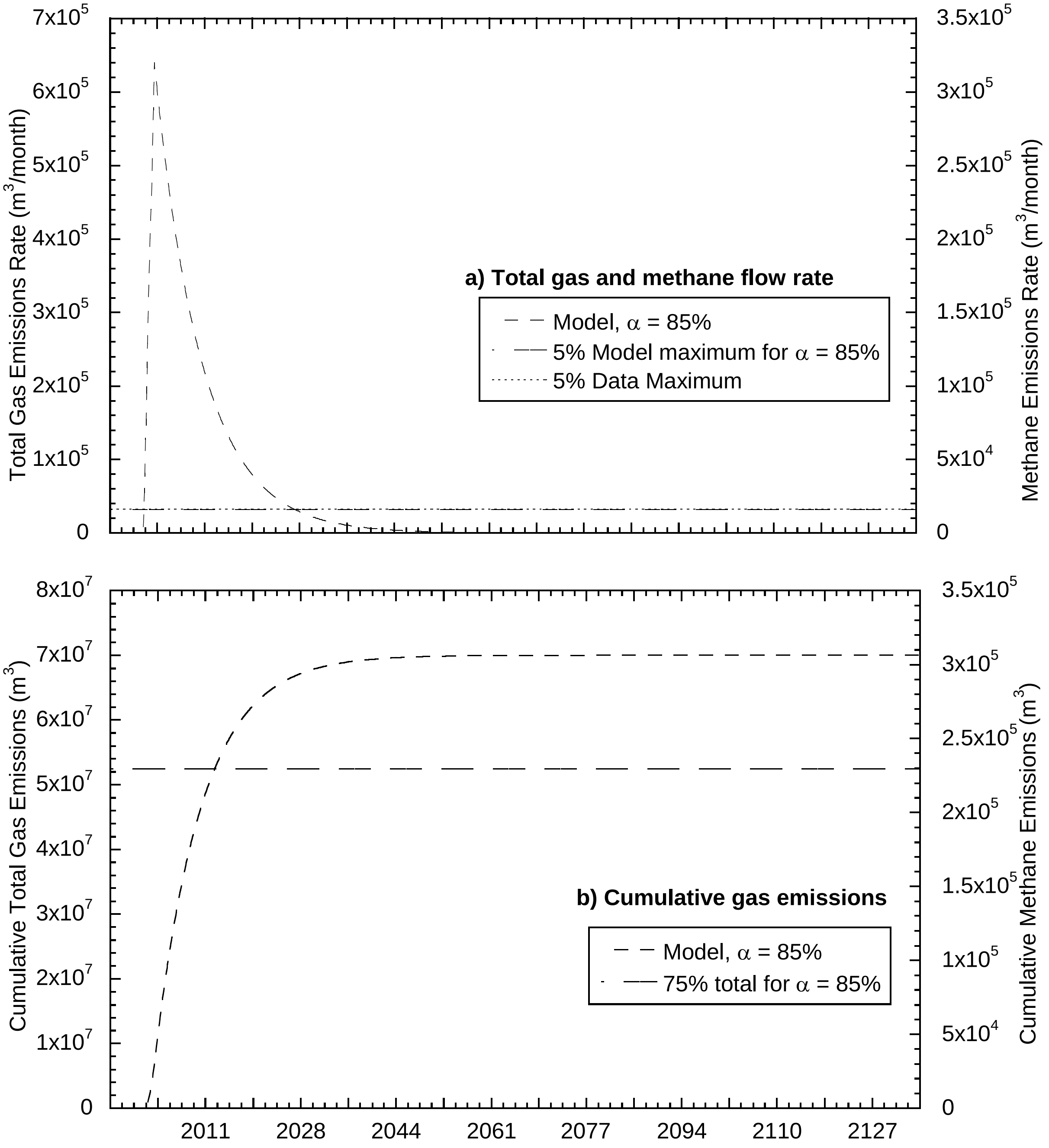

Fig. 4.17. Organic stability analysis for Phase 5 based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

