THESIS

PHASE-BASED ANALYSIS TO DETERMINE FIRST ORDER DECAY RATES FOR A BIOREACTOR LANDFILL

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ABSTRACT

PHASE-BASED ANALYSIS TO DETERMINE FIRST ORDER DECAY RATES FOR A BIOREACTOR LANDFILL

In recent years, the goal of municipal solid waste (MSW) landfill 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 that results from moisture addition to increase the rate of anaerobic biodegradation can have different consequences on landfill operations. 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 this study, 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 and used to estimate methane generation based on two considerations of collection efficiency: constant collection efficiency of 85% and 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) 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*s for the phase-specific analyses ranged between 0.025 and 0.13 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* values 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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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

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.

1.2 Research Objectives and Tasks

The objective of this study was to estimate phase-specific first-order decay rates as a surrogate variable to assess waste stabilization in a bioreactor landfill. In this study, a methodology incorporating estimations of waste disposal in landfill phases coupled with phase-specific LFG collection data was used 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: BACKGROUND

2.1 Landfill Overview

Population growth, technological advancements, urban development, and increased consumption over the last century have increased waste generation throughout the world. The need to develop a safe and reliable long-term method for solid waste disposal resulted in the proliferation of sanitary landfills (Tchobanoglous et al. 1993; Townsend et al. 2015).

A landfill is an engineered facility for solid waste disposal that is designed and operated to protect human health and the environment. The basic design of a landfill consists of a waste containment liner system, leachate and gas management systems, and final cover system to close the landfill (Townsend et al. 2015). A liner system is placed at the bottom of the landfill to minimize off-site migration of leachate. In conventional landfills, solid waste is typically disposed in layers with daily cover (e.g., soil) placed over the waste as per environmental regulations. A final cover is required once the landfilled waste reaches final grades, and typically contains a low-permeability layer to mitigate LFG emissions and infiltration of precipitation.

Landfills are the predominant means for solid waste disposal in the U.S. and many parts of the world. This is primarily due to the economic advantage and design simplicity of landfills compared to alternatives such as incineration, anaerobic digestion, or composting (Hao et al. 2008; Chakma and Mathur 2016). In 2012, 227-million Mg of MSW was generated in the U.S., of which 54% was disposed in landfills, 34% was recycled, and 12% was incinerated (USEPA 2014). Considering all waste management alternatives have their benefits and limitations, landfilling is expected to remain a primary option for MSW in the U.S. and throughout the world for the foreseeable future (Bareither et al. 2010; Barlaz et al. 2010).

MSW landfills in the U.S. are regulated by Subtitle D of the Resource Conservation and Recovery Act and conventionally are operated as “dry tombs” where the moisture content of

waste is intended to remain low due to minimization of moisture infiltration (RCRA 1976; Benson et al. 2007). Moisture ingress into landfilled waste during operation or post-closure that contains undecomposed organic material may result in an increase in gas and leachate production that can have adverse environmental impacts (Reinhart and Al-Yousfi 1996). Thus, regulators are evaluating landfill management operations to reduce long-term environmental risks and post-closure care (PCC) associated with undecomposed organic waste (Morris et al. 2012).

Reducing the risks associated with closed landfills can be achieved through enhanced decomposition of the organic fraction of waste within a landfill to reduce the release of chemical constituents to the environment. For example, in the State of Wisconsin regulations now stipulate that new landfills are to be operated in a manner such that 75% of LFG generation is completed within 40-yr post-closure (Bareither et al. 2017). In addition, available land for the development of new landfills near dense populated areas is becoming scarce, thereby increasing the need for systems that provide waste treatment instead of waste sequestration. Landfill operations that can reduce leachate treatment costs, increase CH_4 generation, accelerate waste decomposition, and enhance landfill air space recovery appeal to landfill owners (Warith 2002; Bareither et al. 2017). These benefits to landfill-based waste management have been demonstrated through the operation of bioreactor landfills, which are operated with the overarching objective to enhance MSW biodegradation (Reinhart and Al-Yousfi 1996; Benson et al. 2007; Bareither et al. 2010; Townsend et al. 2015).

2.2 Bioreactor Landfills

An anaerobic bioreactor landfill (herein referred to as a “bioreactor landfill”) is an MSW landfill (or a portion of an MSW landfill) operated with a deliberate goal to enhance anaerobic biodegradation of the organic fraction of MSW (Bareither et al. 2010). An increase in waste biodegradation (i.e., waste stabilization) can be achieved within the waste mass by promoting

favorable environmental conditions that enhance anaerobic decomposition processes (Reinhart et al. 2002). Environmental conditions that impact waste biodegradation include pH, temperature, nutrient availability, absence of toxins, moisture content, particle size, and oxidation-reduction potential. Moisture content of the waste can be readily increased via operational techniques and has received the most attention as a control parameter for bioreactor landfills (Reinhart and Al-Yousfi 1996; Chakma and Mathur 2016). Thus, the definition of a bioreactor landfill can also include a target average waste moisture content of at least 40% (by weight), which has been demonstrated to improve anaerobic biodegradation (USEPA 2004).

Bioreactor landfills are primarily operated through the addition of leachate or other liquid amendments to accelerate waste decomposition (Reinhart et al. 2002). Waste shredding, pH adjustment, sewage sludge addition, pre-composting, and enzyme addition are other enhancement techniques employed to enhance waste decomposition (DeAbreu 2003). However, a key component of most bioreactor landfills is the addition of liquids to the waste mass (Reinhart et al. 2002; DeAbreu 2003; Bareither et al. 2017).

The most common method of liquid addition in a bioreactor landfill is leachate recirculation (Reinhart et al. 2002; Bareither et al. 2010). Leachate is collected from the leachate collection system and recirculated into the waste mass via trenches, wells, or surface application. The advantages of leachate recirculation include in-situ leachate treatment, distribution of nutrients and enzymes within the waste mass, pH buffering, dilution of inhibitory compounds, acceleration of landfill gas production, and reduction in time and cost of post-closure care (Reinhart et al. 2002; DeAbreu et al. 2003; Benson et al. 2007; Tolaymat et al. 2010). However, the addition of leachate and supplemental liquids can also lead to increased hydraulic head on liners, leachate seeps and ponds, development of acidic conditions, and stability concerns due to reduction in waste shear strength (DeAbreu et al. 2003, Sponza and Agdag 2004).

In addition to leachate recirculation, other means of liquid addition are used in bioreactor landfills. Addition of storm water, groundwater, or surface water, disposal of high water-retaining waste (e.g., wastewater sludge), and disposal of commercial liquid waste are common moisture enhancement techniques in bioreactor landfills (Townsend et al. 2015). The moisture enhancement strategies of concern in this study are leachate recirculation and commercial liquid waste disposal. These moisture enhancement strategies were the primary means of liquid addition at Landfill T.

2.2.1 Leachate Recirculation

Landfill leachate is generated via precipitation entering the waste mass of a landfill and subsequently percolating through the waste to the leachate collection system (Tchobanoglous et al. 1993). Physical, chemical, and biological reactions in the waste transfer chemical constituents from the waste to the percolating water (Kjeldsen et al. 2002). Leachate generally contains high concentrations of soluble organic matter and inorganic ions (Lema et al. 1988; Barlaz et al. 2010). However, leachate quality and quantity vary considerably depending on site-specific factors such as waste composition, age of waste, landfill design, disposal method, liquid and gas transport mechanisms, and climatic conditions (Grugnaletti et al. 2016). For example, leachate sampled during the acidic stage of decomposition will have low pH and high concentrations of chemical oxygen demand (COD), biochemical oxygen demand (BOD), total organic carbon (TOC), and heavy metals; whereas leachate sampled during the methane fermentation phase will have neutral pH (6.5 to 7.5) and lower concentrations of BOD, TOC, and COD (Tchobanoglous et al. 1993).

The chemical composition of leachate can render leachate detrimental to the surrounding environment and to public health in the event leachate leaks through the liner system and migrates into groundwater or surface water. These risks are mitigated via barrier

systems and leachate collection systems. However, leachate treatment and disposal are challenges at most landfills. Currently, methods to treat landfill leachate include transfer and subsequent treatment at a wastewater treatment plant, on-site biological treatment (e.g., lagoons, activated sludge, digesters, etc.), and physico-chemical treatment (e.g., coagulation, membrane filtration, activated carbon adsorption) (Kurniawan et al. 2006; Renou et al. 2008). A cost effective and broadly adopted leachate treatment options is leachate recirculation (Reinhart and Al-Yousfi 1996; Sponza and Agdag 2004; Renou et al. 2008).

Leachate recirculation is the recycling of leachate into the waste mass of a landfill. Current methods of leachate recirculation include pre-wetting of waste, surface application (e.g., spraying, surface ponds, etc.), vertical injection wells, and horizontal infiltration trenches and blankets (Reinhart 1996; Bareither et al. 2010). Recirculation of leachate has been shown to reduce the dissolved organic fraction of the leachate via enhanced anaerobic biodegradation (Sponza and Agdag 2004; Barlaz et al. 2009; Barlaz et al. 2010). Thus, leachate recirculation increases waste stabilization by enhancing microbial degradation via increased waste moisture content, distribution of microbes, substrates, and nutrients throughout mass, and diluting local high concentrations of inhibitors, which all lead to a more favorable environment for proliferation of anaerobic microorganisms (Barlaz et al. 1990; DeAbreu 2003).

Conversely, excessive leachate recirculation can have adverse effects on waste stabilization. Large volumes of recirculated leachate can culminate in problems such as waste saturation and ponding that promotes seepage out of the waste, development of acidic conditions, and accumulation of ammonia-nitrogen that can be inhibitory to methanogenesis (Sponza and Agdag 2004; Hao et al. 2008). Also, large recirculation rates can result in removal of nutrients and substrates.

2.2.2 Commercial Liquid Waste Disposal

Although leachate recirculation is permissible under Subtitle D of RCRA, the addition of liquids other than leachate generally has not been permitted by state regulatory agencies (Benson et al. 2007). To counter this practice, the U.S. EPA promulgated a Research Development and Demonstration (RD&D) rule in March 2004 (USEPA 2004). The RD&D rule grants landfill operators the capacity to experiment with liquid addition as long as there is no detrimental impact on human health and the environment (Benson et al. 2007).

An RD&D permit issued to a landfill grants 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; Bareither et al. 2017). For example, the main objectives of the RD&D program at Landfill T were to (i) evaluate the operational feasibility of disposing liquids other than leachate to the waste mass and (ii) assess the impact of commercial liquid disposal on waste degradation. Diverse factors are considered with the quantity of liquid waste accepted at a given landfill, including the mass of MSW available to store liquid, revenue associated with liquid waste acceptance, and costs associated with leachate generation (Bareither et al. 2017). Common liquid wastes accepted under the RD&D rule include commercial process liquids, cleaning water, and sludge. The predominant means of liquid waste disposal is discharge onto the working face of a landfill (Bareither et al. 2017).

2.3 Landfill Gas

Organic solid waste disposed in landfills undergoes transformation by microbially mediated processes. Anaerobic waste stabilization generally occurs in five sequential stages with the characteristics of the generated leachate and produced gas varying between stages (Barlaz et al. 1992; Reinhart and Al-Yousfi 1996; Kjeldsen et al. 2002).

(i) Stage I: an initial adjustment phase that entails accumulation of moisture and microbial decomposition of organic matter by aerobic microorganisms.

(ii) Stage II: transition phase in which oxygen is depleted and anaerobic conditions develop, which includes an increase in leachate COD via accumulation of volatile fatty acids (VFAs).

(iii) Stage III: an acid formation phase that involves rapid production of VFAs resulting in a decrease in leachate pH and mobilization of metallic species.

