REVIEW OF WISCONSIN'S LANDFILL ORGANIC STABILITY RULE AND ASSESSMENT OF PHASE-BASED LANDFILL GAS GENERATION AND ORGANIC WASTE STABILIZATION

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EXECUTIVE SUMMARY

This report includes two studies: (i) a review the effectiveness of Wisconsin's Organic Stability Rule (OSR); and (ii) a phase-based landfill gas (LFG) modeling assessment to develop estimates of organic waste stabilization. The study comprising the review of Wisconsin's OSR is herein named Research Study 1 and the study detailing the phase-based LFG modeling is herein named Research Study 2. Thus, this report is separated into the two research studies, which include methods, results, conclusions, and recommendations for each study.

Research Study 1

The Wisconsin Department of Natural Resources introduced an organic stability rule (OSR) in 2007 to encourage effective management of organic waste in landfills and ultimately reduce the duration of post-closure care. Landfill organic stability is defined as a state of near complete decomposition of organic waste such that human health, environmental, and financial risks associated with undecomposed waste are minimized. The objective of Research Study 1 was to conduct an independent review of Wisconsin's OSR to (i) evaluate changes that have occurred in waste management practice as a result of the rule and (ii) assess whether the rule is meeting organic stability goals. Ten landfills with varying population demographics, waste disposal rates, leachate recirculation and liquid addition operations, and gas usage were selected. Leachate recirculation and liquid waste addition were the predominant actions implemented to enhance in-situ waste decomposition. Liquid waste disposal was used as both a revenue source and as a method to increase waste moisture content to enhance waste decomposition. Analysis of gas generation data suggests that all sites will meet targets of the OSR of ≥ 75% of total gas generation and ≤ 5% of peak monthly flow within 40-yr post closure. Recommendations for landfill policies that incorporate organic stability actions include the following: (i) incorporate provisions of liquid waste addition into federal and state regulations; (ii) clarify requirements for early and aggressive gas collection; (iii) develop guidance on biochemical compatibility of liquid waste disposal in landfills; (iv) promote beneficial use of landfill gas; (v) develop a standardized gas model analysis protocol to assess OSR goals; (vi) consider metrics to guide transition from an active to passive long-term landfill gas management system; and (vii) consider life cycle analysis as a tool to assess holistic organic stability strategies.

Research Study 2

As illustrated by findings in Research Study 1, the goal of landfill-based municipal solid waste (MSW) management has transitioned from waste sequestration to waste stabilization. A bioreactor landfill is an MSW landfill operated with a deliberate goal to achieve waste stabilization via in situ organic waste decomposition. Enhanced landfill gas (LFG) generation and waste stabilization result from moisture addition to the waste mass to increase the rate of anaerobic biodegradation. Additionally, landfills commonly are constructed and filled in phases (i.e., delineated areas of the landfill where waste is placed) that are operated with different moisture enhancement strategies. Thus, there is a need to simulate and predict LFG generation in a bioreactor landfill on a phase-specific basis to more accurately assess waste decomposition and progression of organic waste stabilization. In Research Study 2, site-wide and phase-specific LFG modeling was conducted for a bioreactor landfill. A phase-specific LFG modeling approach was

developed and used to assess six separate phases of the landfill. This approach included a temporal estimate of waste disposal and separation of LFG collection data for the six phases. Landfill gas collection in each phase was used to compute methane collection based on gas composition analyses, where were then used to estimate methane generation based on two considerations of collection efficiency: (i) constant collection efficiency of 85% and (ii) temporally varying collection efficiency. Methane generation was predicted using the U.S. EPA LandGEM. Model simulations were compared with adjusted methane collection data to optimize the first-order decay rate (*k*), which was the primary variable used to assess waste decomposition and stabilization. First-order decay rates were optimized for site-wide and phase-specific analyses that considered (i) monthly versus annual averaging techniques for LFG data, (ii) two collection efficiencies, and (iii) LFG collected only in the gas wells versus LFG collected in gas wells and perforated pipes in leachate collection and recirculation systems. The recommended gas modeling approach is to use monthly average LFG flow rates, a constant collection efficiency of 85%, and LFG collected from gas wells and leachate collection / recirculation systems. The optimized *k* for the site-wide analysis was 0.078 1/yr, whereas the default *k* for conventional MSW landfills with no moisture enhancement is 0.04 1/yr. Thus, the site-wide *k* supports enhanced organic waste biodegradation and stabilization. The optimized *k* for the phase-specific analyses ranged between 0.025 and 0.127 1/yr, which suggest that although the overall site was operating at an enhanced rate of waste decomposition, the rate varied between landfill phases. Moisture addition via leachate recirculation and liquid waste addition was implemented at the landfill for the five more recent phases. The *k* values for these five phases increased with increasing liquid addition per waste mass whereby the optimized *k* increased from the driest phase, Phase 3 & 4 (0.037 1/yr), to the wettest phase, Phase 6 (0.127 1/yr). The LFG modeling and findings from this study can assist with developing moisture enhancement strategies for bioreactor landfills and assessing LFG collection data to support claims of enhanced waste decomposition and stabilization.

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TABLE OF CONTENTS

EXECUTIVE SUMMARY i
ACKNOWLEDGEMENTS iii
RESEARCH STUDY 1: RETROSPECTIVE ANALYSIS OF WISCONSIN'S LANDFILL ORGANIC STABILITY RULE 1
CHAPTER 1: INTRODUCTION 1
1.1 Organic Stability 1
1.2 Post-closure Management of Landfills 2
CHAPTER 2: RESULTS AND DISCUSSION 3
2.1 Landfill-Based Waste Management 3
2.2 Waste Diversion and Composting 3
2.3 Liquids Acceptance and Management 3
2.4 Moisture Addition Methods 5
2.5 Waste Moisture Content 7
2.6 Gas Production and Management 7
2.7 Gas Production Rates and Organic Stability Assessment 10
2.8 Gas Management Practices and Challenges 14
2.9 Practical Implications of Organic Stability Rule 16
2.9.1 Organic Waste Diversion 16
2.9.2 Liquid Waste 16
2.9.3 Gas Management 17
2.9.4 Gas Prediction and Accounting 17
2.9.5 Other Impacts and Ancillary Benefits 18
CHAPTER 3: CONCLUSIONS 19
CHAPTER 4: MATERIALS AND METHODS 21
4.1 Site Characterization 21
REFERENCES 23
APPENDIX 1 – Supplemental Tables for Research Study 1 25
RESEARCH STUDY 2: PHASE-BASED ANALYSIS TO DETERMINE FIRST-ORDER DECAY RATES FOR A BIOREACTOR LANDFILL 27
CHAPTER 1: INTRODUCTION 27
CHAPTER 2: RESULTS AND DISCUSSION 29
2.1 Summary of Model Simulations 29
2.2 Gas Model Evaluation 40
2.3 Influence of Liquid Addition on Gas Generation 42
2.4 Assessment of Organic Stability 47

CHAPTER 3: CONCLUSIONS 55
CHAPTER 4: MATERIALS AND METHODS 57
4.1 Landfill T Characteristics and Operations 57
4.2 Landfill Data Compilation and Analysis 69
4.3 CAD Waste Volume Estimation 73
4.4 LandGEM Modeling 79
4.4.1 Collection Efficiency 79
4.4.2 Decay Rate Optimizations 79
4.5 Organic Stability Evaluation 81

RESEARCH STUDY 1: RETROSPECTIVE ANALYSIS OF WISCONSIN'S LANDFILL ORGANIC STABILITY RULE[1]

CHAPTER 1: INTRODUCTION

1.1 Organic Stability

Wisconsin's landfill organic stability rule (Section NR 514.07(9), Wis. Adm. Code) requires owners and operators of municipal solid waste (MSW) landfills to "incorporate landfill organic stability strategies into the plans of operation for their facilities." Specifically, the rule requires that owners submit a plan to the Wisconsin Department of Natural Resources (WDNR) to significantly reduce the amount of degradable organic material remaining after landfill closure so to reduce the time required for the landfill to achieve organic stability.

Organic stability is defined as a state of near complete decomposition of organic waste constituents such that human health, environmental, and financial risks associated with undecomposed waste are minimized. Short-term and long-term risks of landfilled waste arise from gaseous emissions, organic and 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 system. Biodegradation of the organic fraction of MSW can mitigate some risks and reduce others via exhausting gas generation potential of the waste, reducing leachate strength, treating leachate contaminants in-situ, and reducing the magnitude of post-closure settlement and subsequent damage to the final cover.

WDNR promulgated the organic stability rule (OSR) in 2007 for three scenarios: (1) new or expanded landfills as of January 2007, (2) landfill plans of operation approved between January 2004 and January 2007, and (3) active landfills that have not achieved 50% of design capacity as of January 2012. WDNR (2006) indicates that an organic stability plan must meet the following goals within 40 yr following landfill closure: (i) monthly average gas (CH_4 + CO_2) production rate ≤ 5% of maximum monthly average 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 decrease in gas production rate; and (iii) cumulative gas yield ≥ 75% of projected total gas generation. Landfill owners and operators have flexibility to select waste stabilization strategies that best fit their needs. Potential waste management strategies for implementation of the OSR include (1) diversion of biodegradable organic material from the landfill, (2) mechanical or biological treatment prior to disposal, and/or (3) in-situ landfill treatment. The third option often involves liquid addition, leachate recirculation, and/or in-situ aeration.

This study was conducted to assess the impact and effectiveness of the OSR five years after implementation. The objectives of this study were to (1) assess the manner in which landfill owners have implemented the OSR, (2) evaluate results of implementation actions on landfill performance and progression towards organic stability, and (3) consider implications of the OSR for solid waste management policy in Wisconsin. Although the focus of this analysis is on Wisconsin, the observations, findings, and recommendations presented herein are generally applicable to solid waste management in the U.S. and in engineered landfills containing biodegradable organic matter worldwide.

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[1] Bareither, C.A., Barlaz, M.A., Doran, M., and Benson, C.H. (2017). Retrospective analysis of Wisconsin's organic stability rule, *Journal of Environmental Engineering*, 143(5), 1-11, 10.1061/(ASCE)EE.1943-7870.0001192

1.2 Post-closure Management of Landfills

Landfill owners in the U.S. are required to monitor and maintain a closed landfill for what is referred to as the post-closure care (PCC) period (USEPA 1993). Regulated PCC activities include leachate management, groundwater monitoring, inspection and maintenance of the final cover, and control and monitoring of off-site methane (CH_4) migration. A 30-yr PCC period is specified in the federal Resource Conservation and Recovery Act (RCRA) Subtitle D rules, but some states require a longer time period (e.g., 40 yr in Wisconsin). Post-closure care requirements under RCRA and state regulations are actually performance- rather than time-based; 30 yr is typically used as a guide, but regulations require that PCC continue until threats to human health and the environment have been shown to be acceptable. A motivating factor for implementation of WDNR's OSR was to stabilize the waste as much as practical during PCC so that long-term risks and liabilities could be managed efficiently when the end of the 40-year PCC period was reached.

Potential alternatives for long-term management of landfills include (1) termination of PCC after a fixed term, (2) perpetual care, (3) complete waste stabilization, (4) meeting pre-defined metrics for solid, liquid, and/or gas phases (e.g., BOD/COD < 0.1), and (5) a performance-based approach (Laner et al. 2012). The current trend in PCC is evolving towards a performance-based approach, which is synonymous with landfill functional stability. In particular, a performance-based methodology termed the Evaluation of Post-Closure Care (EPCC) Methodology, establishes a modular approach for evaluating functional stability based on four PCC elements – leachate management, landfill gas management, groundwater monitoring, and cover maintenance (ITRC 2006; Morris and Barlaz 2011).

While the concept of functional stability is relatively new, there is interest amongst regulatory agencies. For example, landfill regulations in the State of Washington require that PCC be "conducted for thirty years or as long as necessary for a landfill to become functionally stable" (WAC 173-351-500). Recently, guidance has been provided on using a performance-based approach to demonstrate completion or extension of PCC in Florida (FDEP 2016). As described in this study, many landfill owners have adopted operational practices to reduce the duration of gas generation. However, given the underlying driver of the OSR, a more comprehensive strategy that includes leachate generation and integrity of the final cover is required to guide long-term landfill management.

CHAPTER 2: RESULTS AND DISCUSSION

2.1 Landfill-Based Waste Management

A summary of waste disposal and facility-specific capabilities for waste treatment and disposal at the ten landfills is presented in Table S1.1 in the appendix. Also included in Table S1.1 are waste disposal statistics pertaining to the combined ten sites and Wisconsin as a whole. Annual waste disposal was computed for 2007-2012, which encompasses the first six years of OSR implementation. Although the ten sites evaluated represent only 29% of the solid waste landfills in Wisconsin, they are accepting, managing, and treating half of the MSW generated within the state.

Temporal trends in annual waste disposal and MSW disposal normalized to a 2007 baseline are presented in Fig. 1.1. Waste described herein refers to all non-hazardous solid waste that may be disposed at a given landfill (e.g., ash, sludge, MSW, construction and demolition waste, etc.), whereas MSW refers specifically to residential and commercial refuse. The overall trend during the period in which the OSR has been active is a decrease in both total waste and MSW disposal. MSW disposed in Wisconsin landfills from 2010 to 2012 ranged between 61 and 64% of MSW disposed in 2007 (Fig. 1.1b). This decrease is also evident at the ten landfills evaluated in this study, and only Site L reported an increase in MSW disposal. Four of the ten sites reported an increase in total waste disposal since 2007 (Fig. 1.1a). The increase in total waste tonnage in 2012 computed for the average of the ten sites was influenced by the pronounced increase in waste disposal reported at Site G. The increase at Site G was due to disposal of treated contaminated soil and sediment contaminated with PCBs, which accounted for 43% of total waste tonnage at Site G in 2012. Annual increases in total waste tonnage at Sites D, J, and L can be attributed to increased tonnages of foundry waste, wastewater treatment sludge, other non-hazardous solid waste, fee-exempt waste for dikes and berms, shredder fluff and treated contaminated soils used for daily cover, and construction and demolition (C&D) waste.

Factors that likely influenced the decrease in MSW disposal include economic recession, increased recycling, an increase in Wisconsin's landfill disposal environmental fees, and the dynamic nature of landfill economics (e.g., fuel costs). Landfill owners reported that waste generated in Wisconsin has been diverted to neighboring states since the landfill environmental fee on waste disposed in Wisconsin was increased from US$6.50/Mg ($5.90/ton) to US$14.3/Mg ($13/ton) in 2009, and that some waste from neighboring states that used to be disposed in Wisconsin is no longer shipped into the state for disposal. The environmental fee applies to MSW, publically-owned treatment works (POTW) sludge, other non-hazardous solid waste, and C&D waste. The out-of-state waste disposed in Wisconsin landfills decreased from 1.8 million Mg in 2007 to less than 363,000 Mg in 2012, as summarized in Table A1.1.

2.2 Waste Diversion and Composting

Organic waste diversion represents an opportunity to reduce the amount of biodegradable organic waste disposed in a landfill. Four of the ten sites evaluated in this study report some type of organic waste diversion (Table 1.1) as part of their organic stability plan. Sites D, E, and L have on-site composting facilities, whereas Site F diverts organic waste to a local refuse-derived fuel (RDF) facility operated by an electric utility.

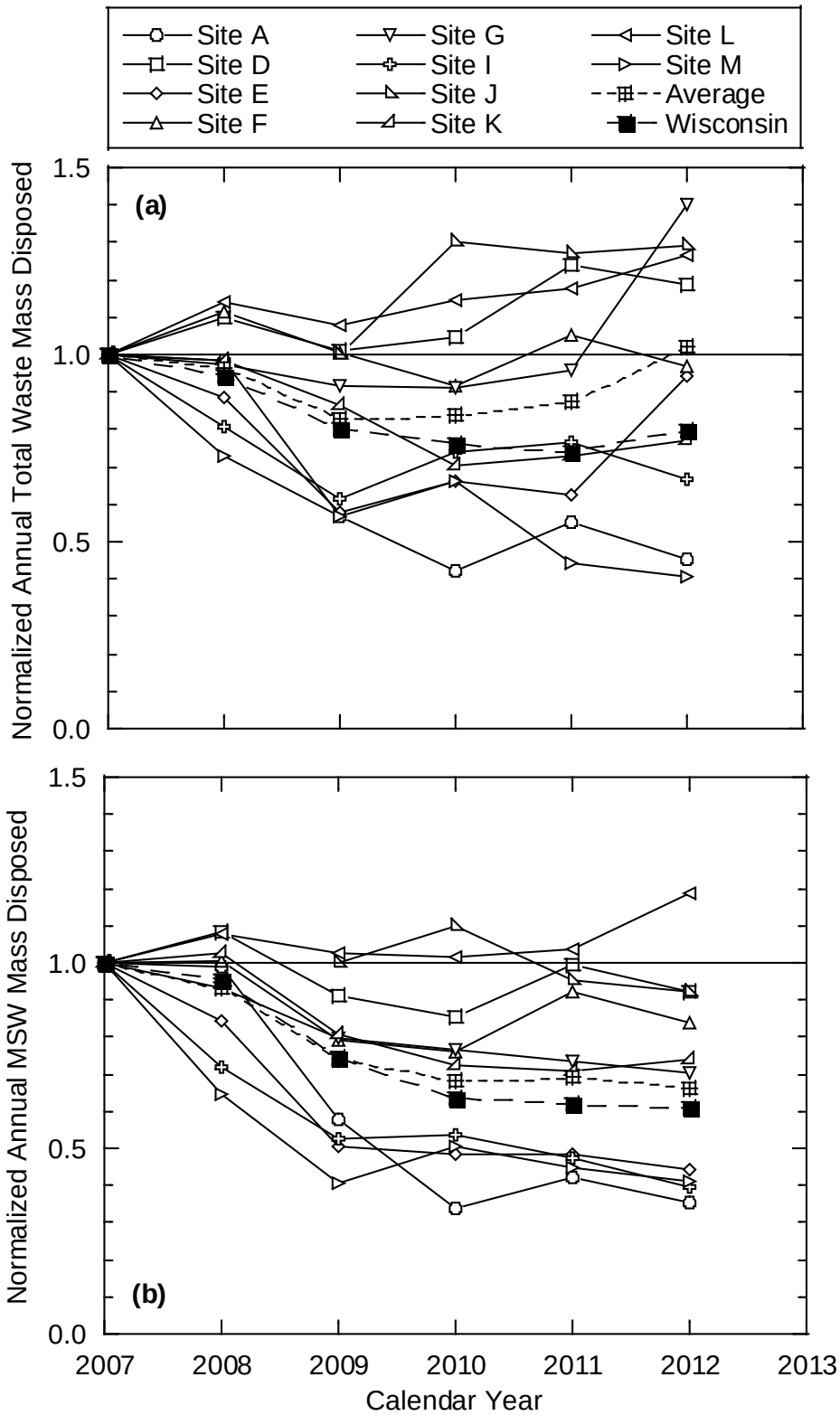

Fig. 1.1. Temporal trends of annual (a) total waste disposal and (b) municipal solid waste (MSW) disposal. Waste masses are normalized with respect to total waste or MSW mass reported for 2007 (2009 for Site J).

Table 1.1. Site characteristics for landfills evaluated in this study.

Site ID	Owner	Initiation of OSR Compliance	Organic Stability Actions[a]	Area Under OSR (ha)	Disposal Rate (Mg/d)[b]	Year Liquid/ Leachate Addition Initiated	RD&D Permit[c]
A	Private	2007	LR	22.3	1070 (740-1620)	2013	—
D	Private	2007	LR; LWA; OD	27.1	1100 (1000-1270)	2001	2007
E	Private	2011	LR; LWA; OD	19.4	1340 (1180-1820)	1998	2007
F	Public	2012	OD; LR	10.5	190 (164-210)	June 2012	—
G	Private	2008	LR; LWA	NA	2760 (2460-3730)	June 2006	2007
I	Private	2007	LR; LWA	11.1	740 (640-820)	2002	2007
J	Private	2007	LR; LWA; DFC	24.7	640 (560-670)	NA	2008
K	Private	2007	LR; LWA; DFC	25.9	1010 (870-1230)	2002	2009
L	Private	2007	LR; LWA; OD	39.7	950 (820-1000)	1999	2007
M	Private	2012	LR; LWA; DFC	16.2	330 (210-520)	2001	2010

Notes: OSR = organic stability rule; NA = not available; RD&D = Research, Development, and Demonstration.
[a] LR = leachate recirculation; LWA = liquid waste addition; OD = organics diversion; DFC = delay final cover
[b] Average with range in parentheses for 2007-2012.
[c] Year permit approved if applicable; otherwise not applicable (—).

Composting operations at Sites D, E, and L were all initiated as a way to manage yard waste, and subsequent efforts were initiated to expand operations to manage additional source-separated food waste as part of organic stability plans. Site D reports a relatively small composting operation for pre-consumer food waste that is mixed approximately 1:1 with yard waste and composted for 60 to 120 d. Mature compost is sold to a local business for landscaping; however, any compost that is not sold is used on-site as top soil. Site L has an existing 15,300-m^3 yard waste composting facility and received WDNR approval to accept food waste starting in March 2010. As of 2014, Site L had yet to implement co-treatment of yard and food waste within the composting facility. In addition to source-separated food waste, owners at Sites E and L are considering farm crop residue, manure, and other organic materials for future composting feedstocks. These wastes are not currently disposed at the landfill.

Residential solid waste diversion from Site F to the local RDF facility was initiated in 1988. Site F is small for Wisconsin, having received an average of approximately 69,000 Mg/yr between 2007 and 2012. An estimated 57% of the MSW collected in the region is processed at the RDF facility, with the low BTU fraction and ash subsequently disposed at the landfill.

2.3 Liquids Acceptance and Management

The two approaches for waste moisture enhancement that were practiced at the study sites were leachate recirculation and liquid waste addition. Leachate recirculation decreases the amount of leachate requiring off-site treatment, to the extent that recirculated liquids are retained within the waste. Liquid waste addition is advantageous as this practice generates revenue, relieves loading of industrial liquid waste to wastewater treatment plants, provides a service to liquid waste generators that may otherwise require long-distance hauling of liquids, and provides a liquid source to enhance waste degradation and biogas generation that allows compliance with the OSR. While both leachate recirculation and liquid waste addition enhance waste decomposition and increase methane generation via stimulating anaerobic biodegradation of the organic waste fraction (e.g., Reinhart et al. 2005; Barlaz et al. 2010), liquid waste addition offers opportunities to increase waste moisture content substantially while also increasing disposal revenue. All landfill owners indicated that actions implemented to enhance the waste moisture content have been influenced strongly by economic considerations.

A summary of liquid management parameters is presented in Table 1.2 and liquid management and application methods are presented in the supplemental information in Table A1.2. Annual average leachate generation volumes were greater than leachate recirculation volumes for all sites, meaning that operators could not recirculate 100% of the leachate generated. As described below, Site A is still considering when to initiate recirculation.

The balance between acceptance of liquid wastes and recirculating leachate to enhance waste moisture content at a given site was influenced by the cost for off-site leachate treatment as well as other factors including the mass of waste available to absorb liquid. The percent contribution of liquid waste to the total liquid added in a given year and the cost of off-site treatment are tabulated in Table 1.2. Sites D and L have the highest cost of off-site leachate treatment (≥ US$10/$m^3$) and report the smallest percent contribution of liquid waste addition among the sites with an active RD&D permit. These two sites also reported the largest percentage of generated leachate that was subsequently recirculated. In essence, these landfills accepted external liquids and tried to maximize leachate recirculation to minimize leachate treatment costs. In contrast,

Table 1.2. Leachate and liquid waste management and leachate treatment cost.

ID	Leachate Generated (m^3/yr)[a]	Total Liquid Added (m^3/yr)[b]	Leachate Recirculated (m^3/yr)[a]	Liquid Waste Added (m^3/yr)	Leachate Recirculated/ Generated (%)	Liquid Waste Fraction of Total Liquid Added (%)	Cost of Off-Site Leachate Treatment ($/$m^3$)
A[c]	30,083	0	0	0	0	0	5.28
D	27,014	31,600	25,249	1,459	93.5 (82.7-100)	4.6 (1.1-7.1)	10.57
E	47,460	33,739	27,522	1,457	29.5 (6.0-56)	3.8 (1.3-59)	NA
F[d]	33,854	636	636	0	1.9	0	0.53
G	59,848	13,016	7,301	5,714	12.2 (21.6-60)	44 (0-100)	5.28
I[e]	21,900	5,471	3,860	11,916	17.6 (0.0-43.1)	0 or 100	2.38
J	14,509	626	626	NA	4.3 (0.0-8.0)	NA	7.13
K	61,272	1,637	557	1,134	0.9	69 (26-100)	NA
L	29,314	21,687	20,003	1,684	68.2 (36.5-92.0)	7.8 (4.0-19)	13.21
M	24,977	3,574	5,556	1,591	22.2 (0.0-27.4)	0 or 100	NA

Notes: NA = not available; 1 m^3 = 1000 L
[a] Annual average volumes for entire landfill between 2007-2012
[b] Sum of all liquids added; including recirculated leachate and liquid waste plus other acceptable liquids (e.g., gas condensate)
[c] Leachate recirculation initiated on a trial basis in 2013.
[d] Leachate only added in 2012
[e] Liquid waste only added in 2012

Sites G and I reported larger contributions of liquid waste disposal used to moisten the waste for organic stability. Leachate generated at these sites can be directed to off-site treatment facilities at a considerably lower cost compared to Sites D and L, which reduces the need for on-site leachate management via recirculation.

Bar charts representing the fraction of leachate generated that was recirculated in a given year are shown in Fig. 1.2a. All sites except D indicate an overall decrease in the fraction of leachate recirculated during the study period (2007-2012). Site D systematically recirculated as much leachate as possible (80-100%) to enhance in-situ waste decomposition and minimize off-site leachate treatment. Although small increases in leachate recirculation are shown for Sites F and J in 2012, the majority of the sites reported recirculating less than 10% of generated leachate in 2012 and four sites that had previously practiced leachate recirculation reported zero leachate recirculation (i.e., Sites D, G, I and M).

Bar charts representing the annual percent contribution of liquid waste to total liquid addition are shown in Fig. 1.2b. Liquid waste has increased as a fraction of the total liquid added at all but one landfill actively practicing liquid waste addition (Site K). Sites I, K, and M initially reported zero liquid waste addition, and subsequently changed their operational strategy so that all liquid addition was from commercial liquids. Liquid waste was not practiced at Site F during this study and liquid waste volumes were not available for Site J (Table 1.2; Fig. 1.2b).

The decreasing amount of leachate recirculation and the increasing fraction of liquid waste addition were attributed to two factors: (i) gas wells routinely flooding due to prior recirculation and (ii) favorable revenue from liquid waste disposal. In many cases, the revenue associated with liquid waste disposal was larger than the costs for leachate treatment. At sites where leachate recirculation may be less economically attractive compared to liquid waste addition (e.g., Site I), liquid waste provides a means to add moisture to the waste and enhance organic waste stability due to the favorable revenue from disposal.

Sites A and F do not have an RD&D permit and have not added supplemental liquids to the waste (Table 1.2). Additionally, recirculation at Site A was only initiated on a trial basis in 2013. Although the organic stability plan for Site A was approved in 2009, the landfill operator indicated that recirculation was not initiated until the gas management system was improved to manage increased gas generation and minimize potential odors.

2.4 Moisture Addition Methods

Liquid waste was predominantly added via a trench and cover technique, whereby a trench is excavated on the working face, liquid waste is discharged into the trench, and waste is pushed back into the trench and mixed with the liquid. Leachate recirculation was typically implemented via horizontal and vertical injection systems as well as surface application (e.g., tanker truck and hose, trench and cover) (Table S1.2). Site owners and operators reported a preference for surface application due to lower infrastructure costs and ease of operation. In general, surface application is replacing liquid distribution via horizontal trenches and vertical well injection systems, which were common in the previous decade (e.g., Benson et al. 2007; Bareither et al. 2010). The latter approaches require additional resources (e.g., personnel, materials, time) and are affected adversely by pipe clogging and “watering out” of the waste. Surface application has neither of these problems, results in a more uniformly wetted waste, can result in higher waste density during compaction, and was stated by the operators to reduce the

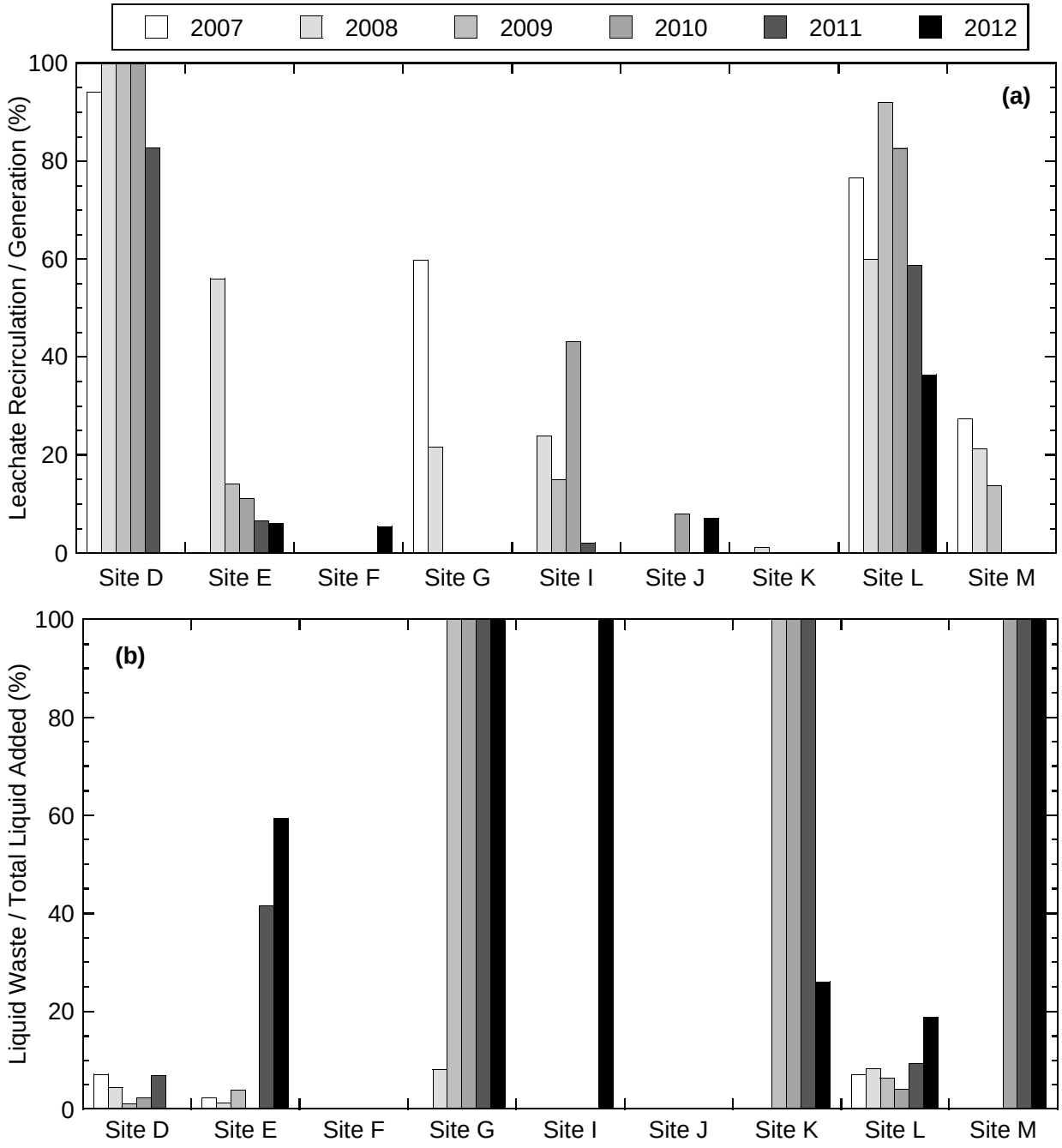

Fig.1.2. Bar charts of (a) percent leachate generated that was recirculated and (b) percent contribution of liquid waste addition to total liquid added. Note: leachate was not recirculated and no liquid waste was added at Site A.

time prior to the onset of gas production. However, moistening waste near the surface results in increased landfill gas earlier in landfill operations, when capture can be difficult.

Thus, surface application of leachate has the potential to increase gaseous emissions and odors.