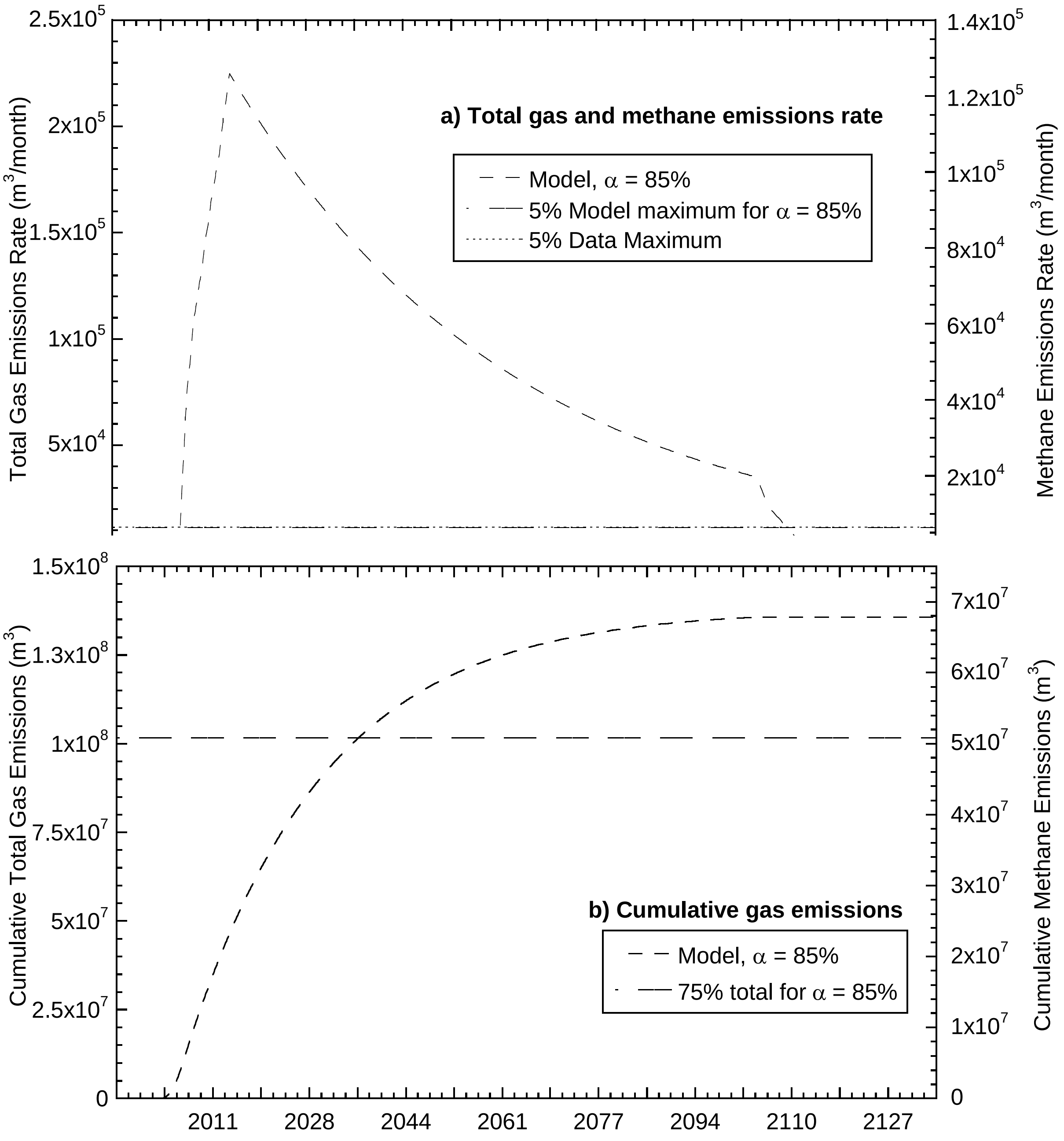

Fig. 4.18. Organic stability analysis for Phase 6 based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

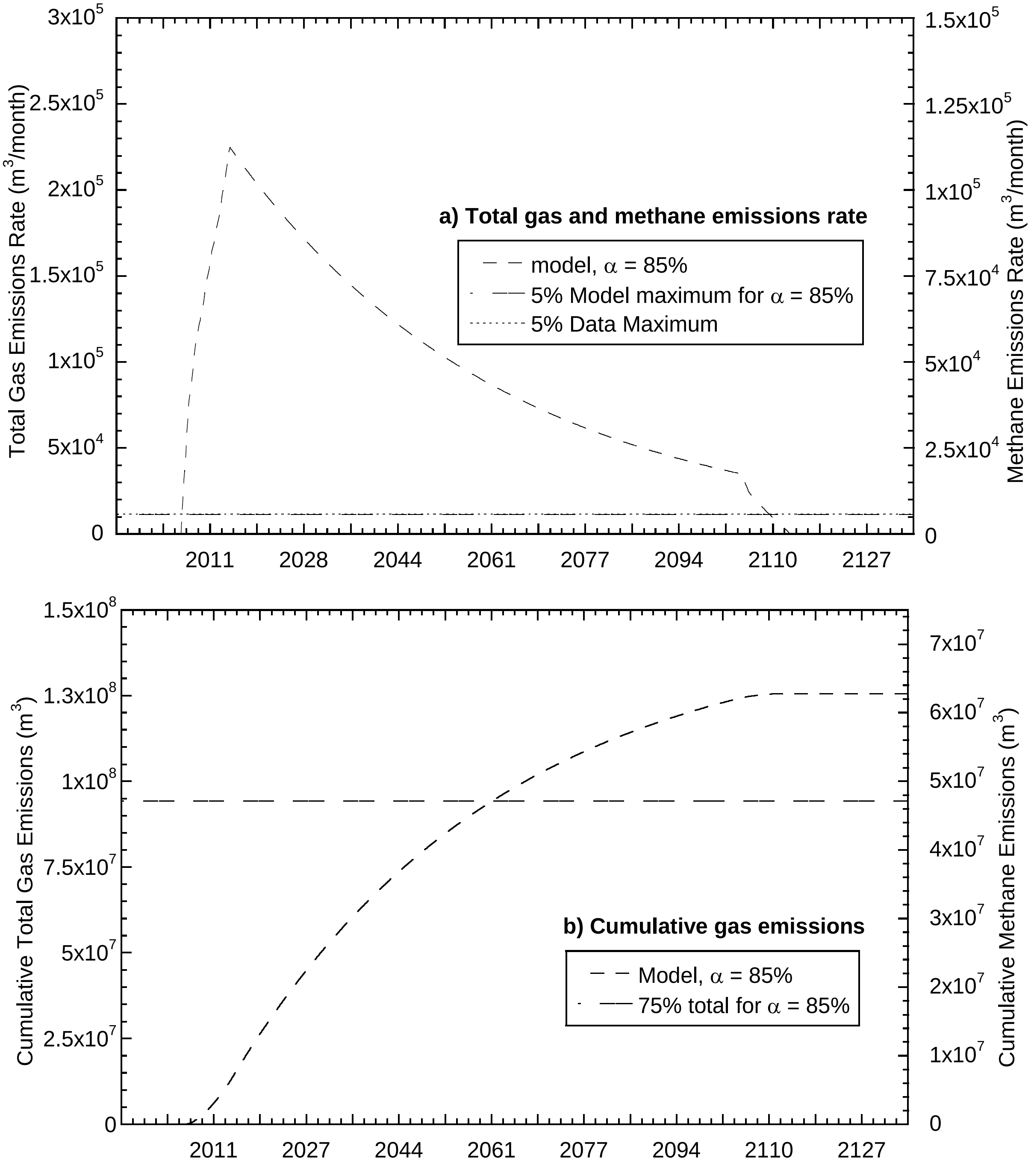

Fig. 4.19. Organic stability analysis for Phase 7 based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