(iv) Stage IV: a methane fermentation phase in which VFAs are consumed and converted to CH_4 and CO_2 by methanogenic organisms. Leachate pH increases and CH_4 generation increases.

(v) Stage V: a maturation phase where readily available substrates become limiting and biological activity slows down. In this phase, there is a decrease in the rate of waste biodegradation and gas production.

The major end product of waste decomposition is the production of LFG, which primarily consists of CH_4 and CO_2 at concentrations of approximately 50% CH_4 and 50% CO_2 (Tchobanoglous et al. 1993; Amini et al. 2012; Fei et al. 2015). Landfill gas also contains trace concentrations of organic compounds, including alkanes, aromatics, chlorinated aliphatic hydrocarbons, alcohols, ketones, terpenes, chlorofluoro compounds (CFCs), and siloxanes (Staley et al. 2006). Although CH_4 and CO_2 are both greenhouse gases, CH_4 has a global warming potential 25 times that of CO_2 on the basis of a 100-yr time frame (Barlaz et al. 2009). Thus, minimizing CH_4 emissions is a regular requirement at all solid waste landfills.

Ideally, all generated CH_4 would be captured by the landfill gas collection system (GCS) and used as an energy source. However, collection efficiency is not 100% in landfills as some CH_4 is released before the installation of a GCS and some CH_4 is released due to imperfect gas collection systems, lateral off-site migration, and transport through cover systems (Barlaz et al. 2009). The ratio of the LFG collected in a GCS to the amount of LFG generated in a landfill is referred to as the LFG collection efficiency. There is considerable interest in enhancing LFG collection efficiencies to reduce emissions and increase available LFG for energy generation.

2.4 Landfill Gas Modeling

There has been agreement amongst regulatory agencies and landfill operators for the development of models to predict CH_4 generation in landfills. Over the years, numerous CH_4 generation models have been proposed, developed, and implemented based on zero-, first-, and second-order waste degradation kinetics (Amini et al. 2013). However, the use of first-order decay (FOD) models is recommended for industrial and regulatory applications (Scharff and Jacob, 2006; Amini et al. 2013). Typical FOD models are based on first-order kinetics of biological degradation that incorporate a first-order CH_4 generation rate coefficient, (k), and CH_4 generation potential (L_0) of the landfilled waste (Sormunen et al. 2013; Amini et al. 2013). Common examples of FOD models used to calculate landfill methane emissions include the TNO model, EPER model, Afvalzorg multi-phase model, LandGEM, and GasSIM (Scharff and Jacobs. 2006; Mou et al. 2015). However, LandGEM is the most commonly used CH_4 prediction model in the U.S. (USEPA 2005; Tolaymat et al. 2010).

2.4.1 LandGEM

The Landfill Gas Emissions Model (LandGEM) is a FOD model developed by the U.S. EPA to inventory landfill gas emissions (USEPA 2005). LandGEM uses a Microsoft Excel interface to estimate emissions for total landfill gas, methane, carbon dioxide, nonmethane organic compounds, and individual air pollutants from MSW landfills (USEPA 2005). Site-specific data or recommended default parameters can be used in LandGEM to estimate LFG emissions. The recommended default parameters are based on emission factors in the U.S. EPA's Compilation of Air Pollutant Emission Factors (AP-42) (USEPA 2005). These default parameters provide average emissions and can be used for predicting future emission inventories for landfills in the absence of site-specific test data (USEPA 2005). The default values for k and L_0 are 0.04 1/yr and 100 m^3-CH_4/Mg-MSW, respectively (USEPA 2005). However, the AP-42 default k = 0.04 1/yr does not reflect enhanced waste degradation

processes in bioreactor landfills (Faour et al. 2007; Amini et al. 2012). LandGEM has been widely used in previous studies to estimate *k* for bioreactors on the basis of field data (Faour et al. 2007; Barlaz et al. 2009; Amini et al. 2012; Sormunen et al. 2013; Wang et al. 2013); however, this approach has not been extended to estimate *k* in specific phases of a bioreactor. In addition, landfill operators do not record phase-specific waste disposal data and this can result in difficulties when attempting to model gas generation in specific phases. Hence, there is a need to develop a framework to estimate *k* for specific phases of a given landfill, especially in bioreactors with phases operated under different moisture enhancement strategies.

CHAPTER 3: METHODOLOGY

3.1 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. 1. 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 1. Temporal trends of the average daily filling rate of MSW at Landfill T are shown in Fig. 2. 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).

Characteristics of the waste moisture enhancement strategies for the phases of Landfill T are summarized in Table 2. 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 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. 3. 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. 4. 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. 3b). The average daily rate of leachate recirculation was similar between Phase 3 & 4, Phase 6, and Phase 7 (Fig. 4).

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. 5. Cumulative volumes of the main types of liquid wastes disposed in each phase are shown in Fig. 6. 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. 5). 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. 7. 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. 8. 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 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 3, 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. 9. The daily total LFG flow rates in Fig. 9 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). 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).

3.2 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. 10. 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 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.

3.3 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. 11. 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 12. 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. 13. 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. 14. 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. 15. 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.

3.4 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:

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

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).

3.4.1 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 4.

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.

3.4.2 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-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.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Landfill Gas Model Simulations

Landfill gas model simulations for Landfill T focused on CH_4 generation, since CH_4 is a direct output from LandGEM and CH_4 flow rates at landfill T were computed from LFG flow rates and the measured percent CH_4 contribution. The CH_4 generation modeling approach included two temporal averages for CH_4 flow rates (monthly and annual averages), two considerations for LFG collection efficiency [α = 85% and $\alpha = f(t)$], and two considerations for the collected LFG volumes. The LFG volume considerations included (i) LFG collected only in gas wells and (ii) LFG collected in gas wells plus LFG collected in the LCRs and LRTs. The first scenario, *Scenario I*, only considered CH_4 collected from the gas extraction wells, whereas the second scenario, *Scenario II*, considered CH_4 collected from gas wells, LCRs, and LRTs. The goal of these LFG model simulations was to compare statistical significance and practicality to develop recommendations for future LFG modeling to assess waste decomposition and organic waste stability.

4.1.1 Scenario I: Modeling Gas Extracted from Gas Wells

Temporal relationships of the adjusted CH_4 flow rates and optimized LandGEM model simulations for the site-wide and phase-specific analyses conducted for Scenario I are shown in Figs. 16 through 23. The adjusted CH_4 flow rates reflect the two different collection efficiency considerations [α = 85% and $\alpha = f(t)$] that were applied to CH_4 collected. In general, the $\alpha = f(t)$ yielded higher adjusted CH_4 flow rates relative to α = 85% during the early stages of gas generation, and subsequently $\alpha = f(t)$ yielded lower adjusted CH_4 flow rates relative to α = 85%. This was attributed to low collection efficiencies assumed for the $\alpha = f(t)$ consideration early in life of a landfill, which yielded higher adjusted CH_4 flow rates. In contrast, as final cover was

deployed during the lifespan of a landfill, $\alpha = f(t)$ was increased to account for more collection and ultimately considered $\alpha > 85\%$, which implied that the majority of gas generated during biodegradation of organic waste was collected.

A summary of optimized k for all gas analyses conducted for Scenario I is shown in Fig. 24 and tabulated in Table 5. The summary in Table 5 includes the coefficient of determination (R^2) computed for each model simulation. First-order decay rates for the site-wide analysis ranged from 0.052 to 0.055 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. An average k = 0.045 1/yr was determined for Site-Wide 2, which was lower than the k obtained in the Site-Wide 1 analysis. 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. 18). There is a possibility that 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 = 0.045 1/yr.

Monthly and annual CH_4 flow rate simulations for Phase 1A & 2A and Phase 1B & 2B are shown in Figs. 18 and 19, respectively. The *k*s for Phase 1A & 2A ranged between 0.119 and 0.127 1/yr, whereas the *k*s for Phase 1B and 2B ranged between 0.080 and 0.090 1/yr (Table 5). 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 0.025 and 0.065 1/yr (Table 5). 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 1). 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. 18), 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.

Temporal trends of adjusted CH_4 flow rates and model predictions for Phase 3 & 4 are shown in Fig. 20. Phase 3 & 4 was the first phase at Landfill T to receive substantial recirculated leachate (Table 2), but the optimized *k* from the CH_4 generation modeling ranged between 0.026 to 0.029 1/yr. These *k* for Phase 3 & 4 are lower than the AP-42 default value of 0.04 1/yr for a conventional landfill. The low *k* for Phase 3 & 4 may be as a result of lower liquid addition relative to more recent phases (Table 2) and/or the absence of LFG collection data from the LRC and LRT connections in this phase. Thus, the possibility of additional LFG generation in Phase 3 & 4 that was not accounted for in the adjusted CH_4 flow rates would lead to a lower *k*.

Temporal tends of annual and monthly adjusted CH_4 flow rates and LandGEM simulations for Phase 5, 6, and 7 are shown in Fig. 21, Fig. 22, and Fig. 23, respectively. The *k* values decreased with decreasing waste age from Phase 5 (0.058 to 0.065 1/yr) to Phase 6 (0.042 to 0.043 1/yr) to Phase 7 (0.030 to 0.037 1/yr). These ranges of *k* are low for landfills

that have had liquid added to increase the waste moisture content. However, the highest R^2s were obtained for these three phases relative to the other phase-specific gas model simulations completed for Scenario 1. The largest R^2 = 0.27 was obtained for Phase 6 for annual CH_4 flow rates with α = 85%. In general, the R^2s obtained for Scenario I were low and do not instill confidence in the gas flow simulation procedure. Larger R^2s and higher *k* values were obtained for Scenario II when additional LFG collected in the LCRs and LRTs was considered.

4.1.2 Scenario II: Modeling Gas Extracted from Gas Wells and Leachate Systems

Temporal relationships of adjusted CH_4 flow rates and gas model simulations for the site-wide and phase-specific analyses performed in Scenario II are shown in Figs. 25 through 32. The optimized *k* values from model simulations completed for Scenario II are shown in Fig. 33 and tabulated in Table 6 along with the corresponding R^2. In general, all *k* values obtained for the site-wide and phase-specific analyses in Scenario II were larger than the *k* values obtained for Scenario I. The increase in *k* for each model simulation in Scenario II was due to an increase in CH_4 flow rates by including LFG collected in the LCRs and LRTs (Fig. 9). This increase in LFG, increased CH_4 used in the model simulations and forced all simulations to increase the predicted CH_4 flow rates for the same MSW masses, which resulted in an increase in *k* when all other variables in LandGEM were held constant (Eq. 1).

The Site-Wide analysis in Scenario II yielded *k* ranging between 0.093 and 0.104 1/yr. The Site-Wide 2 analysis in Scenario II, which omitted MSW masses and LFG collected in Phase 1A & 2A and Phase 1B & 2B, yielded lower *k*s ranging between 0.076 and 0.080 1/yr. Thus, similar to Scenario I, including LFG from the oldest two landfill phases increased the site-wide *k*, which was believed non-representative of waste decomposition processes at Landfill T. The R^2 for the Site-Wide 2 analyses in Scenario 2 were > 0.32 for all four considerations (Table 6) and exemplify an improved fit between LandGEM and CH_4 collection data when factoring in

LFG collected in the LRCs and LRTs. The best fit *k* for Site-Wide 2 (*k* = 0.076 1/yr) compares favorably with *k* values obtained from previous studies on bioreactor landfills (Tolaymat et al. 2010; Wang et al. 2013). The *k* values for the Site-Wide 2 analysis in Scenario II supports enhanced waste decomposition and gas generation via liquid addition across the landfill.