Common liquid waste sources included cleaning water from manufacturing processes, automobile wash water, and industrial sludge (Table S1.2). In addition to these liquids, non-leachate liquids generated on-site that were added to the waste mass include gas condensate and haul-vehicle cleanout water. The commercial liquid waste streams that are sent to a landfill are those for which another, less expensive option does not exist (e.g., POTW, land application). Most of the liquid wastes were generated in rural areas with relatively small POTWs that did not have the capacity to accept industrial liquid wastes. Each landfill has site-specific acceptance criteria. However, liquid waste streams typically were not evaluated for compatibility with waste decomposition, which has potential to result in problems. For example, high sugar content waste would result in carboxylic acid accumulation and an acidic pH, which would in turn depress methane generation.

2.5 Waste Moisture Content

A summary of moisture content measurements conducted on waste exhumed during gas well installation is presented in Table 1.3. The average wet weight water content (w_w = weight water / total weight) based on 307 individual measurements is 37.4%, and ranges between 21.0% and 57.0%. Water content measurements on exhumed solid waste are variable and reflect inherent heterogeneity in the waste composition (e.g., Bareither et al. 2010).In general, the average and upper bound water contents in Table 1.3 capture a target w_w range of 40-45% for moisture enhancement strategies that was typically noted in the organic stability plans.

Box plots of w_w for a recirculation area and control area at Site M are shown in Fig. 1.3 as a function of waste depth. Higher w_w*s* were measured at all depths in the recirculation area as compared to the control area. The average w_w for the recirculation and control areas was 45.4% and 36.2%, respectively. The larger range of w_w in the recirculation area suggests a progressive wetting with depth, which has been shown at other landfills practicing leachate recirculation (e.g., Bareither et al. 2010).

The maximum and minimum w_w determined for the different sites indicate that some relatively dry waste is present even at landfills that attempt to wet the entire waste mass. Fluctuations in leachate generation volumes that require management have prompted interest among landfill operators in developing guidance on the amount of liquid that can be added to the waste as a function of climatic conditions (e.g., precipitation), cell surface area and volume, waste in-place, and the rate of waste disposed in the landfill. An additional metric used to monitor the progression of waste wetting is the liquid level in gas wells. The ideal scenario is to moisten waste to the point at which gas wells do not flood and gas can be collected under application of a small vacuum.

2.6 Gas Production and Management

A summary of gas collected at each landfill is presented in Table 1.4 and the relationship between annual gas collected and annual MSW tipping rate is shown in Fig. 1.4 (MSW tipping rate = mass of waste disposed per day in a landfill). The volume of gas collected increases with increasing MSW tipping rate, as expected. For a given site, however, data in Fig. 1.4 are scattered because tipping rate is only one of several

Table 1.3. Compilation of water content measurements completed on waste exhumed during gas well installation.

ID	Analysis Date	No. of Samples	Wet Weight Water Content (%)		
			Average	Maximum	Minimum
A	—	—	—	—	—
D	Mar. 2007	14	31.7	47.0	20.1
	Apr. 2008	12	40.0	61.3	27.6
	Dec. 2009	13	37.8	54.3	22.0
E	Apr. 2012	58	41.2	73.0	11.0
F	Apr. 2009	3	25.7	27.5	22.4
G	Aug. 2008	25	38.7	65.0	16.4
	Apr. 2009	12	26.3	37.3	15.4
	Dec. 2012	11	36.0	61.5	24.4
I	—	—	—	—	—
J	—	—	—	—	—
K	Jul. 2008	57	35.9	59.6	14.5
L	Mar. 2007	10	41.2	60.0	14.3
	Nov. 2007	14	33.5	56.0	22.6
	Aug. 2009	12	33.6	50.8	25.5
M	2007	21	44.7	60.8	25.7
	2008	18	47.5	80.7	31.5
	2009	17	42.1	61.0	16.2
	2011	10	42.9	56.4	26.4
Average	—	307	37.4	57.0	21.0

Note: wet weight water content = weight water/total weight

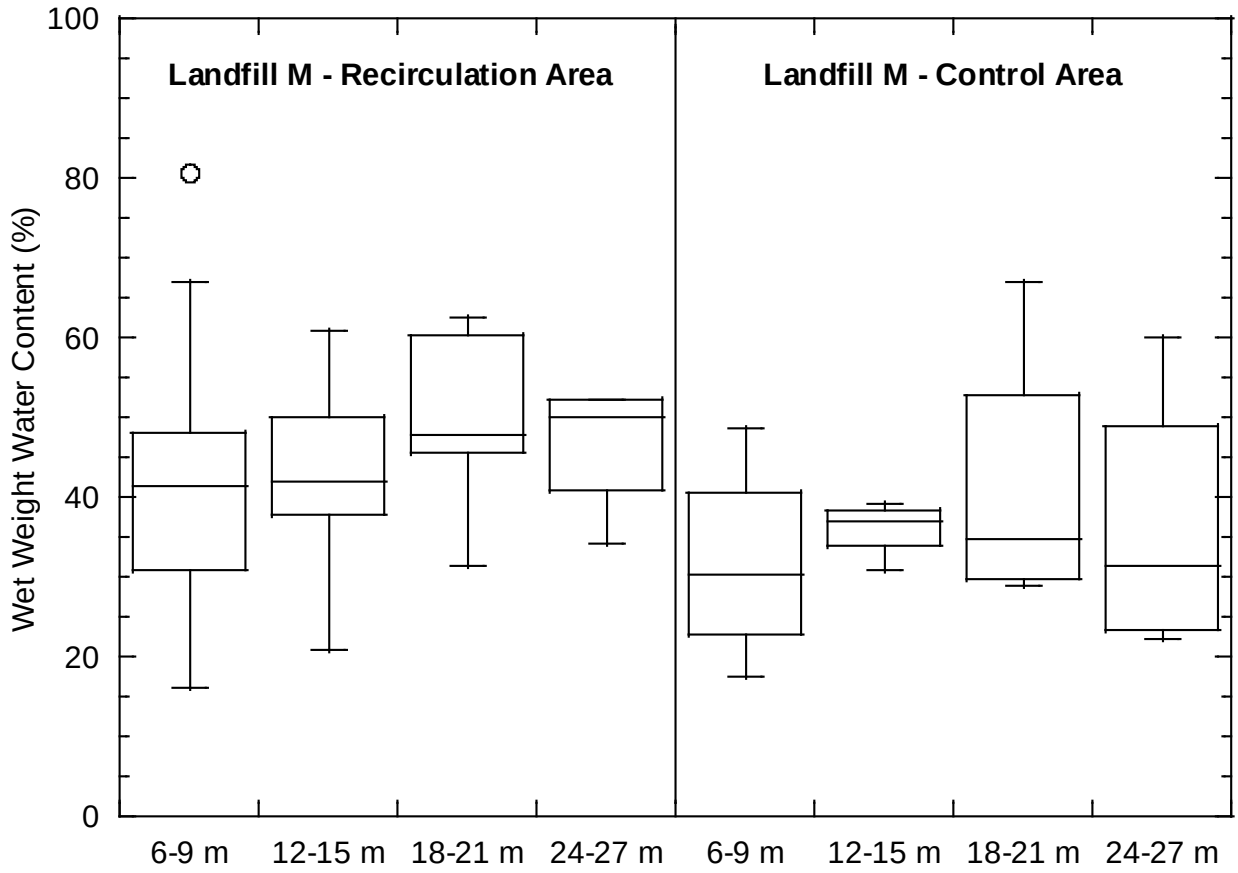

Fig.1.3. Box plots of wet weight water contents for waste exhumed from different depths in a recirculation area and control area at Site M. The box represents the middle 50% of the data; the central line in the box represents the median; the outer boundaries represent the interquartile range, i.e., 25th and 75th percentile; and the upper and lower whiskers extending from the box constitute the 5th and 95th percentiles.

factors affecting gas production and collection. Other factors include total mass and average age of waste in place, and gas well density, which varies with time. For example, the MSW tipping rate at Site J is approximately 266 Mg-MSW/d and annual gas collection ranged from 0.2 to 8.6 million-m^3. Waste filling began at Site J in 2009 with gas collection

beginning in 2010. Annual gas collection at Site J has increased since collection was initiated and can be expected to increase as waste filling and gas collection continue.

All sites reported use of landfill gas for energy generation although the fraction of gas used beneficially and the methods to generate energy varied. Energy generation methods included internal combustion engines, turbines, transmission by pipeline to a POTW, and sales to a neighboring rendering plant and local power company (Table 1.4).

The fraction of gas that was flared ranged from 0% for Site F to 97% for Site E (Table 1.4). Gas that was not flared was used beneficially for energy generation. The fraction of gas flared at Site E was high because the pipeline had not yet been brought online when this survey was conducted. In contrast, Site F has a small amount of gas to manage and can manage all collected gas via pipeline to a commercial power company; therefore, Site F sends no gas to a flare. The range in the relative fractions of gas used beneficially and flared varied at the other sites depending on capacity of existing engines and economic feasibility of adding additional electricity generation capacity.

2.7 Gas Production Rates and Organic Stability Assessment

Landfill gas modeling is required in WDNR's OSR to document progression towards organic stability and attainment of OSR goals within 40 yr of post closure. A summary of gas modeling techniques, model parameters, and evaluation of organic stability employed by engineers for each of the landfills is presented in Table 1.5. The two OSR goals evaluated via gas modeling include achieving (i) a monthly gas flow rate ≤ 5% of the maximum monthly gas flow rate observed during the life of the facility, or ≤ 278 L-gas/m^3-waste/yr and (ii) a cumulative gas yield ≥ 75% of projected total gas production, both within 40 yr of post closure.

Site engineers at each landfill used US EPA's LandGEM gas model (USEPA 2005) to predict gas generation and demonstrate compliance with organic stability plans. The two input parameters in LandGEM that are affected by organic stability plans are the CH_4 generation potential of the waste (L_0) and first-order decay rate (k). The majority of LandGEM analyses conducted by site engineers employed L_0 = 100 m^3-CH_4/Mg, which is the default value in LandGEM (Table 1.5). The actual L_0 of landfilled waste likely varies between sites and is a function of waste composition (Staley and Barlaz 2009). However, recent analyses of field data suggest that an L_0 of 100 m^3-CH_4/Mg provides a best fit between LandGEM predictions and gas collection measurements (Wang et al. 2013). Site engineers employed k = 0.04 1/yr (default value in LandGEM) and k = 0.08 1/yr for most analyses (Table 1.5), the latter recommended by Reinhart et al. (2005) based on an assessment of gas generation in wet landfills. This higher k is also consistent with decay rates reported by Barlaz et al. (2010) in their state-of-the-practice review of North American bioreactor landfills, but is lower than k = 0.09-0.12 1/yr reported by Wang et al. (2013). All gas modeling completed to assess the OSR gas yield and flow rate assumed continuation of current waste acceptance rates and relative contributions of MSW plus biodegradable special wastes.

Two approaches were employed by site engineers to evaluate progression towards organic stability. The first approach was a site-wide basis that incorporated a single L_0 and single k for the entire landfill, whereas the second approach employed a single L_0, but two different ks corresponding to waste in areas with conventional

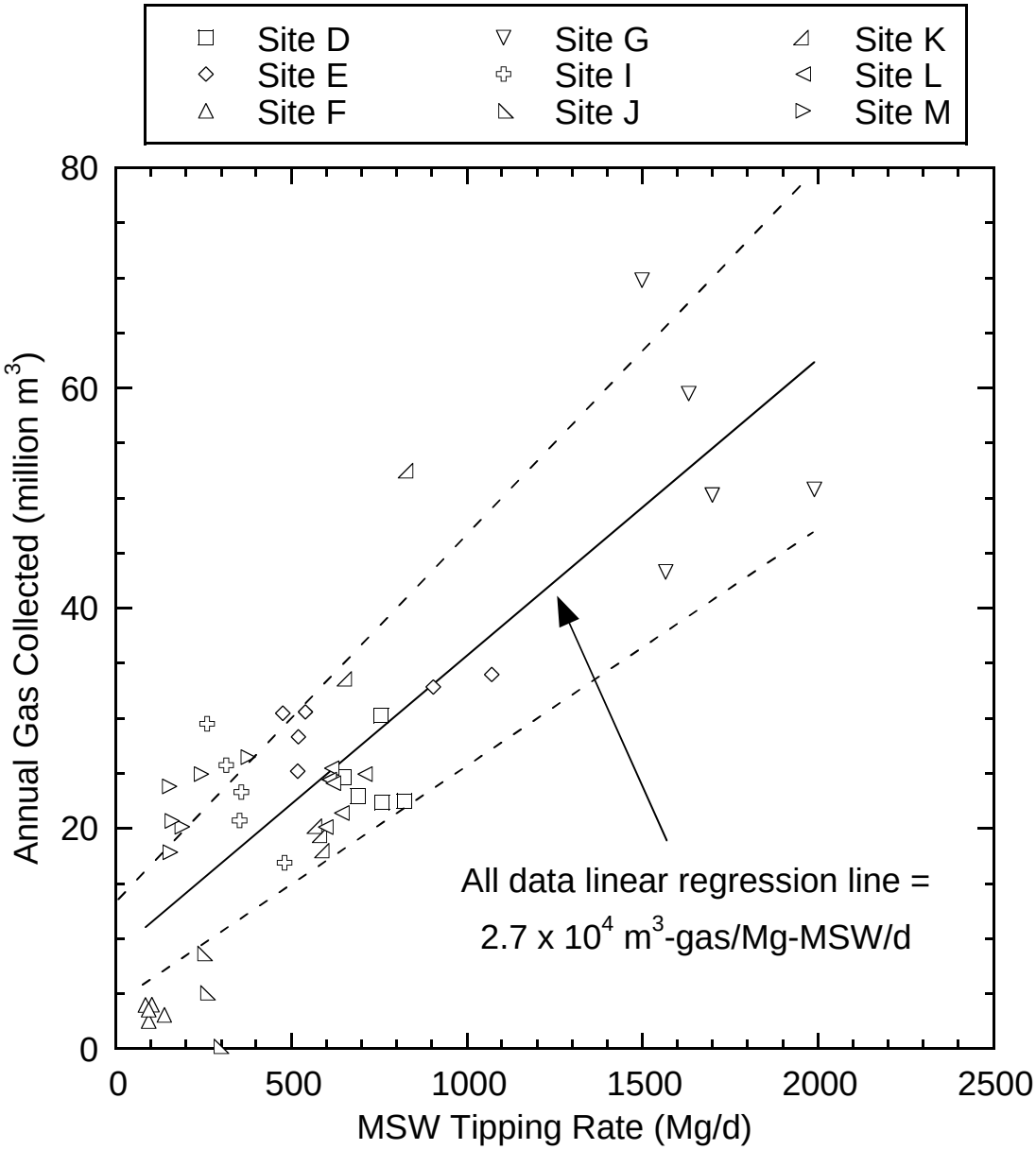

Fig.1.4. Relationship between annual gas collected and annual municipal solid waste tipping rate. Dashed lines represent the upper and lower 95% confidence bounds for the linear regression line.

Table 1.4. Landfill gas generation and utilization at the studied landfills.

ID	Gas Collected (million m^3/yr)[a]	Gas Flow Rate (m^3/d)[a]	Fraction Flared (%)[a]	Gas Utilization
A	NA	NA	NA	NA
D	24.5	46.6	56	Approximately 33% sold to 3rd party contractor for electricity generation; 3 on-site engines that are all old and need maintenance
E	30.2	57.5	97	Transported via pipeline to local POTW for energy source in treatment operations
F	3.38	6.43	0	Transported via pipeline to commercial energy provider
G	54.7	104	16	Gas turbines (4 x 36.8 m^3/min); 42.5 m^3/min flare
I	23.2	44.2	NA	Gas sold to neighboring rendering plant; collaboration between landfill, plant owner, and power company to install 3 landfill-owned engines at rendering plant
J	4.63	9.34	NA	Implemented 4-engine gas plant in 2002; permit for additional 6-engines = 10-engine plant; relocated two engines to other sites due to decrease in gas collection
K	28.7	54.7	NA	Two on-site turbines installed in 1985 and 4 additional engines installed in 1986
L	23.4	44.5	66	Two on-site engines (~10 m^3/min combined); gas sold to energy company to operate two microturbines (2.8-3.5 m^3/min); flare (25.5 m^3/min)
M	22.3	42.5	7.1	Four engines in 2006; added 3 engines in 2007; excess flared. Currently, 4 engines remain with 3 operating; other 3 engines were due to decrease in gas collection

Note: NA = not available

[a] Annual averages for entire landfill between 2007-2012

Table 1.5. Summary of LandGEM model parameters, gas modeling techniques, and observations of organic stability.

ID	Assumed Methane Yield, L_0 (m^3/Mg-MSW)	Assumed First-Order Decay Rate, k (1/yr)	Gas Modeling Technique[a]	Organic Stability Assessment
A	100	0.05, 0.08	k = 0.05 for waste placed prior to OSR; k = 0.08 for waste placed following OSR implementation	38-yr post closure to reach 95% of total landfill gas generation and 44-yr post closure to reach 278 L-gas/m^3-waste/yr
D	100	0.04, 0.08	k = 0.04 for waste placed prior to 2006; k = 0.08 for waste placed since 2006 and future waste disposal	98% gas generation and flow rate at 4.1% of peak for 40-yr post closure
E	80, 100	0.04, 0.08	k = 0.04 or 0.08 for entire landfill	99% gas generation and flow rate at 4.1% of peak for 40-yr post closure
F	80	0.08	NA	99% gas generation and flow rate at 4% of peak for 40-yr post closure
G	NA	NA	NA	NA
I	100	0.027, 0.15	k = 0.027 for waste placed prior to OSR; k = 0.15 computed for waste placed during OSR via fitting model to gas data assuming 85% collection efficiency	Determined k = 0.077 to meet > 75% total gas generation and < 5% maximum monthly flow rate 40 yr post closure
J	100	0.088	k = 0.088 determined via fitting model to gas data assuming 100% collection efficiency	Determined k = 0.077 to meet > 75% total gas generation and < 5% maximum monthly flow rate 40 yr post closure
K	100	0.068	k = 0.068 based on assumed 75% increase to account for enhanced gas generation due to leachate recirculation	96% gas generation and flow rate at 5% of peak for 40-yr post closure
L	80, 100	0.04, 0.08	k = 0.04 for waste placed prior to OSR; k = 0.08 for waste placed following OSR implementation	For L_0 = 100 and k = 0.08 for new waste, 98.7% total gas generation within 40-yr post closure
M	100	0.062, 0.050	k = 0.062 determine via fitting model to gas data and assuming 75% collection efficiency; k = 0.050 determined in same manner but with assumed 85% collection efficiency	Estimated > 75% total gas generation 2-yr post closure and 278 L-gas/m^3-waste/yr 37-yr post closure

NA = not available

[a] Gas collection efficiency assumed equal to 100% where not mentioned

operations and waste in areas being managed for organic stability. The first approach is simpler, but does not account for different gas generation rates in areas with and without programs to enhance waste decomposition. Engineers for Sites E, F, J, K, and M used the single-*k* approach, whereas engineers for Sites A, D, I, and L employed the dual-*k* approach with a lower *k* for waste in areas of the landfill in which decomposition was not accelerated and a higher *k* for waste in areas where decomposition was enhanced (Table 1.5). Both approaches were used at Site I and the results are in Table 1.6. The analysis for Site I indicates that the gas generation rate constant increased from 2009 to 2012. Regardless of whether the gas modeling incorporated a single-*k* or dual-*k* analysis, the modeling conducted at all sites indicated that the OSR goals for gas yield and gas flow rate could be achieved with a post closure period of 40 yr (Table 1.5).

An alternative evaluation to assess if organic stability operations are meeting OSR goals was conducted by the site engineer at Sites I and J. The site engineer determined the value of *k* necessary to meet the organic stability goals. The engineer then determined whether the organic stability goal was met by comparing the target *k* to a *k* obtained by fitting the LandGEM model to measured gas data, with the field-fit *k* greater than the target *k* indicative of meeting the organic stability goals. This approach may underestimate actual organic stability if the organic fraction of the waste stream changes (e.g., if L_0 is < 100 m^3-CH_4/Mg) or if collection efficiency is less than 100%.

A more advanced site-wide analysis can be completed if more representative L_0 and *k* are incorporated for specific areas of a landfill. This level of analysis requires separation of waste mass and gas collection data based on landfill areas and can be used to evaluate the performance of organic stability plans that have been implemented. However, this option is the most technically challenging and time-intensive to evaluate. Additionally, as described in Wang et al. (2013), the gas collection efficiency changes with time at most landfills. Gas collection efficiency was directly noted in only three of the gas modeling analyses conducted by the sites in this study and should be considered in the estimation of *k* and assessment of OSR goals.

2.8 Gas Management Practices and Challenges

The capability to manage gas effectively was a common theme among the sites in this study, with one site owner specifically reiterating the importance of “staying ahead of the gas” to avoid gas and odor problems associated with accelerated gas production. Active gas collection systems were installed early (i.e., before the NSPS requirement) at each of the sites visited, except Site K, to manage gas effectively, minimize odors, and, in some cases, to ensure adequate gas supply to gas-to-energy facilities.

Vertical wells were the most common technique used for gas extraction at each of the sites. However, unique strategies to manage gas during filling and operations were employed at several sites, especially to manage gas produced early due to added moisture. Some sites reported odors associated with gas production within 6 to 9 months following waste placement. The use of perforated gas collection pipes places along the leachate collection layer at the base of a landfill cell (belly pipes), was reported by site owners to be effective in the early stages of waste placement, and some sites reported that collection with belly pipes was effective with only a few lifts of waste (2-3 m each) above the pipes. Horizontal collection trenches were also reported to be effective for the first 3 to 4 yr, after which they tended to clog depending on the aggressiveness with which liquids were added to the waste.

The aggressiveness with which site owners and operators initiated measures to enhance gas production was related to their ability to manage and use biogas. In some cases, sites had available capacity to increase energy generation and desired additional

Table 1.6. Calculated first-order decay rates (*k*) for Site I determined with respect to a single gas generation rate for the entire landfill and enhanced rate for waste deposited under the organic stability rule.

Year	2009	2010	2011	2012
Single *k* for entire landfill (1/yr)[a]	0.038	0.035	0.041	0.061
Enhanced *k* for waste placed since OSR initiated (1/yr)[b]	0.051	0.093	0.107	0.153

Note: *k* computed via least squares optimization between gas collection data and gas generation predicted with LandGEM

[a] Calculated using average gas flow and assuming 85% collection efficiency

[b] Assumed *k* = 0.027 1/yr for waste in-place prior to organic stability plan and computed *k* for waste placed during active organic stability plan operations

gas collection. For example, Site J implemented aggressive actions to stimulate organic decomposition and increase gas generation due to the availability of on-site energy-generation infrastructure. These actions were undertaken in the absence of organic stability concerns, but were incorporated into the organic stability plan developed subsequently. At other sites, a fraction of the gas was flared as markets did not warrant investment in additional engines or other equipment to use the gas beneficially. Site engineers reported consistently that the drop in price of natural gas over the period of the OSR analysis (i.e., 2007 to 2012) reduced the economic viability of beneficial use of landfill gas at most sites.

2.9 Practical Implications

2.9.1 Organic Waste Diversion

The predominant strategy for meeting the OSR at the landfills in this study was accelerated anaerobic decomposition of organic waste within the landfill. Organic waste diversion has been modest, and the general perception among landfill owners in this study was that organic waste diversion has not had a measureable effect on the waste stream managed in Wisconsin landfills. Those sites with organic waste diversion programs generally accepted commercial source-separated organic waste streams to provide control on feedstock quality so that the compost would meet end-use alternatives. Without greater economic incentives, the fraction of organic waste managed by diversion is unlikely to increase appreciably.

The largest fraction of organic waste diversion in the study was conducted by Site F using non-traditional means. A large fraction of the MSW at Site F is diverted to an RDF facility, with the ash from the RDF facility landfilled. Under the current OSR, Site F is required to submit an organic stability plan for the waste that is managed within the landfill, and does not receive credit for the organic fraction diverted as RDF. The owners of Site F reported limited incentive to implement leachate recirculation, despite landfill gas being used beneficially as an energy source (Table 1.4), as leachate recirculation is approximately US$13.2/m^3 and the cost for leachate disposal to the local POTW is US$0.53/m^3. Nevertheless, Site F has been recirculating leachate to enhance in-situ waste decomposition since 2012 to comply with the OSR.

2.9.2 Liquid Waste

Disposal of commercial liquids has proven to be a valuable means to wet waste to meet OSR goals and as source of revenue. Liquid waste disposal to meet OSR goals has led to reduced leachate recirculation. Site owners unanimously indicated a desire to continue accepting liquid waste under their RD&D permits, and there were no reports of pronounced or sustained problems related to liquid waste disposal (e.g., seeps, stability, elevated head on liner, etc.).

Landfill owners may be challenged if the RD&D rule expires and other means to wet waste must be undertaken to comply with the OSR. Some landfills may not have enough leachate to enhance decomposition sufficiently to achieve organic stability goals. Updating federal and state regulations to permit liquid waste disposal under appropriate conditions would make continued compliance with the OSR practical.

Biochemical compatibility between microbial communities in MSW and liquid waste is essential to ensure that organic stability is achieved when commercial liquids are used to enhance degradation. Guidance is needed on methods to assess biochemical compatibility with a diversity of solid waste streams to ensure that disposal of liquid waste

achieves the goal of enhanced decomposition. For example, at sites where leachate treatment costs are high and liquid waste represents a revenue stream, landfill owners and operators sought out special wastes with high moisture retention capacity (e.g., utility ash, foundry waste, shredder fluff) that could be co-disposed with liquid waste. Compatibility testing is needed to ensure that interactions with these wastes do not have unintended effects (e.g., reduced biodegradation).

2.9.3 Gas Management

Early and aggressive gas collection is needed at landfills that are operated to enhance organic decomposition to minimize odors and reduce greenhouse gas emissions. Collecting this gas can present advantages if energy uses for the gas exist. At Site J, for example, a gas collection system was installed early during waste disposal to collect gas for energy generation.

Landfill operators report economic and regulatory challenges with managing increased gas production via on-site energy generation. For example, Site G has been operating four turbine generators near maximum capacity. Maintenance or replacement of one of the generators requires an air pollution control construction permit, which is cumbersome and expensive to obtain. Site G's Clean Air Act permit does not allow installation of additional generators, which is a disincentive to produce and recover additional landfill gas for energy production. In addition, revenue from electricity sales is no longer sufficient to justify investments in gas-to-energy infrastructure. The combination of these regulatory and economic constraints results in flaring a substantial fraction (16%) of the gas collected at Site G (Table 1.4). Although the OSR includes no benefit to gas collection for energy generation compared to flaring, landfill owners may have to decrease gas generation to maximize economic benefits associated with landfill gas-to-energy systems while still complying with the OSR. Alternatively, finding collaborative partners that can use landfill gas beneficially may provide additional incentives for a landfill owner to enhance waste decomposition. For example, Site E treats, compresses, and transports landfill gas to a local POTW via pipeline

2.9.4 Gas Prediction and Accounting

Gas yield and flow rate goals in the OSR currently focus on total gas generation (CH_4 + CO_2) and include an option to compare gas flow rates to a percentage of peak flow or to a target flow rate. The use of CH_4 in place of total gas to assess OSR goals may be more appropriate as CH_4 production can decrease before CO_2 production at the end of the decomposition cycle. Methane is a more important gas from a greenhouse gas perspective, is predicted directly within LandGEM, and CH_4 generation can be determined based on gas flow rate and composition.

A standard protocol to assess landfill gas decay rates and to account for collection efficiency is needed to ensure consistency. At present, compliance is assessed in various ways, and none of the operators are accounting for changes in landfill gas collection over time. Only three of the ten sites considered gas collection efficiency in their LandGEM modeling.

Criteria are also needed to define when a landfill operator can transition from active to passive gas collection (or no gas collection and control), which should occur earlier for landfills operating under the OSR. For example, a gas generation metric could be defined where the generation rate is low enough that CH_4 production can be managed by attenuation or oxidization in the cover or through a biofilter.

2.9.5 Other Impacts and Ancillary Benefits

The OSR was developed to reduce long-term risks associated with MSW landfills under the assumption that landfill stabilization is concomitant with organic stability. Strategies that promote landfill organic stability (e.g., organic waste diversion, pretreatment, in-situ landfill treatment, etc.) have benefits and impacts that are analyzed explicitly via the OSR, and externalities that are more difficult to quantify. For example, alternative treatment processes for diverted organic wastes (e.g., compositing, anaerobic digestion, etc.) consume or produce energy and create emissions, the impacts of which are not accounted for in organic stability analyses. Similarly, using a landfill for disposal of industrial wastewater can avoid additional energy consumption and emissions associated with transporting wastewater to a treatment plant, and these benefits are not accounted for in an analysis of the OSR. A more holistic assessment of environmental benefits and impacts associated with organic stability should be considered using life cycle analysis as illustrated in Levis and Barlaz (2011).

Actions undertaken to meet the OSR can have ancillary benefits. For example, Site L is permitted for a 10% waste overfill because the organic stability plan will enhance settlement and waste will settle back to allowable final grades within the regulated air-space volume. This increased revenue due to higher airspace utilization would have been more difficult to justify under conventional operations in the absence of the OSR.

CHAPTER 3: SUMMARY AND CONCLUSIONS

Ten landfills with approved organic stability plans were evaluated to assess the impact and effectiveness of Wisconsin's organic stability rule (OSR) five years after implementation, and to understand changes in waste management practice and landfill operations that could be attributed to the OSR. All ten landfills, which varied widely in characteristics and operations, complied with the OSR. Implementation of the OSR is resulting in more rapid waste decomposition with no apparent deleterious environmental impacts at the landfill.

Enhanced degradation of waste by addition of moisture was the primary strategy for compliance with the OSR for all ten landfills. Organic waste diversion was a small component, and was conducted under specific conditions to ensure the byproducts of compositing organic waste had attributes for commercial applications. Combustion of MSW in a refuse-derived fuel plant with landfilling of the ash was employed at one landfill to reduce the organic waste disposed, but the landfill is not credited for combustion of the organic fraction in their organic stability plan.

All of the landfill operators interviewed for this study indicated that the goals of the OSR coincide with industry goals. Operating a landfill in accordance with the OSR results in enhanced gas production for energy generation, increased waste settlement for air-space recovery, and waste stabilization expected to reduce long-term maintenance costs and environmental risks. Operating under the OSR can be advantageous as well. At one landfill, overfilling was possible under the organic stability plan, recognizing that waste settlement would increase with enhanced degradation and result in increased airspace utilization. Liquid waste was accepted for disposal to enhance in-situ anaerobic waste decomposition at eight of the ten landfills evaluated, while providing additional revenue without consuming airspace. Recirculation of leachate to enhance moisture content of the waste diminished as liquid waste disposal increased, largely because leachate treatment is less expensive than operating a recirculation system in Wisconsin.

Interviews with site owners and observations made during this review indicated that several practices could be revised to better support the OSR and the effectiveness of organic stability plans. The following recommendations are made.

1. Federal and state regulations should be modified to permit liquid waste disposal in MSW landfills that are implementing organic stability plans to comply with state regulations like Wisconsin's OSR, rather than relying on temporary RD&D permits. Experience in Wisconsin illustrated in this study has shown that liquid waste is a practical means to moisten MSW to enhance biodegradation, and that modern containment systems are capable of managing the additional liquid without impact to the environment.

2. Requirements are needed for early and aggressive gas collection in organic stability plans to ensure that greenhouse gas emissions and odors are minimized, especially for landfills disposing liquid wastes directly into the waste to enhance moisture content. Clarity is needed regarding when gas collection should and must begin.

3. Guidance should be developed regarding methods to evaluate biochemical compatibility of liquid wastes that are disposed directly into MSW landfills so that unintended consequences (e.g., adverse impact on the microbial community, unexpected abiotic reactions) are avoided. Incompatibility was not observed at any of the landfills in this study, but the potential exists for incompatibilities given the interest in attracting liquid wastes for disposal.

4. The larger volumes of landfill gas available earlier in the life of a landfill should be an attractive source of alternative energy. However, natural gas prices and complex relationships with electrical utilities have made beneficial use of landfill gas less attractive. Means to make beneficial use of landfill gas more attractive should be explored by regulatory agencies that create and promote regulations like Wisconsin's OSR.

5. The gas generation goals in the OSR should be modified to focus on methane instead of total gas generation and standardized procedures for gas prediction and analysis should be developed to ensure consistency across the industry in Wisconsin.

6. Metrics for cessation of gas collection should be incorporated into the OSR to aid the transition from active gas collection to a long-term passive system for managing landfill gas emissions.