REFERENCES

Abichou, T., Clark, J., Tan, S., Chanton, J. (2011a). Reporting central tendencies of chamber measured surface emission and oxidation, *Waste Management,* 31(5), 1002-1008

Abichou, T., Mahieu, K., Chanton, J., Romdhane, M., Mansouri, I. (2011b). Scaling methane oxidation: from laboratory incubation experiments to landfill cover field conditions, *Waste Management,* 31(5), 978-986

Alvarez, J., and Martinez-Viturtia, A. (1986). Laboratory simulation of municipal solid waste fermentation with leachate recycle. *Journal of Chemical Technology and Biotechnology,* 36, 547.

Amini, H. R., Reinhart, D. R., Mackie, K. R. (2011), Determination of first-order landfill gas modeling parameters and uncertainties, *Waste Management*, 32(2), 305-326

Amini, H. R., Reinhart, D. R., Niskanen, A. (2013), Comparison of first-order-decay modeled and actual field measured municipal solid waste landfill methane data, *Waste Management*, 33(12), 2720-2728

Bareither, C., Benson, C., Edil, T., and Barlaz, M. (2012). Abiotic and Biotic Compression of Municipal Solid Waste, *Journal of Geotechnical and Geoenvironmental Engineering*, 10.1061/(ASCE)GT.1943-5606.0000660, 877-888.

Bareither C. A., Barlaz, M. A., Doran, M., and Benson, C. H. (2014). *Retrospective Analysis of Wisconsin's Landfill Organic Stability Rule: Is the Rule Meeting its Objectives?*, Sustainability Report No. 13-07, Office of Sustainability, University of Wisconsin-Madison, Madison, Wisconsin, USA.

Barlaz, M. A., Ham, R. K., and Schaefer, D. M. (1990). Methane production from municipal refuse: a review of enhancement techniques and microbial dynamics, *Manual for Environmental Microbiology*, American Society of Microbiology, Washington, DC, 541-557.

Barlaz, M. A., Chanton, J. P., Green, R.B. (2009). Controls on landfill gas collection efficiency: instantaneous and lifetime performance, *Journal of the Air and Waste Management Association,* 59(12), 1399-1404

Barlaz, M. A., Bareither, C. A., Hossain, A., Saquing, J., Mezzari, I., Benson, C. H., Tolaymat, T. M., and Yazdani, R. (2010). Performance of North American bioreactor landfills: II. chemical and biological characteristics, *Journal of Environmental Engineering*, 136(8), 839-853.

Chan G. Y. S., Chu, L. M., Wong, M. H. (2002). Effects of leachate recirculation on biogas production from landfill co-disposal of municipal solid waste, sewage sludge and marine sediment, *Environmental Pollution*, 118(3), 393-399

Cruz, F. B. and Barlaz, M. A. (2010). Estimation of waste component-specific landfill decay rates using laboratory-scale decomposition data, *Environmental Science & Technology,* 44(12), 4722-4728

El-Fadel, M., Massoud, M. (2001). *Methane Emissions from Wastewater Management*, Environmental Pollution, 114(2), 177-185

Garg, A., Achari, G., Joshi, R. C. (2006). A model to estimate the methane generation rate constant in sanitary landfills using fuzzy synthetic evaluation, *Waste Management and Research,* 24(4), 363-375

ITRC (2006). *Evaluating, optimizing, or ending post-closure care at MSW landfills based on site-specific data evaluations*, ALT-4, Interstate Technology & Regulatory Council (ITRC), Alternative Landfill Technologies Team, Washington, DC.

Jain A. K., West, T. O., Yang, X., Post, W. M. (2005). Assessing the impact of changes in climate and CO_2 on potential carbon sequestration in agricultural soils, *Geophysical Research Letters,* 32(19), L19711

Jung Y., Imhoff., P. T., Augenstein, D., Yazdani, D. (2011). Mitigating methane emissions and air intrusion in heterogeneous landfills with a high permeability layer, *Waste Management,* 31(5), 1049-1058

Karanjekar, R. V., Bhatt, A., Altouqui, S., Jangikhatoonabad, N., Durai, V., Slatter, M. L., Hossain, M. D. S., Chen, V. (2015). Estimating methane emissions from landfills based on rainfall, ambient temperature, and waste composition: The CLEEN model, *Waste Management,* 46, 389-398

Kim, H., Townsend, T. (2012). Wet landfill decomposition rate determination using methane yield results for excavated waste samples, *Waste Management,* 32(7), 1427-1433

Lamborn, J. (2012), Observations from using models to fit the gas production of varying volume test cells and landfills, *Waste Management, 3*2(12), 2353-2363.

Laner, D., Crest, M., Scharff, H., Morris, J.W.F. and M. A. Barlaz (2012). A Review of Approaches for the Long-Term Management of Municipal Solid Waste Landfills, *Waste Management*, 32, 498-512.