An assessment of total LFG flow rate at Landfill T (Fig. 9) demonstrated that more than half of the total gas collected during select years (2005-2007) was collected from LRCs and LRTs. Overall, the contribution of LFG collected in these leachate collection and recirculation systems increased total LFG and correspondingly total CH_4 flow rates at Landfill T from 2002 to 2015. The increase in CH_4 flow rates that were used in the LandGEM simulations yielded higher *k* values for all phase-specific analyses (Table 6) and these higher *k* values were associated with higher R^2s (Table 6) that indicate less variance between measured and predicted CH_4 flow rates. Thus, LandGEM simulations completed in Scenario II were considered more appropriate based on (i) physical representation of the landfill system and (ii) statistical significance of the model simulations.

The LandGEM simulations for Phase 3 & 4 (Fig. 29), Phase 5 (Fig. 30), and Phase 6 (Fig. 31) 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 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. 30. 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. 30 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. 31) 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) predicts CH_4 generation immediately upon placement of waste in a given month, which corresponds to the model simulation shown in Fig. 31 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 in Scenario 2 was for Phase 7, which is shown in Fig. 32. 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.

4.2 Gas Model Evaluation

Comparisons between monthly and annual optimized k values for Scenarios I and II are shown in Fig. 34. The data in Fig. 34 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. 34 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.

Comparisons of *k* values determined from the monthly CH_4 flow rates analyses that considered α = 85% and α = f(t) for Scenarios I and II are shown in Fig. 35. Decay rates in Fig. 35 plot on or close to the 1:1 line, which indicates negligible difference between *k* calculated with α = f(t) versus *k* computed with α = 85%. The α = 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 α = 85%. However, there is no standardized or repeatable method for implementing α = f(t) since the actual collection efficiency will vary with landfill operations and practices. In contrast, the constant α = 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 α = 85% for LFG modeling.

The LandGEM simulations completed for the phase-specific analyses indicated that the statistical significance of the model (i.e., R^2) improved for Scenario II relative to Scenario I. The LFG assessment in Scenario II included LFG collected in the gas extraction wells, LRCs, and LRTs, which led to improved physical and statistical significance of the LandGEM simulations. In addition, 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). Thus, the most appropriate LandGEM analyses were conducted in Scenario II 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.

4.3 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. 36. The optimized *k*s in Fig. 36 are representative of the monthly average CH_4 flow rate analyses with α = 85% in Scenario II. Furthermore, the *k*s plotted in Fig. 36 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 37. A shorter duration leachate recirculation approach was conducted in Phase 5 that initiated approximately 2 yr after initial waste placement (Fig. 37a). 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) and transitioned seamlessly into the start of liquid waste addition in Year 7 (Fig. 37a, 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. 37a). Despite the varying moisture enhancement strategies in Phase 5 and Phase 6, these phases had comparable cumulative liquid addition per waste mass (Fig. 37c).

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. 38. 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. 38b). 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. 38a). The cumulative CH_4 generation curves for all four phases in Fig. 38c 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 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. 30 and 38b). 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. 38b). 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. 38a). 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) 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). 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. 38c

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. 6). Regardless, increased CH_4 generation was observed in Phases 3 & 4, 5 and 6 following the onset of liquid waste disposal (Fig. 38). 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. 38b). 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.

CHAPTER 5: CONCLUSION AND PRACTICAL IMPLICATIONS

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 to develop the following recommendations for LFG modeling and moisture enhancement strategies.

- 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.

Table 1. 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.

Table 2. 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

Table 3. 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

Table 4. Range of estimated gas collection efficiencies adapted from Mantell (2016) with supporting information on criteria evaluated to calculate temporally varying gas collection efficiencies ($\alpha = f(t)$).

Estimated Gas Collection Efficiency,α (%)	Range of Gas Well Density (wells/ha)	Fraction of Phase Area with an Active Gas Collection System	Fraction of Active Waste Area with Final Cover System
50	0.25 - 0.49	0 - 0.50	0.30 - 0.45
70	0.74 - 1.5	0.50 - 0.55	0.45 - 0.55
85	1.5 - 2.2	0.58 - 0.67	0.55 - 0.65
90	2.2 +	0.7	0.7

Table 5. Optimized decay rates (*k*) for site-wide and phase-specific analyses using temporally varying and constant collection efficiencies in Scenario I.

Analysis	Parameter	Annual Methane, α = f(t)	Annual Methane, α = 85%	Monthly Methane, α = f(t)	Monthly Methane, α = 85%
Site-Wide 1	k (yr^{-1})	0.055	0.052	0.055	0.053
	R^2	0.63	0.68	0.42	0.51
Site-Wide 2 [a]	k (yr^{-1})	0.044	0.045	0.045	0.045
	R^2	0.64	0.66	0.45	0.50
Phase 1A & 2A	k (yr^{-1})	0.121	0.119	0.128	0.127
	R^2	-1.22	-1.27	-0.88	-0.97
Phase 1B & 2B	k (yr^{-1})	0.081	0.080	0.088	0.090
	R^2	-0.47	-0.48	-0.39	-0.44
Phase 3 & 4	k (yr^{-1})	0.029	0.025	0.027	0.026
	R^2	0.10	0.07	0.01	0.01
Phase 5	k (yr^{-1})	0.058	0.062	0.060	0.065
	R^2	0.17	0.16	0.11	0.11
Phase 6	k (yr^{-1})	0.042	0.042	0.042	0.043
	R^2	0.03	0.27	-0.06	0.09
Phase 7	k (yr^{-1})	0.037	0.033	0.033	0.030
	R^2	-0.01	-0.02	0.18	0.20

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

Table 6. Optimized decay rates (*k*) for site-wide and phase-specific analyses using temporally varying and constant collection efficiencies in Scenario II.

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

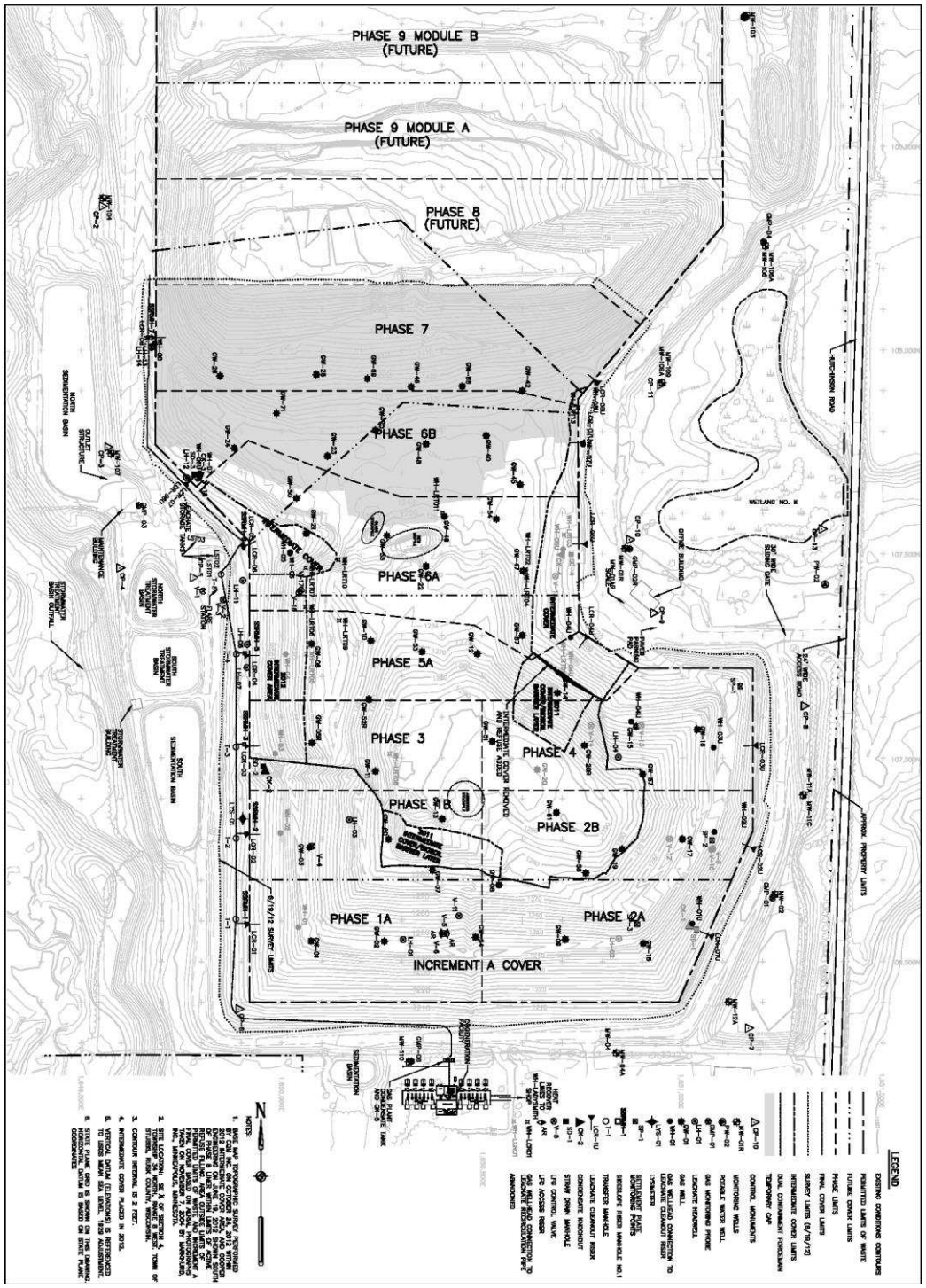

Fig. 1. Plan view of Landfill T with delineated existing and future phases.