7. The environmental impacts of organic stability plans extend beyond the landfill. A more holistic assessment of strategies to promote organic stability should be considered as part of the OSR and when developing organic stability plans. Life-cycle analysis can be a valuable tool to make this type of assessment.

CHAPTER 4: MATERIALS AND METHODS

The objective of this study was to provide an independent evaluation of WDNR's OSR. Data and information were collected via site visits, interviews with landfill owners, WDNR personnel, operators, and engineers, and review of annual reports submitted by landfill owners that included leachate and gas monitoring data.

Ten landfills were selected from a WDNR list of Wisconsin landfills with approved organic stability plans. Selection criteria required that landfills (i) had organic stability plans in place for at least one year so that the impact could be assessed, (ii) were geographically distributed throughout the state to the extent practical, (iii) represented both private and public ownership and operation, and (iv) had management personnel willing to work with the review team. In 2012, there were 66 active non-hazardous landfills in Wisconsin, of which 34 were MSW landfills. This study incorporated information from 10 of the 34 active MSW landfills in Wisconsin. These 10 landfills receive approximately 50% of Wisconsin's MSW.

4.1 Site Characterization

Characteristics of the ten landfills are summarized in Table 1.1. Nine of the ten landfills are privately owned. At each site, the landfill cells or areas included in the organic stability plan are expansions to existing disposal areas, range from 10.5 to 40 ha, and had an average waste disposal rate from 2008 to 2012 between 190 and 2760 Mg/d (1 Mg = 1000 kg). Although the majority of the sites are privately owned, the broad range of waste disposal rates provides a representative cross-section of Wisconsin landfills. Only a limited number of publically-owned landfills had organic stability plans in place.

Most of the sites had their organic stability plan in place by the end of 2007. Collectively, organic stability actions adopted at the study sites include leachate recirculation, liquid waste addition, delayed final cover placement to enhance infiltration into the waste, and organics diversion. Leachate recirculation was reported by all site owners to enhance in-situ waste decomposition and organic stability. Initiation of leachate recirculation at all privately-owned sites except Site A started prior to implementation of the organic stability plans. The one publically-owned landfill (Site F) reported initiation of leachate recirculation concurrent with implementation of their organic stability plan.

Every privately-owned site except Site A has been approved by WDNR for a RCRA Subtitle D Research, Development, and Demonstration (RD&D) permit (Table 1.1). An RD&D permit provides owners the flexibility to reduce run-on surface water control, add supplemental liquids other than leachate, and use alternative final cover designs to enhance waste moisture content (USEPA 2004). Approved operations under an initial RD&D permit are limited to a 3-yr period. Currently, six renewals of the RD&D permit can be obtained under US EPA regulations (USEPA 2016), culminating in a maximum period of 21 yr for RD&D actions.

The most common action implemented under RD&D permits for the landfills evaluated was the acceptance of commercial liquid wastes, with direct disposal into the landfill waste mass. In all cases, owners noted that this practice is economically and environmentally attractive due to revenue from tipping fees and the promotion of in-situ anaerobic waste decomposition that enhances stability and restores disposal capacity due to enhanced settlement. There were many considerations associated with the quantity of liquid waste accepted at a given landfill, including the mass of waste in-place to retain liquid, revenue associated with liquid waste acceptance, and costs associated with increased leachate management and treatment. The balance between liquid waste addition, leachate recirculation, leachate treatment, and enhanced waste moisture content

is discussed throughout this study. In several cases, owners had been accepting liquid waste prior to RD&D permits and were solidifying the liquids prior to disposal via mixing with solid wastes that have high moisture retention capacity (e.g., incinerator ash or saw dust). Direct disposal of these liquids to enhance organic decomposition reduced pre-treatment costs.

REFERENCES

Bareither, C. A., Benson, C. H., Barlaz, M. A., Edil, T. B., Tolaymat, T. M. (2010). Performance of North American bioreactor landfills: I. leachate hydrology and waste settlement, *Journal of Environmental Engineering*, 136(8), 824-838.

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.

Benson, C. H., Barlaz, M. A., Lane, D. T., and Rawe, J. M. (2007). Bioreactor landfills in North America: review of the state-of-the-practice, *Waste Management*, 27(1), 13-29.

Busch, J., Ahrens, L., Sturm, R., Ebinghaus, R. (2010). Polyfluoroalkyl compounds in landfill leachates, *Environmental Pollution*, 158, 1467-1471.

De la Cruz, F. B. and Barlaz, M. A. (2010). Estimation of waste component specific landfill decay rates using laboratory-scale decomposition data, *Environmental Science and Technology*, 44, 4722 – 28

Environmental Research and Education Foundation (2006). Performance-based system for post-closure care at municipal solid waste landfills: a procedure for providing long-term stewardship under RCRA Subtitle D. Prepared by Geosyntec Consultants for EREF, Alexandria, Virginia, September 2006.

FDEP (2016). *Guidance Document SWM-04.45: LTC at Solid Waste Disposal Facilities*, Florida Department of Environmental Protection, Bob Martinez Center, Tallahassee, FL, 20 Feb. 2016, www.dep.state.fl.us.

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.

Kelly, R.J., Shearer, B.D., Kim, J., Goldsmith, C.D., Hater, G.R., Novak, J.T. (2006). Relationships between analytical methods utilized as tools in the evaluation of landfill waste stability, *Waste Management*, 26, 1349–1356.

Kjeldsen, P.K., Barlaz, M.A., Rooker, A.P, Baun, A., Ledin, A., Christensen, T.H. (2002). Present and long term composition of MSW landfill leachate: A review, *Critical Reviews in Environmental Science and Technology*, 32, 297-336.

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.

Levis, J. and M. Barlaz (2011). What's the Most Environmentally Beneficial Way to Treat Commercial Food Waste" *Environ. Sci. and Tech*., 45(17), 7438–7444.

Morris, J.W.F., Crest, M., Barlaz, M. A., Spokas, K. A., Åkerman, A. and L. Yuan (2012). Improved Methodology to Assess Modification and Completion of Landfill Gas Management in the Aftercare Period, *Waste Management*, 32, 2364-2373.

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.

Prevedouros, K., Cousins, I.T., Buck, R.C., Korzeniowski, S.H. (2006). Sources, fate and transport of perfluorocarboxylates, *Environmental Science and Technology*, 40, 32-44.

Reinhart, D.R., Faour, A.A., and You, H. (2005). First-Order Kinetic Gas Generation Model Parameters for Wet Landfills. USEPA, Report No EPA-600/R-05/072, Washington, DC.

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

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 (2016) *Revision to the Research, Development and Demonstration Permits Rule for Municipal Solid Waste Landfill*s, EPA-HQ-RCRA-2015-0126, 81 FR 28720, Office of Land and Emergency Management, U.S. Environmental Protection Agency, Washington, DC.

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

WDNR (2005). Strategies for reducing degradable organic wastes in landfills, Rev. 12/16/05, Wisconsin Department of Natural Resources, Madison, WI, dnr.wi.gov/topic/Landfills/documents/stabilizationstrategies-rev.pdf.

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

APPENDIX 1 – Supplemental Tables for Research Study 1

Table A1.1. Summary of waste tonnage and management.

ID	Annual Waste Tonnage (Mg/yr)[a]	MSW Fraction (%)	Contribution of Total Wisconsin Waste (%)	Contribution of Total Wisconsin MSW (%)	Contribution of Out-of-State Waste (%)[b]	Contributing States	Notes
A	392,148	74.3	4.6	6.4	35 (13-62)	IL	Biopile system to treat petroleum-contaminated soils; treated soils used for daily cover
D	370,355	72.3	4.5	6.1	32 (31-40)	IA, MN, MI	Approximately 10% C&D waste; contaminated soils and auto shredder fluff for interim cover; small composting operation for pre-consumer food waste
E	516,767	47.4	6.2	5.3	—	—	Plan to expand composting facility to source-separated materials (e.g., farm crop residue, manure, other organics)
F	69,321	54.0	0.94	0.83	12 (4.5-20)	IA, MN	Foundry sand, RDF bottom ash, and street sweepings for ADC
G	1,007,180	62.8	12.2	14.5	0.02 (0.0-0.06)	IL, IN, IA, MN, MI, other	—
I	269,667	47.8	3.5	3.2	—	—	Dredged sediments not monofilled, mixed in with waste; geotextile tarps for daily cover
J	232,605	45.3	2.0	1.7	0.17 (0.0-0.4)	IA, MN, MI, other	OSR approved in 2007, waste filling in Southern Expansion initiated in 2009
K	334,933	64.2	4.6	5.5	0.53 (0.0-1.5)	IL, IN, IA	—
L	336,745	68.7	4.1	5.4	7.2 (6.5-7.7)	IL, IA	Facilities include 15,300-m^3 composting facility for yard waste with potential to accept food waste
M	120,001	65.1	1.4	1.7	7.0 (0.3-20)	MN, MI	Increase in % MSW from 64 to 85 % from 2008 to 2013
All Sites	3,639,975	62.1	44.0	50.6	8.9 (4.5-13.2)	IL, IN, IA, MN, MI, other	—
WI	8,319,958	53.7	100	100	10.7 (4.4-17.6)	IL, IN, IA, MN, MI, other	—

[a] Average disposal for years 2007-2012.

[b] Computed as percent of annual waste disposal; average listed and range in parentheses for 2007-2012.

Table A1.2. Summary of liquid operations, application methods, types of liquid wastes, and off-site leachate treatment.

ID	Operational Notes	Liquid Application Methods	Types of Commercial Liquid	Off-Site Leachate Treatment Method
A	—	—	—	NA
D	Leachate generation and recirculation volumes for active area; all recirculation in active area; leachate from closed area added to active area as supplemental liquid under RD&D permit	French drains; surface application	Cleaning water from glue & paint facilities; corn syrup	NA
E	Reduced leachate recirculation in 2009 due to decreasing organic waste and elevated NH_3-N levels in leachate; increased liquid waste disposal. Leachate volumes prior to 2009 may be high due to in-line flow meter issues.	Surface application; infiltration trenches; vertical wells	General commercial wastes; haul vehicle cleanout water; storm water; gas condensate; dredged materials;	Direct connection to local POTW
F	Leachate only added in 2012	Tank truck and surface application	Does not accept third-party liquids	NA
G	No leachate recirculated during 2009-2012	Horizontal & vertical injection; surface application	Soap residual; food waste residues; general commercial wastes	Direct connection to local POTW
I	Leachate recirculation during 2008-2011, switched to all liquid waste addition in 2012	Horizontal & vertical injection; surface application	Automobile wash water; industrial process sludge	Direct connection to local POTW
J	Limited data on recirculation and liquid addition	Horizontal injection; recirculation pads; surface application	General commercial wastes	Transported via tanker truck
K	Discontinued leachate recirculation in 2007, prefer liquid waste addition; Leachate collection not reported during 2010-2012	Horizontal injection; surface application	Liquid-containing food wastes; industrial wastes; sludge	Direct connection to local POTW
L	All liquids added in South Expansion. Reduced leachate recirculation volumes (e.g., 2012) may partly be due to flow meter modifications.	Horizontal injection; surface application; leachate vaults	POTW sludge; industrial wastewater; hydrovac loads from hydro-excavations	Transported via tanker truck
M	Leachate recirculation prior to 2010 and only liquid waste addition during 2010-2012; liquid wastes accepted prior to 2010 were solidified	Horizontal injection; surface application	Special liquids; scrubber waste; wash-pad water; recovery waste; herbicide rinse water; sump sludge	Transported via tanker truck

NA = not available

RESEARCH STUDY 2: PHASE-BASED ANALYSIS TO DETERMINE FIRST-ORDER DECAY RATES FOR A BIOREACTOR LANDFILL

CHAPTER 1: INTRODUCTION

Landfills are the predominant means for municipal solid waste (MSW) disposal in the U.S. and many parts of the world (Hao et al. 2008; Tolaymat et al. 2010). Stabilization of the organic fraction of MSW, i.e., organic stability, is defined as a state of near complete decomposition of organic waste such that human health, environmental, and financial risks associated with undecomposed wastes are reduced (Bareither et al. 2017). The organic fraction of MSW in landfills decomposes via microbially-mediated biodegradation that produces leachate and landfill gas (Faour et al. 2007). Landfill gas (LFG) generated from this biodegradation process consists primarily of methane (CH_4) and carbon dioxide (CO_2) (Tchobanoglous et al. 1993). As a result, landfills are a major source of anthropogenic CH_4 emissions, which has a global warming potential 28 times that of CO_2 (Mou et al. 2015).

Conventionally, landfills are filled in phases, which are delineated areas of the landfill where waste is placed. Landfills include engineered barrier systems (i.e., liners and covers), which mitigate subsurface contamination and fugitive gas emissions. The use of cover systems can result in slow degradation of organic waste due to reduced availability of liquid required for anaerobic decomposition, which results in conventional landfills serving as storage systems for relatively undecomposed waste. However, managing landfills as bioreactors can promote enhanced waste decomposition, in situ leachate treatment, increased landfill settlement, and reduced post-closure care (Reinhart and Al-Yousfi 1996; DeAbreu 2003; Bareither et al. 2010; Townsend et al. 2015; Bareither et al. 2017).

Bioreactor landfills are operated to control, and ideally optimize, waste stabilization rather than simply contain waste as prescribed by conventional regulations (Reinhart et al. 2002; Townsend et al. 2015). In anaerobic bioreactor landfills, moisture is added to the waste to create environmental conditions required for waste biodegradation. Moisture is commonly added via leachate recirculation and liquid waste disposal, which accelerates waste stabilization, promotes in-situ leachate management / treatment, and enhances the rate of gas production. Enhanced LFG generation as a result of moisture addition can have different consequences on landfill operations as well as meeting the prescribed regulations for organic stability and post-closure care. Hence, there is a need to estimate LFG generation, particularly in bioreactor landfills that are operated to enhance LFG (Faour et al. 2007; Mou et al. 2015; Bareither et al. 2017). Additionally, the presence of distinct phases in landfills that are operated with different moisture enhancement strategies suggests that phase-specific LFG predictions are needed to more appropriately assess landfill performance.

Landfill gas generation and emissions are commonly estimated with first-order decay (FOD) models (Mou et al. 2015). In the U.S., the U.S. Environmental Protection Agency's (EPA) Landfill Gas Emission Model (LandGEM) is the industry standard used to assess landfill emissions and assist landfill operators with energy recovery projects (US EPA 2005; Tolaymat et al. 2010; Townsend et al. 2015). LandGEM is based on a FOD equation to predict CH_4 generation. The main input variables for LandGEM are the mass of MSW, first-order rate coefficient (k), and potential CH_4 generation capacity (L_0).

The mass of MSW disposed in a landfill is an important variable in LandGEM because the mass controls the quantity of substrate available for CH_4 generation.

Generally, landfill operators record the total mass of waste disposed in the entire landfill, and are less concerned with recording the mass of waste placed in specific phases. The unavailability of phase-specific waste disposal data can result in difficulties when attempting to model gas generation in specific phases due to inaccurate allocation of waste mass in each phase.

Landfills are heterogeneous systems with spatial and temporal variation in waste composition, moisture content, and temperature. Hence, CH_4 emissions from landfills can also exhibit temporal and spatial variability (Abichou et al. 2011). Recommendations for modeling gas generation in conventional MSW landfills using LandGEM include a default k = 0.04 1/yr and L_0 = 100 m^3-CH_4/Mg-MSW. However, k varies as a function of operational and climatic conditions and L_0 varies as a function of waste composition (Faour et al. 2007; Staley and Barlaz 2009; Barlaz et al. 2010). Previous studies have estimated k and L_0 for entire landfills that have operational strategies ranging from conventional to bioreactor (Faour et al. 2007; Barlaz et al. 2009; Amini et al. 2012; Wang et al. 2013); however, few studies have evaluated LFG generation in specific phases within a given landfill that have different operational strategies (Tolaymat et al. 2010). Furthermore, a recent Organic Stability Rule promulgated by the Wisconsin Department of Natural Resources in the state of Wisconsin stipulates requirements for organic stability assessments that can vary between landfill phases depending on waste age and percent filling (Bareither et al. 2017). Thus, there is a need to develop a phase-specific LFG methodology that incorporates phase-specific assessments of waste disposal, LFG collection, and LFG prediction to yield more accurate estimates of organic waste decomposition and stabilization.

The objective of this study was to develop a methodology for conducting phase-specific LFG analyses. This methodology incorporated estimations of waste disposal in landfill phases, which were coupled with phase-specific LFG collection data to estimate phase-specific first-order decay rates. A full-scale landfill operated in the state of Wisconsin under the Organic Stability Rule, herein named Landfill T, was used in this study to develop and assess the phase-specific LFG assessment methodology.

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

1. Developed and implemented a waste disposal estimation technique based on digital analysis of computer-aided design (CAD) drawings for phases of Landfill T;
2. Developed a procedure for evaluating landfill gas generation data to be used for gas modeling; and
3. Applied the U.S. EPA LandGEM to predict LFG generation in specific phases and the entire site of Landfill T to yield optimized first-order decay rates.

CHAPTER 2: RESULTS AND DISCUSSION

2.1 Summary of Model Simulations

Temporal relationships of adjusted CH_4 flow rates and gas model simulations for the site-wide and phase-specific analyses are shown in Figs. 2.1 through 2.8. A summary of optimized *k* for all gas analyses conducted is shown in Fig. 2.9 and tabulated in Table 2.1. The summary in Table 2.1 includes the coefficient of determination (R^2) computed for each model simulation. The Site-Wide analysis yielded *k* ranging between 0.093 and 0.104 1/yr. The optimized *k* values for the site-wide analysis were higher than the default AP-42 *k* value for conventional landfills (0.04 1/yr), which reflects an increase in the rate of organic waste decomposition via leachate recirculation and supplemental liquid addition. The site-wide CH_4 model simulations had R^2 ranging from 0.42 to 0.68. Considering that there was available data from the landfill operators for MSW disposed in the entire landfill, there was no error attributed to inaccurate waste masses in the site-wide gas model.

A second site-wide analysis (Site-Wide 2) was conducted that disregarded data from the two oldest phases, Phase 1A & 2A and Phase 1B & 2B. These two phases had lag times of 5.2 yr and 4.2 yr, respectively, between initial waste placement and gas collection. Also, there was no liquid addition in Phase 1A & 2A and Phase 1B & 2B received minimal liquid. The Site-Wide 2 analysis was conducted to exclude older data and evaluate the impact of liquid addition on gas generation across the landfill that experienced moisture enhancement. The Site-Wide 2 analysis yielded lower *k*s than the Site Wide 1 analysis with decay rates ranging between 0.076 and 0.080 1/yr. This difference was attributed to the discrepancy between high CH_4 flow rates for Phase 1A & 2A versus the CH_4 flow rates predicted with LandGEM (Fig. 2.3). The authors believe a fraction of MSW disposed in Phase 1A & 2A may not have been accounted for, which resulted in an under prediction of CH_4 flow rates. Thus, removing the CH_4 flow rates for Phase 1A & 2A from the site-wide analysis in Site-Wide 2 resulted in a lower overall k = 0.078 1/yr.

Monthly and annual CH_4 flow rate simulations for Phase 1A & 2A and Phase 1B & 2B are shown in Figs. 2.3 and 2.4, respectively. The *k*s for Phase 1A & 2A ranged between 0.108 and 0.113 1/yr, whereas the *k*s for Phase 1B and 2B ranged between 0.116 and 0.129 1/yr (Table 2.1). These *k* values are considerably higher compared to *k*s for the site-wide analyses as well as *k*s for the Phases 3 & 4, 5, 6, and 7, which ranged between 0.024 and 0.156 1/yr (Table 2.1). The reason for the high *k* values in Phase 1A & 2A and Phase 1B & 2B was believed to be the low mass of waste allocated to these phases; particularly Phase 1A & 2A. There were no CAD files available from 1995 to 2002, which was the primary period of active waste disposal in these phases (Table 2.3). As previously discussed, a waste filling log was used to allocate waste tonnages disposed in these phases. Although Wang et al. (2013) reported that landfill phases with older waste tend to have higher *k* values, the possibility of low waste masses coupled with the high predicted CH_4 flow rates (Fig. 2.3), rendered gas modeling results from Phase 1A & 2A and Phase 1B & 2B questionable. Thus, these phases were not considered in the subsequent discussion on the influence of moisture addition on CH_4 generation at Landfill T.

The LandGEM simulations for Phase 3 & 4 (Fig. 2.5), Phase 5 (Fig. 2.6), and Phase 6 (Fig. 2.7) all show reasonable representations of CH_4 flow rates in Landfill T. The corresponding *k* values for these simulations increased from Phase 3 & 4 (0.037 to 0.044 1/yr) to Phase 5 (0.081 to 0.118 1/yr) to Phase 6 (0.120 to 0.156 1/yr). The optimized *k* for Phase 3 & 4 is comparable to the AP-42 default (0.04 1/yr) for

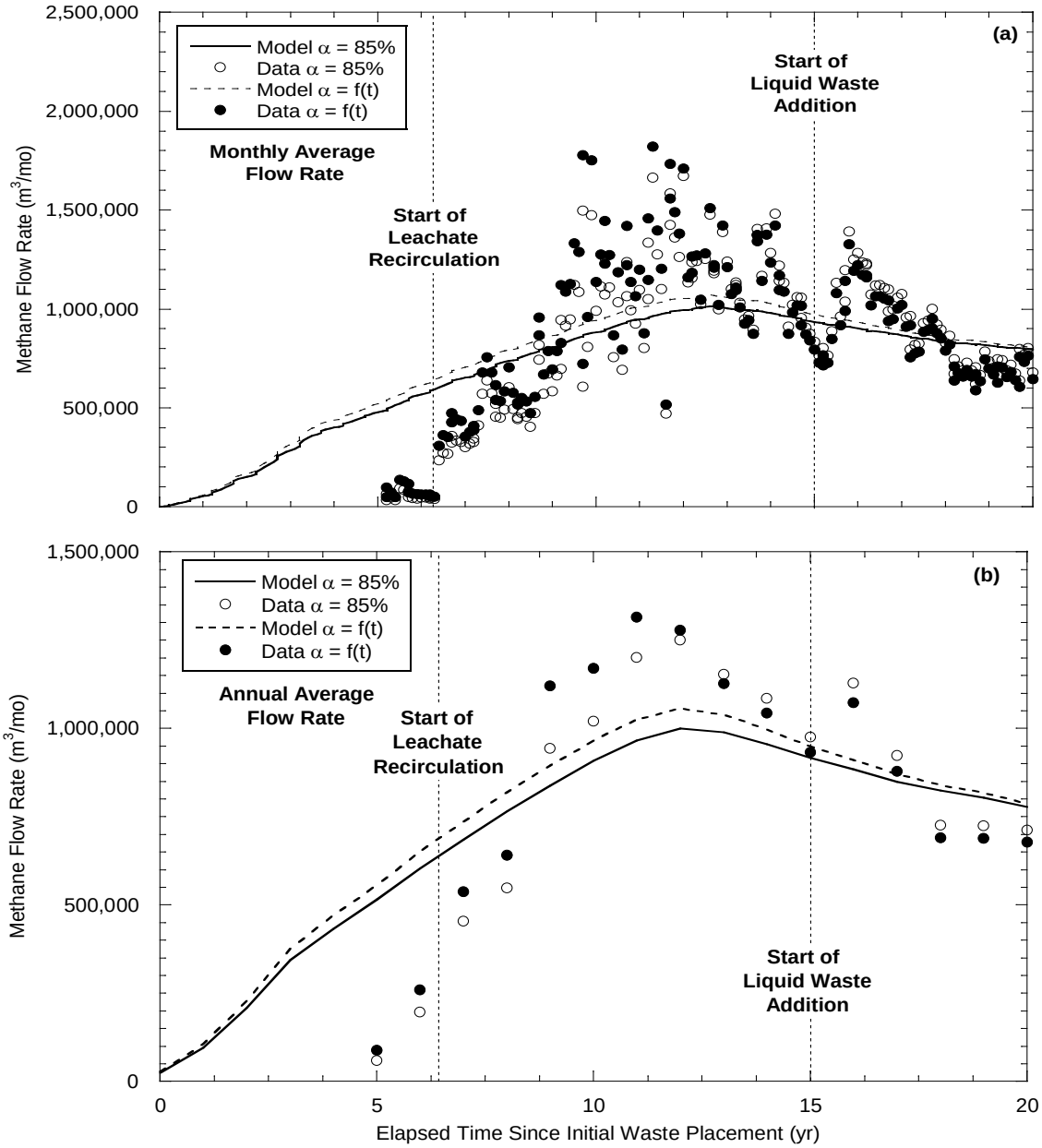

Fig. 2.1. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for the entire landfill (i.e., site-wide analysis). LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

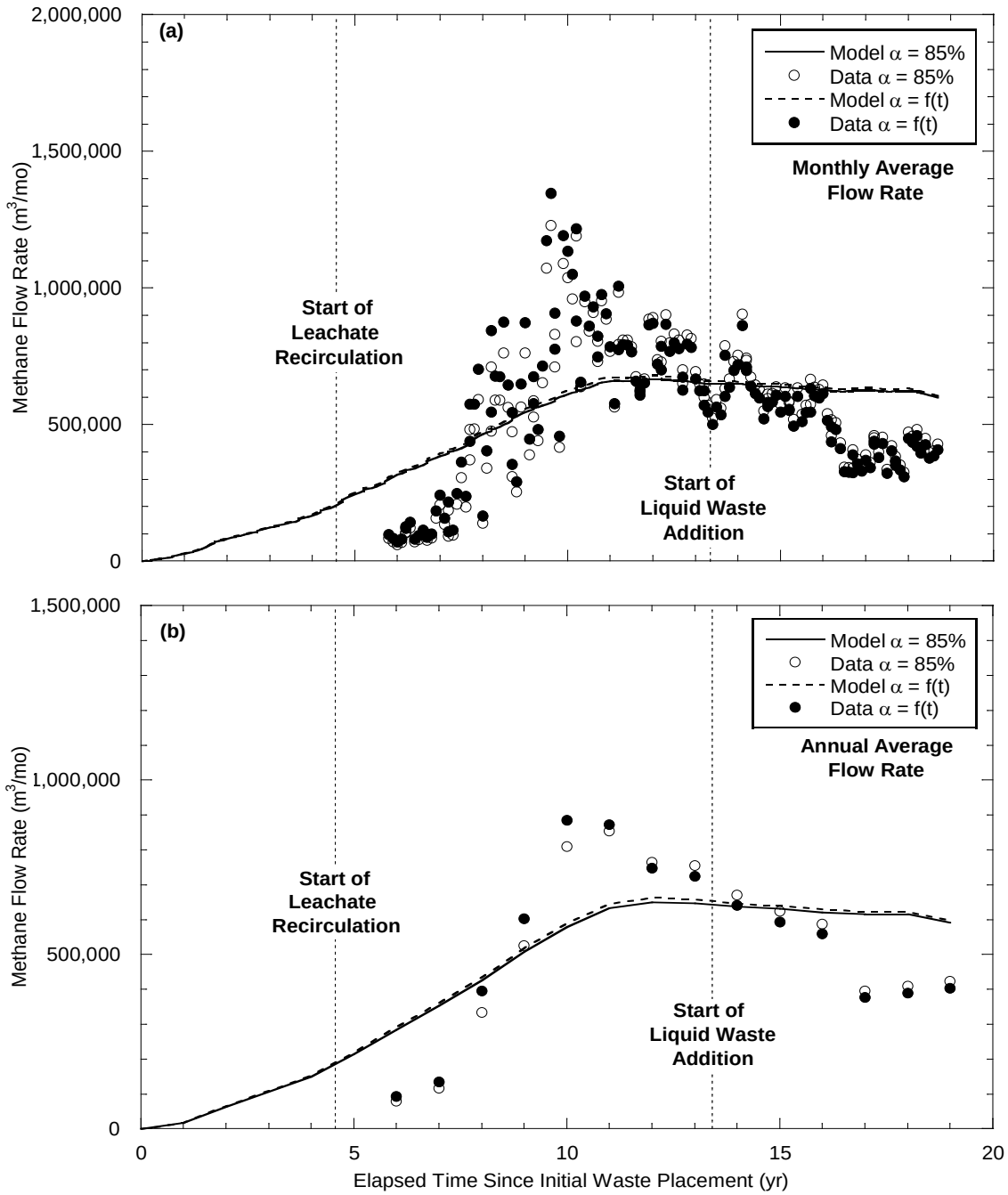

Fig. 2.2. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for a site-wide analysis excluding Phase 1A & 2A and Phase 1B & 2B. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

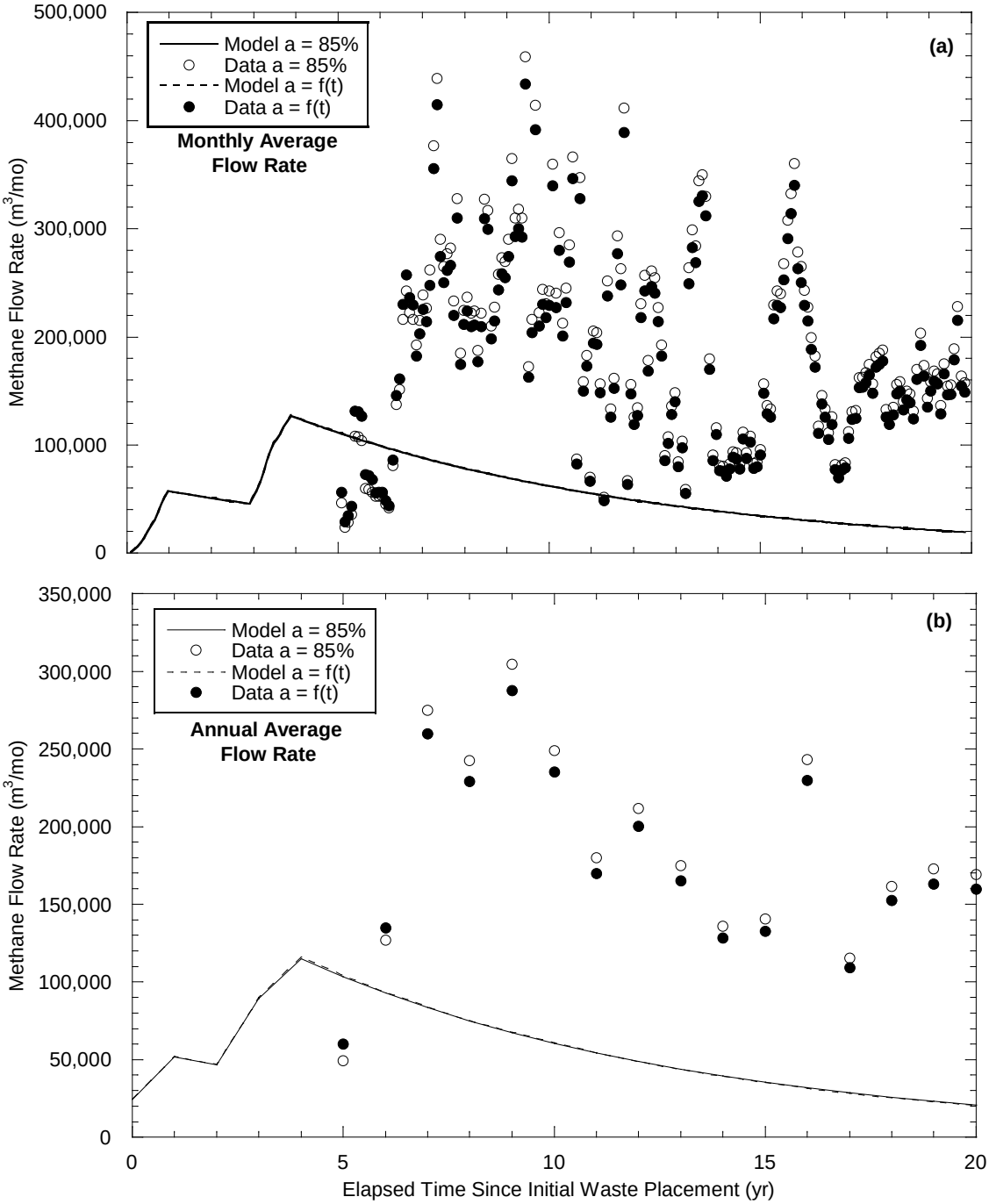

Fig. 2.3. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 1A & 2A. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