Lizik, W., Im, J., Semrau, J. D. (2013), A field trial of nutrient stimulation of methanotrophs to reduce greenhouse gas emissions from landfill cover soils, *Journal of Air & Waste Management Association,* 64(3), 300-309

Machado, S. L. and Carvalho, M. (2009). Constitutive model for municipal solid waste incorporating mechanical creep and biodegradation-induced compression. *Waste Management*, 30(1), 11-22.

Mehta, R., Barlaz, M. A., Yazdani, R., Augenstein, D., Bryars, M., and Sinderson, L. (2002). Refuse decomposition in the presence and absence of leachate recirculation, *J. Environ. Eng.*, 128(3), 228-236.

Morris, J. W. F. and M. A. Barlaz (2011). A Performance-Based System for the Long-Term Management of Municipal Waste Landfills, *Waste Management*, 31, 649-662

Ogor, Y., and Guerbois, M. (2005). Comparison of landfill methane emission models; a case study. In: Tenth International Waste Management and Landfill Symposium, Sardinia, Italy.

Oonk, H., Weenk, A., Coops, O., Luning, L. (2010). Validation of Landfill Gas Formation Models; TNO Institute of Environmental and Energy Technology: Apeldoorn, The Netherlands, 1994; pp 94−315.

Powrie, W., Beaven, R., Hudson, A. (2008). The influence of landfill gas on the hydraulic conductivity of waste, GeoCongress 2009, 254-271

RCRA (1976). *The Solid Waste Disposal Act*, or Resource Conservation and Recovery Act of 1976, 42 United States Congress 6901-6992k, Public Law 94-580.

Reinhart, D. R., Faour, A. A., You, H. (2005), First-order kinetic gas generation model parameters for wet landfills, U. S. Environmental Protection Agency, (EPA-600/R-05/072)

SCS Engineers(2008), Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills, *Solid Waste Industry for Climate Solutions*

Solid Waste Association of North America Bioreactor Committee, 2004, cit. in EREF, 2006

Spokas, K., Bogner, J., Chanton, J. P., Morcet, M., Aran, C., Graff, C., Golvan, Y. M., Hebe, I. (2006), Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems?, *Waste Management,* 26(5), 516-525

Staley, B. F. and Barlaz, M. A. (2009). Composition of municipal solid waste in the U.S. and implications for carbon sequestration and methane yield, *Journal of Environmental Engineering*, 135(10), 901-909.

SWANA, 2007. Landfill gas collection system efficiencies. SWANA Applied Research

Thompson , S., Sawyer, J., Bonam, R. Valdivia, J. E. (2009), Building a better methane generation model; validating models with methane recover rates from 35 Canadian landfills. Waste Management 2009 (29), 2085-2091

USEPA (1993). Solid waste disposal facility criteria: Technical manual. EPA530-R-93-017, United States Environmental Protection Agency, Washington, DC. (revised 1998).

US EPA AP-42 (1998), Emission factors for Municipal Solid Waste Landfills – Supplement E. 1998, Environmental Protection Agency

USEPA (2004). Research, Development, and Demonstration Permits for Municipal Solid Waste Landfills, United States Environmental Protection Agency, 40 CFR Part 258, *Federal Register*, 69(55), 13242-13256.

USEPA (2005). *Landfill gas emissions model (LandGEM) version 3.02 user's guide*, EPA/600/R-05/047, United Stated Environmental Protection Agency, Research Triangle Park, NC 2005.

USEPA (2008). Municipal solid waste generation, recycling, and disposal in the United States: facts and Figures for 2008, United States Environmental Protection Agency, Washington, DC.

Wang, X., Nagpure, A. S., DeCarolis, J. F., Barlaz, M. A. (2013). Using observed data to improve estimated methane collection from select U.S. landfills*, Environmental Science and Technology*, 47(7), 3251-3257

Wang, X., Jia, M., Chen, X., Xu, Y., Lin, X., Kao, C. M., Chen, S. (2014), Greenhouse gas emissions from landfill leachate treatment plants: A comparison of young and aged landfill, *Waste Management,* 34(7), 1156-1164

Wang, X., Nagpure, A. S., DeCarolis, J. F., Barlaz, M. A. (2015), Characterization of uncertainty in estimation of methane collection from select U.S. landfills, *Environmental Science & Technology,* 49(3), 1545-1551

WDNR (2006). Plan of operation and closure plans for landfills, Chapter NR 514, Wisconsin Department of Natural Resources, Madison, WI, docs.legis.wisconsin.gov/code/admin_code/nr/500/514.pdf

Wreford, K. A., Atwater, J. W., Lvkulich, L. M. (2000), The effects of moisture inputs on landfill gas production and composition and leachate characteristics at the Vancouver landfill site at Burns Bog, *Waste Management and Research,* 18(4), 386-392

Zhan, T., Xu, X., Chen, Y., Ma, X., Lan, J. (2015), Dependence of gas collection efficiency on leachate level at wet municipal solid waste landfills and its improvements in China, *Journal of Geotechnical and Geoenvironmental Engineering,* 141(4), 04015002