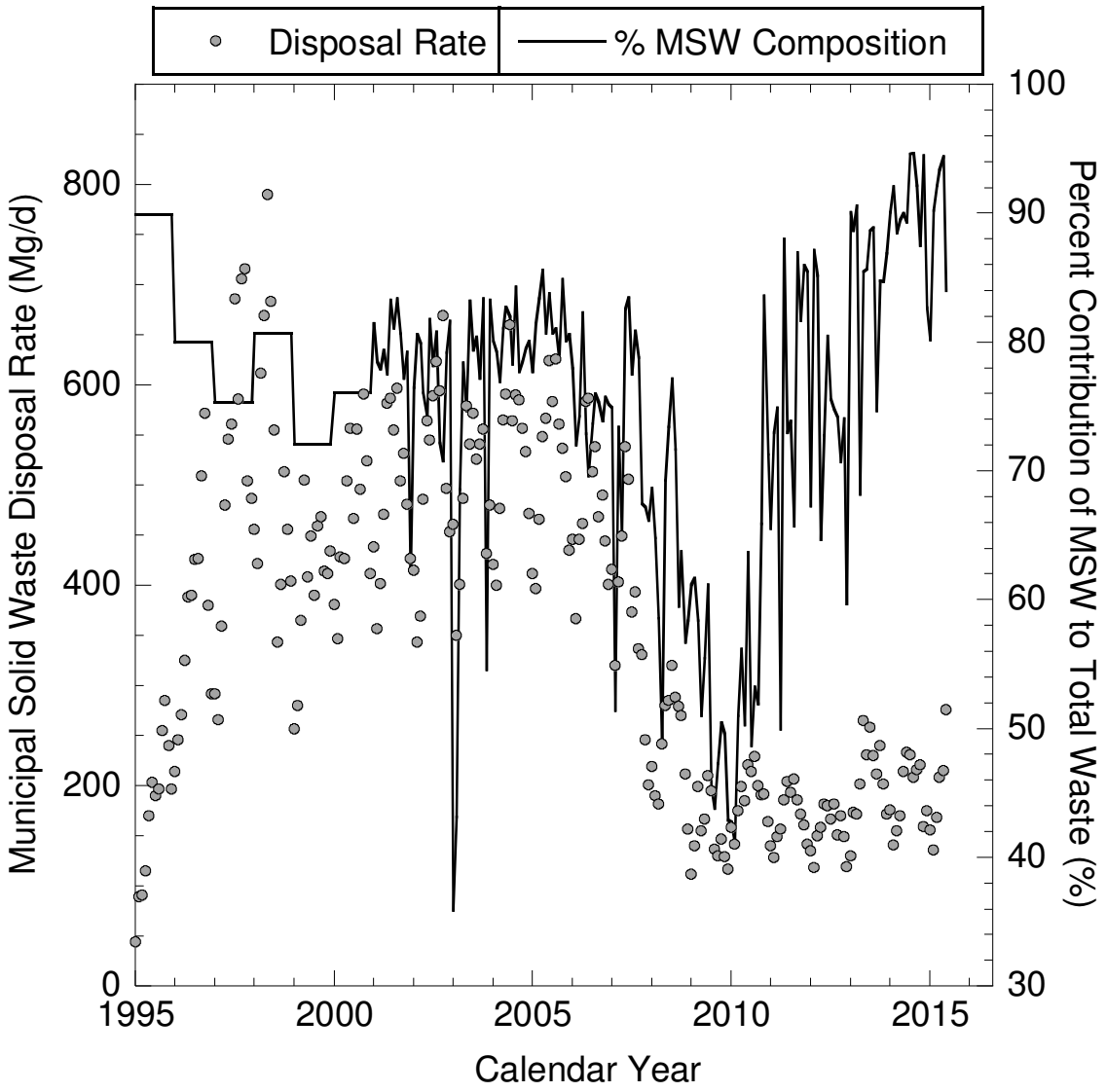

Fig. 2. Temporal trends of municipal solid waste (MSW) disposal rate and percent MSW fraction of total waste at Landfill T.

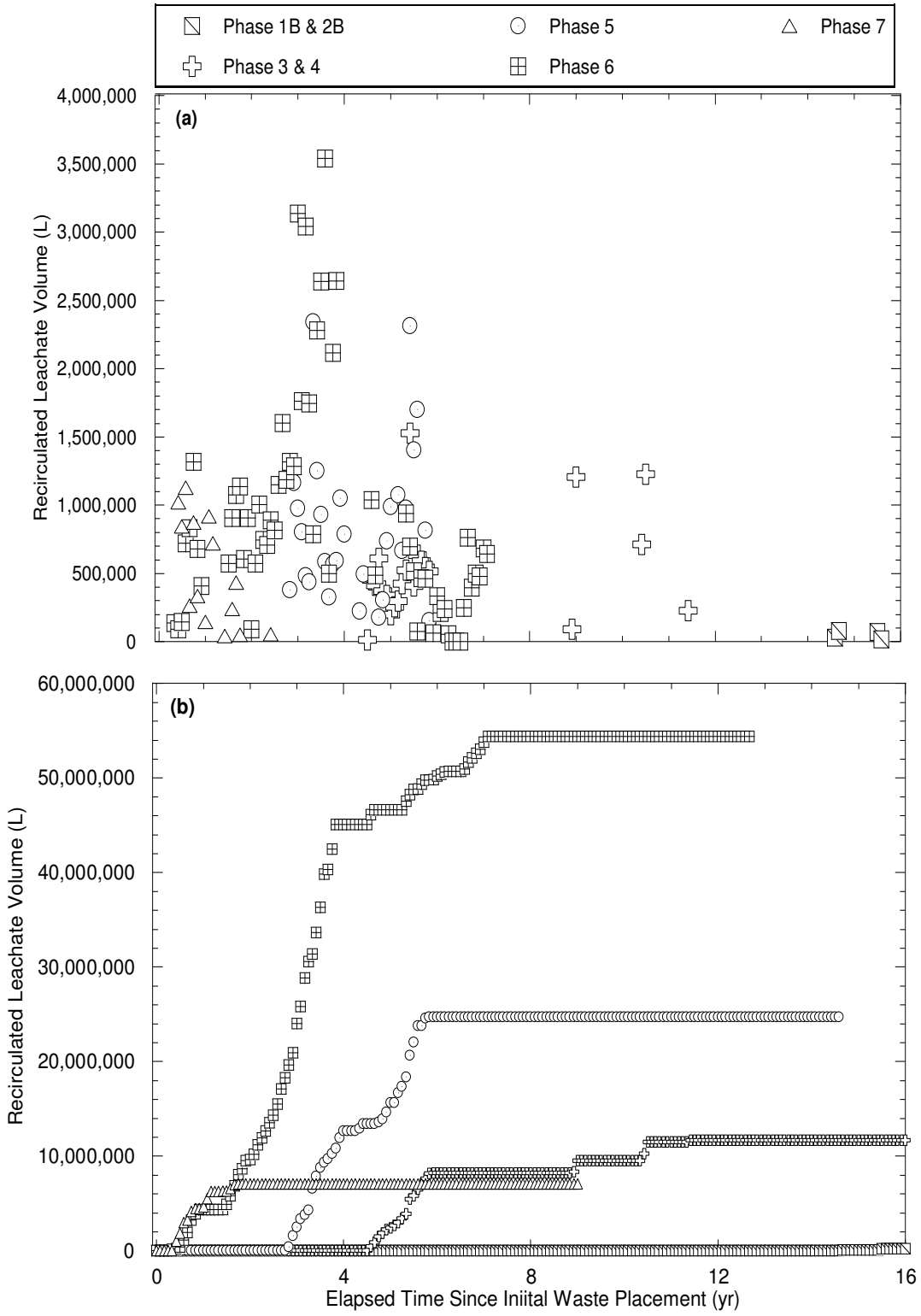

Fig. 3. Temporal trends of (a) leachate recirculation and (b) cumulative leachate recirculation across all phases.

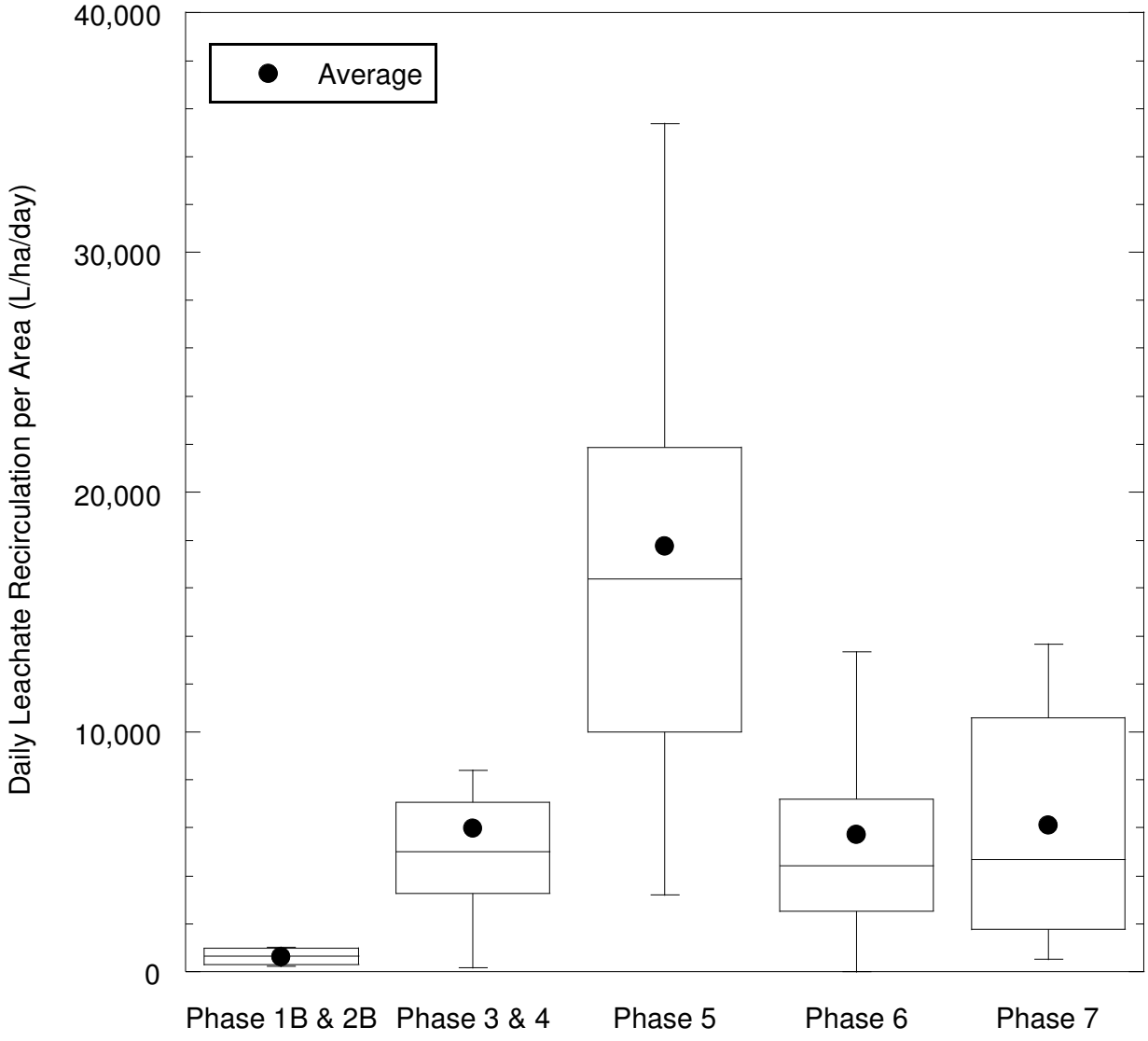

Fig. 4. Box plot of daily leachate recirculation rates in phases during periods of leachate recirculation. The central line is the median, the outer boundaries of the box represent the interquartile range (i.e., 25th and 75th percentile), and the upper and lower whiskers constitute the 10th and 90th percentiles of the data. The average is shown as a solid circle.