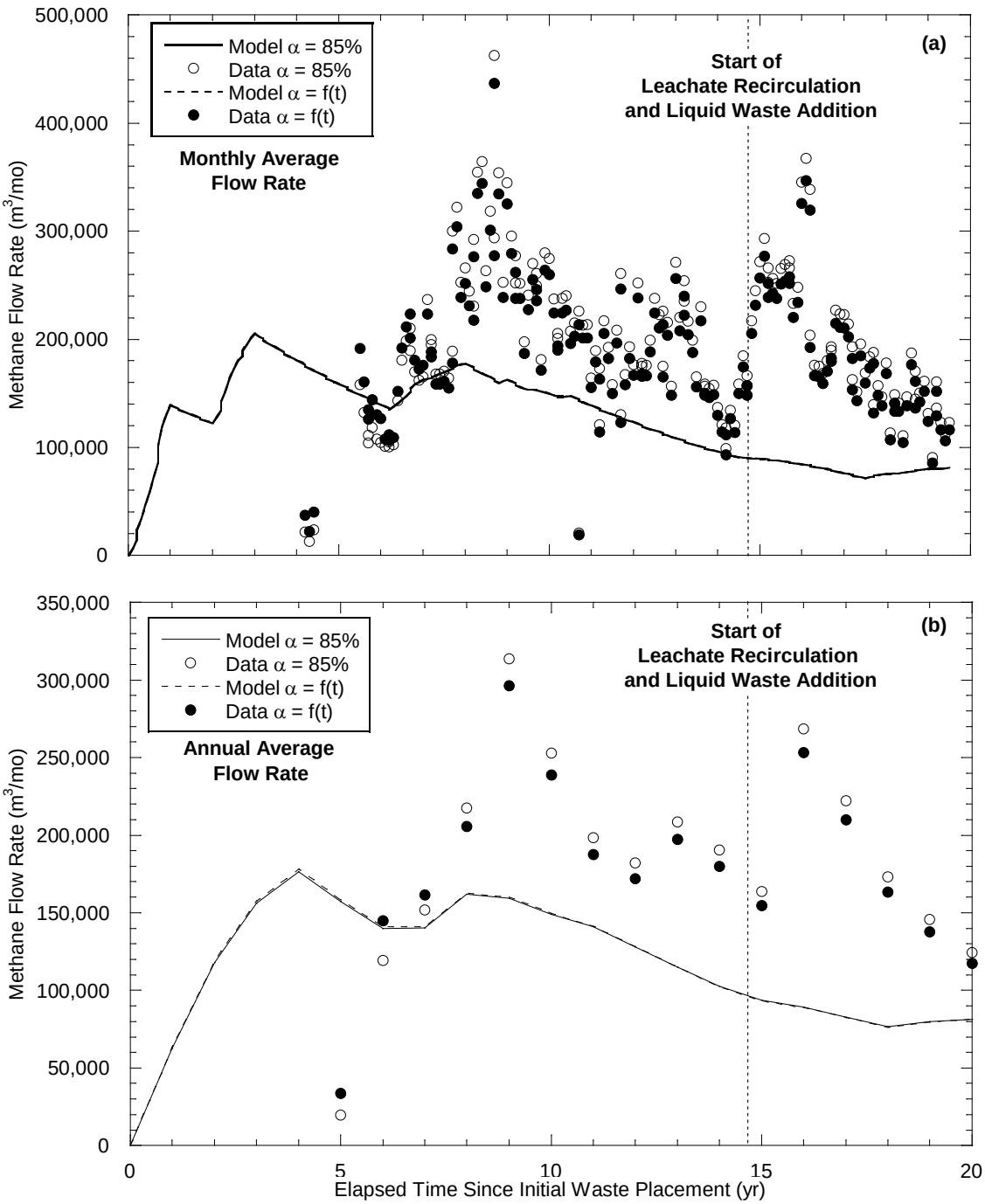

Fig. 2.4. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 1B & 2B. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

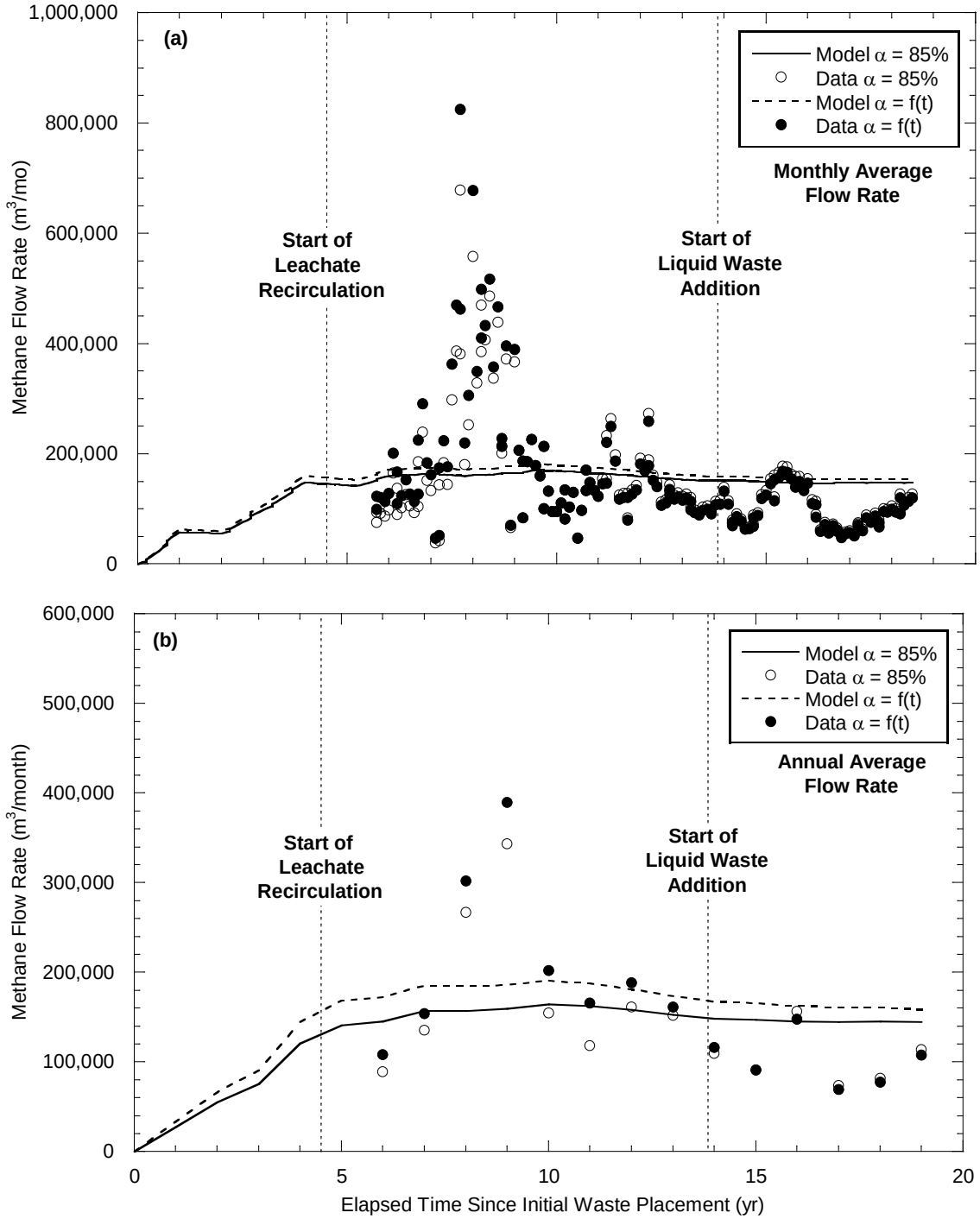

Fig. 2.5. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 3 & 4. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

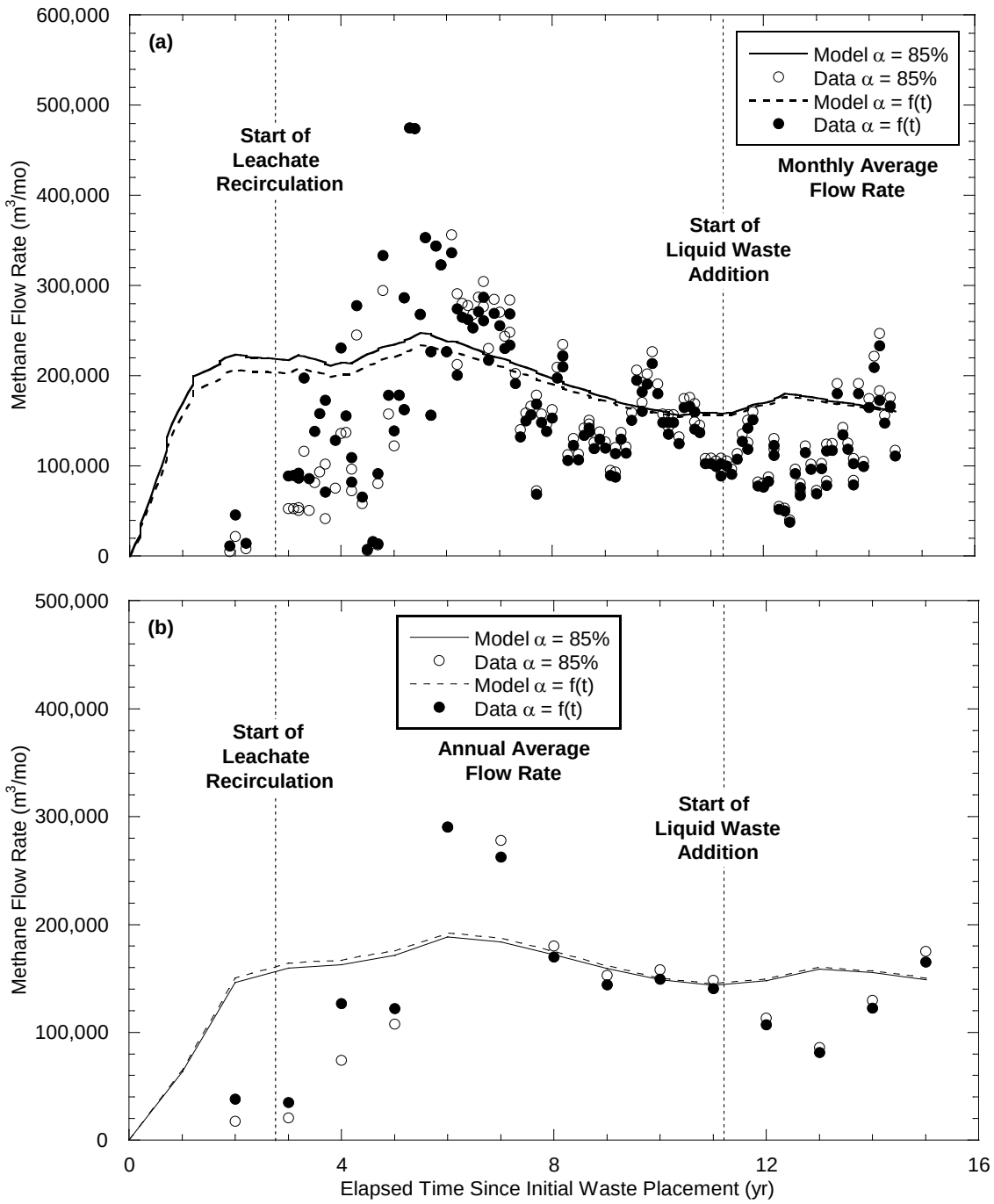

Fig. 2.6. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 5. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

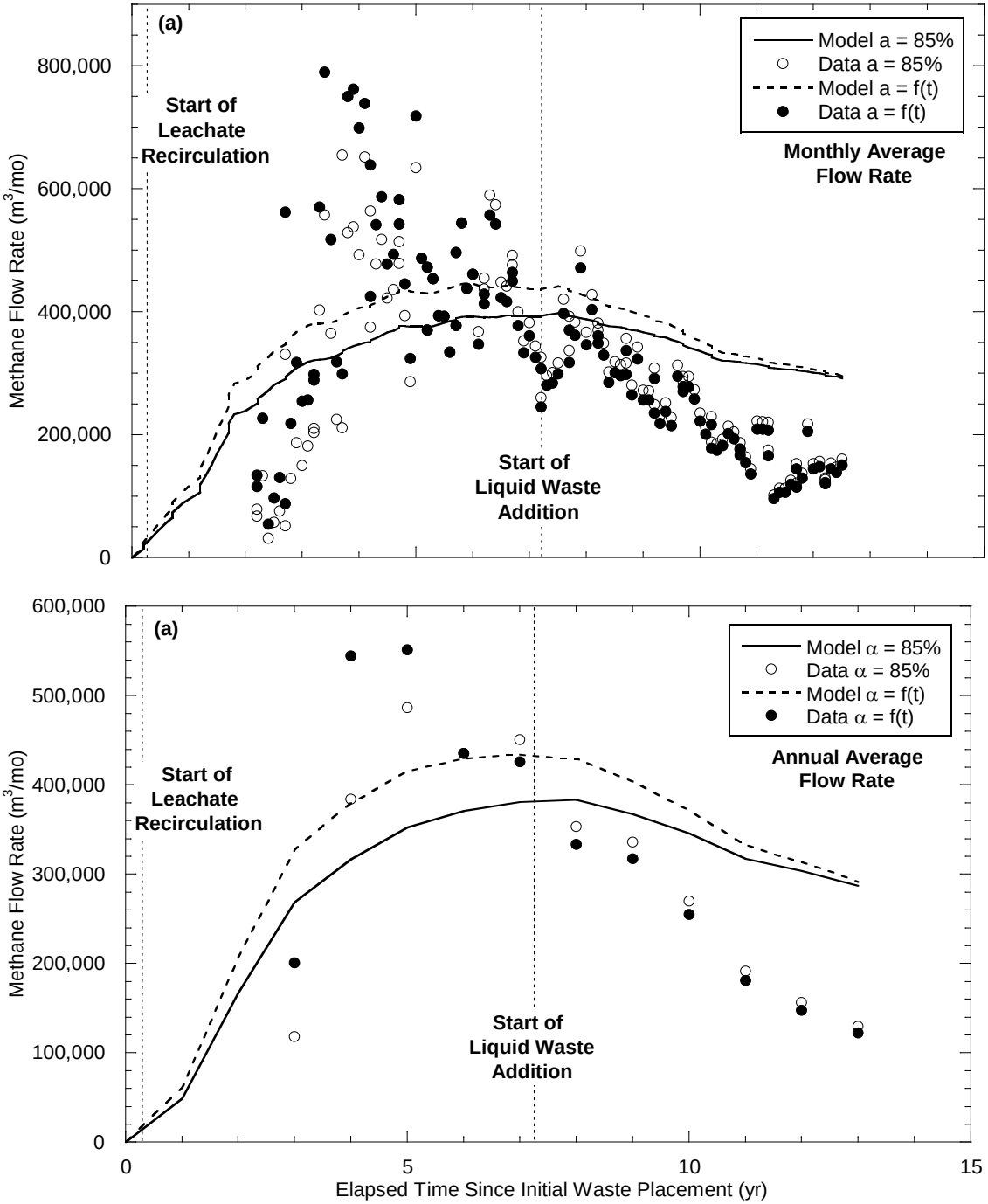

Fig. 2.7. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 6. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

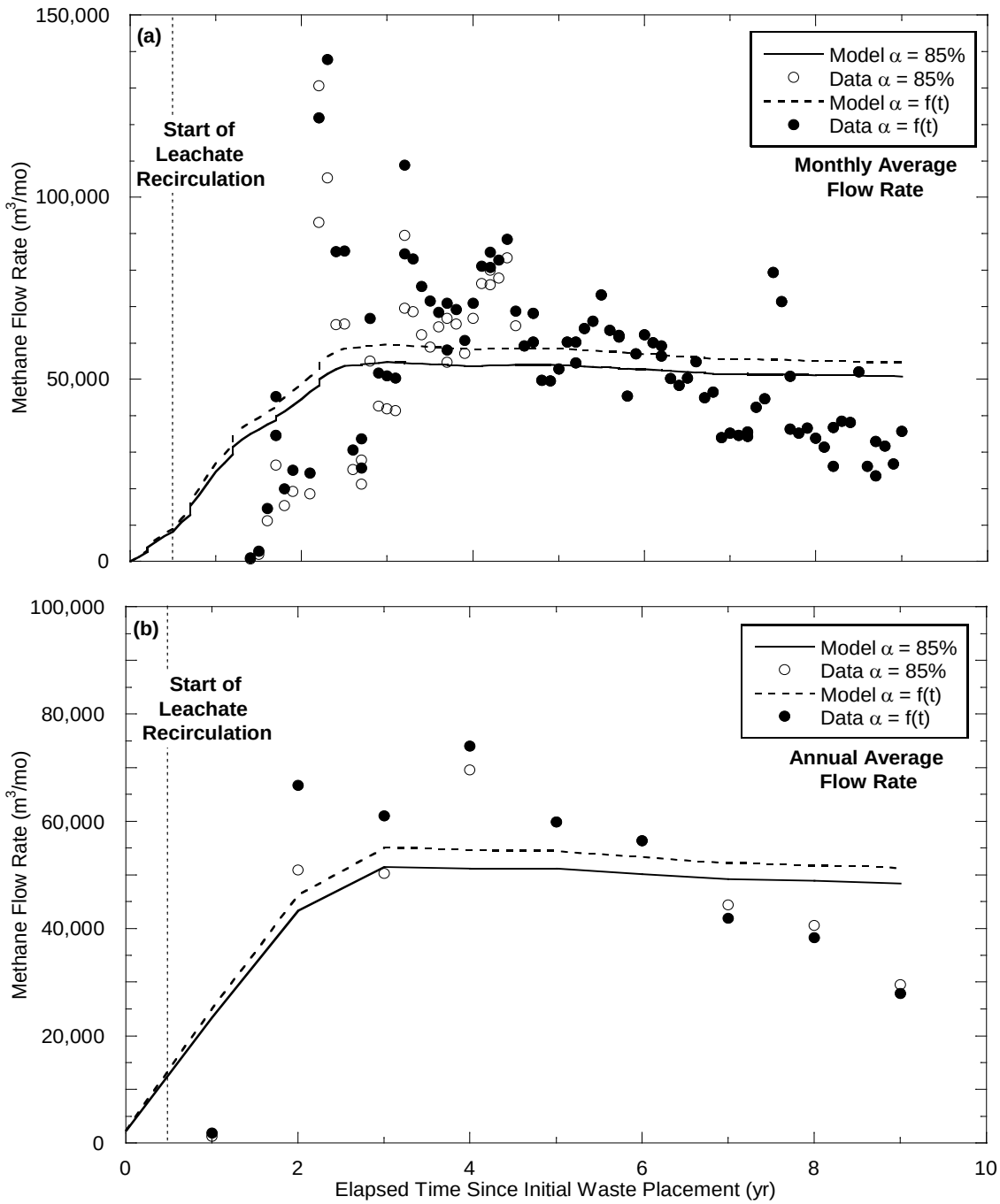

Fig. 2.8. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 7. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

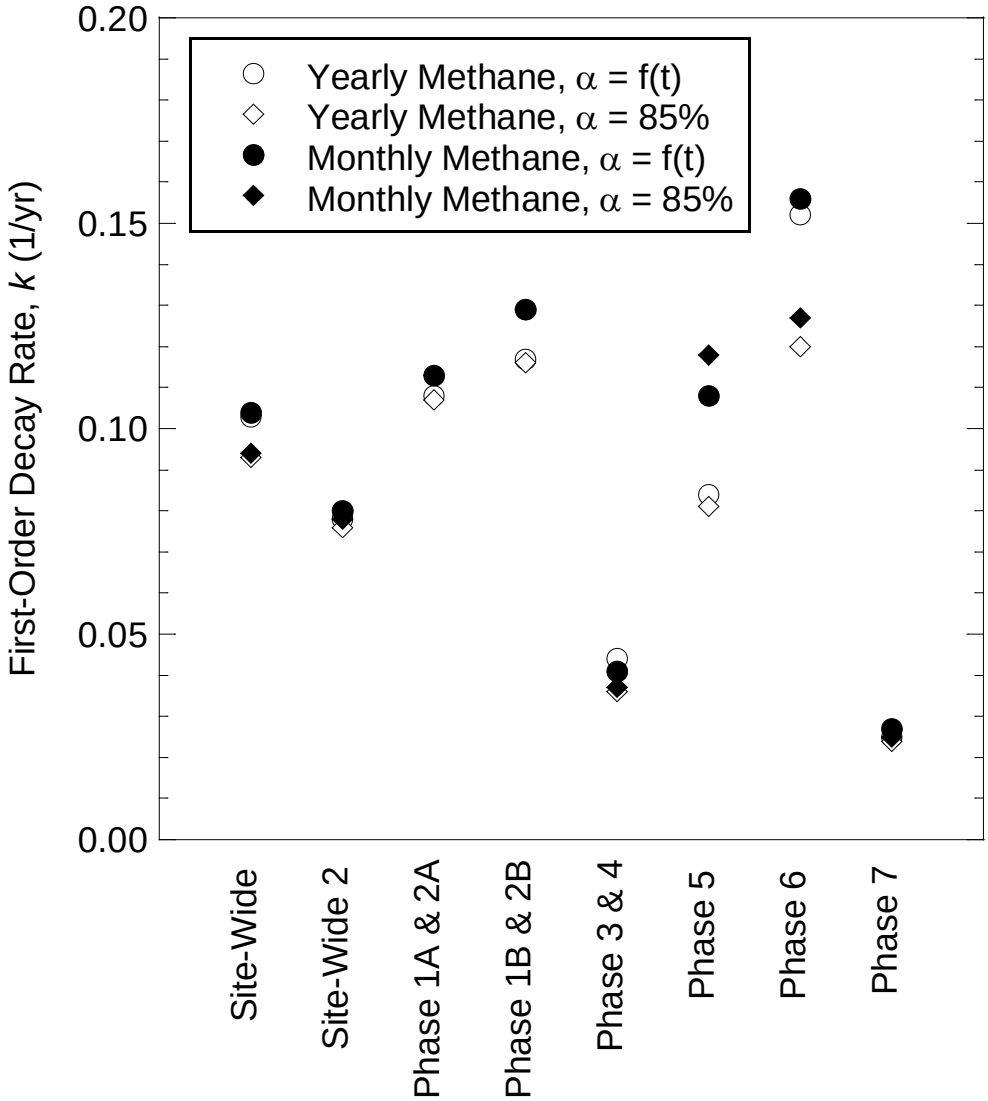

Fig. 2.9. Graphical summary of optimized first-order decay rates for all gas analyses.

Table 2.1. Optimized decay rates (k) for site-wide and phase-specific analyses using temporally varying and constant collection efficiencies.

Analysis	Parameter	Annual Methane, α = f(t)	Annual Methane, α = 85%	Monthly Methane, α = f(t)	Monthly Methane, α = 85%
Site-Wide	*k* (1/yr)	0.103	0.093	0.104	0.094
	R^2	0.60	0.61	0.48	0.50
Site-Wide 2 [a]	*k* (1/yr)	0.078	0.076	0.080	0.078
	R^2	0.47	0.54	0.32	0.40
Phase 1A & 2A	*k* (1/yr)	0.108	0.107	0.113	0.113
	R^2	-4.66	-4.39	-2.61	-2.68
Phase 1B & 2B	*k* (1/yr)	0.117	0.116	0.129	0.129
	R^2	-1.23	-1.17	-1.27	-1.33
Phase 3 & 4	*k* (1/yr)	0.044	0.036	0.041	0.037
	R^2	0.15	0.09	0.05	0.04
Phase 5	*k* (1/yr)	0.084	0.081	0.108	0.118
	R^2	0.28	0.22	0.27	0.29
Phase 6	*k* (1/yr)	0.152	0.120	0.156	0.127
	R^2	0.25	0.32	0.20	0.25
Phase 7	*k* (1/yr)	0.025	0.024	0.027	0.025
	R^2	0.45	0.54	0.12	0.16

[a] Excludes data from Phase 1A & 2A and Phase 1B & 2B

conventional landfills, whereas *k* for Phases 5 and 6 are more representative of bioreactor landfills (Barlaz et al. 2010; Wang et al. 2013).

Temporal trends of adjusted CH_4 flow rates and LandGEM simulations for Phase 5 are shown in Fig. 2.6. Increased gas generation in Phase 5 that corresponded to *k* ranging from 0.081 to 0.118 1/yr were attributed to moisture enhancement strategies employed in this phase. The LandGEM simulations in Fig. 2.6 accurately capture the temporal fluctuations in CH_4 collection, which supports the LandGEM methodology used in this study. Similarly, the CH_4 flow rates and LandGEM simulations for Phase 6 (Fig. 2.7) demonstrate the effectiveness of capturing both the increase and decrease in CH_4 flow rate that corresponds to theoretical anaerobic waste decomposition process.

The LandGEM simulations for Phase 6 also demonstrate disconnect between the temporal processes of waste decomposition, predicted CH_4 generation, and LFG collection. For example, the LandGEM equation (Eq. 1.1) predicts CH_4 generation immediately upon placement of waste in a given month, which corresponds to the model simulation shown in Fig. 2.7 that starts at the origin. However, CH_4 was not collected until Year 2. Thus, a shift in the entire LandGEM simulation that corresponds to a lag-time between waste placement and the onset of CH_4 generation can improve the R^2 for the model simulation and also lead to higher predicted *k* (Mantell 2016). This shift in the LandGEM equation via including a lag-time is not common practice, but may need to be considered in the future to improve the physical and statistical significance of LandGEM simulations.

The final phase-specific LFG assessment was for Phase 7, which is shown in Fig. 2.8. Phase 7 yielded the lowest optimized *k* ranging from 0.024 to 0.025 1/yr. These low *k* values were attributed to Phase 7 having the youngest waste and limited leachate recirculation.

2.2 Gas Model Evaluation

Comparison between monthly and annual optimized *k* values is shown in Fig. 2.10a. The data in Fig. 2.10a plot on or close to the 1:1 line, indicating that *k* values obtained from monthly and annual average CH_4 flow rates were comparable. A slight bias towards higher *k* for monthly analyses was observed in Fig. 2.10a since these monthly analyses included higher flow rates relative to the annual analyses. The monthly CH_4 flow rate analysis is recommended relative to the annual analysis as the monthly LFG analysis is easier to implement in LandGEM since waste disposal and gas collection data are typically collected and reported on a monthly basis. Additionally, higher *k* values from monthly analyses can lead to more appropriate representations of enhanced waste decomposition and gas generation commonly associated with bioreactor landfills.

Comparison of *k* values determined from the monthly CH_4 flow rates analyses that considered $\alpha = 85\%$ and $\alpha = f(t)$ are shown in Fig. 2.10b. Decay rates in Fig. 2.10b plot on or close to the 1:1 line, which indicates negligible difference between *k* calculated with $\alpha = f(t)$ versus *k* computed with $\alpha = 85\%$. The $\alpha = f(t)$ method was adopted in this study as an attempt to reflect landfill operations, which led to higher CH_4 predictions early in the LandGEM simulations that modestly increased *k* compared to $\alpha = 85\%$. However, there is no standardized or repeatable method for implementing $\alpha = f(t)$ since the actual collection efficiency will vary with landfill operations and practices. In contrast, the constant $\alpha = 85\%$ approach is straight-forward and leads to a slightly more conservative gas generation simulation. The analyses conducted in this study and other CH_4 modeling studies (Wang et al. 2013, 2015) support the use of a constant $\alpha = 85\%$ for LFG modeling.

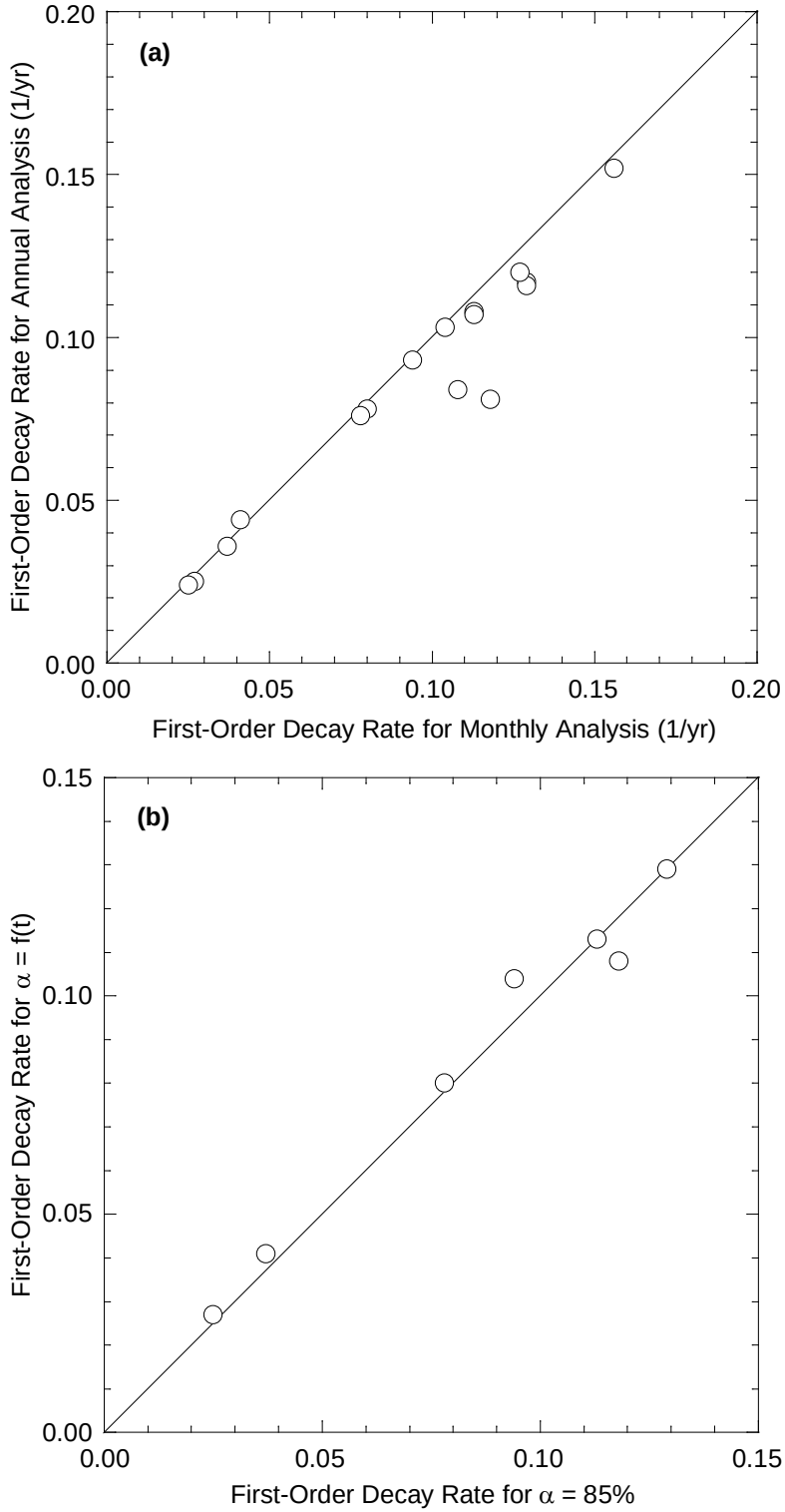

Fig. 2.10. Comparison between (a) optimized first-order decay rates from annual versus monthly methane flow rate analyses (b) optimized first-order decay rates determined from the monthly CH_4 flow rates analyses that considered α = 85% and α = f(t)

The phase-specific waste disposal assessment using CAD improved the distribution of waste among landfill phases relative to an alternative analysis where landfill phases were assumed to be filled individually and completely before moving to the subsequent phase (Mantell 2016). The LandGEM simulations completed for the phase-specific analyses in this study improved the statistical significance of the model (i.e., R^2) relative to the analyses conducted by Mantell 2016. Thus, the most appropriate LandGEM analyses were conducted for Phases 3 & 4, Phase 5, Phase 6, and Phase 7. These analyses accounted for all LFG collected and MSW was distributed among the phases based on CAD analysis.

2.3 Influence of Liquid Addition on Gas Generation

Relationships between *k* versus liquid addition per waste mass and wet weight water content are shown in Fig. 2.11. The optimized *k*s in Fig. 2.11 are representative of the monthly average CH_4 flow rate analyses with α = 85%. Furthermore, the *k*s plotted in Fig. 2.11 are for phase-specific analyses completed for Phase 3 & 4, Phase 5, Phase 6, and Phase 7. These phases included leachate recirculation and liquid waste addition throughout the majority of operation for each phase and can be used to compare the effects of moisture enhancement on LFG generation and waste decomposition. In general, as the amount of liquid addition per waste mass increased there was an increase in *k*. The relationship between *k* and wet weight water content also reflects the same positive trend. These trends indicate that there was enhanced LFG generation and waste decomposition in phases with more aggressive moisture enhancement strategies.