APPENDIX A – MUNICIPAL SOLID WASTE DISPOSAL BY PHASES

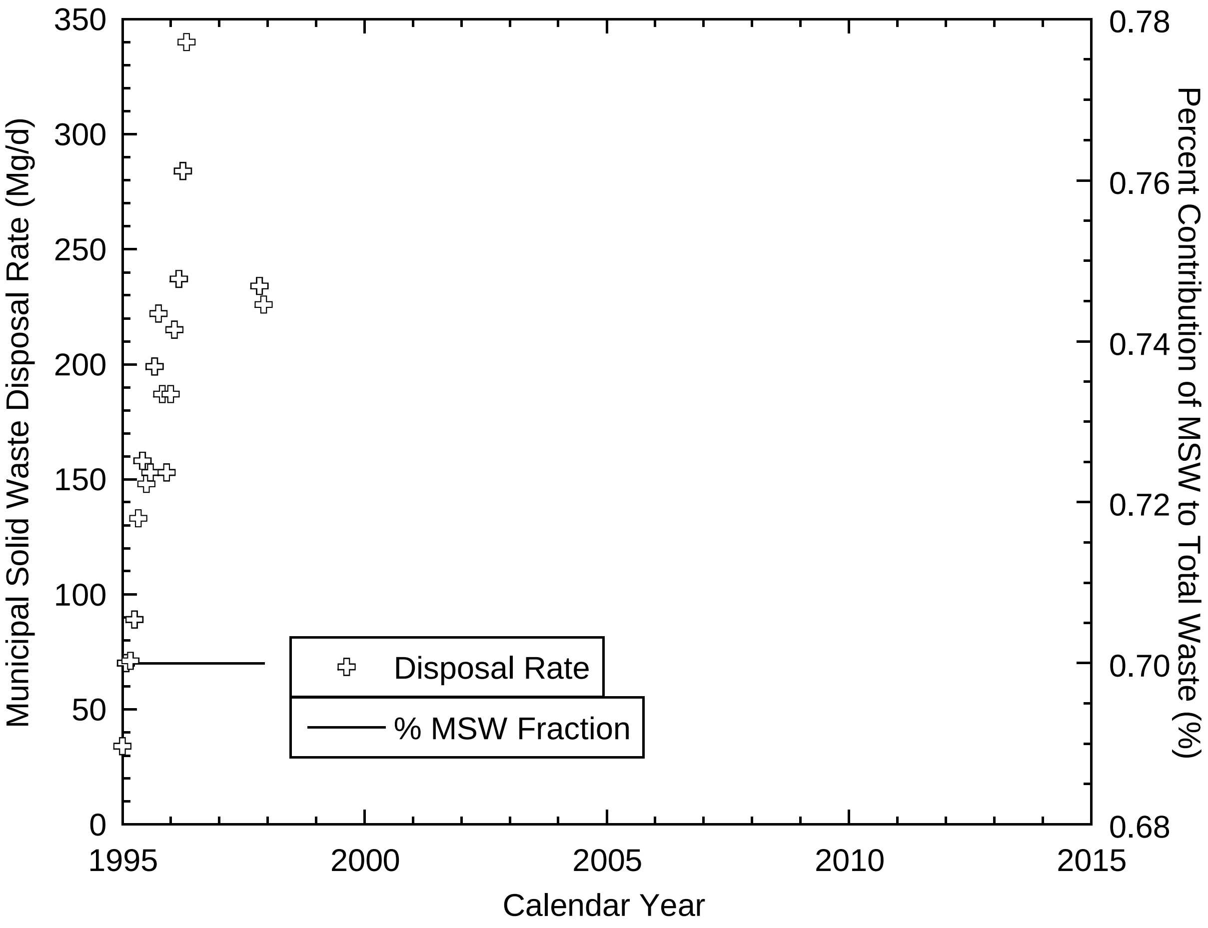

Fig. A.1. Temporal trend of municipal solid waste (MSW) disposal rate and percent MSW fraction of total waste at Phase 1A & 2A.