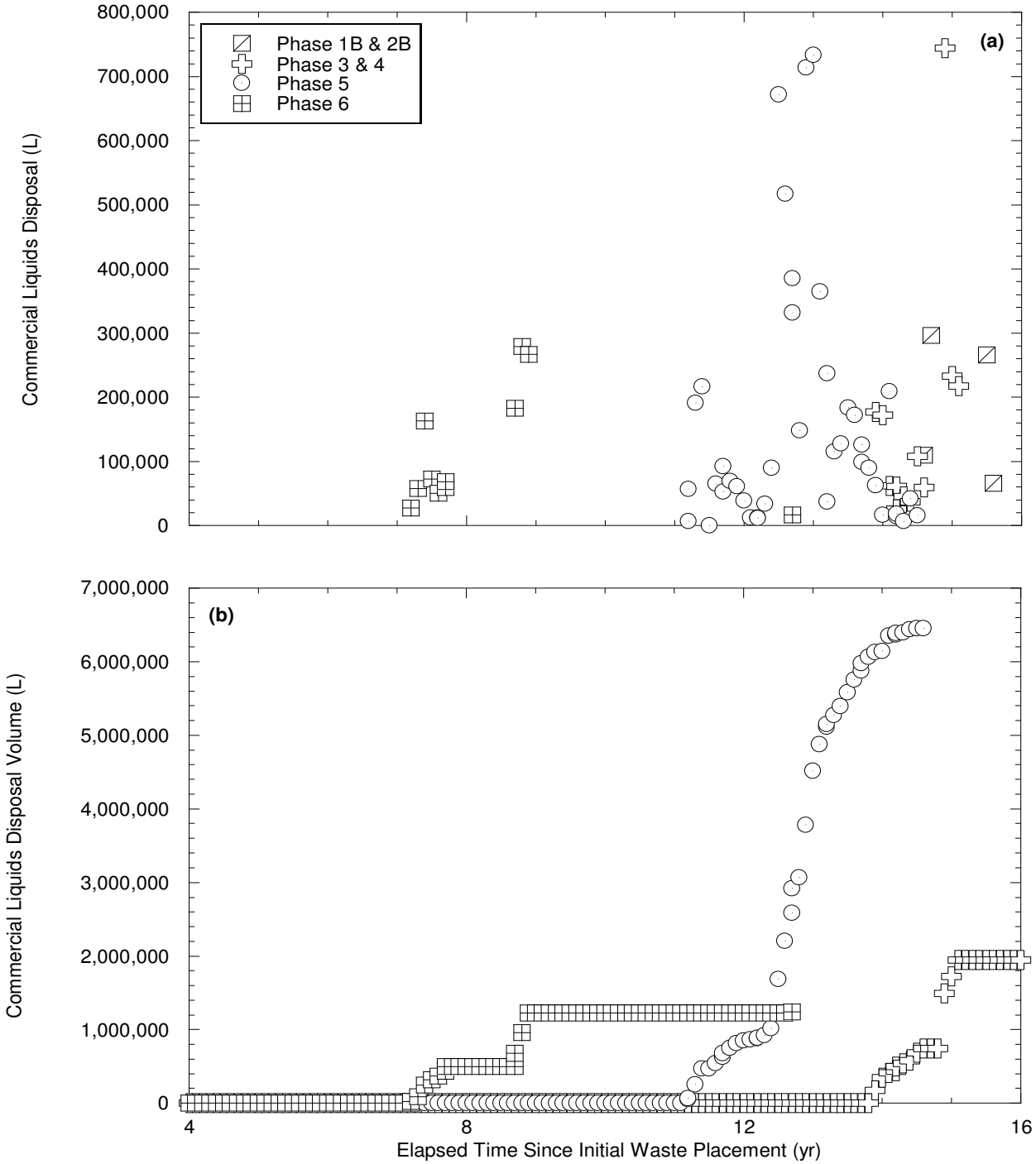

Fig. 5. Temporal trends of (a) commercial liquid waste disposal and (b) cumulative liquid waste disposal across all phases.

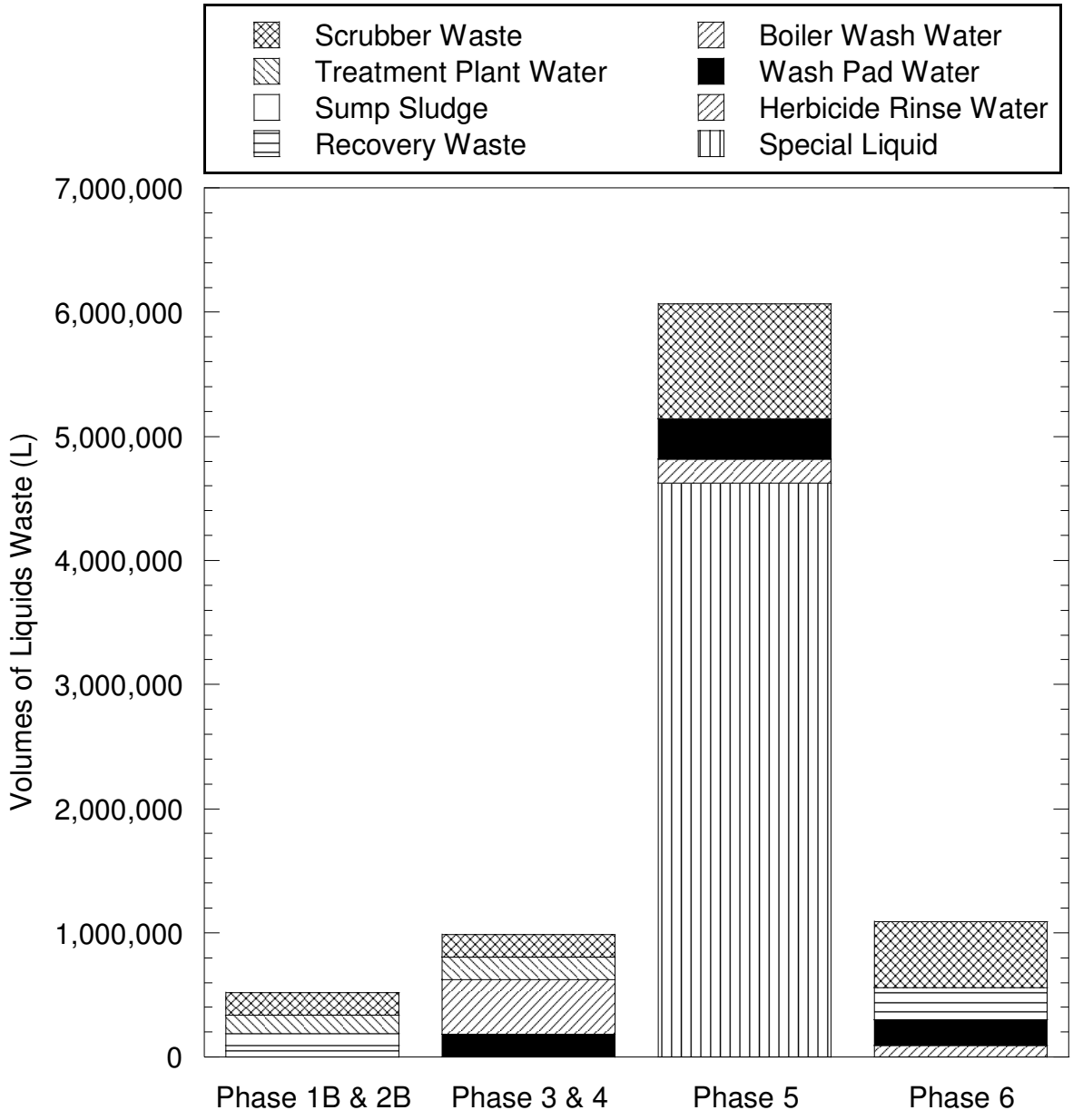

Fig. 6. Bar chart of volumes of different types of liquid waste disposed in Phases 1B & 2B, 3 & 4, 5, and 6 at Landfill T.

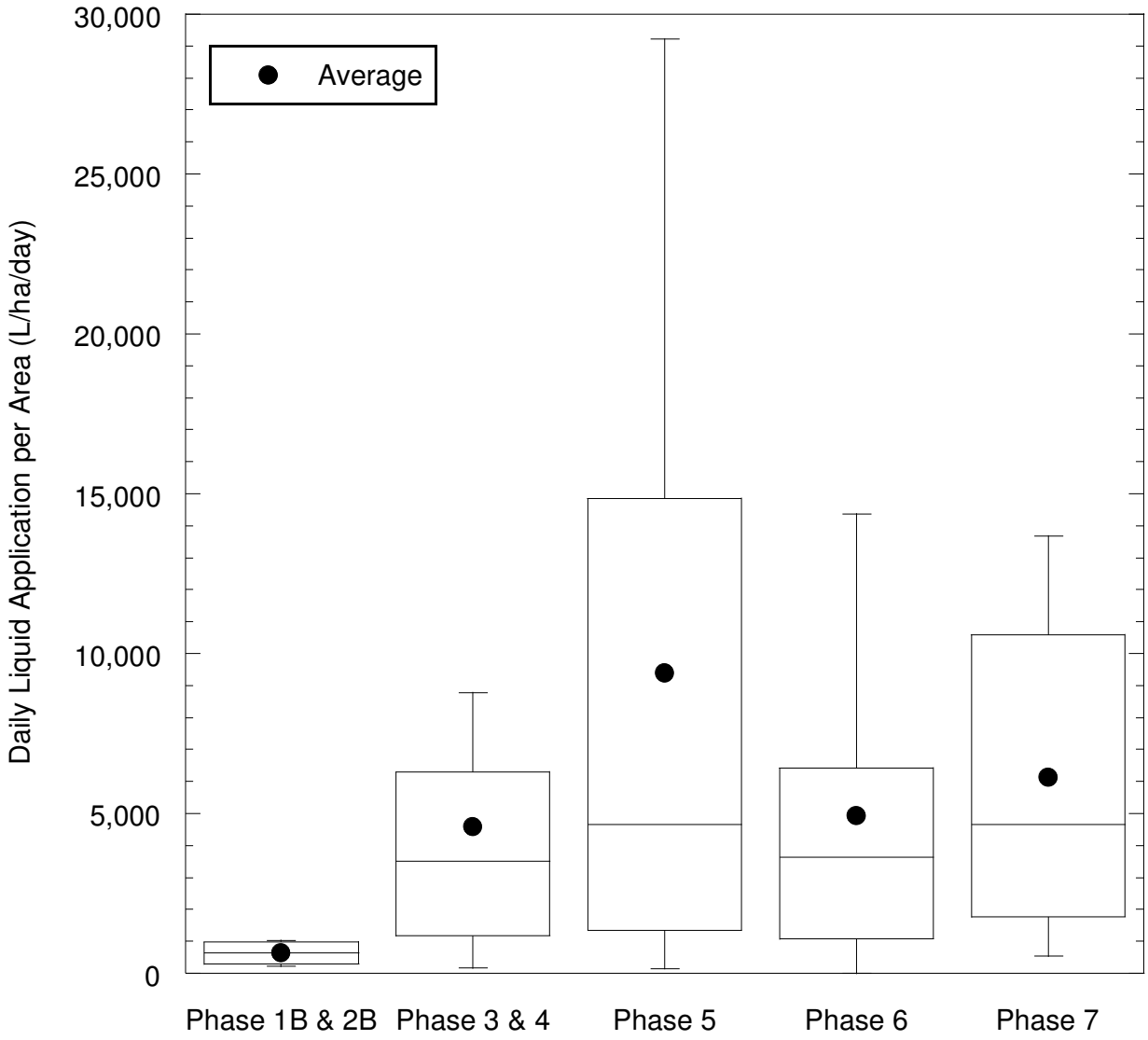

Fig. 7. Box plot of daily liquid application per surface area in each landfill phase.