Approximately 73% of the total liquid addition in Landfill T occurred in Phases 5 and 6. However, the two phases had different liquid addition strategies. Temporal trends of leachate recirculation per MSW placed, liquid waste addition per MSW placed, and cumulative liquid addition per MSW placed in Phases 5 and 6 are shown in Fig 2.12. A shorter duration leachate recirculation approach was conducted in Phase 5 that initiated approximately 2 yr after initial waste placement (Fig. 2.12a). The onset of liquid waste addition in Phase 5 was more than 5 yr after then end of leachate recirculation. In contrast, leachate recirculation was implemented early in Phase 6 (0.3 yr, Table 2.4) and transitioned seamlessly into the start of liquid waste addition in Year 7 (Fig. 2.12a, b). Furthermore, leachate recirculation in Phase 6 started with larger dose volume per MSW mass that tapered to approximately three years of steady liquid addition (i.e., Years 2-4, Fig. 2.12a). Despite the varying moisture enhancement strategies in Phase 5 and Phase 6, these phases had comparable cumulative liquid addition per waste mass (Fig. 2.12c).

Temporal trends of CH_4 flow rates and cumulative CH_4 generation per MSW placed in Phases 3 & 4, 5, 6, and 7 are shown in Fig. 2.13. The leachate recirculation scheme in Phase 6 had a more pronounced effect on CH_4 generation at the onset of LFG collection, as shown by the higher CH_4 flow rates between Years 2-5 in Phase 6 compared to Phase 5. The low initial methane flow rates at the start of LFG collection in Phase 5 can be attributed to the absence of liquid addition until 2.8 yr after waste placement began (Fig. 2.13b). Similar effects of leachate recirculation on CH_4 flow rates can be observed in Phase 3 & 4 and Phase 7, whereby the methane flow rate peaked following the onset of leachate recirculation (Fig. 2.13a). The cumulative CH_4 generation curves for all four phases in Fig. 2.13c shows increased cumulative CH_4 for Phase 5 and Phase 6 that received more moisture and had higher *k* values.

The moisture enhancement techniques in Phase 6 included (i) early, aggressive leachate recirculation after waste placement initiated, (ii) a preference for leachate recirculation over liquid waste addition, and (iii) continuous liquid addition (leachate and

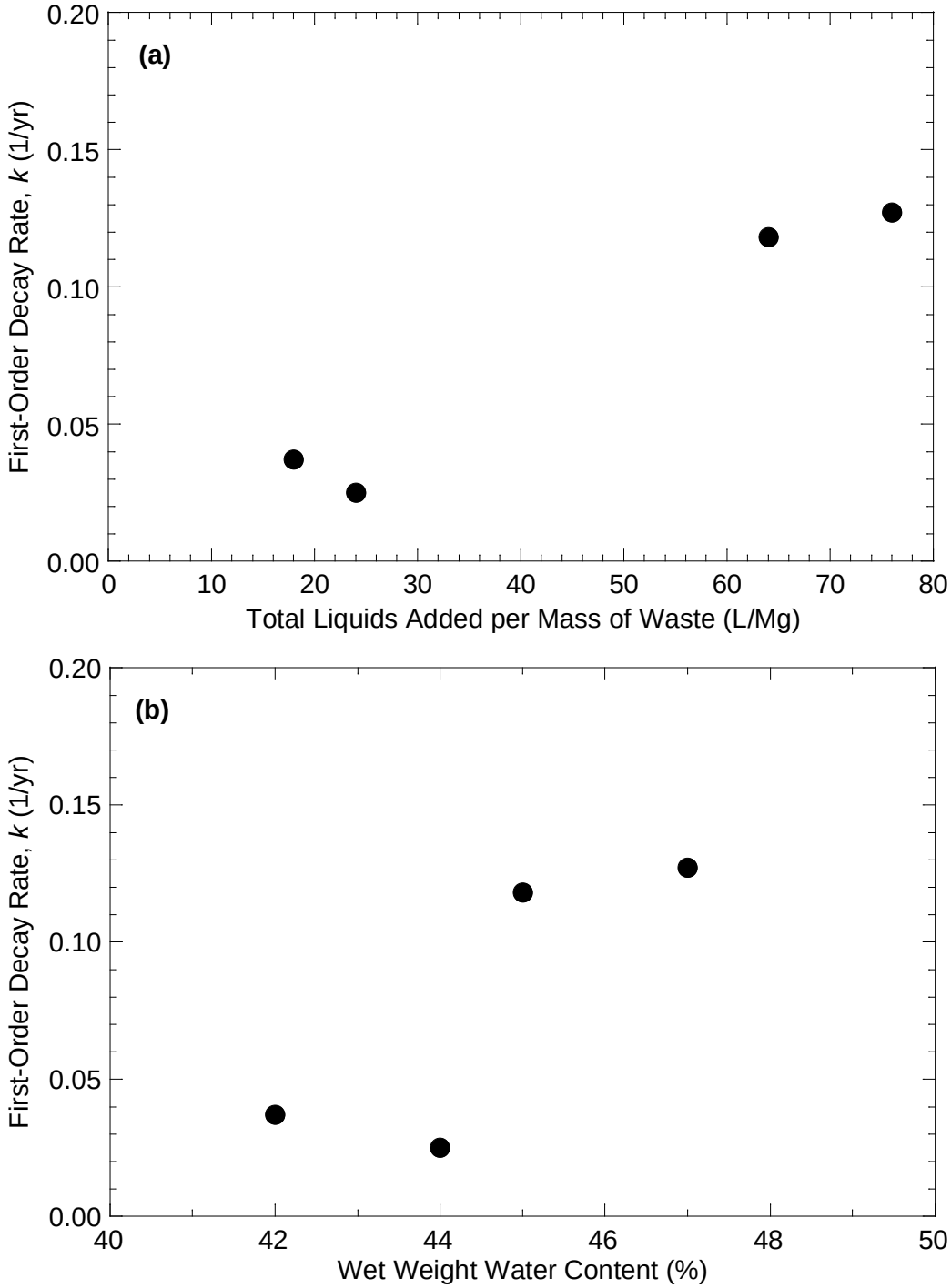

Fig. 2.11. Relationships between optimized first order decay rates versus (a) total liquid added per waste and (b) wet weight water content.

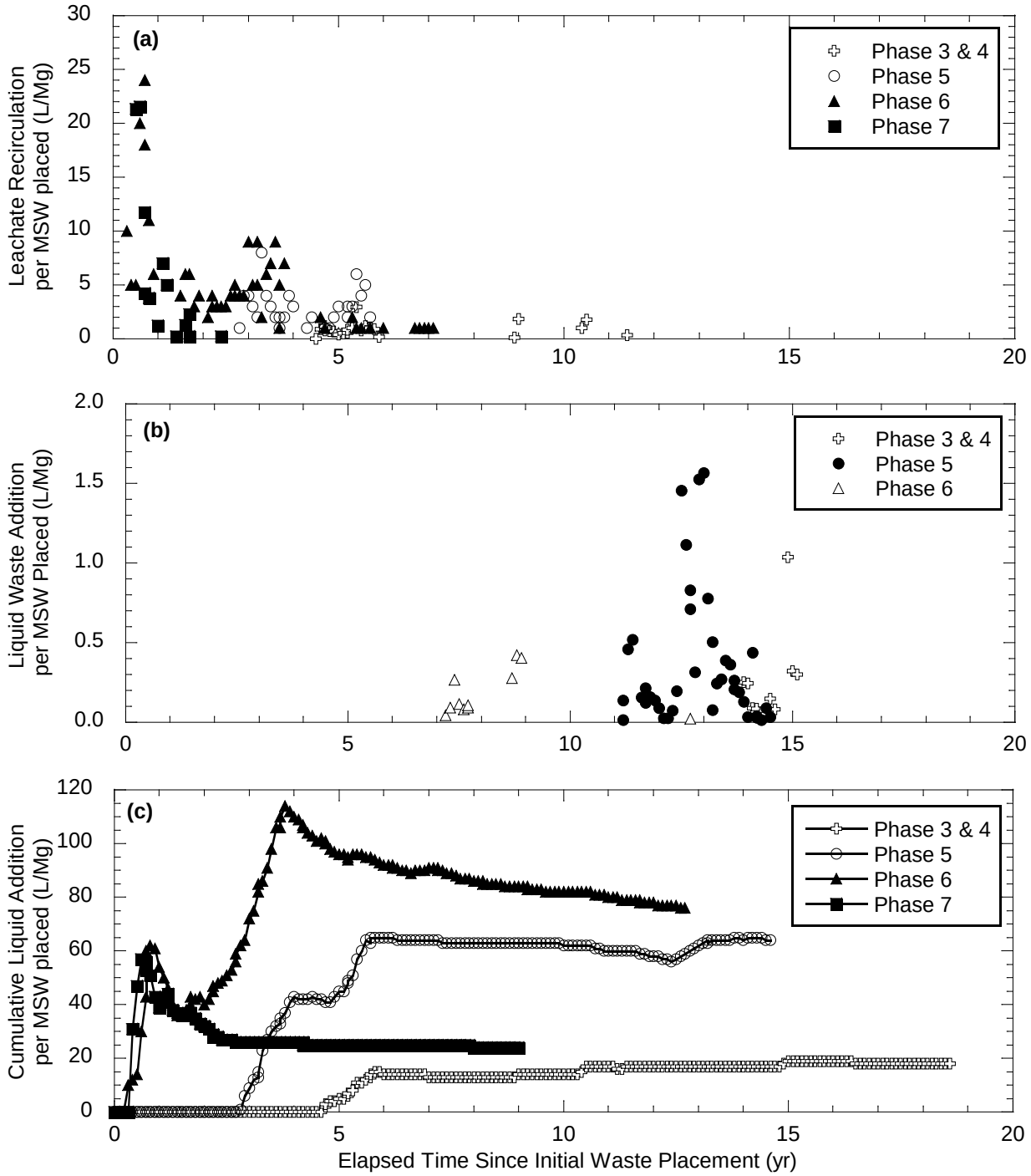

Fig. 2.12. Temporal trends of (a) leachate recirculation per total municipal solid waste (MSW) placed (b) liquid waste addition per total MSW placed and (c) cumulative liquid addition per total MSW placed in Phases 3 & 4, 5, 6 and 7.

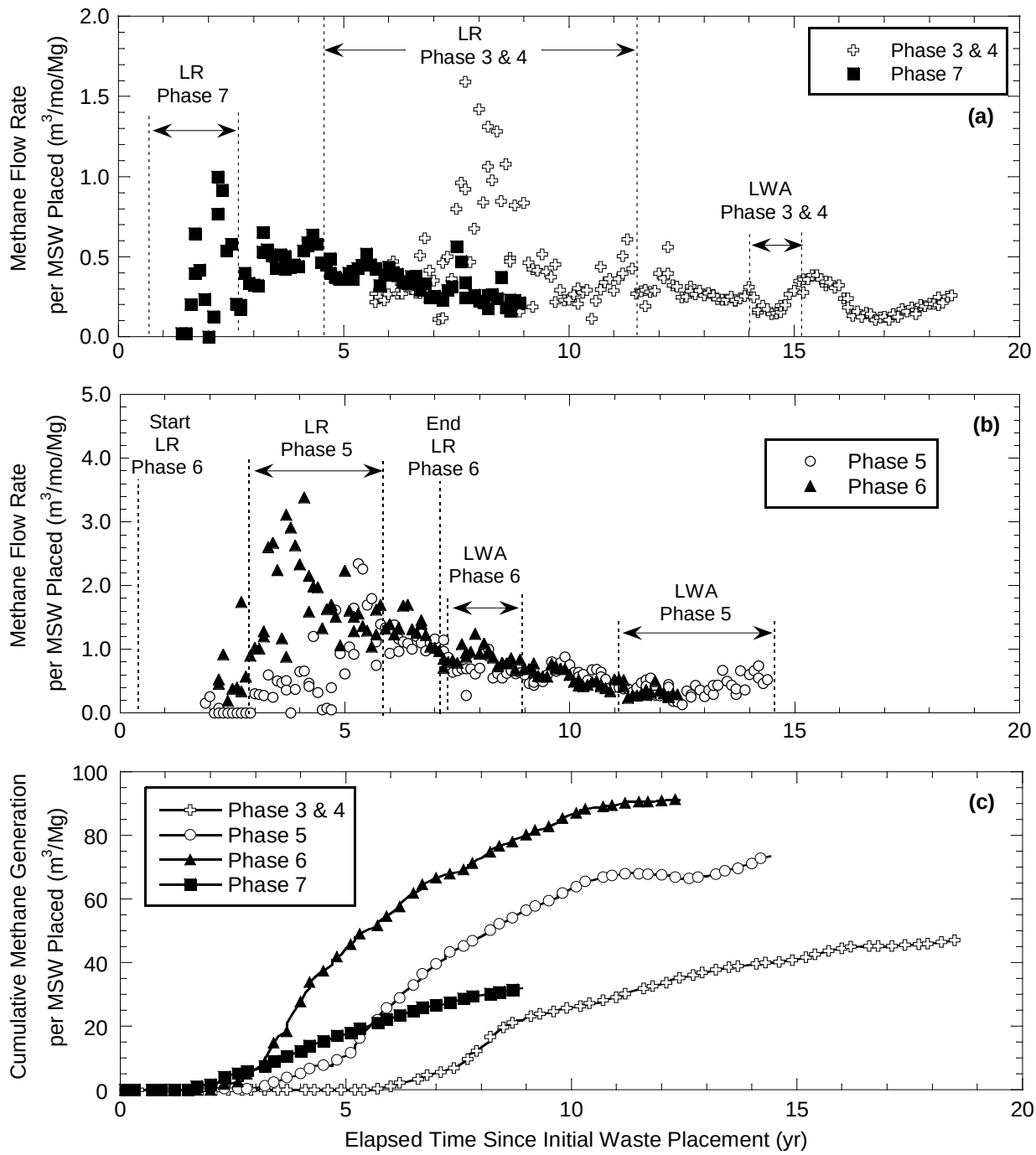

Fig. 2.13. Temporal trends of (a) methane flow rate per total mass of municipal solid waste (MSW) laced in Phases 3 & 4 and 7, (b) methane flow rate per mass of total MSW placed in Phases 5 and 6, and (c) cumulative methane generation per total MSW placed in Phases 3 & 4, 5, 6, and 7. Notes: LR = leachate recirculation; LWA = liquid waste addition.

liquid waste) for approximately 9 yr. The early leachate recirculation in Phase 6 would have supplied microorganisms to the waste mass with sufficient moisture to initiate hydrolytic waste degradation (Reinhart and Al-Yousfi, 1986; Barlaz et al. 1990). The steady recirculation of liquids over a relatively long period of time would have provided a

more consistent supply of nutrients throughout the waste (Barlaz et al. 1990). This moisture enhancement strategy appears to be effective at increasing the rate of LFG generation that corresponds to increased waste decomposition and stabilization.

An increase in CH_4 flow rate was observed in Phase 5 after the onset of leachate recirculation (Figs. 2.6 and 2.13b). This addition of leachate to the waste mass in Phase 5 stimulated anaerobic biodegradation similar to Phase 6. However, the lag time between initial waste placement and the onset of leachate recirculation was 2.5 yr longer in Phase 5 relative to Phase 6. This longer lag time allowed more waste to be placed in Phase 5 prior to liquid addition, which likely limited the overall effectiveness of wetting the waste. This hypothesis of less effective initial waste wetting is supported by higher initial CH_4 flow rates per mass of waste in Phase 6 versus Phase 5 (Fig. 2.13b). The peak CH_4 flow rates in Phase 5 do not reach the same magnitude as in Phase 6, which implies that for comparable masses of MSW there was less CH_4 generation in Phase 5. In other words, the waste in Phase 5 was not degrading as effectively as compared to Phase 6.

Phase 3 & 4 and Phase 7 accounted for 12% and 7%, respectively of the total leachate recirculated in Landfill T. Increased CH_4 flow rates were observed in both phases after leachate recirculation commenced and after liquid waste disposal initiated in Phase 3 & 4 (Fig. 2.13a). During the corresponding periods of leachate recirculation in these phases, CH_4 generation in Phase 3 & 4 was marginally greater than in Phase 7. This increase in CH_4 generation was attributed to the larger volumes of leachate recirculated in Phase 3 & 4 compared to Phase 7.

Although an increase in CH_4 generation was observed following liquid addition in Phase 3 & 4 and Phase 7, the k values estimated for both phases were less than the default value of 0.04 1/yr for conventional landfills (k = 0.037 1/yr for Phase 3 & 4 and k = 0.025 1/yr for Phase 7). In Phase 3 & 4, leachate recirculation and LFG collection started 4.5 and 5.7 yr, respectively, after initial waste placement. The lag time for the onset of leachate recirculation combined with the low amount of leachate added (Table 2.4) likely resulted in limited effectiveness in wetting the waste mass to stimulate waste decomposition. Thus, the moisture enhancement strategy in Phase 3 & 4 appears insufficient to yield an increase in LFG generation.

The low k for Phase 7 was attributed to the lower magnitude of leachate recirculation in this phase as compared to Phase 5 or Phase 6 (Table 2.4). In particular, a comparison between the CH_4 generation in Phase 7 and Phase 6 highlights the different effects of leachate recirculation strategy on CH_4 generation. Leachate recirculation began in these phases within 0.3 yr (Phase 6) and 0.4 yr (Phase 7) after initial waste placement. However, both the duration of leachate recirculation and volume of leachate recirculated in Phase 7 were less relative to Phase 6. The cumulative CH_4 generation relationships for Phase 6 and Phase 7 in Fig. 2.13c clearly show that the moisture enhancement strategy in Phase 6 led to considerably more CH_4 generation relative to the moisture enhancement strategy in Phase 7. Thus, a more aggressive, early leachate recirculation strategy can lead to increased LFG generation and waste decomposition.

An assessment of the effects of specific types of RD&D liquid waste addition on waste stabilization was not possible since chemical composition of the commercial liquids disposed at Landfill T were not available. The only information pertaining to the liquid wastes was a general categorization (Fig. 2.25). Regardless, increased CH_4 generation was observed in Phases 3 & 4, 5 and 6 following the onset of liquid waste disposal (Fig. 2.13). Approximately 67% of the commercial liquids accepted in Landfill T were disposed in Phase 5. An increase in CH_4 flow rates immediately followed the start of liquid waste disposal in Phase 5, which steadily increased for the last three years during active liquid waste addition (Fig. 2.13b). Thus, the addition of liquid waste to an MSW landfill does

beneficially increase the rate of LFG generation to enhance organic waste decomposition and stabilization.

2.4 Assessment of Organic Stability

Summaries of organic stability analyses based on total gas and methane are presented in Table 2.2. The numbers reported in Table 2.2 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. 2.14 through Fig. 2.19. 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 short (i.e., about 4 years). 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. However, the duration to meet organic stability is also short in Site-Wide 2 analysis. The short duration to achieving organic stability in phases that underwent concerted moisture addition indicates that the goal of enhancing waste stabilization is being attained. All analyses, except for Phase 3 & 4 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 2.2). 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.

Table 2.2. 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 Waste Filling (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 [a]	Ongoing	0.094	29 (20)	23 (14)	4 (0)	29 (20)	23 (13)	4 (0)
Site-Wide 2 [a,b]	Ongoing	0.078	37 (28)	29 (19)	9 (0)	37 (28)	29 (20)	9 (0)
Phase 3 & 4	18.4	0.037	77	44	22	77	42	22
Phase 5	14.5	0.118	22	16	3	22	16	3
Phase 6	Ongoing	0.127	21	15	3	21	15	3
Phase 7	Ongoing	0.025	91	79	39	91	87	39

Notes: (i) 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. (ii)Two considerations were used for assuming the end of filling for both site wide analyses. The first consideration assumed a closing date of June 1st, 2015 and the second consideration assumed a closing date of January 1st, 2025. (iii) A closing date of June 1st, 2015 was assumed for Phases 6 and 7.

[a] Numbers in parentheses are years to meet organic stability requirements for second closure date consideration i.e. a closing date of January 1st, 2025.

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

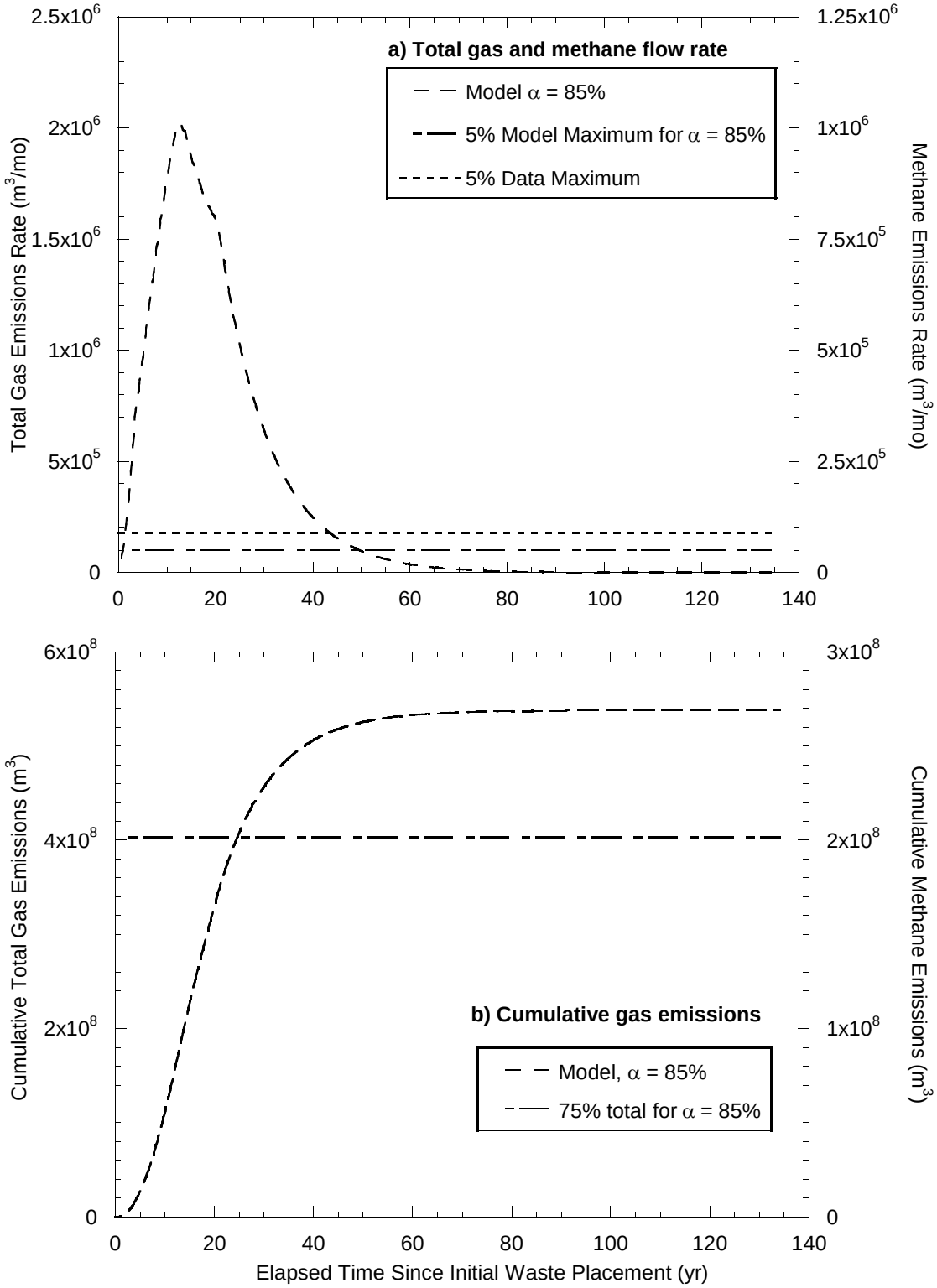

Fig. 2.14. Site-wide organic stability analysis based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

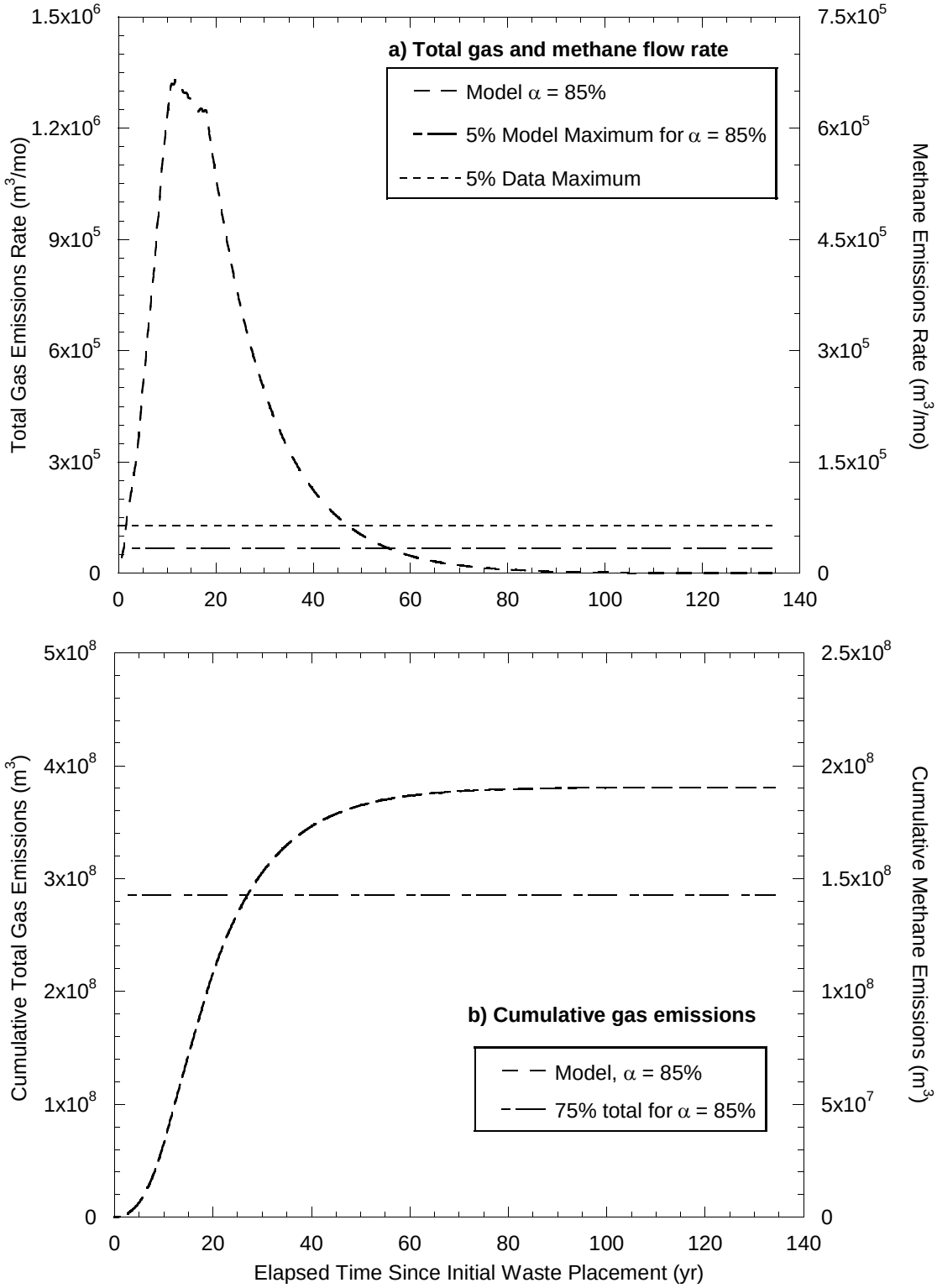

Fig. 2.15. Site-wide 2 organic stability analysis based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

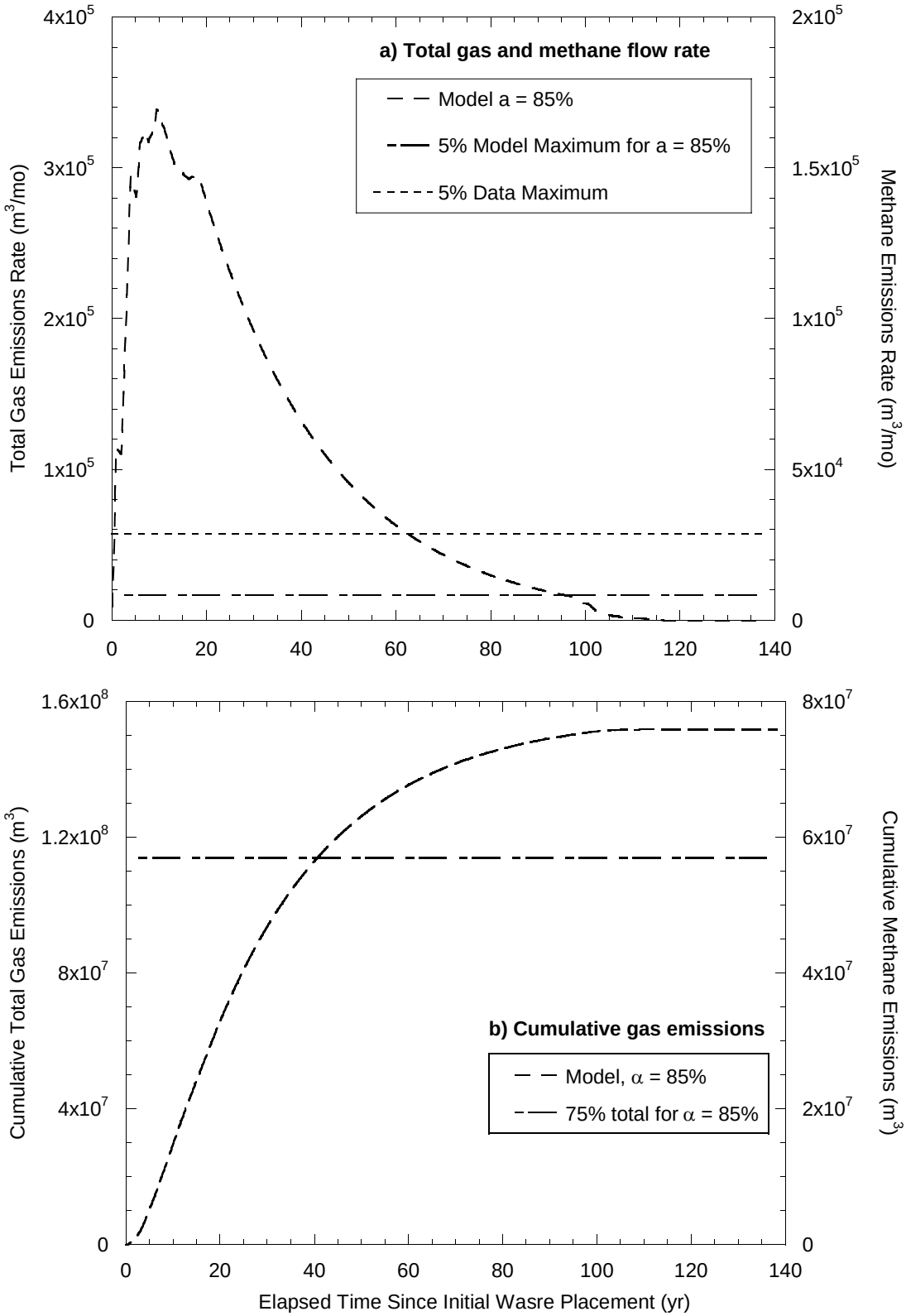

Fig. 2.16. Organic stability analysis for Phase 3 & 4 based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