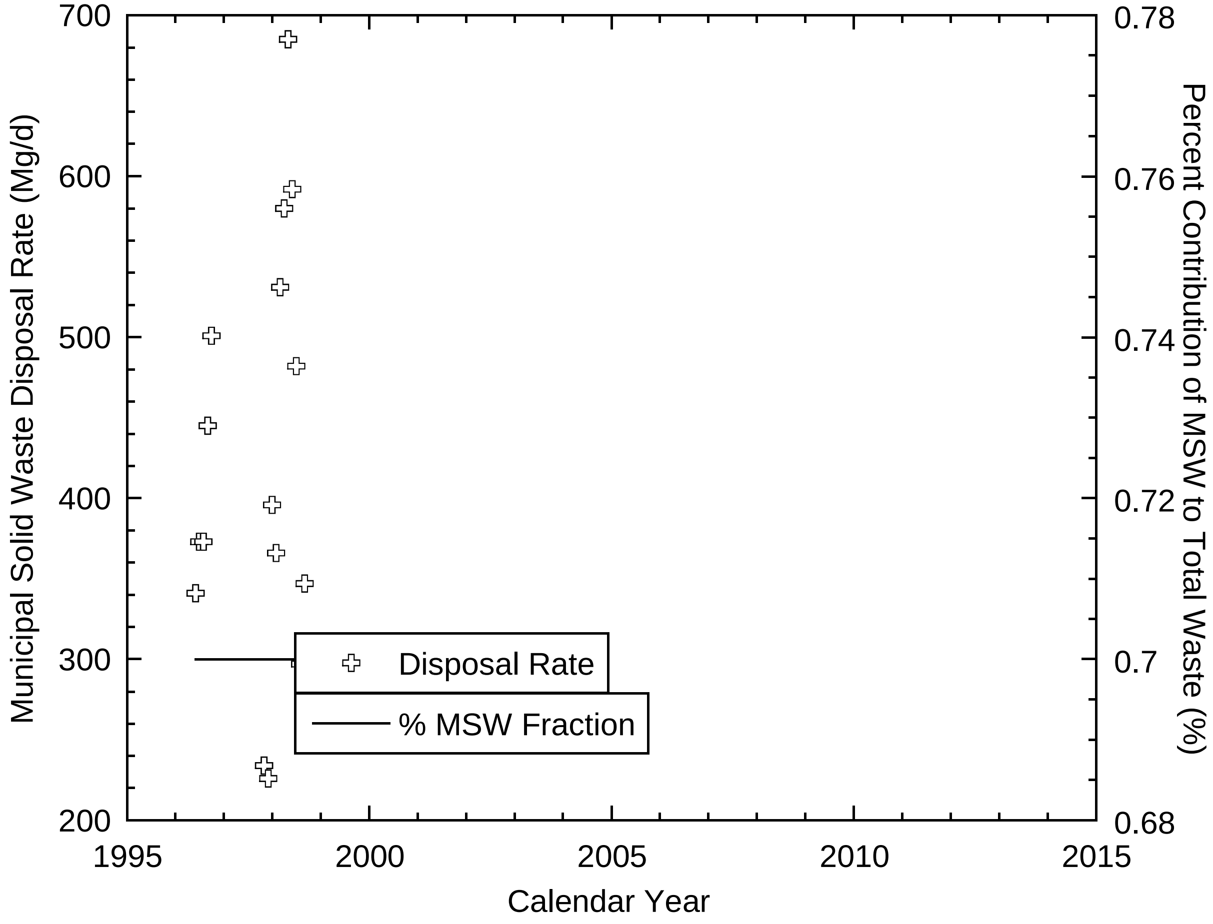

Fig. A.2. Temporal trend of municipal solid waste (MSW) disposal rate and percent MSW fraction of total waste at Phase 1B & 2B.

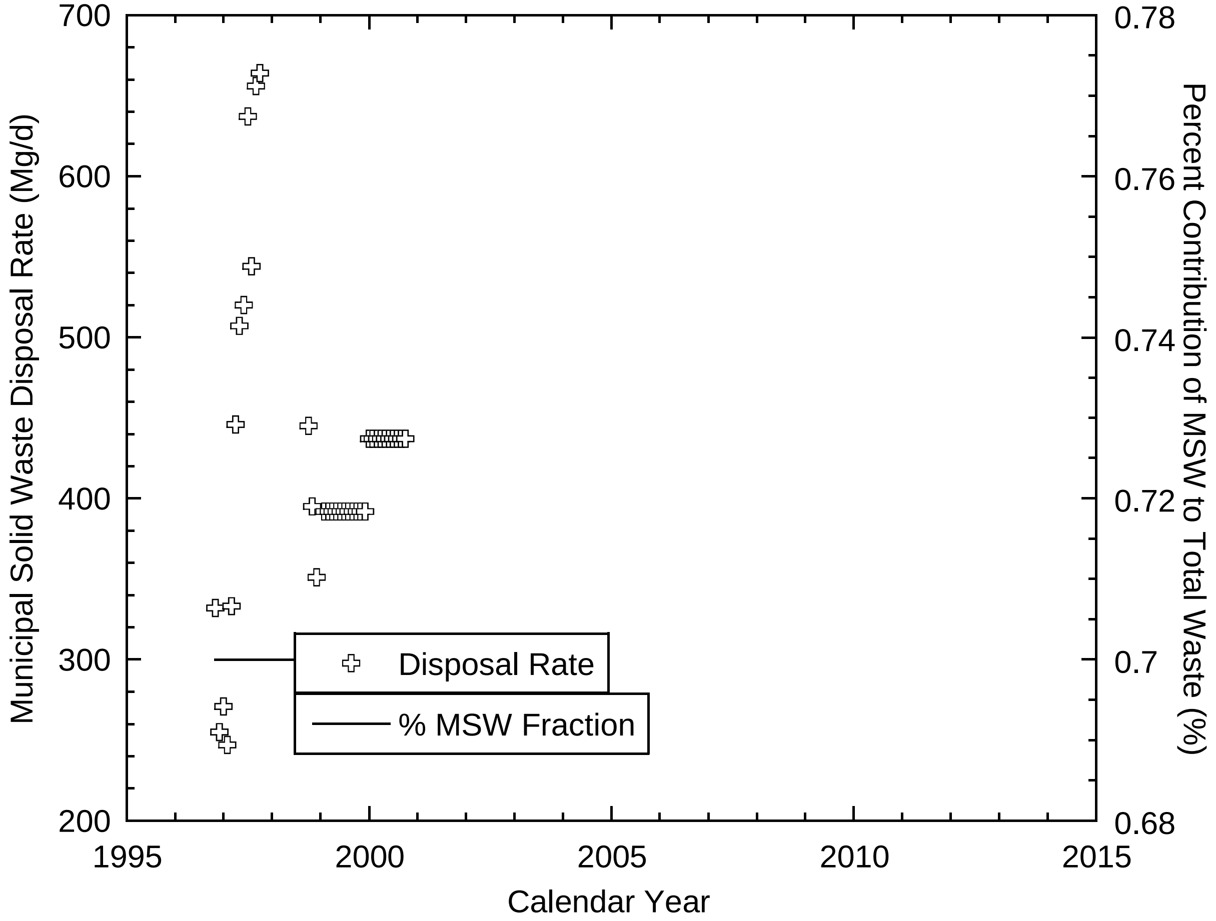

Fig. A.3. Temporal trend of municipal solid waste (MSW) disposal rate and percent MSW fraction of total waste at Phase 3 & 4.