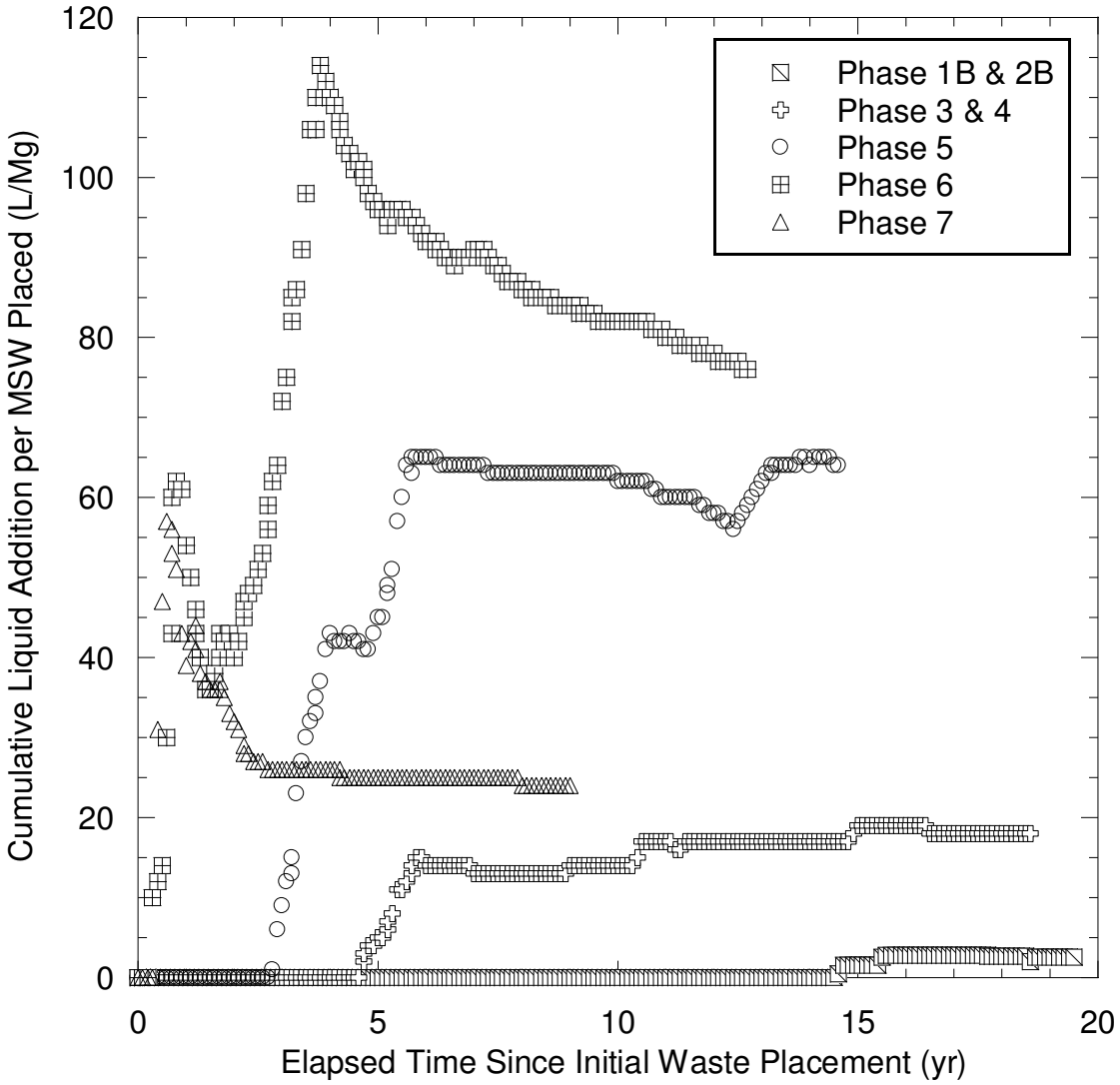

Fig. 8. Temporal trends of cumulative liquid addition per mass of waste in Phases 1B & 2B, 3 & 4, 5, 6, and 7.

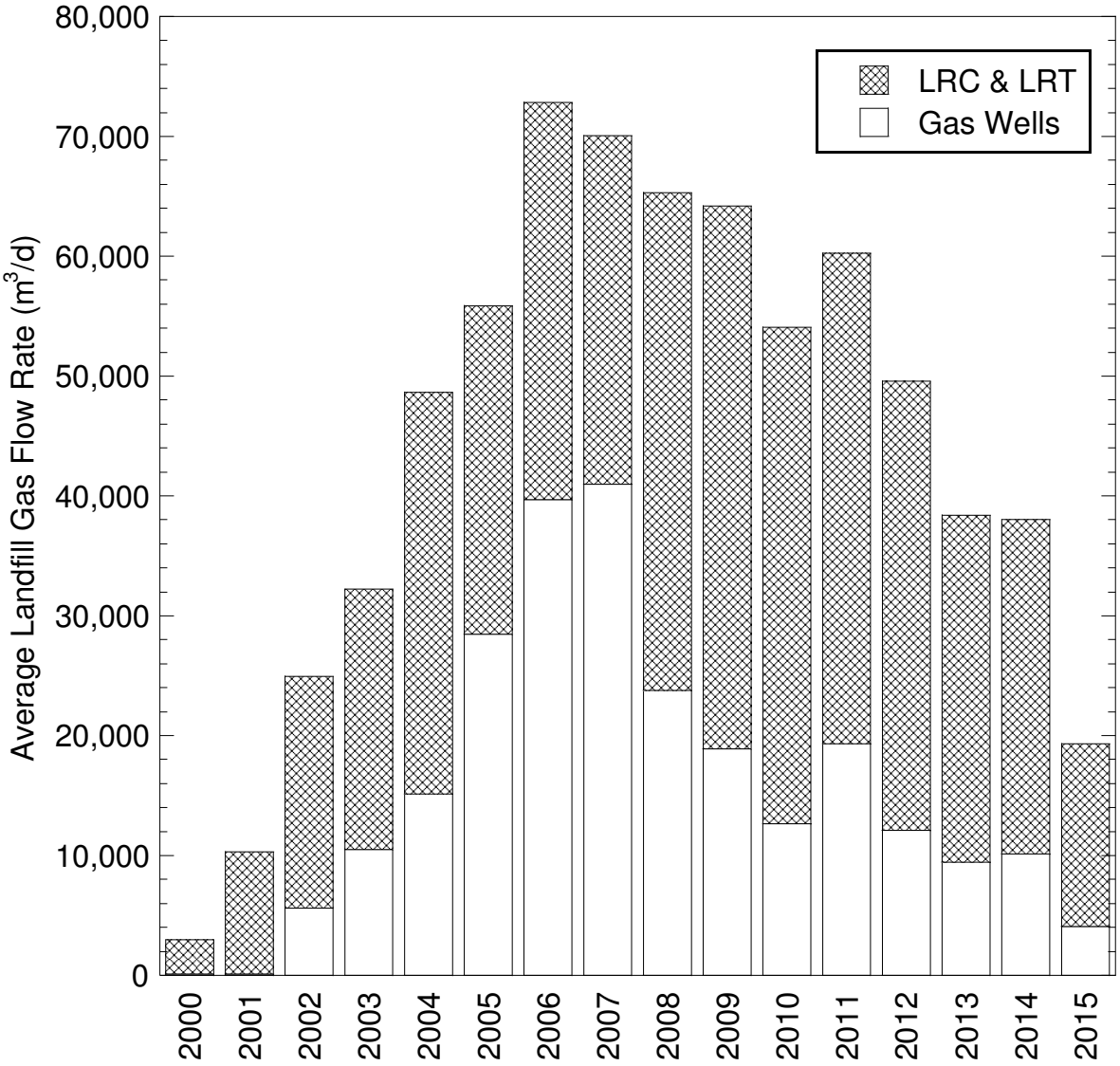

Fig. 9. Contributions to the total landfill gas flow for Landfill T from gas collected in the vertical gas wells and gas collected in the leachate collection and recirculation systems (LCR and LRT).

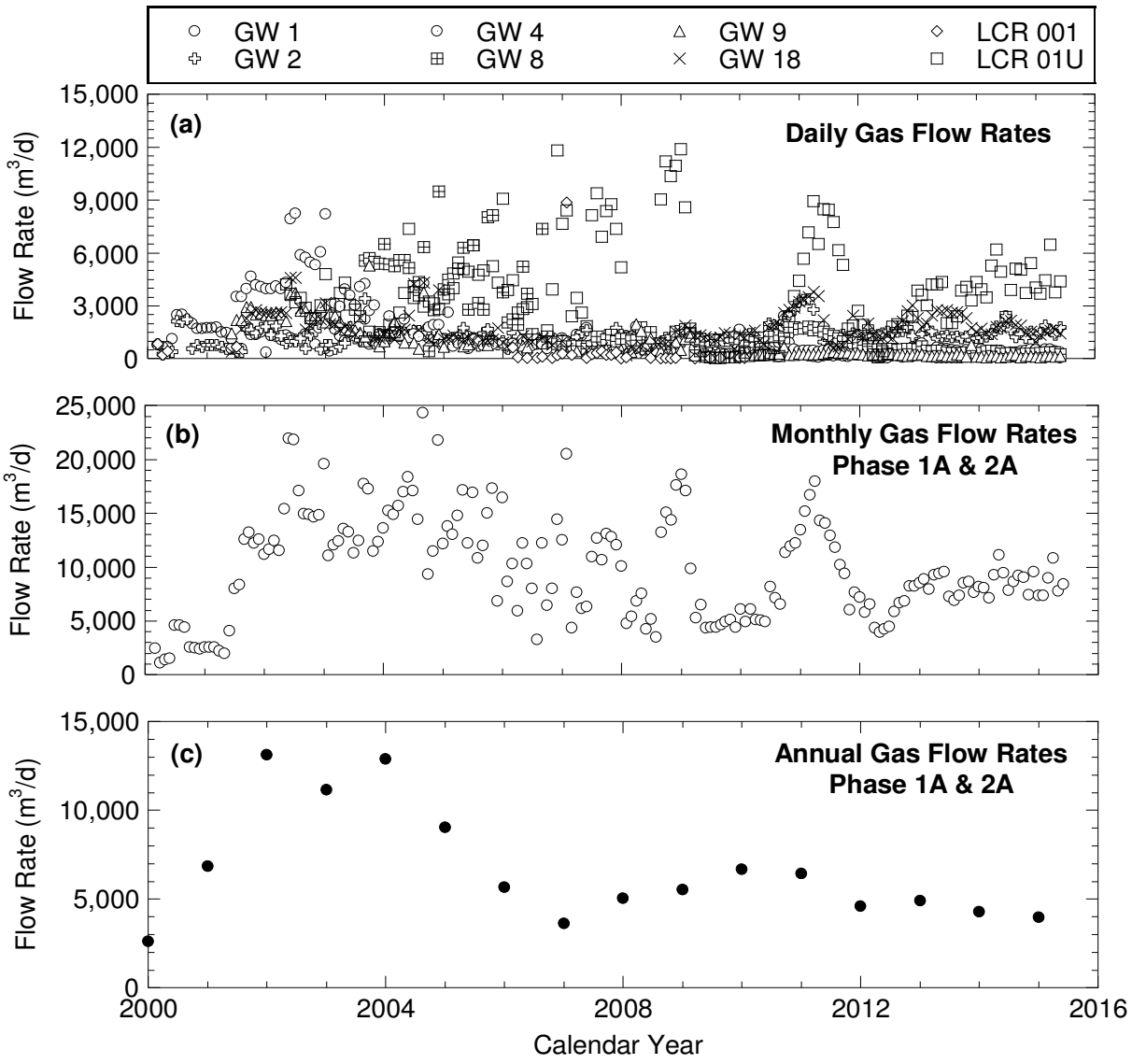

Fig. 10. Gas flow rate data for Phase 1A & 2A: (a) individual gas well, LCR, and LRT measurements; (b) monthly gas flow rates for the entire phase; (c) annual gas flow rates for the entire phase.

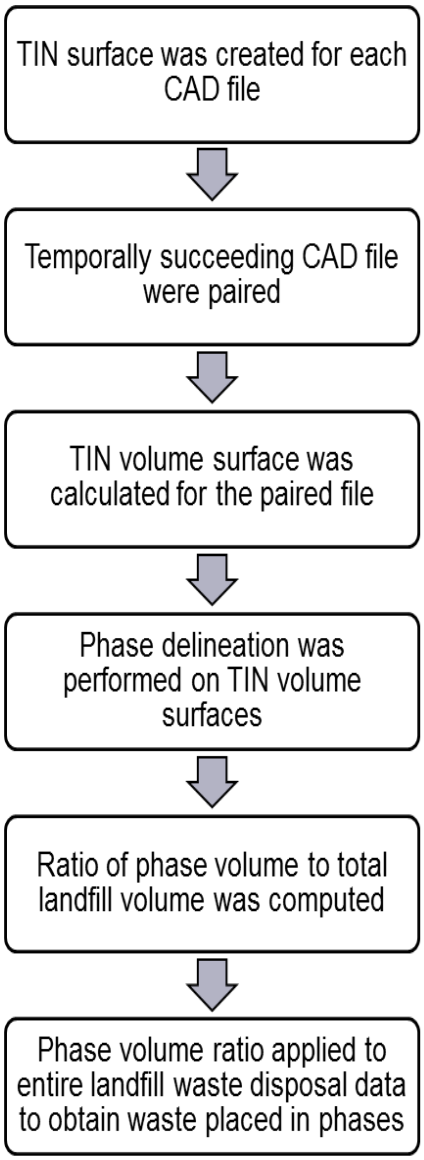

Fig. 11. Flowchart depicting steps of the CAD volume analysis to determine relative waste filling volumes of each phase at Landfill T.