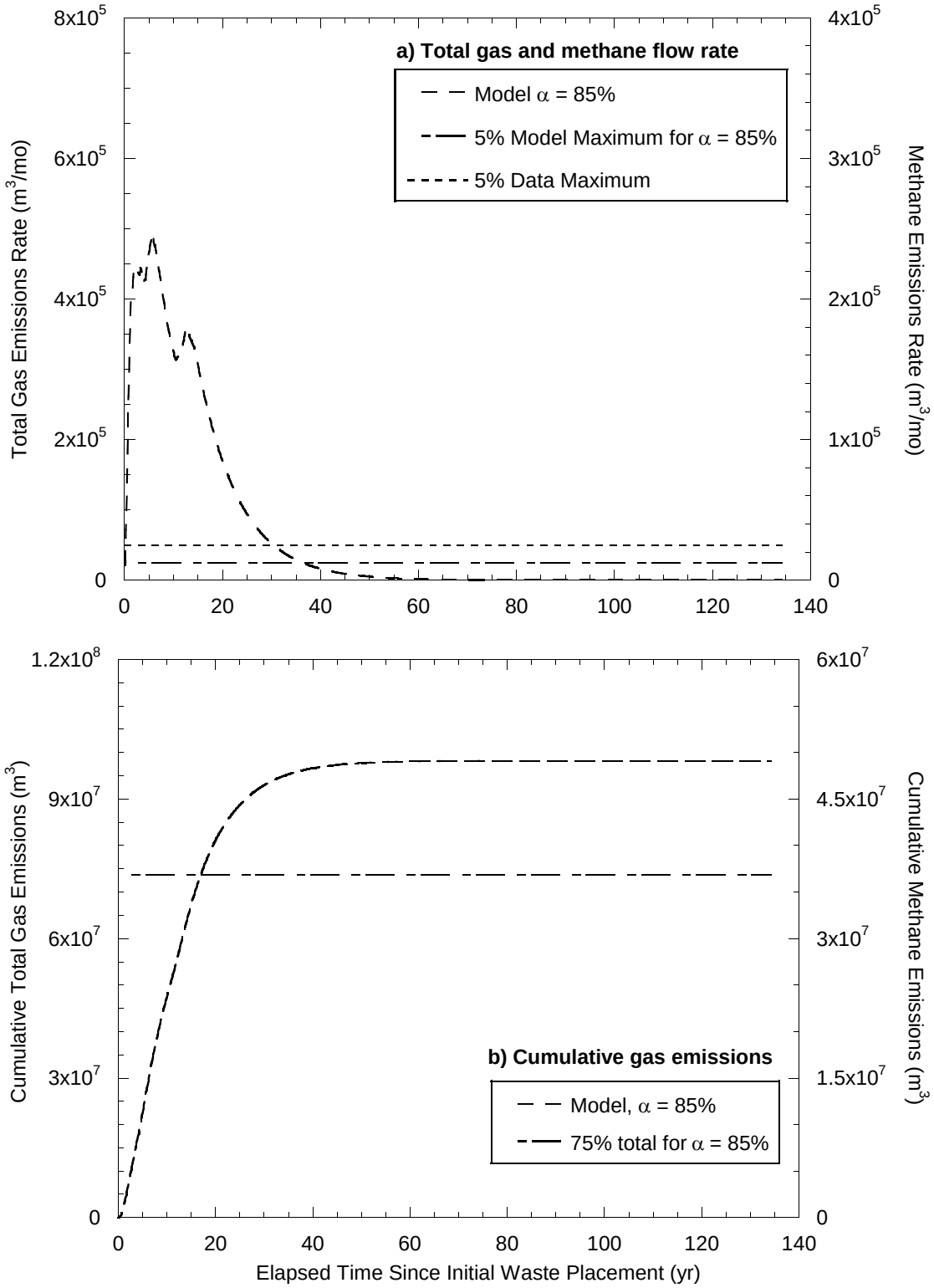

Fig. 2.17. Organic stability analysis for Phase 5 based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

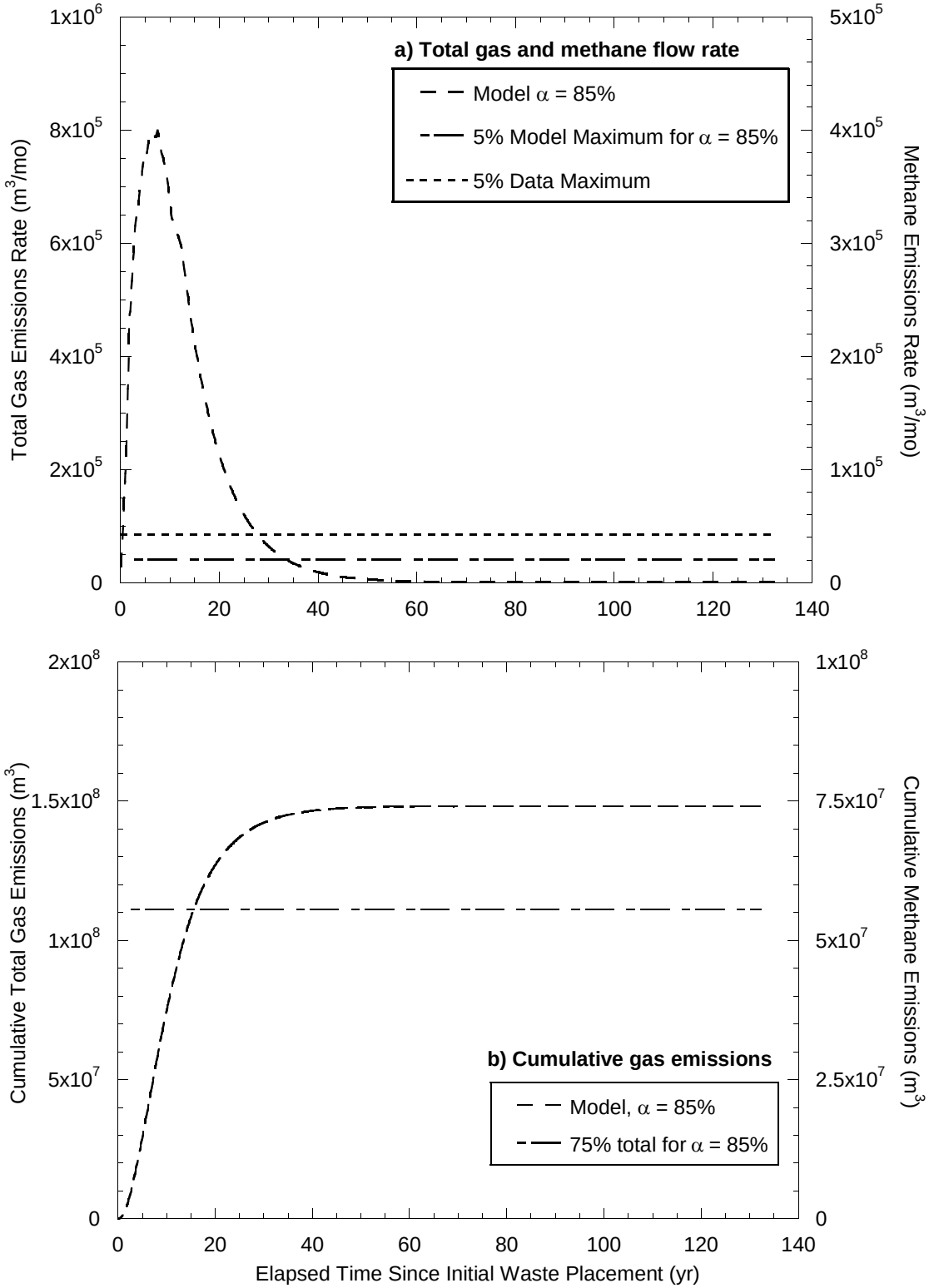

Fig. 2.18. Organic stability analysis for Phase 6 based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

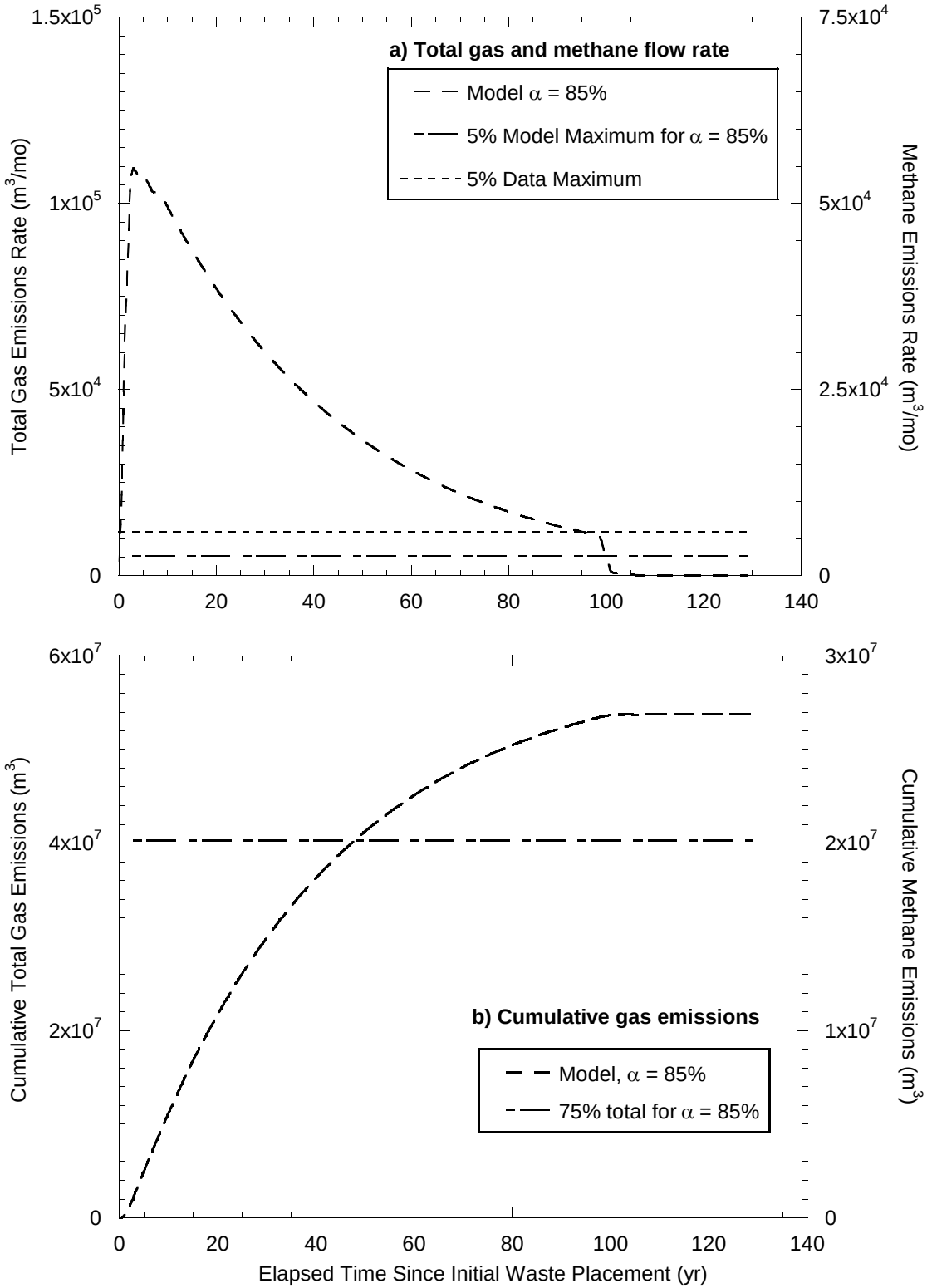

Fig. 2.19. Organic stability analysis for Phase 7 based on (a) total gas and methane flow rates and (b) cumulative total gas and cumulative methane generation.

CHAPTER 3: CONCLUSIONS

Site-wide and phase-specific landfill gas (LFG) modeling was conducted using LandGEM for a bioreactor landfill (Landfill T). An AutoCAD technique was developed to allocate waste tonnages disposed in the landfill to specific phases for use in LFG modeling. The gas models focused on methane (CH_4) flow rates and accounted for (i) monthly versus annual average flow rates, (ii) varying gas collection efficiencies, and (iii) different LFG volumes to be used in the modeling approach. The recommended modeling approach for both the site-wide and phase-specific analyses includes monthly average CH_4 flow rates, constant LFG collection efficiency of 85%, and inclusion of LFG collected in gas wells as well as leachate collection and recirculation systems. The following observations and conclusions were drawn from this study.

- The waste moisture enhancement strategies implemented in Landfill T promoted waste degradation as evidenced by increased gas generation across the entire landfill. Increased LFG flow rates were observed following the onset of leachate recirculation and liquid waste disposal.
- The optimized first-order decay rate (*k*) for the entire landfill was 0.094 1/yr, or 0.078 1/yr when removing LFG and waste mass data from the oldest two phases (i.e., Phase 1A & 2A and Phase 1B & 2B). The *k* = 0.078 1/yr reflects an increase in LFG generation across the landfill phases (Phases 3 & 4, 5, 6, and 7) where there was a concerted effort to enhance waste moisture content via leachate recirculation and liquid waste addition.
- The *k* values for Phases 3 & 4, 5, 6, and 7 ranged from 0.025 to 0.127 1/yr, and positive correlations were obtained between (i) *k* and liquid addition per mass of waste and (ii) *k* and wet weight water content of the waste.
- The highest CH_4 flow rates per MSW mass and largest cumulative CH_4 generation per MSW mass were measured in Phase 6. The moisture enhancement strategy in Phase 6 was characterized by early, aggressive leachate recirculation and continuous liquid addition via leachate and liquid waste. This strategy was shown to be superior for stimulating LFG generation that is reflective of organic waste decomposition and stabilization.

Past studies have investigated methods to improve LandGEM CH_4 predictions via comparing model predictions to collected LFG data. In this study, CH_4 generation simulations were performed for phases of a bioreactor landfill using phase-specific CH_4 flow rates and a CAD-based waste allocation technique. These phase-specific LFG models were paired with moisture enhancement strategies for the different phases at Landfill T. The following observations for LFG modeling and moisture enhancement strategies were drawn from the study.

- CAD files can be used to develop a basis for waste allocation to specific phases of a landfill. The CAD files are used to develop a volume-based weighting factor to determine the contribution of waste mass disposed in a given phase for a given time.
- Landfill gas collected from gas wells and any leachate recirculation or collection system pipe should be summed to provide the most appropriate measure of LFG flow rates for a given phase and across the entire landfill.
- Leachate recirculation implemented early (e.g., within the first year) within the waste filling schedule of a landfill and at consistent recirculation volumes over an extended period of time were shown to lead to higher CH_4 flow rates that indicate increased waste decomposition and stabilization.

- Installation and operation of a gas collection system should be completed as soon as possible following the onset of moisture enhancement to capture early LFG generation.
- Optimization of *k* in LandGEM should be completed on a monthly basis, account for gas collection efficiency (e.g., 85% in the absence of known collection efficiency), and include a constant methane potential of 100 m^3-CH_4/Mg-waste. This recommendation is consistent with recent research on LFG modeling.
- Laboratory-scale and field-scale research is needed to assess the effects of similar leachate recirculation and commercial liquid wastes disposal rates on accelerating waste degradation and gas generation.

CHAPTER 4: MATERIALS AND METHODS

4.1 Landfill T Characteristics and Operations

Landfill T is a non-hazardous solid waste landfill with a total area of 26.2 ha (313,600 yd^2) and a design capacity of 7.2-million m^3 of solid waste (9.6-million yd^3). Landfill T was selected for this study based on data availability and implementation of waste moisture enhancement under an active RD&D permit. Waste disposal in Landfill T commenced in January 1995 and the landfill is currently in operation. Common wastes disposed in Landfill T include non-hazardous MSW, power plant ash, papermill sludge, and foundry waste.

A site map of landfill T is shown in Fig. 2.20. The landfill consists of nine delineated phases, Phase 1 through Phase 7, which have been operated with different moisture enhancement strategies. The phases at Landfill T were filled with waste sequentially and concurrently. This means that although the general order of waste filling was from the oldest phase (Phase 1) to the youngest phase (Phase 7), there was concurrent waste disposal in multiple phases.

The start and end of waste filling operations, areal extent, rate of waste disposal, and estimated total waste disposal for each phase are summarized in Table 2.3. Temporal trends of the average daily filling rate of MSW at Landfill T are shown in Fig. 2.21. The rate of MSW disposal initially increased and then remained constant between 1998 and 2007 at approximately 460 Mg/d. From 2008 to the present, the disposal rate of MSW decreased and subsequently remained constant at approximately 180 Mg/d. The decrease in MSW acceptance was attributed to the economic recession and waste volume swap agreements between Landfill T and surrounding landfills. The MSW component of the total waste disposed in Landfill T ranged between 41% and 95%, and was 76% on average (Fig. 2.21).

Characteristics of the waste moisture enhancement strategies for the phases of Landfill T are summarized in Table 2.4. These characteristics include the elapsed time between waste placement and onset of liquid addition, cumulative volumes of recirculated leachate and liquid waste disposal, duration of leachate recirculation, percent leachate recirculation of total liquid addition, cumulative liquid addition per mass of MSW, and average wet weight water content. The initial methods of liquid addition were leachate recirculation and solidification of liquid wastes with high moisture retention capacities. Leachate recirculation was conducted in all phases except Phase 1A & 2A, which received no liquid addition because these phases were closed before commencement of liquid addition operations. Leachate recirculation commenced at Landfill T in May 2001 via surface application. This technique consists of hauling leachate to the working face of the landfill via a tanker truck and applying leachate to the waste with a spray bar. This method of recirculation was used in Phases 1B, 2B, 3, 4, 5, 6, and 7.

In September 2003, Landfill T began using a horizontal leachate recirculation system, which consisted of pumping leachate to trenches within the waste mass via a pump installed in the leachate storage tank. Trenches were typically 1.0- to 1.5-m deep and backfilled with tire chips with a 100-mm-diameter perforated pipe passing through the center of the trench. In this system, only one trench was used at a time to maximize infiltration and allow sufficient time for leachate pressure within the waste mass to stabilize. Leachate was added via horizontal trench recirculation in Phases 3, 4, 5, 6, and 7. Between 2010 and 2012, a local publically owned treatment works (POTW) reduced the volume of leachate accepted from Landfill T for treatment, which caused the

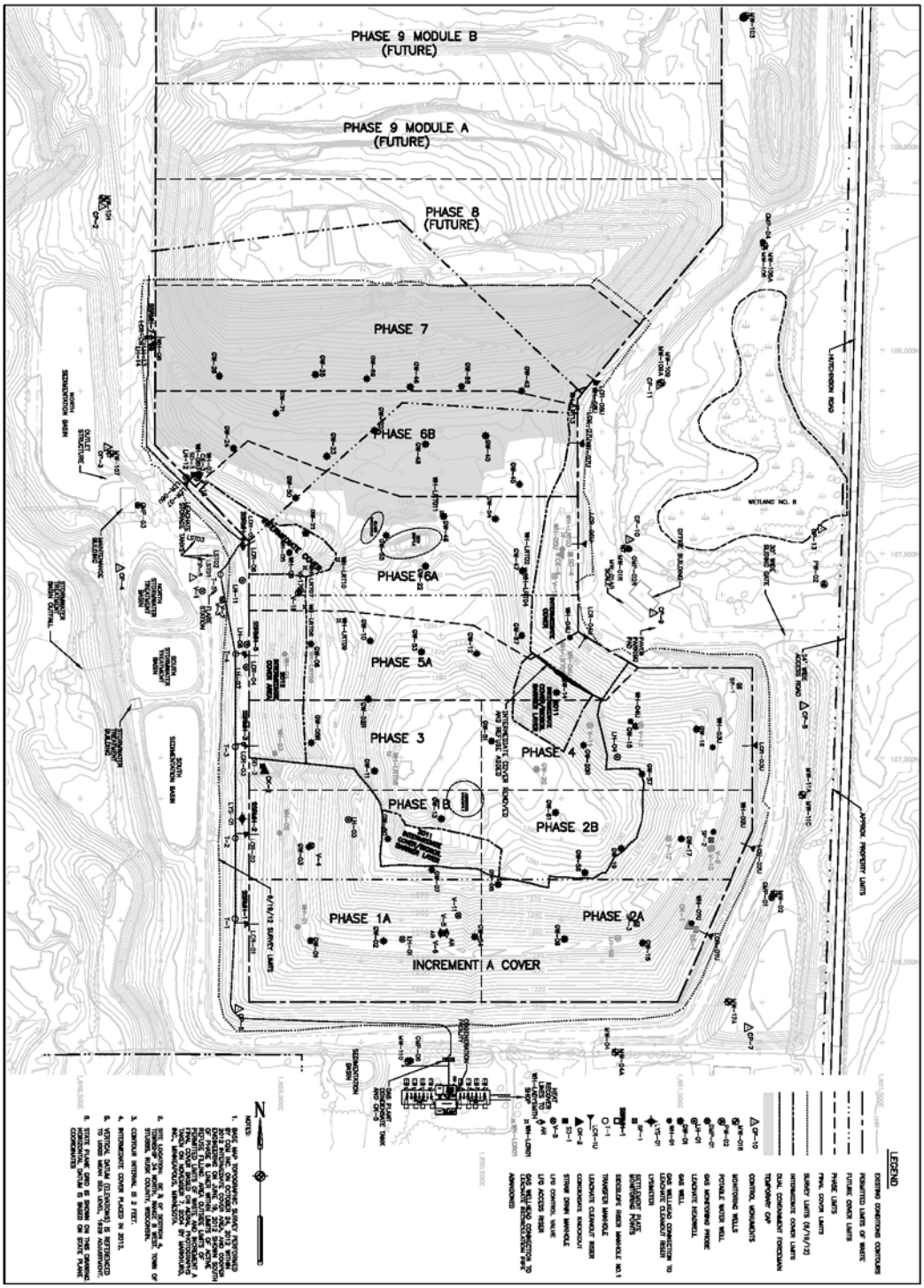

Fig. 2.20. Plan view of Landfill T with delineated existing and future phases.

Table 2.3. Summary of disposal phases at Landfill T, including waste filling dates, landfill dimensions, filling rate, disposed municipal solid waste (MSW), and estimated total waste volume as of June 2015.

Phase	Start Date of Waste Filling	End Date of Waste Filling	Area (ha)[a]	Filling Rate (Mg/d) [b]	Mass of Disposed MSW (Mg)[c]	Estimated MSW Volume (m^3) [d]
1A & 2A	Jan. 1995	Jan. 1998	3.16 (7.8)	108 (120)	159,086	141,876
1B & 2B	June 1996	May 2015	2.51 (6.2)	49 (54)	364,912	325,437
3 & 4	Nov. 1996	May 2015	2.79 (6.9)	114 (125)	775,833	691,905
5	Nov. 2000	May 2015	1.58 (3.9)	91 (100)	484,157	431,782
6	Oct. 2002	Ongoing	5.22 (12.9)	160 (177)	729,278	650,386
7	June 2006	Ongoing	2.71 (6.7)	89 (98)	292,705	261,041
Site-Wide	Jan. 1995	Ongoing	18 (44.5)	355 (391)	2,805,971	2,502,427

[a] Area in acres shown in parentheses.

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

[c] Mass of disposed MSW in phases is obtained from CAD volume estimations.

[d] MSW volume is estimated based on total unit weight of compacted MSW in the midpoint of a landfill (11kN/m^3) via Zekkos et al. 2006.

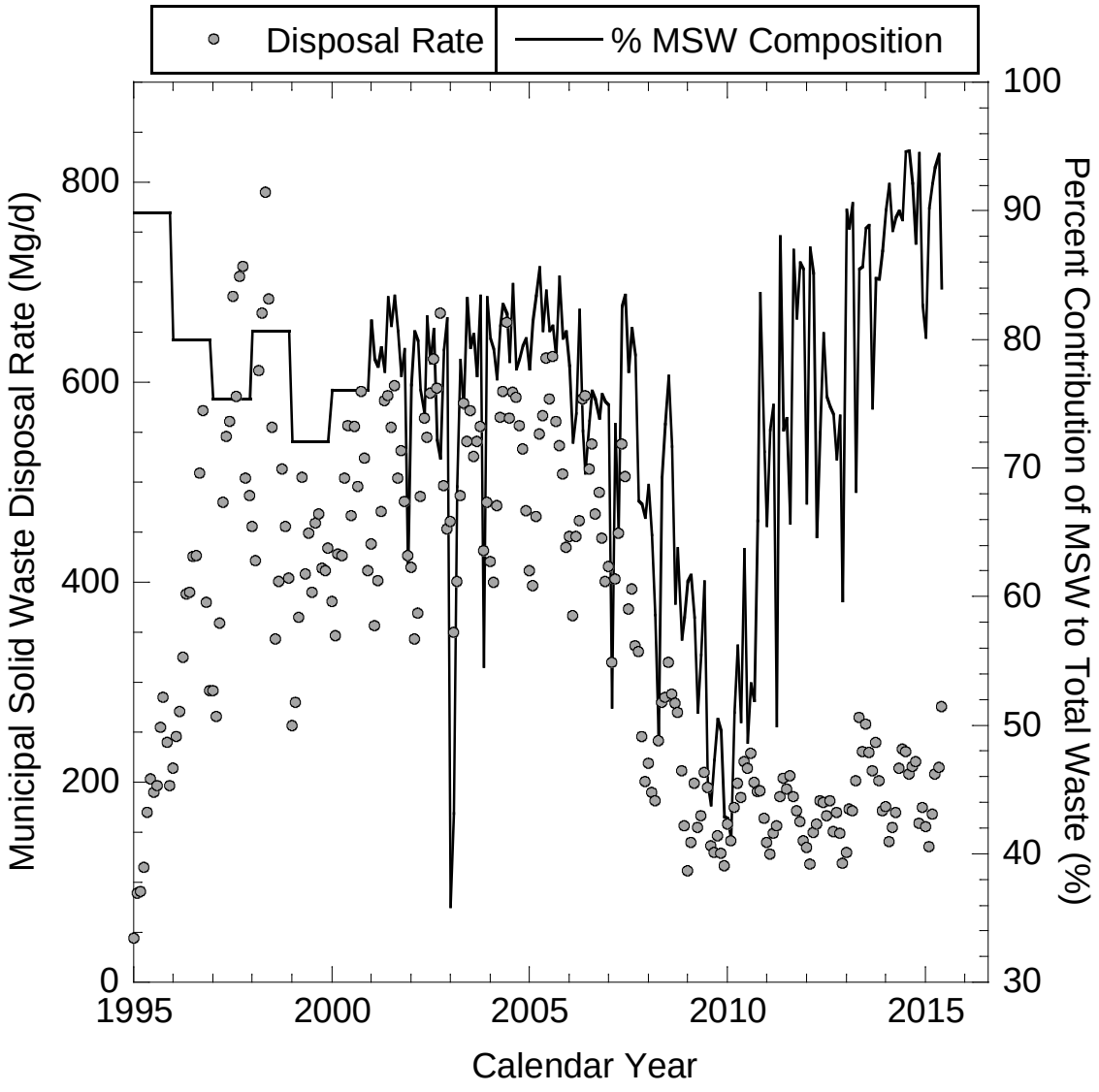

Fig. 2.21. Temporal trends of municipal solid waste (MSW) disposal rate and percent MSW fraction of total waste at Landfill T.

Table 2.4. Phase specific summary of leachate recirculation, duration of leachate recirculation, liquid waste addition, and average wet weight water content as of June 2015.

Phase	Duration Between Initial Waste Placement and Initial Liquid Addition (yr)	Leachate Recirculated (m^3)	Duration of leachate recirculation (yr)	Commercial Liquids Disposal (m^3)	Percent Leachate Recirculation of Total Liquids Added (%)	Average Liquid Addition per Mass of Waste (L/Mg)	Average Wet Weight Water Content (%)[a]
1A & 2A	-	0	0	0	0	0	-
1B & 2B	14.6	195	0.3	718	21	0.6	37 (10)
3 & 4	4.5	11,688	1.9	1,876	86	12	42 (5.1)
5	2.8	24,726	2.4	6,339	79	64	45 (4.7)
6	0.3	54,401	5	1,200	98	76	47 (4.3)
7	0.4	7,071	1.2	0	100	27	44 (3.5)
Site-Wide	5	98,081	10	10,133	91	28	43 (6.4)

[a] Standard deviation included in parentheses

operators to stop leachate recirculation. This measure was taken to reduce leachate generation and the ammonia concentration of the leachate.

Temporal trends of leachate recirculation dose volumes and cumulative leachate addition for each phase at Landfill T are shown in Fig. 2.22. The largest volume of recirculated leachate recirculation was in Phase 6, whereas the lowest volume of recirculated leachate was in Phase 1B & 2B. The shortest lag time between initial waste placement and onset of leachate recirculation was in Phase 6, whereas the longest duration for the onset of leachate recirculation after initial waste placement was in Phase 1B & 2B. Similar to Phase 1A & 2A, Phase 1B & 2B was actively filled before the start of a site-wide liquid addition strategy, which resulted in minimal leachate recirculation in this phase.

The range of daily leachate recirculation rates for each phase in Landfill T are shown in Fig. 2.23. The average daily leachate recirculation rate ranged from 639 to 17,740 L/ha/d. Although the majority of leachate recirculation in Landfill T was conducted in Phase 6, the rate of leachate recirculation was most intense in Phase 5. This aggressive leachate recirculation in Phase 5 was performed within a 29-mo span, whereas a steady and consistent recirculation approach spanning 60 mo was implemented in Phase 6 that cumulated to the largest volume of recirculated leachate (Fig. 2.21b). The average daily rate of leachate recirculation was similar between Phase 3 & 4, Phase 6, and Phase 7 (Fig. 2.22).

Landfill T has solidified liquid and sludge wastes from March 2003 until the present. Solidification was conducted via a paint filter test, which is a method to assess the presence of free liquids in a waste sample (EPA Method 9095B). Liquid wastes that were solidified included paint, papermill sludge, and special wastes. No liquid wastes were solidified from 2011 to 2012 because of the aforementioned measure by Landfill T to reduce leachate generation. Commercial liquid waste disposal was initiated in January 2010 after Landfill T obtained an RD&D permit. Liquid wastes were primarily discharged via surface application on the working face of the landfill.

Temporal trends of commercial liquid waste dose volumes (i.e., liquids disposed under the RD&D permit) and cumulative liquid waste addition for each phase at Landfill T are shown in Fig. 2.24. Cumulative volumes of the main types of liquid wastes disposed in each phase are shown in Fig. 2.25. There was no liquid waste disposal in Phase 1A & 2A or Phase 7. Typical liquid wastes disposed at Landfill T included scrubber waste, treatment plant water, herbicide rinse water, wash pad water, and special liquids. The largest volumes of liquid waste disposal occurred in Phase 5, whereas the smallest volumes of liquid waste were disposed in Phase 1B & 2B (Fig. 2.25). Similar to the leachate recirculation regime, there was intense disposal of liquid waste in Phase 5 compared to other phases. The majority of the commercial liquid waste in Phase 5 consisted of special liquids and was predominantly disposed between 2012 and 2014.