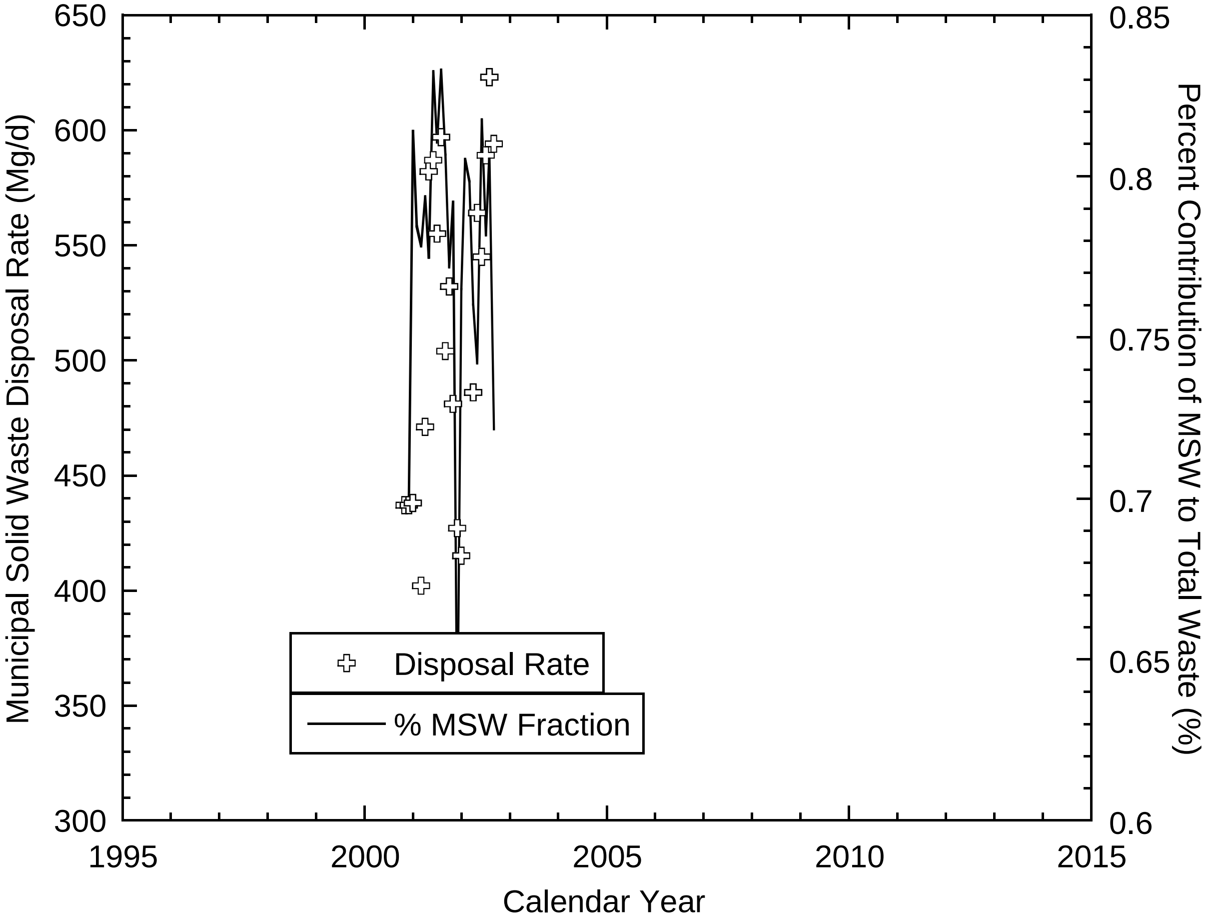

Fig. A.4. Temporal trend of municipal solid waste (MSW) disposal rate and percent MSW fraction of total waste at Phase 5.