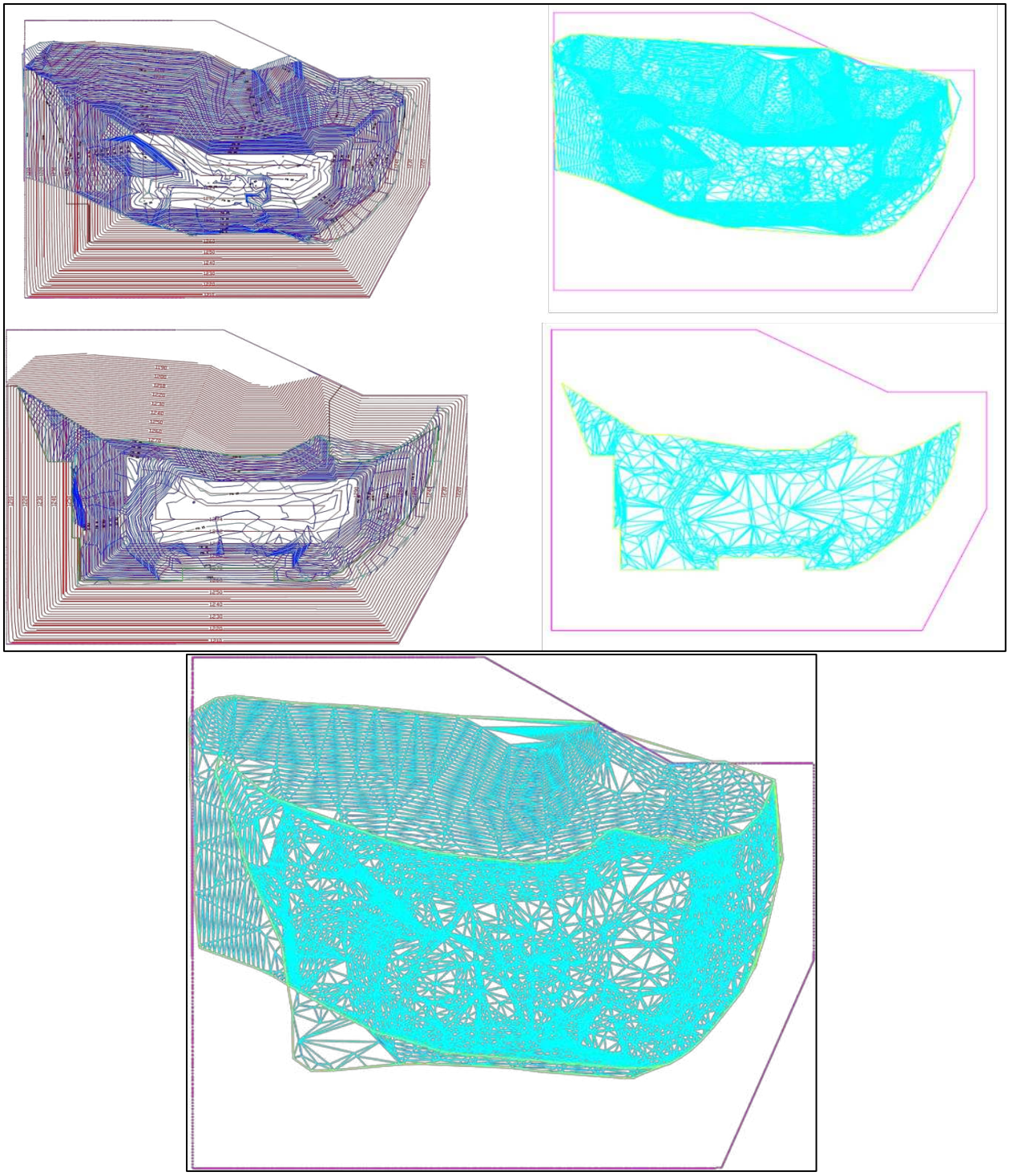

Fig. 12. Triangular Irregular Network (TIN) surface for (a) single CAD file and (b) for paired CAD files.

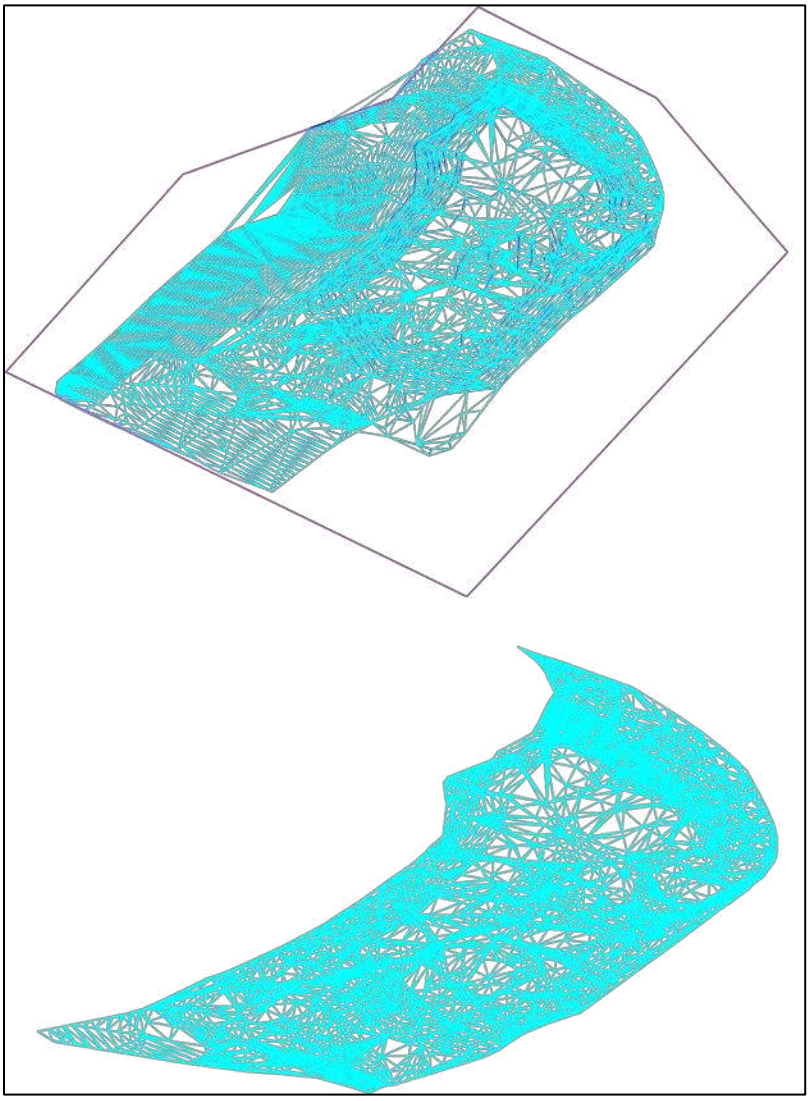

Fig. 13. Triangular Irregular Network volume surface for a paired CAD file.

Fig. 14. Phase delineation of a Triangular Irregular Network volume surface.

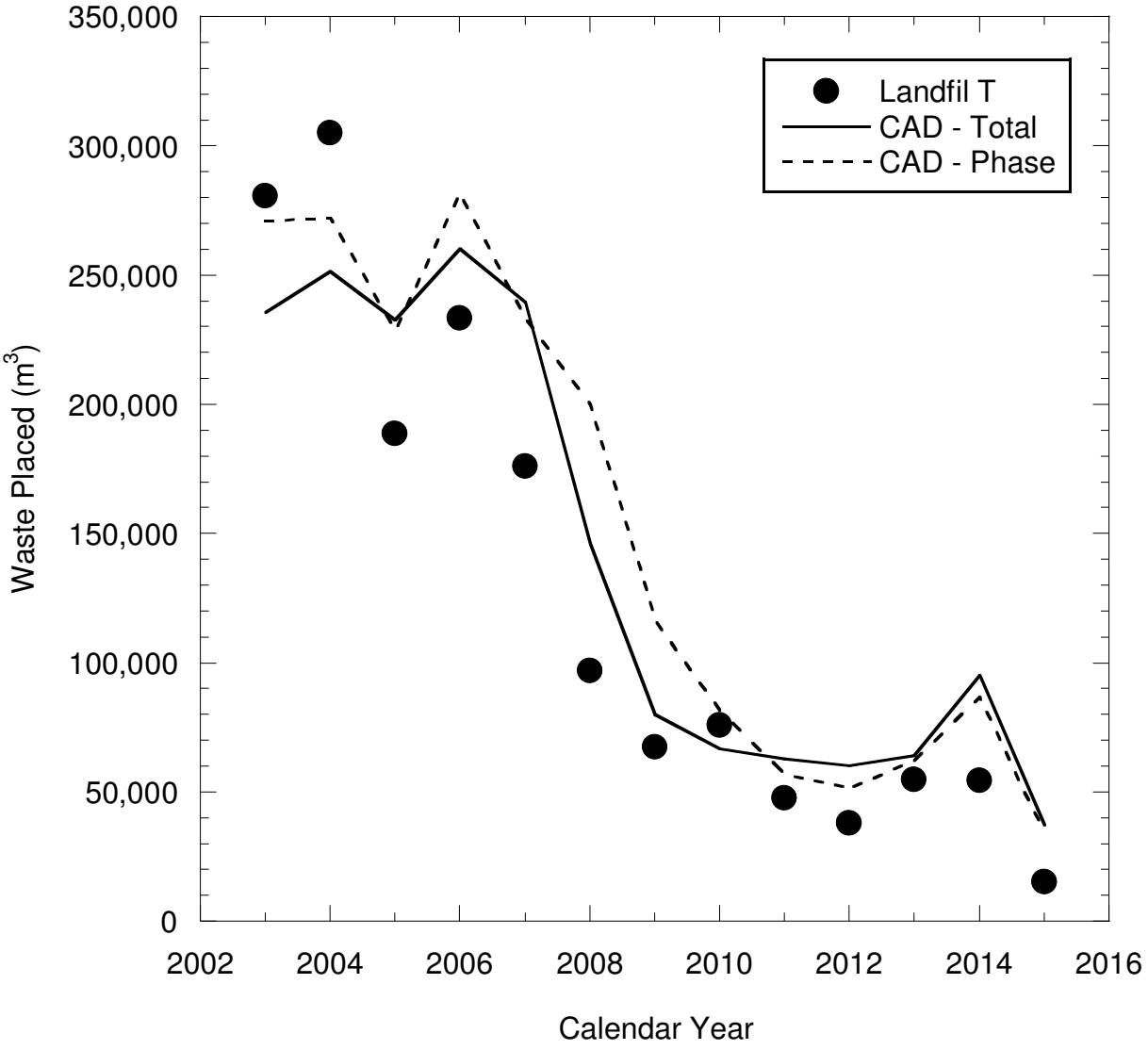

Fig. 15. Temporal relationships of total waste volume disposed in Landfill T based on CAD volume estimates and Landfill T monitoring data.