The range of daily total liquid application rates (i.e., recirculated leachate plus liquid waste) are shown in Fig. 2.26. The average liquid application rates per area ranged from 639 to 9,402 L/ha/d. The highest liquid application rates were observed in Phase 5 and the lowest liquid application rates were in Phase 1B & 2B. Temporal trends of cumulative liquid addition per waste mass for the phases of Landfill T are shown in Fig. 2.27. In spite of the high liquid rates in Phase 5, the largest cumulative liquid addition per mass of waste occurred in Phase 6. The ratio of cumulative liquid addition per waste mass in Phase 5 was 64 L/Mg, whereas the ratio of cumulative liquid addition per waste mass in Phase 6 was 76 L/Mg. The other three phases at Landfill T (Phase 1B & 2B, Phase 3 & 4, and Phase 7) all received considerably less cumulative liquid addition relative to the mass of waste placed. Although the most aggressive liquid

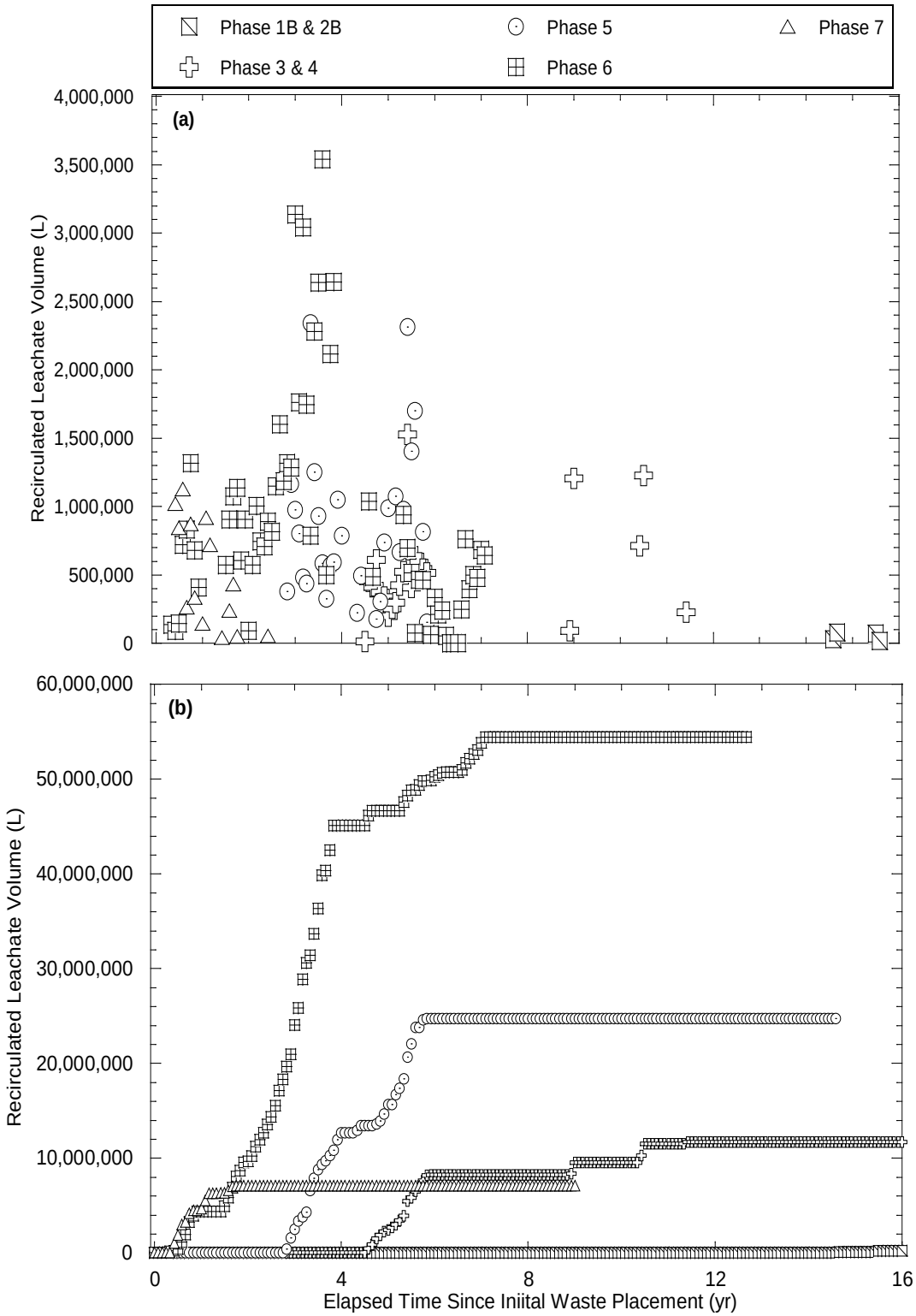

Fig. 2.22. Temporal trends of (a) leachate recirculation and (b) cumulative leachate recirculation across all phases.

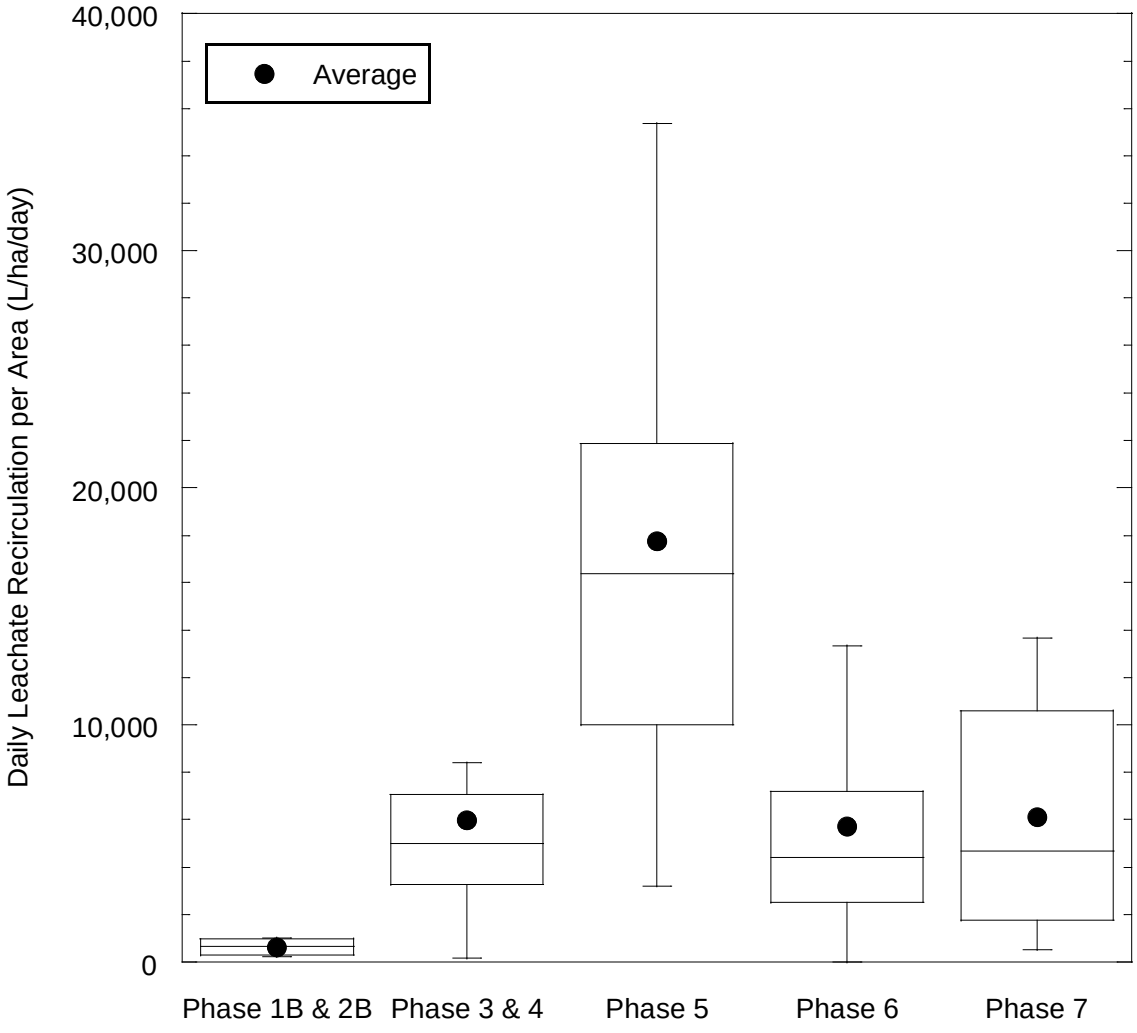

Fig. 2.23. Box plot of daily leachate recirculation rates in phases during periods of leachate recirculation. The central line is the median, the outer boundaries of the box represent the interquartile range (i.e., 25th and 75th percentile), and the upper and lower whiskers constitute the 10th and 90th percentiles of the data. The average is shown as a solid circle.

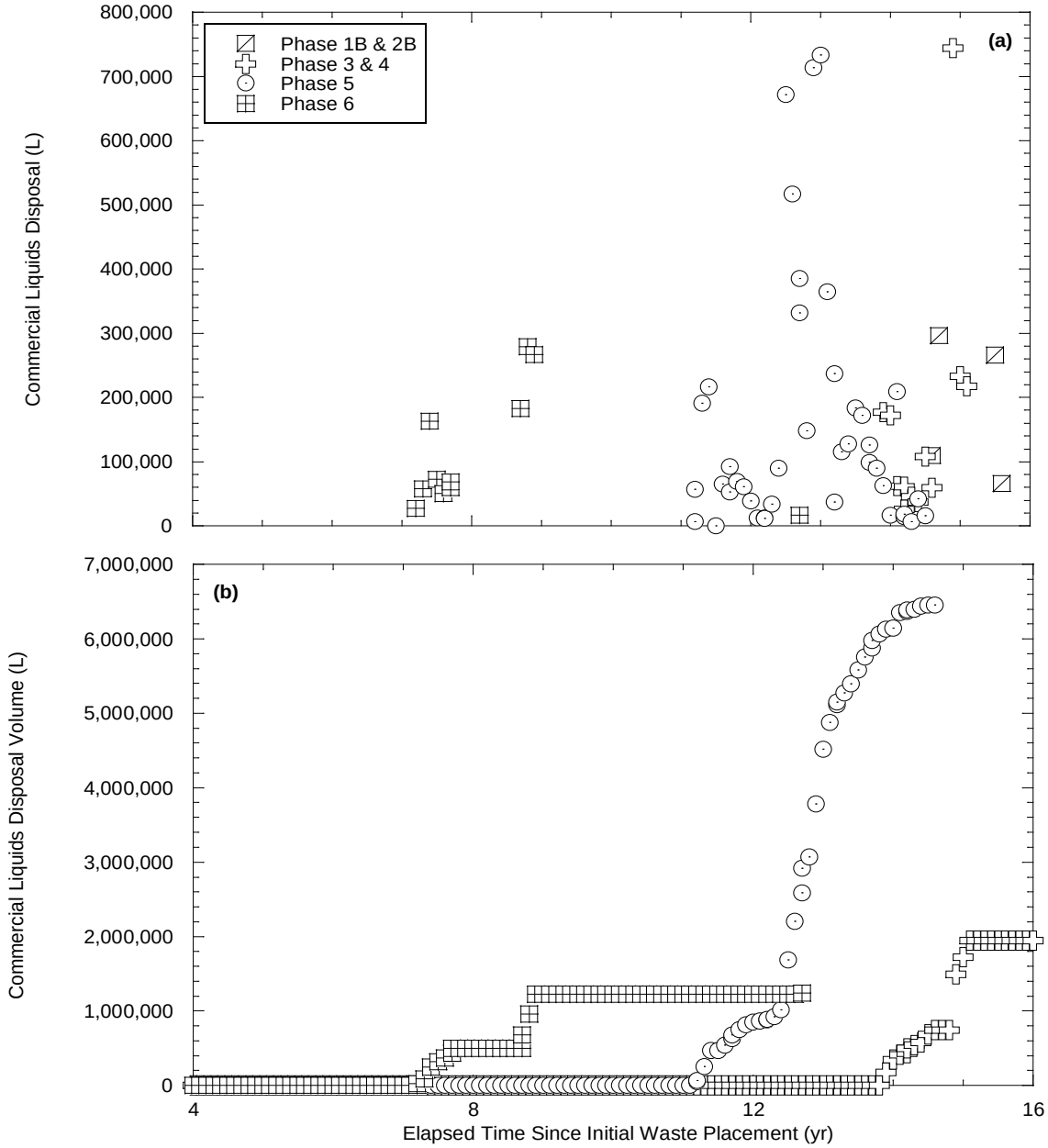

Fig. 2.24. Temporal trends of (a) commercial liquid waste disposal and (b) cumulative liquid waste disposal across all phases.

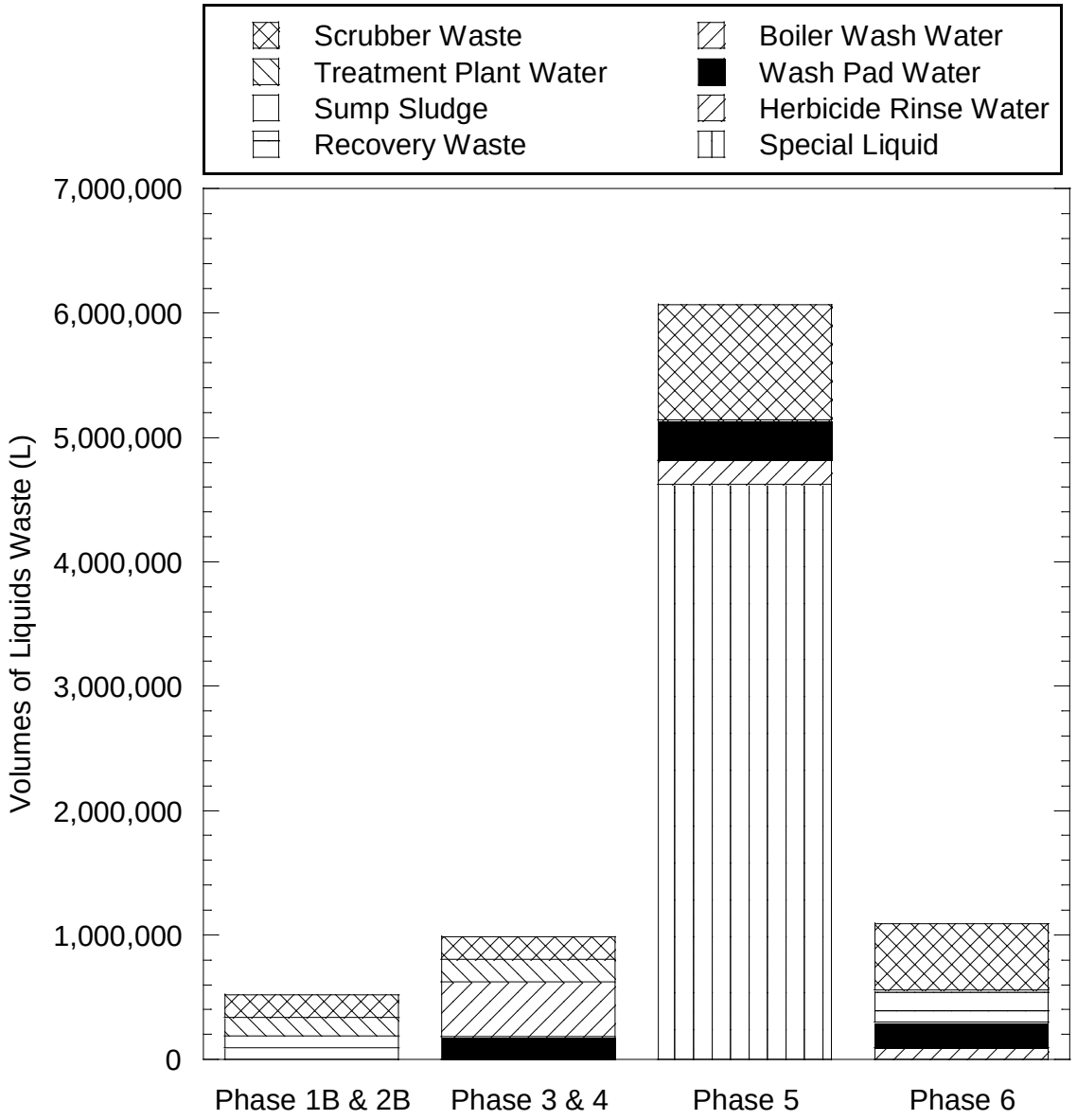

Fig. 2.25. Bar chart of volumes of different types of liquid waste disposed in Phases 1B & 2B, 3 & 4, 5, and 6 at Landfill T.

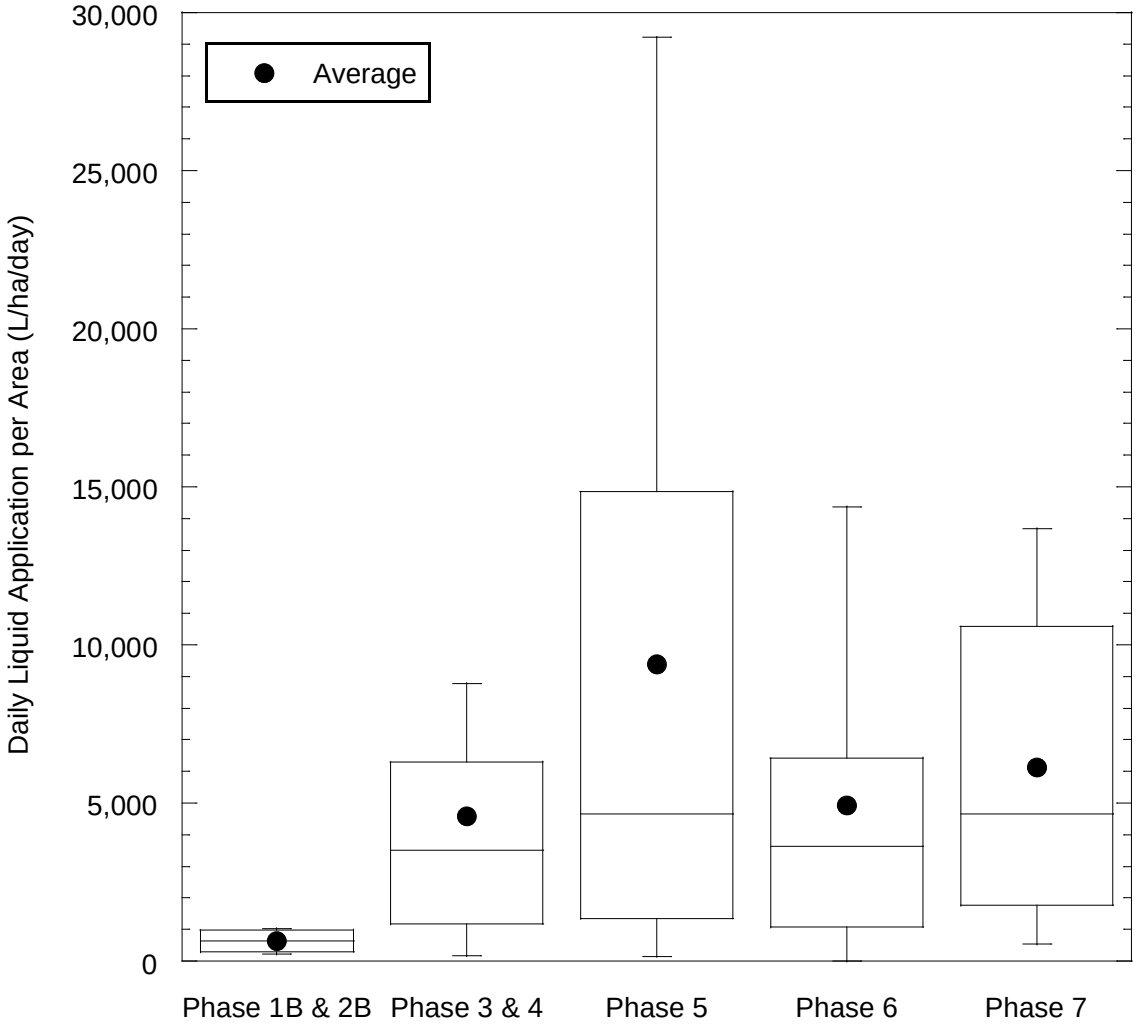

Fig. 2.26. Box plot of daily liquid application per surface area in each landfill phase.

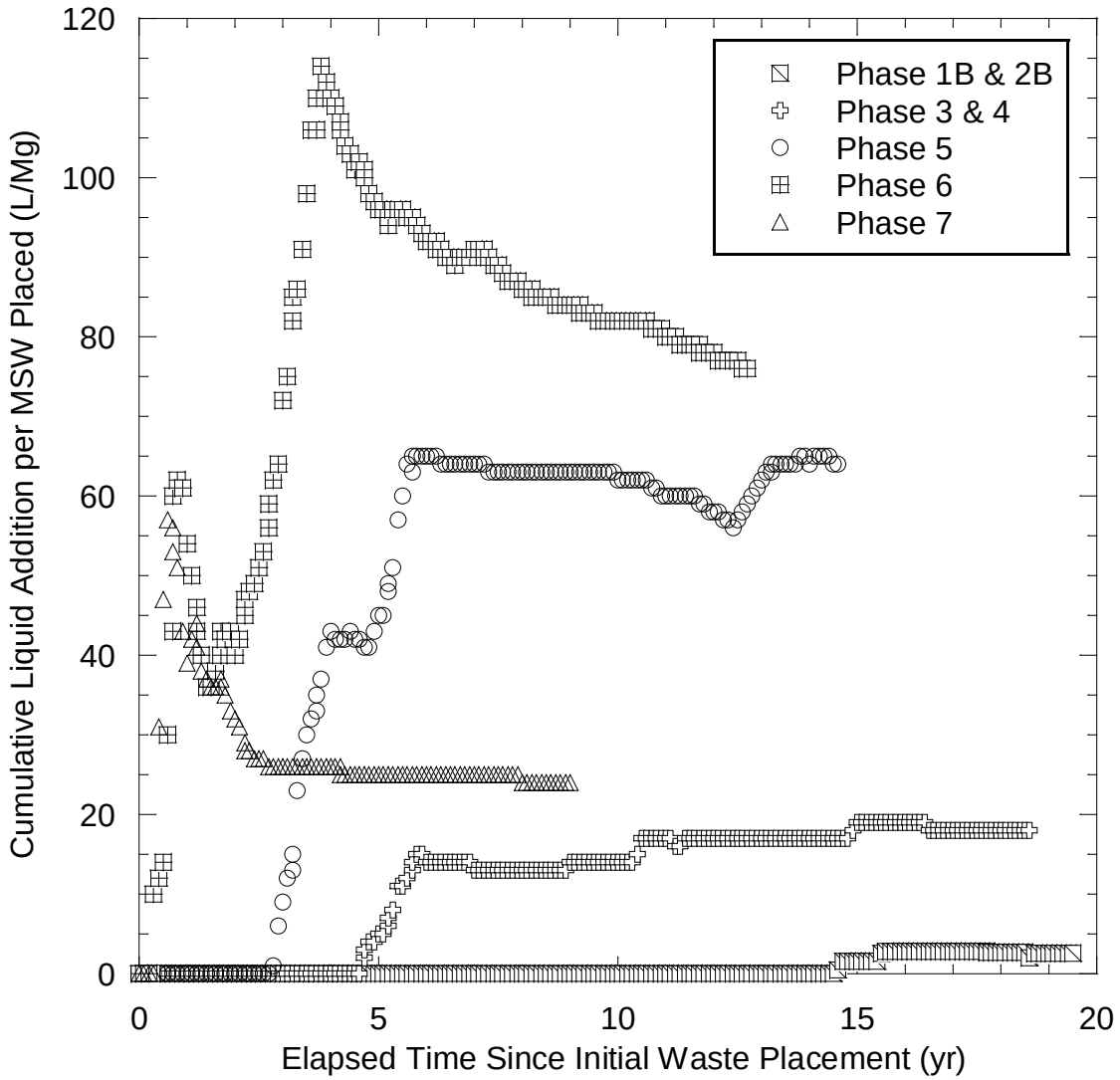

Fig. 2.27. Temporal trends of cumulative liquid addition per mass of waste in Phases 1B & 2B, 3 & 4, 5, 6, and 7.

addition strategies were implemented in Phase 5 and Phase 6, the strategy in Phase 5 was characterized by larger liquid dose volumes applied over a shorter duration, whereas the strategy in Phase 6 was characterized by more consistent, smaller liquid dose volumes applied over a longer duration.

A summary of gas collection information, gas flow rates, and CH_4 fraction for each phase is in Table 2.5, which was updated based on the analysis conducted by Mantell (2016). The gas collection system at Landfill T includes 82 extraction points that consist of 54 extraction wells, 16 connections to leachate clean-out pipes (LCRs), and 12 connections to leachate recirculation trenches (LRTs). Phase 6 has the most LFG extraction points, which included 15 extraction wells and 15 connections to LCRs and LRTs. Phase 1A & 2A and Phase 7 have the least LFG extraction points (6 extraction wells and 2 connections to LCRs and LRTs). The number of gas wells per area ranged between 2.5 and 8.2 gas wells per hectare, with Phase 1B & 2B and Phase 5 having the lowest and highest gas well densities, respectively. A discernible trend in the gas collection system at Landfill T was the increase in the number of gas extraction points in phases that had substantial liquid addition. The highest average total gas flow rates were measured in Phase 6 and the average CH_4 composition across all phases was 51%.

The temporal trend of annual average LFG flow rate at Landfill T from 2000 through 2015 is shown in Fig. 2.28. The daily total LFG flow rates in Fig. 2.28 are a combination of LFG collected in gas wells and the leachate collection and recirculation systems (LCR and LRT connections). The period of largest LFG collection at Landfill T was between 2006 and 2009, with the average daily flow rate peaking at 72,845 m^3/d in 2006. This period of elevated LFG collection (2006-2009) was subsequent to the duration of high waste disposal at Landfill T, which started in 1998 and continued through 2007 (Fig. 2.27). The contribution of LFG collection from the LCRs and LRTs ranged between 1% and 58% of the total LFG collection, with an average contribution of 30%. Thus, there was considerable LFG collection in the leachate collection and recirculation systems at Landfill T, which was accounted for in landfill gas modeling (described subsequently).

4.2 Landfill Data Compilation and Analysis

Data obtained from Landfill T included monthly measurements from 1995 to 2015 of the MSW fraction of total waste placed, leachate recirculation volumes, liquid waste disposal volumes, gas flow rates, and CH_4 fraction of the collected gas. With exception of MSW disposal rates, all data were available on a phase specific basis. CAD files that included topographic maps of Landfill T were made available from 2002 to 2015, which were used to estimate the volume and mass of MSW placed in each phase. The monthly monitoring data and CAD files were used for the gas modeling and liquid management analyses conducted in this study.

Landfill gas data was processed based on an approach developed in Mantell (2016). An example of the LFG data processing for estimating total flow rates in a phase (e.g., Phase 1A & 2A) is shown in Fig. 2.29. Daily LFG flow rate measurements recorded from gas wells, LCRs, and LRTs within a phase were used to compute average monthly and annual flow rates. Monthly average flow rates for a given phase were calculated by multiplying the mean flow rate among functioning gas connections (wells, LCRs, and LRTs) by the number of gas connections. Annual average gas flow rates for a phase were computed as the average of the monthly flow rates for a given year. The monthly and annual flow rates for a given landfill phase were used in the LFG prediction.

Table 2.5. Summary of gas collection system installation, lag time between initial waste placement and initial gas collection, gas well density, gas flow rate, and percent methane composition as of June 2015.

Phase	Start Date for Gas Collection	Lag Time Between Initial Waste Placement and Gas Collection (yr)	No. of Gas Wells in Waste Mass	No. of Gas Flow Points in LCRs & LRTs	Gas Well Density (wells/ha)	Gas Collection Devices Density (devices/ha)	Average Total Gas Flow Rate (m^3/d)	Range of Total Gas Flow Rate (m^3/d)	Average Percent Methane (%)
1A & 2A	Mar. 2000	5.2	6	2	1.9	2.5	9,906	1,114 - 24,329	53
1B & 2B	Mar. 2000	4.2	8	2	3.2	4.0	10, 274	460 - 10,274	53
3 & 4	Aug. 2002	5.7	10	3	3.6	4.7	7,739	2,172 - 32,83	52
5	Nov. 2002	2	9	4	5.7	8.2	8,346	546 - 27,978	52
6	Feb. 2005	2.3	15	15	2.9	5.7	17,444	1,864 - 47,442	51
7	Nov. 2007	1.4	6	2	2.2	2.9	3,413	126 - 7,832	42

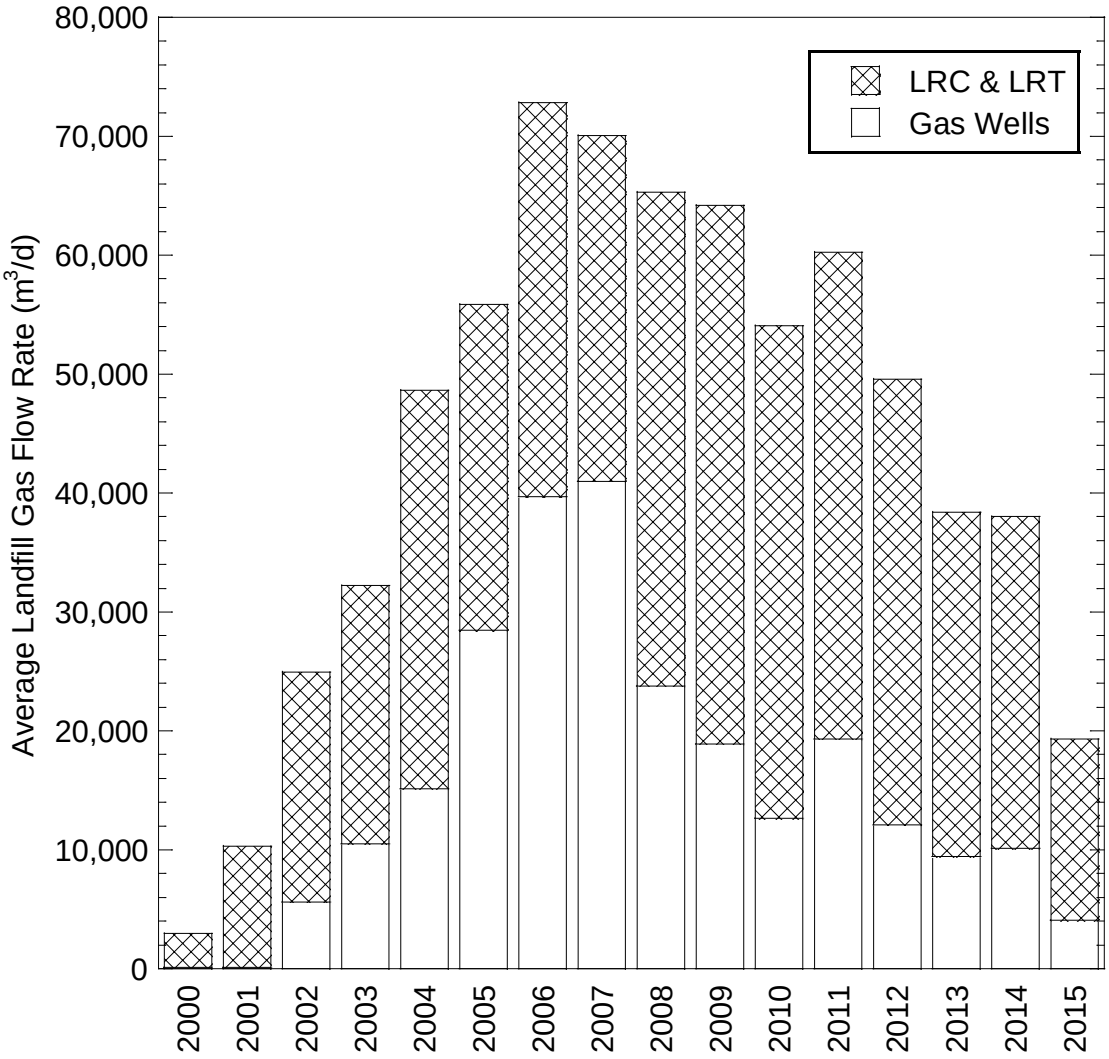

Fig. 2.28. Contributions to the total landfill gas flow for Landfill T from gas collected in the vertical gas wells and gas collected in the leachate collection and recirculation systems (LCR and LRT).