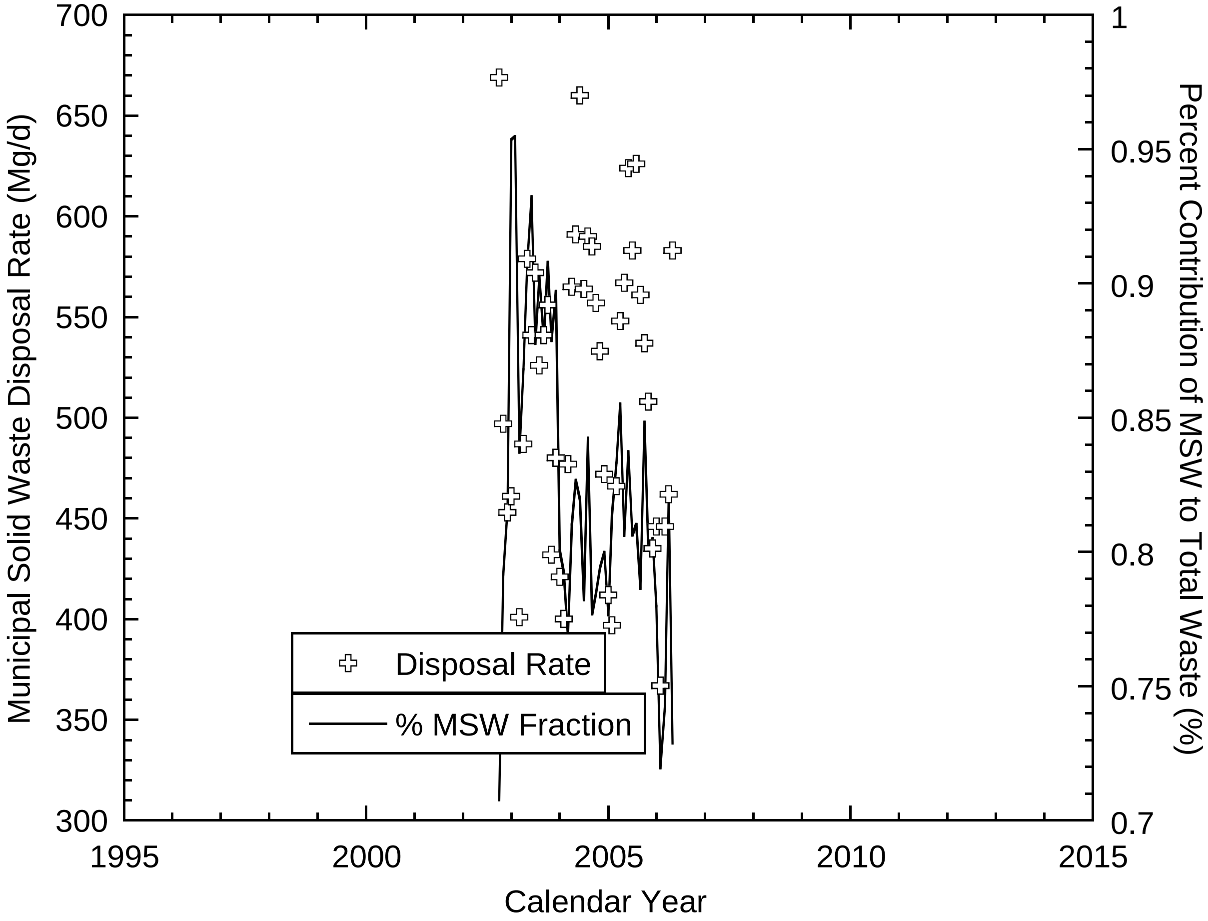

Fig. A.5. Temporal trend of municipal solid waste (MSW) disposal rate and percent MSW fraction of total waste at Phase 6.

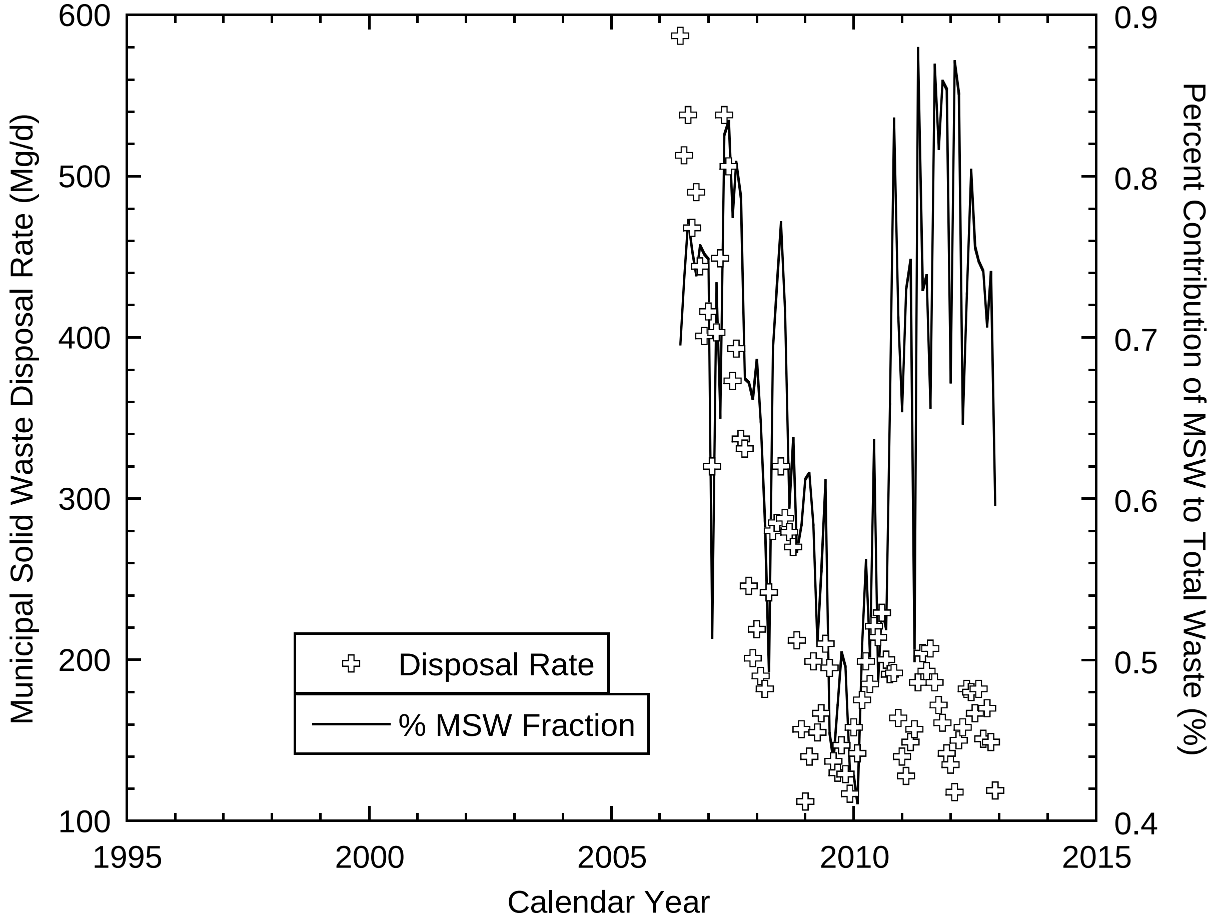

Fig. A.6. Temporal trend of municipal solid waste (MSW) disposal rate and percent MSW fraction of total waste at Phase 7.