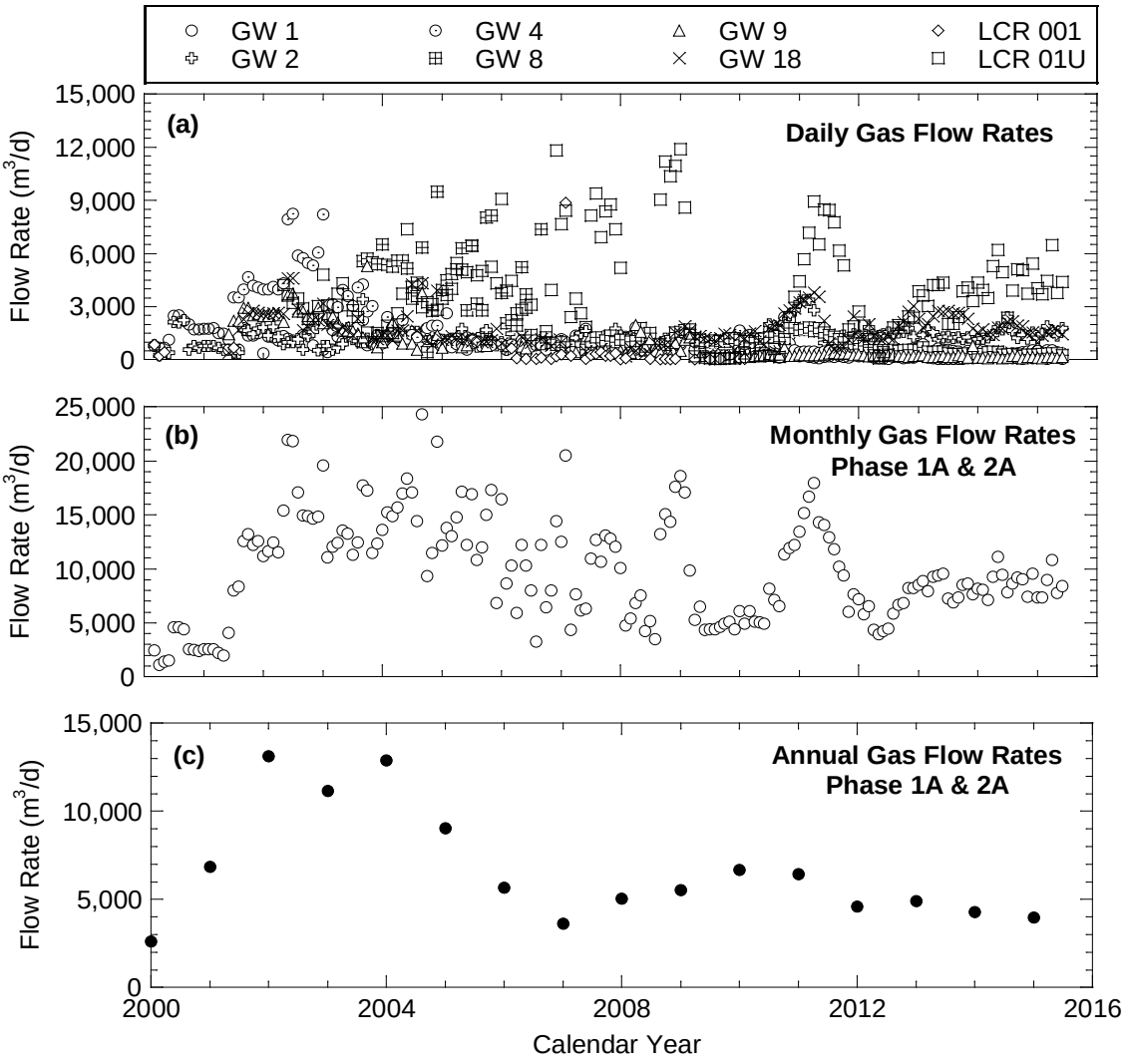

Fig. 2.29. Gas flow rate data for Phase 1A & 2A: (a) individual gas well, LCR, and LRT measurements; (b) monthly gas flow rates for the entire phase; (c) annual gas flow rates for the entire phase.

simulations. Site-wide monthly and annual gas flow rates were summed from the average monthly or annual gas flow rates computed for the individual phases

4.3 CAD Waste Volume Estimation

Estimates of MSW volumes for the phases of Landfill T were determined through surface volume calculations in AutoCAD Civil 3D (Autodesk Inc., San Rafael, CA, USA). The goal of the phase-specific CAD volume analysis was to develop a basis for allocating waste tonnages to specific phases at Landfill T.

A flow chart of procedures performed in the CAD volume analysis conducted for this study is shown in Fig. 2.30. A Triangular Irregular Network (TIN) surface was created from waste contour lines for each CAD file by connecting surface points (i.e., contour lines) that were closest together. An example of a typical TIN surface created from a CAD file and an example of two paired TIN surfaces are shown in Fig. 2.31. The paired TIN surfaces represent surfaces created from subsequent surveys (i.e., TIN surfaces from subsequent CAD files). The paired TIN surfaces were used to estimate the change in landfill volume between the subsequent surveys. In total, 29 TIN surface pairings were created from the CAD files available from April 2002 to June 2015.

An example of a TIN volume determined from a TIN surface pairing is shown in Fig. 2.32. The TIN volume was used to estimate the increase in volume between two subsequent surveys, which was taken as a measure of waste placed in the landfill for a given time increment. The total TIN volume obtained between subsequent TIN surfaces was then dissected into phase-specific waste volumes based on polylines representing the phase delineations. An example of the phase delineation of a given TIN volume is shown in Fig. 2.33. The ratio of waste volume increase in a given phase to total waste volume increase for the landfill was computed for each time period defined by a TIN surface pairing. These volumetric waste fractions were applied to landfill waste tonnage data provided by Landfill T to estimate waste tonnage placed in each phase.

A comparison of waste disposal volumes computed from the total landfill and phase-specific CAD analyses to annual waste disposal volumes reported by Landfill T is shown in Fig. 2.34. Good comparison was obtained between the CAD volume estimation technique and the reported waste disposal volumes. Modest differences in waste volumes may be attributed to factors such as assumed densities at Landfill T (ranging from 540 kg/m^3 to 1,963 kg/m^3) to compute waste volume, settlement of the waste mass between subsequent surveys, or conversion of spatial measurements to digital resolution in CAD. The waste volume estimation in CAD reflected the general trend of waste disposal in Landfill T and provided a basis for phase-specific allocation of waste disposal between subsequent surveys.

The CAD files made available to determine the phase-specific waste disposal volumes ranged from April 2002 to June 2015, which did not cover the extent of waste filling at Landfill T. Phase-specific waste filling from the start of landfill operations (January 1995) to the first available CAD file (April 2002) was estimated from a waste filling log provided by the landfill operators. The filling log included notes relating to which phase waste was deposited in between 1995 and 2002. However, the notes did not specify the amount of waste disposed in a given phase when waste was disposed in multiple phases simultaneously. Thus, waste was assumed disposed equally among phases for the time period between 1995 and 2002 when waste was simultaneously placed in multiple phases.

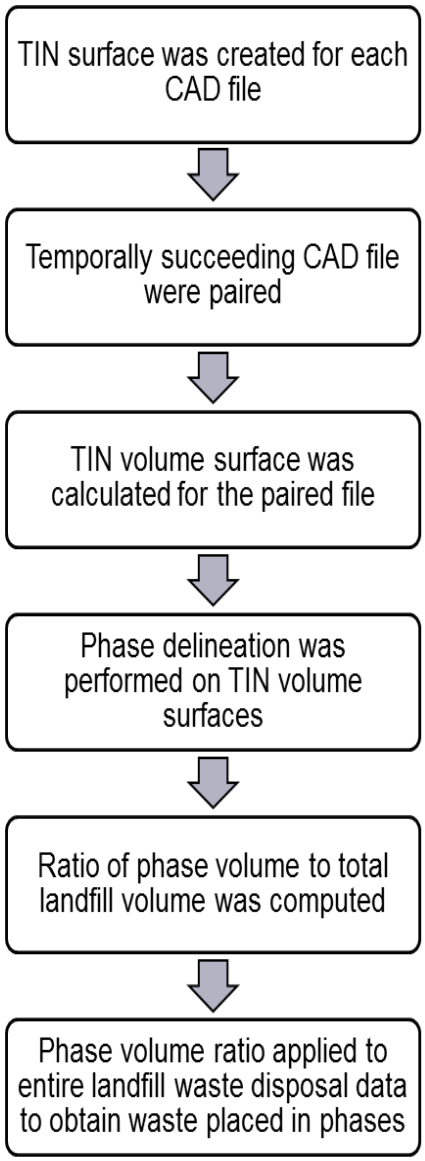

Fig. 2.30. Flowchart depicting steps of the CAD volume analysis to determine relative waste filling volumes of each phase at Landfill T.

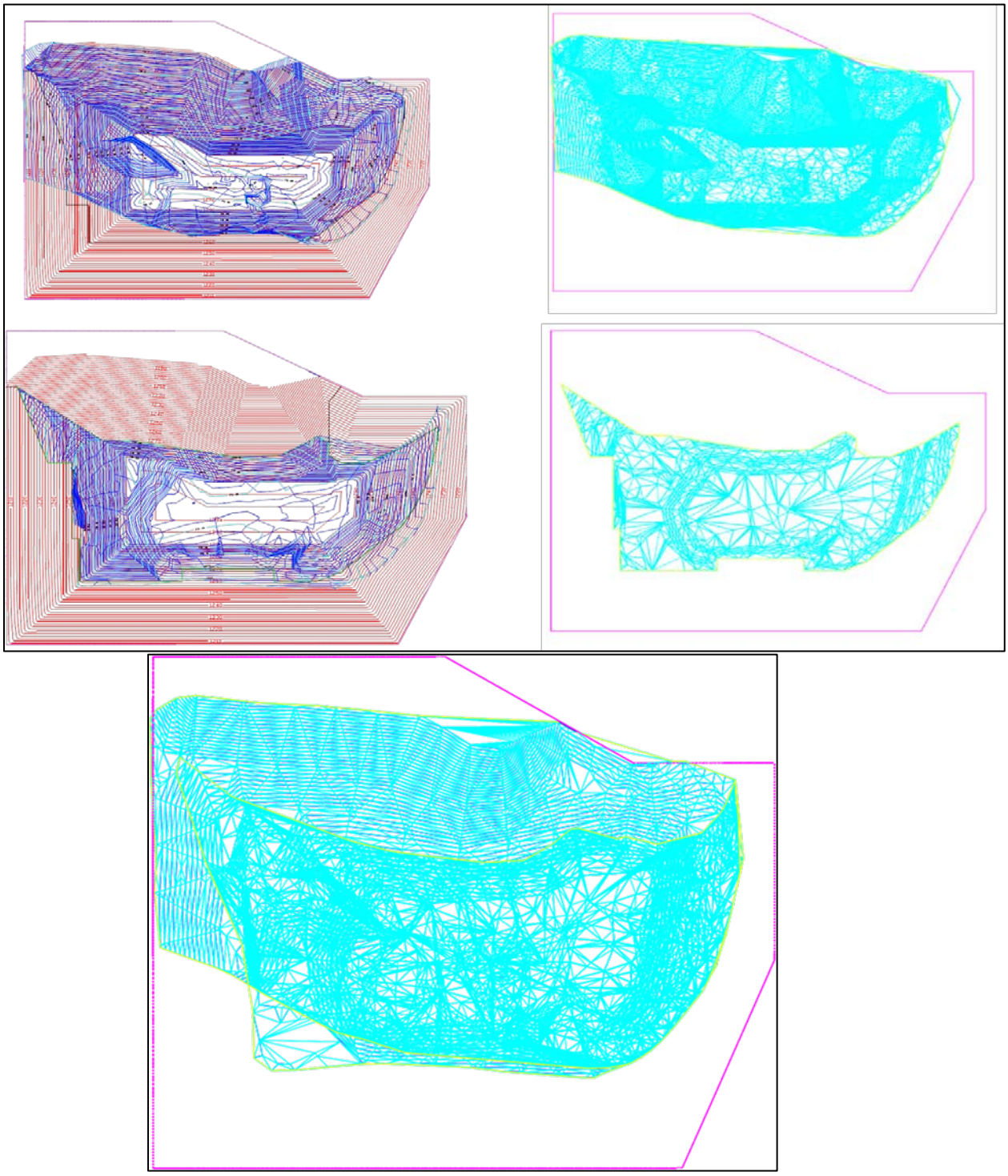

Fig. 2.31. Triangular Irregular Network (TIN) surface for (a) single CAD file and (b) for paired CAD files.

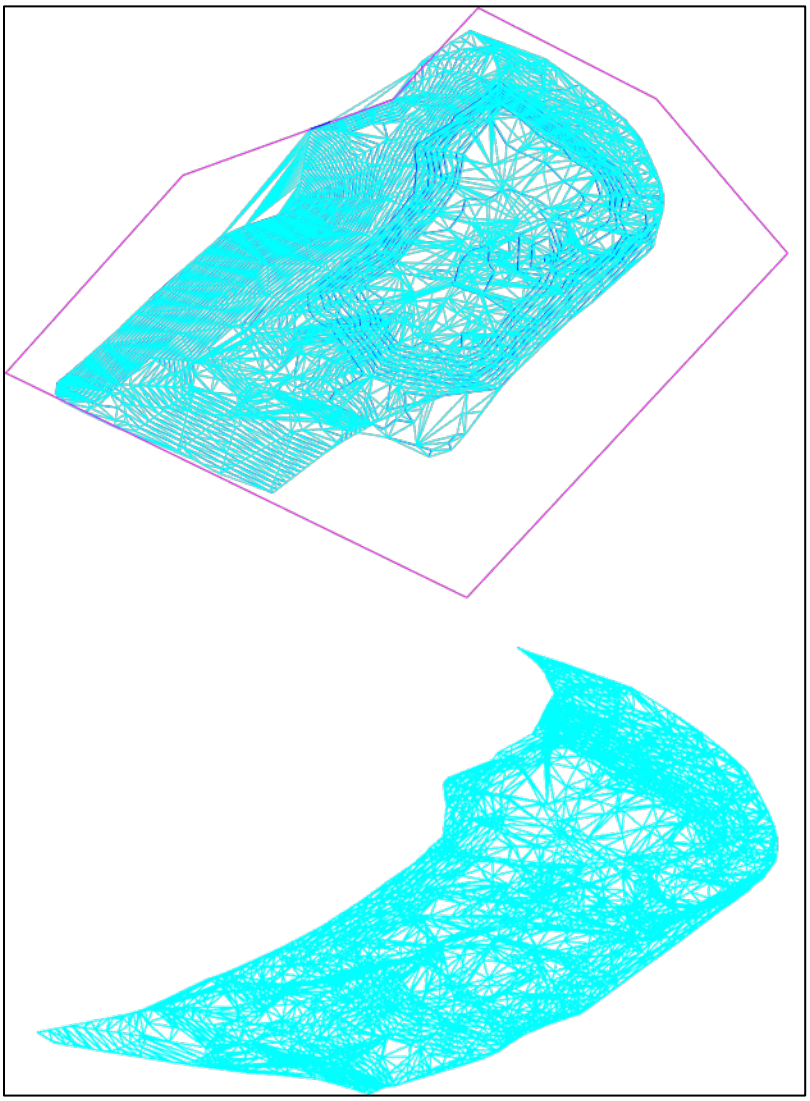

Fig. 2.32. Triangular Irregular Network volume surface for a paired CAD file.

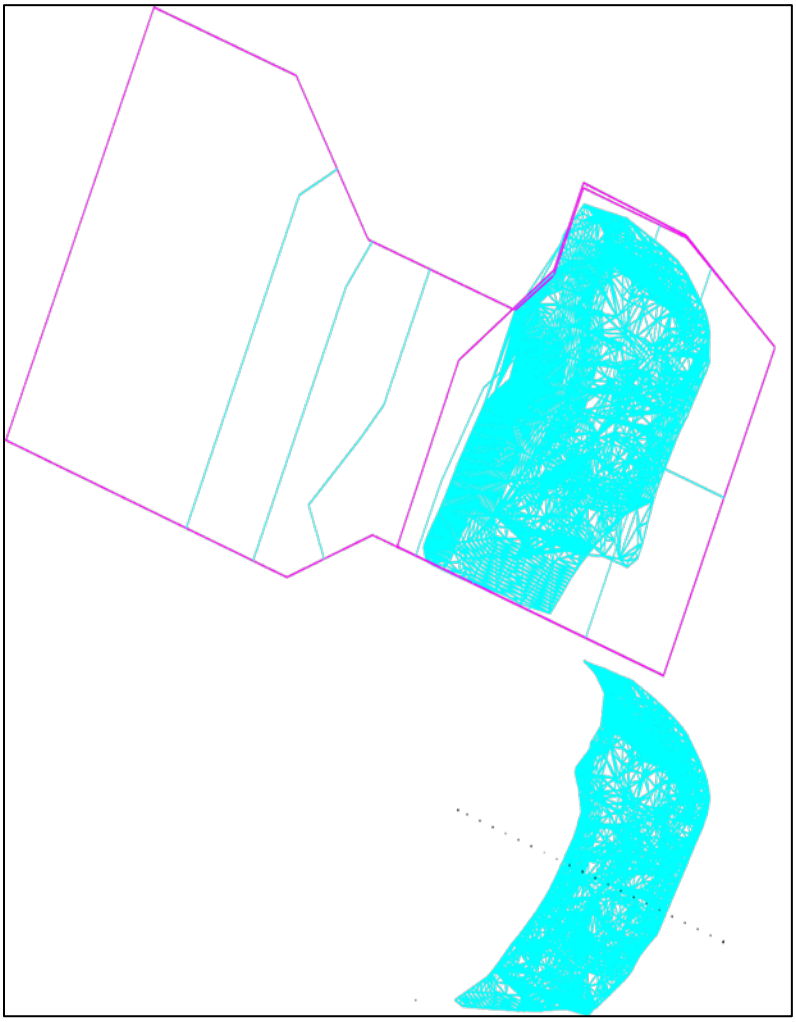

Fig. 2.33. Phase delineation of a Triangular Irregular Network volume surface.

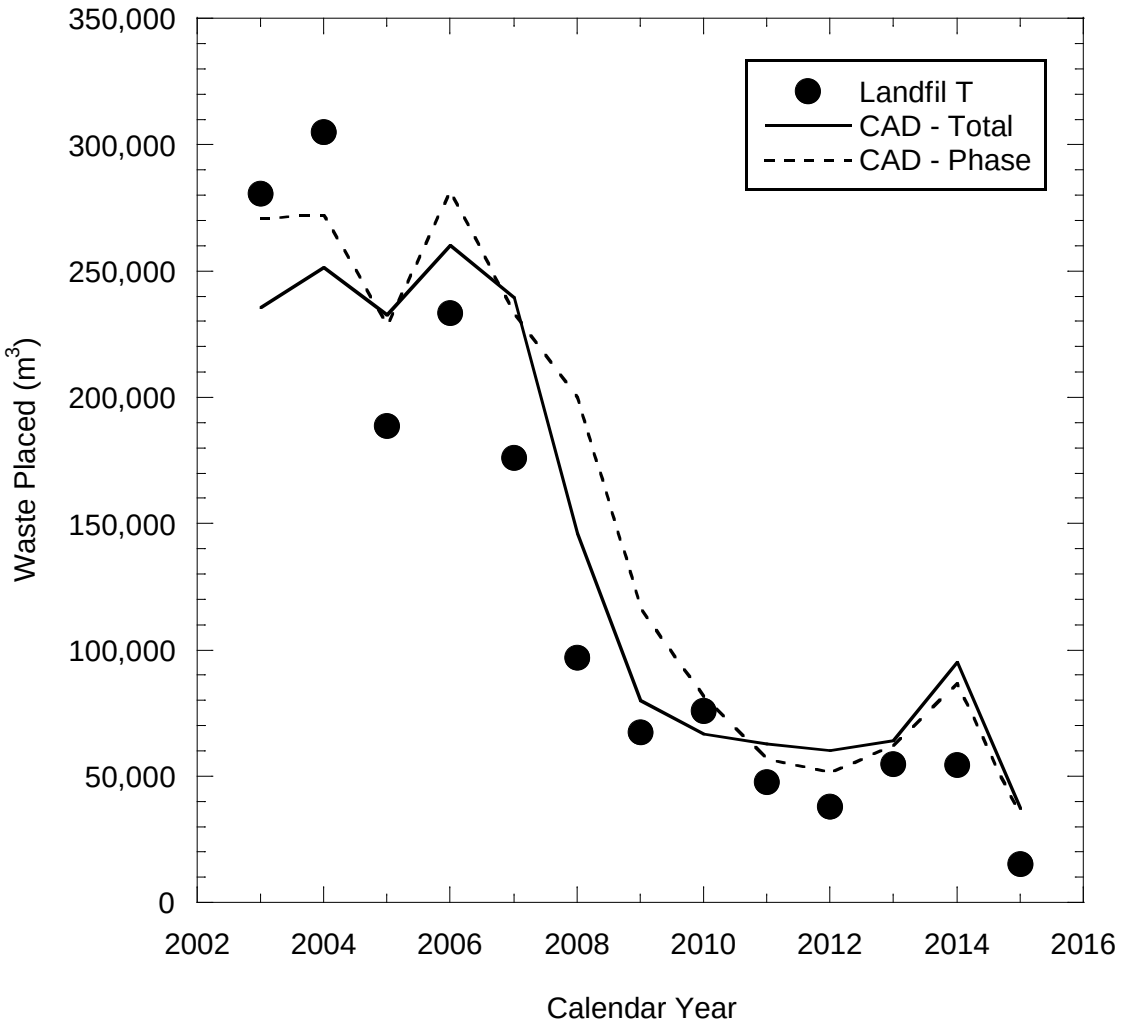

Fig. 2.34. Temporal relationships of total waste volume disposed in Landfill T based on CAD volume estimates and Landfill T monitoring data.

4.4 LandGEM Modeling

The U.S. EPA LandGEM was modified to include a collection efficiency term and to estimate CH_4 generation on a monthly basis as opposed to the deci-year equivalent used in the conventional model. This reformulation of LandGEM was adopted from Wang et al. (2013, 2015), and is conducive for direct comparison with landfill monitoring data. The modified version of LandGEM used in this study was the following:

$$Q_j = \frac{k \cdot L_0}{12} \sum_{i=1}^{j} \alpha \cdot M_i \cdot e^{\left[-k\left(\frac{j-i}{12}\right)\right]} \tag{1.1}$$

where Q_j is the CH_4 generation rate (m^3/month) in month j, k is the first-order decay coefficient (1/yr), L_0 is the CH_4 generation potential (m^3-CH_4/Mg-waste), α is the gas collection efficiency, and M_i is the mass of MSW deposited in month i (Mg).

4.4.1 Collection Efficiency

Gas collection efficiency (α) was incorporated into the LFG modeling to account for the fact that not all LFG generated during waste decomposition is collected in a GCS. To account for temporal variations in operation conditions, GCS, and extent of landfill cover, two gas collection efficiencies were used in the landfill gas models: (i) constant α of 85% and (ii) temporally varying α [α = *f(t)*] based on site-specific conditions.

A constant, site-wide α = 85% was chosen based on the current state 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 implemented to account for temporal and spatial variability in deployment and operation of a GCS. The range of α values used to evaluate the temporally varying collection efficiency was adopted from Mantell (2016) and from observations reported in literature (Spokas et al. 2006; SWANA 2007; SCS Engineers 2008; US EPA 2008). A summary of the temporally varying α used in this study is in Table 2.6. 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 (Mantell 2016). The two LFG collection efficiency procedures were applied to collected (i.e., measured) CH_4 data to increase flow rates and approximate actual CH_4 generation.

4.4.2 Decay Rate Optimizations

Landfill gas simulation was conducted on a site-wide basis at Landfill T, which accounted for all gas flow measurements throughout the entire site. Landfill gas modeling was also conducted for phase-specific analyses, which only incorporated gas collected and waste placed within a particular phase. The modified LandGEM model in Eq. 1 was applied based on the following conditions: (i) assumed L_0 = 100 m^3-CH_4/Mg-waste; (ii) assumed α = 100%, since the two α values [α = 85% and α = *f(t)*] were applied to modify LFG flow rate data; (iii) assumed the mass of CH_4 generating waste consisted of MSW; and (iv) optimized k to minimize the sum of square residuals between LFG collection data and gas flow predicted via LandGEM. These conditions were applied to monthly CH_4 flow rates and annual average CH_4 flow rates to assess if there was any difference in k based on averaging the flow rate data.

The value of L_0 has been reported to range between 6 and 270 m^3-CH_4/Mg-waste depending on composition of the waste stream (US EPA AP-42 1998; Staley and Barlaz

2009; Oonk 2010). The actual L_0 most likely varies between landfills and across a given landfill. Staley and Barlaz (2009) reported that L_0 varies from 59 to 64 m^3-CH_4/Mg-

Table 2.6. Range of estimated gas collection efficiencies adapted from Mantell (2016) with supporting information on criteria evaluated to calculate temporally varying gas collection efficiencies (α = 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 +	0.7	0.7

waste based on U.S. EPA and U.S. state-specific waste characterization data. However, recent investigations of full-scale LFG data suggest that L_0 = 100 m^3-CH_4/Mg-waste provides a best fit between LandGEM predictions and gas collection measurements (Wang et al. 2013). Hence, 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 the 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 differences between the measured and predicted CH_4 flow rates were summed to compute the SSR. A coefficient of determination (R^2) was computed as 1 minus the ratio of SSR to total sum of squares (SST). The AP-42 default *k* = 0.04 1/yr was used as the starting value in all simulations to provide consistency between optimizations.

4.5 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 2.5) 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 5 was completed in May 2015 prior to this study and the end dates for waste filling (Table 2.3) 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 Phases 6 and 7 were completed assuming waste placement stopped in June 2015, the last month MSW disposal data were recorded. For the site wide analysis of the organic stability evaluation, two scenarios were considered for the end date of waste filing. The first scenario was an end of filling date of June 2015 (i.e. last available waste placement data) which provides a basis for assessing site-wide organic stability for in-place waste in the entire landfill. The second scenario considered an end of filling date of January 2025 assuming Landfill T is operated for 30 yr, which is a typical design life for a landfill. Finally, all site-wide and phase specific 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 2.7. 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 2.7 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 $\alpha = 85\%$ (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.

Table 2.7 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	20.4	2,502,427	9,708 (480)	4,860 (240)	17,028 (852)	8,688 (432)
Site-Wide 2	18.4	2,035,114	7,872 (396)	3,936 (192)	15,156 (756)	7,428 (372)
3 & 4	18.4	691,905	5,880 (288)	2,940 (144)	19,968 (996)	10,992 (552)
5	14.5	431,782	13,728 (684)	6,864 (348)	27,828 (1,392)	13,992 (696)
6	12.5	650,386	14,724 (732)	7,368 (372)	31,320 (1,560)	15,660 (780)
7	9	261,041	5040 (252)	2,508 (120)	12,888 (648)	5,280 (264)

Notes: (i) 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). (ii) Flow rates corresponding to 5% of total gas or methane flow rate are included in parentheses.

REFERENCES

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

Amini, H. R., Reinhart, D. R., and Mackie, K. R. (2012). Determination of first-order landfill gas modeling parameters and uncertainties. *Waste Management*, 32(2), 305–316.

Amini, H. R., Reinhart, D. R., and 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. A., Benson, C. H., Barlaz, M. A., Edil, T. B., and Tolaymat, T. M. (2010). Performance of North American Bioreactor Landfills. I: Leachate Hydrology and Waste Settlement. *Journal of Environmental Engineering*, 136(8), 839–853.

Bareither, C. A., Barlaz, M. A., Doran, M., and Benson, C. H. (2017). Retrospective Analysis of Wisconsin's Landfill Organic Stability Rule, *Journal of Environmental Engineering*, 143(3), 1–11.

Barlaz, M., Ham, R., and Schaefer, D. (1990). Methane production from municipal refuse: a review of enhancement techniques and microbial dynamics. *Critical Reviews in Environmental Control*, 19(6), 557–584.

Barlaz, M. A., Ham, R. K., and Schaefer, D. M. (1992). Microbial, chemical and methane production characteristics of anaerobically decomposed refuse with and without leachate recycling. *Waste Management and Research*, 10(3), 257–267.

Barlaz, M. A., Chanton, J. P., and Green, R. B. (2009). Controls on Landfill Gas Collection Efficiency: Instantaneous and Lifetime Performance. *Journal of the Air & Waste Management Association*, 59(12), 1399–1404.

Barlaz, M.A., Bareither, C.A., Hossain, A., Saquing, J., Mezzari, I., Benson, C.H., Tolyamat, 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.

Benson, C. H., Barlaz, M. A., Lane, D. T., and Rawe, J. M. (2007). Practice review of five bioreactor/recirculation landfills. *Waste Management*, 27(1), 13–29.

Chakma, S., and Mathur, S. (2016). Modelling gas generation for landfill. *Environmental Technology*, 3330, 1–8.

DeAbreu, R. (2003). *Facultative Bioreactor Landfill: An Environmental and Geotechnical Study*. University of New Orleans, Theses and Dissertations. Paper 39.

Faour, A. A., Reinhart, D. R., and You, H. (2007). First-order kinetic gas generation model parameters for wet landfills. *Waste Management*, 27(7), 946–953.

Fei, X., Zekkos, D., and Raskin, L. (2015). Quantification of parameters influencing methane generation due to biodegradation of municipal solid waste in landfills and laboratory experiments. *Waste Management*, 55, 276–287.

Grugnaletti, M., Pantini, S., Verginelli, I., and Lombardi, F. (2016). An easy-to-use tool for the evaluation of leachate production at landfill sites. *Waste Management*, 55, 204–219.

Hao, Y. J., Wu, W. X., Wu, S. W., Sun, H., and Chen, Y. X. (2008). Municipal solid waste decomposition under oversaturated condition in comparison with leachate recirculation. *Process Biochemistry*, *43*(1), 108–112.

Kjeldsen, P., Barlaz, M. A., Rooker, A. P., Baun, A., Ledin, A., and Christensen, T. H. (2002). Present and Long-Term Composition of MSW Landfill Leachate: A Review. *Critical Reviews in Environmental Science and Technology*, 32(4), 297–336.

Kurniawan, T. A., Lo, W. H., and Chan, G. Y. S. (2006). Physico-chemical treatments for removal of recalcitrant contaminants from landfill leachate. *Journal of Hazardous Materials*, 129(1–3), 80–100.

Lema, J. M., Mendez, R., and Blazquez, R. (1988). Characteristics of landfill leachates and alternatives for their treatment: A review. *Water, Air, and Soil Pollution*, 40(3–4), 223–250.

Mantell, S. (2016). *Landfill gas analysis to support an assessment of organic waste stability*, M.S. Thesis, Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, Colorado, USA.

Method 9095, Revision 1, November 2004, Final Update III to the Third Edition of the Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, EPA publication SW-846.

Morris, J. W., Crest, M., Barlaz, M. A., Spokas, K. A., Åkerman, A., and Yuan, L. (2012). Improved methodology to assess modification and completion of landfill gas management in the aftercare period. *Waste Management*, 32(12), 2364–2373.

Mou, Z., Scheutz, C., and Kjeldsen, P. (2015). Evaluation and application of site-specific data to revise the first-order decay model for estimating landfill gas generation and emissions at Danish landfills. *Journal of the Air & Waste Management Association*, 65(6), 686–698.

Ogor, Y., and Guerbois, M. (2005). Comparison of landfill methane emission models; a case study. Proc. *10th International Waste Management and Landfill Symposium*, Sardinia, Italy.

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

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., and Basel Al-Yousfi, A. (1996). The Impact of Leachate Recirculation On Municipal Solid Waste Landfill Operating Characteristics. *Waste Management & Research*, 14(4), 337–346.

Reinhart, D. R., McCreanor, P. T., and Townsend, T. (2002). The bioreactor landfill: Its status and future. *Waste Management & Research*, 20(2), 172–186.

Renou, S., Givaudan, J. G., Poulain, S., Dirassouyan, F., and Moulin, P. (2008). Landfill leachate treatment: Review and opportunity. *Journal of Hazardous Materials*, 150(3), 468–493.

Scharff, H., and Jacobs, J. (2006). Applying guidance for methane emission estimation for landfills. *Waste Management*, 26(4), 417–429.

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.*

Sormunen, K., Laurila, T., and Rintala, J. (2013). Determination of waste decay rate for a large Finnish landfill by calibrating methane generation models on the basis of methane recovery and emissions. *Waste Management & Research*, 31(10), 979–985.

Spokas, K., Bogner, J., Chanton, J. P., Morcet, M., Aran, C., Graff, C., Golvan, Y. M., and 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.

Sponza, D. T., and Ağdağ, O. N. (2004). Impact of leachate recirculation and recirculation volume on stabilization of municipal solid wastes in simulated anaerobic bioreactors. *Process Biochemistry*, 39(12), 2157–2165.

Staley, B. F., Xu, F., Cowie, S. J., Barlaz, M. A., and Hater, G. R. (2006). Release of trace organic compounds during the decomposition of municipal solid waste components. *Environmental Science and Technology*, 40(19), 5984–5991.

Staley, B. F., and Barlaz, M. A. (2009). Composition of Municipal Solid Waste in the United States 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*.

Tchobanoglous G, Theisen H and Vigil SA. 1993. Integrated solid waste management: Engineering principles and management issues. McGraw-Hill, New York.

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

Tolaymat, T. M., Green, R. B., Hater, G. R., Barlaz, M. A., Black, P., Bronson, D., and Powell, J. (2010). Evaluation of Landfill Gas Decay Constant for Municipal Solid

Waste Landfills Operated as Bioreactors. *Journal of the Air & Waste Management Association*, 60(1), 91–97.

Townsend, T.G., Powell, J., Jain, P., Xu, Q., Tolaymat, T., and Reinhart, D. (2015). *Sustainable practices for landfill design and operation*, Waste Management Principles and Practice, New York: Springer. https://dx.doi.org/10.1007/978-1-4939-2662-6

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 Stated Environmental Protection Agency*, 40 CFR Part 258.

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.

US EPA (2014). Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012. *US Environmental Protection Agency*, 1–13.

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

Warith, M. (2002). Bioreactor landfills: Experimental and field results. *Waste Management*, 22(1), 7–17.

Zhan, T., Xu, X., Chen, Y., Ma, X., and 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.