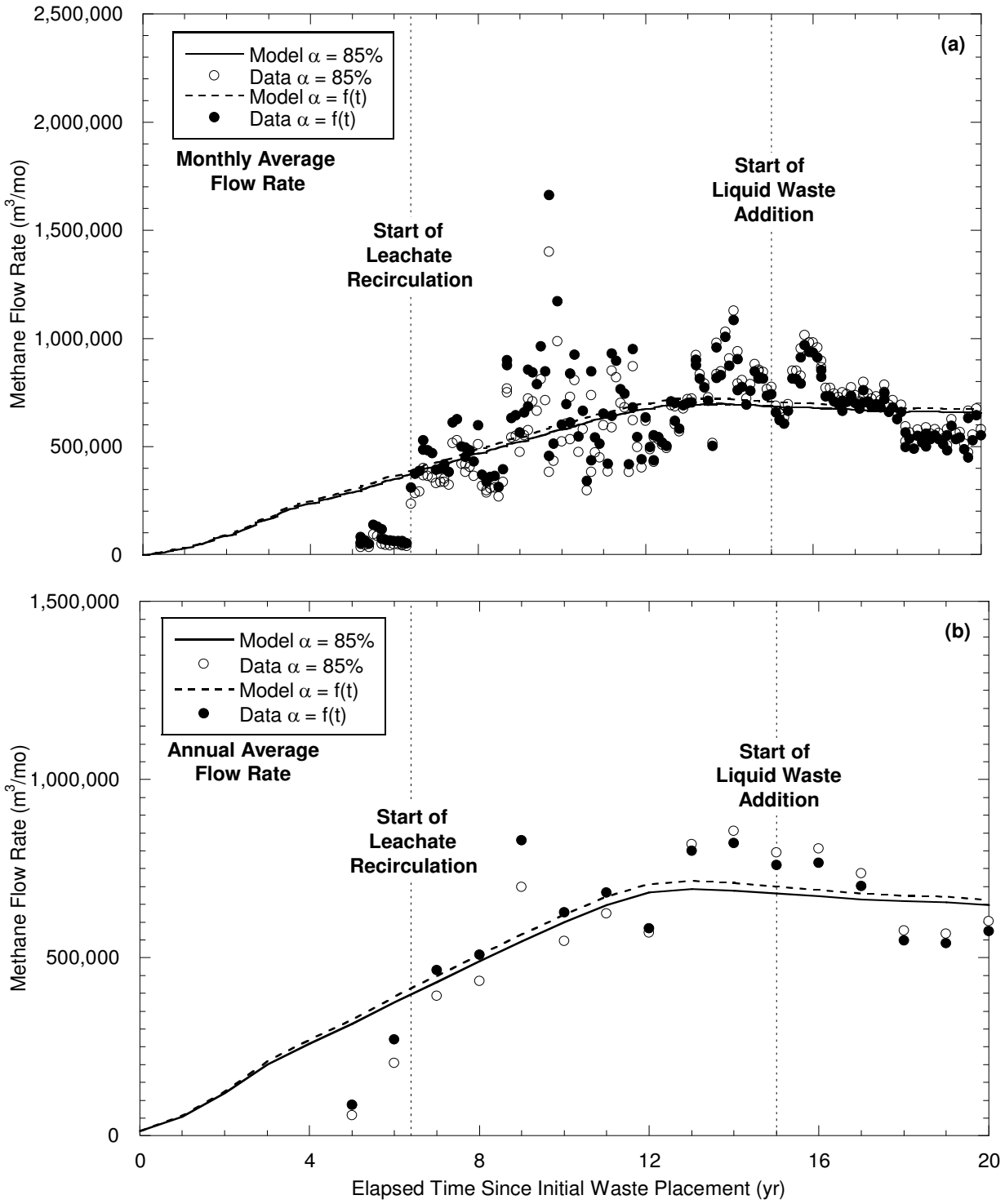

Fig. 16. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for the entire landfill (i.e., Site-Wide 1) in Scenario I. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

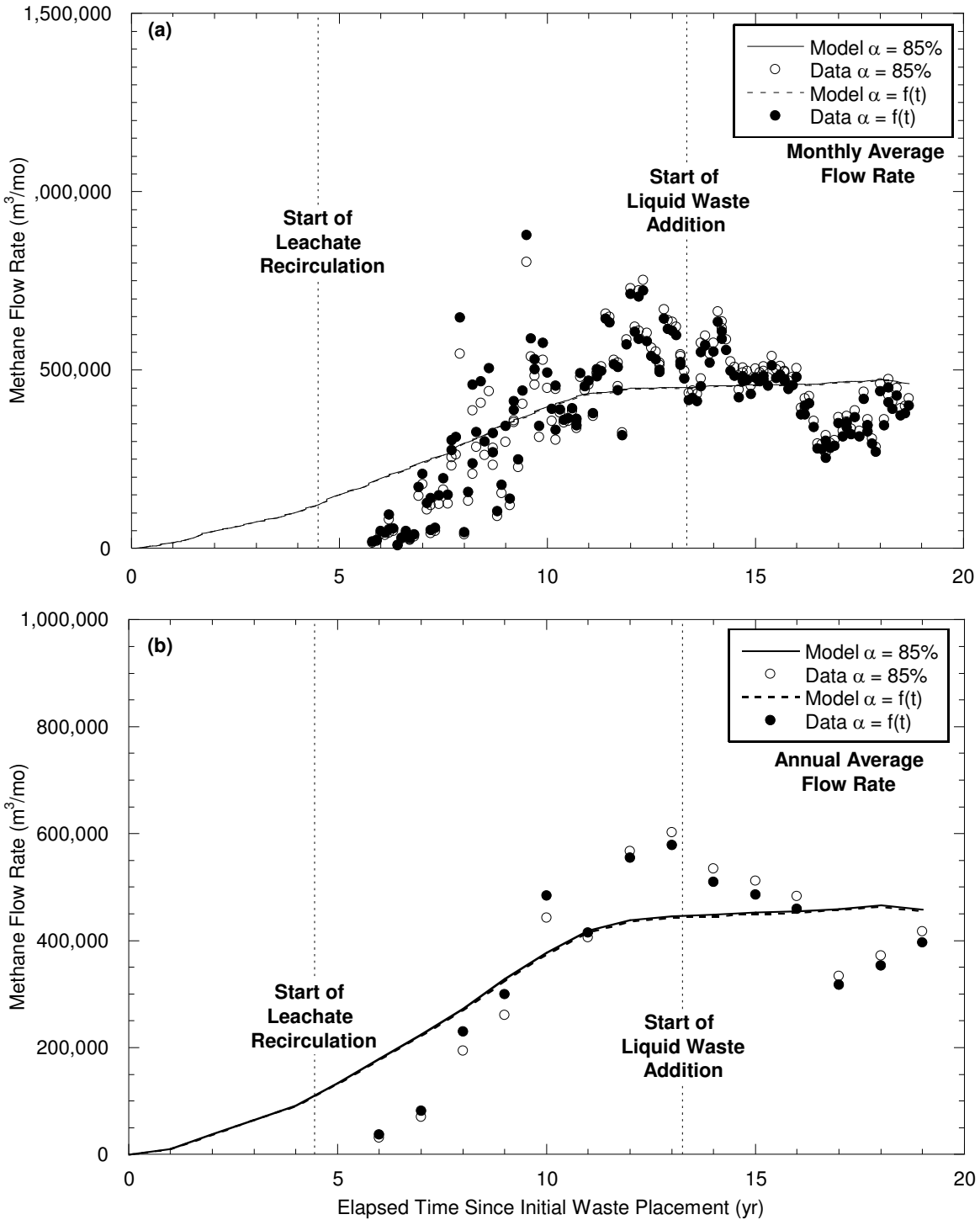

Fig. 17. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for a site-wide analysis excluding Phase 1A & 2A and Phase 1B & 2B in Scenario I. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

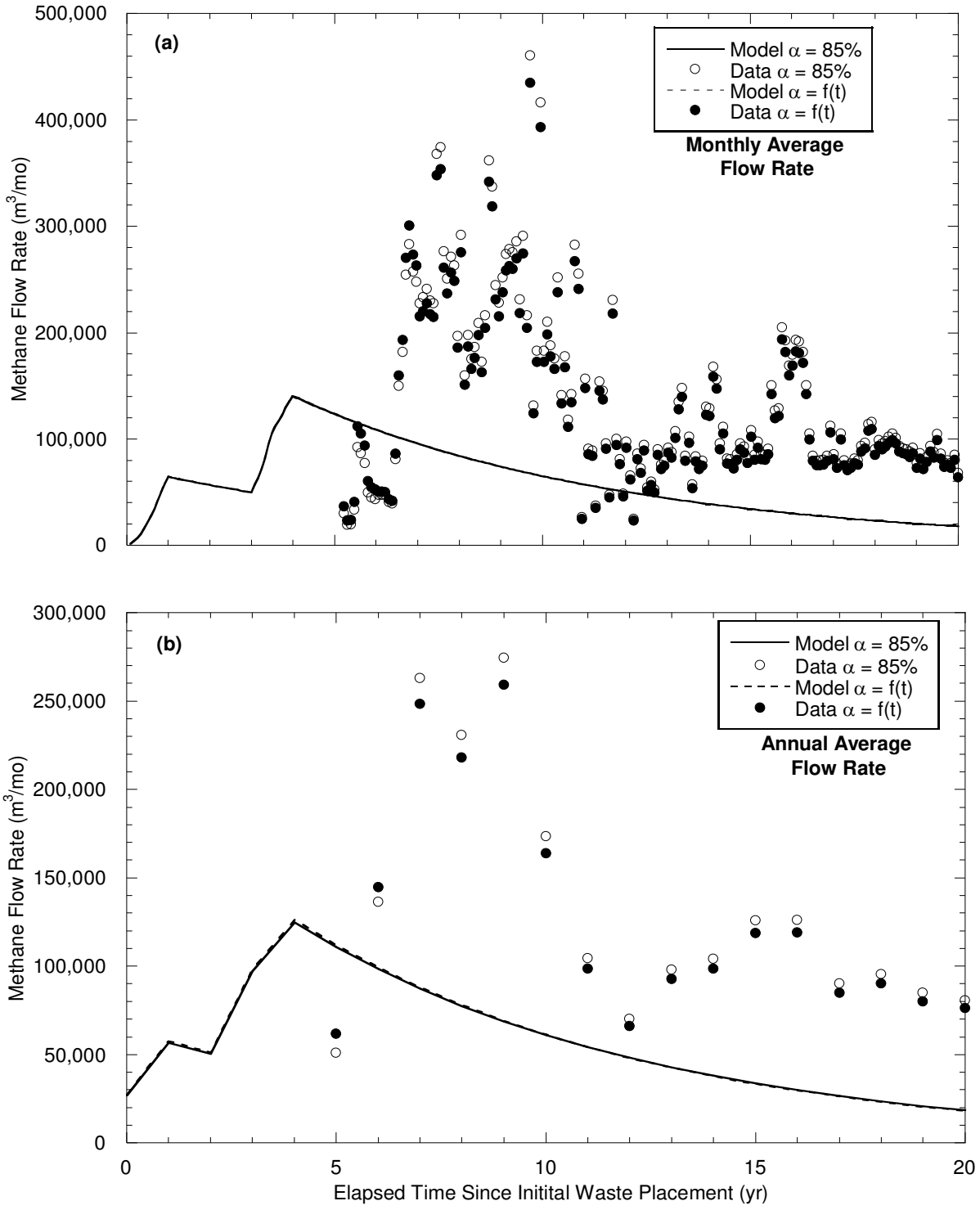

Fig. 18. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 1A & 2A in Scenario I. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

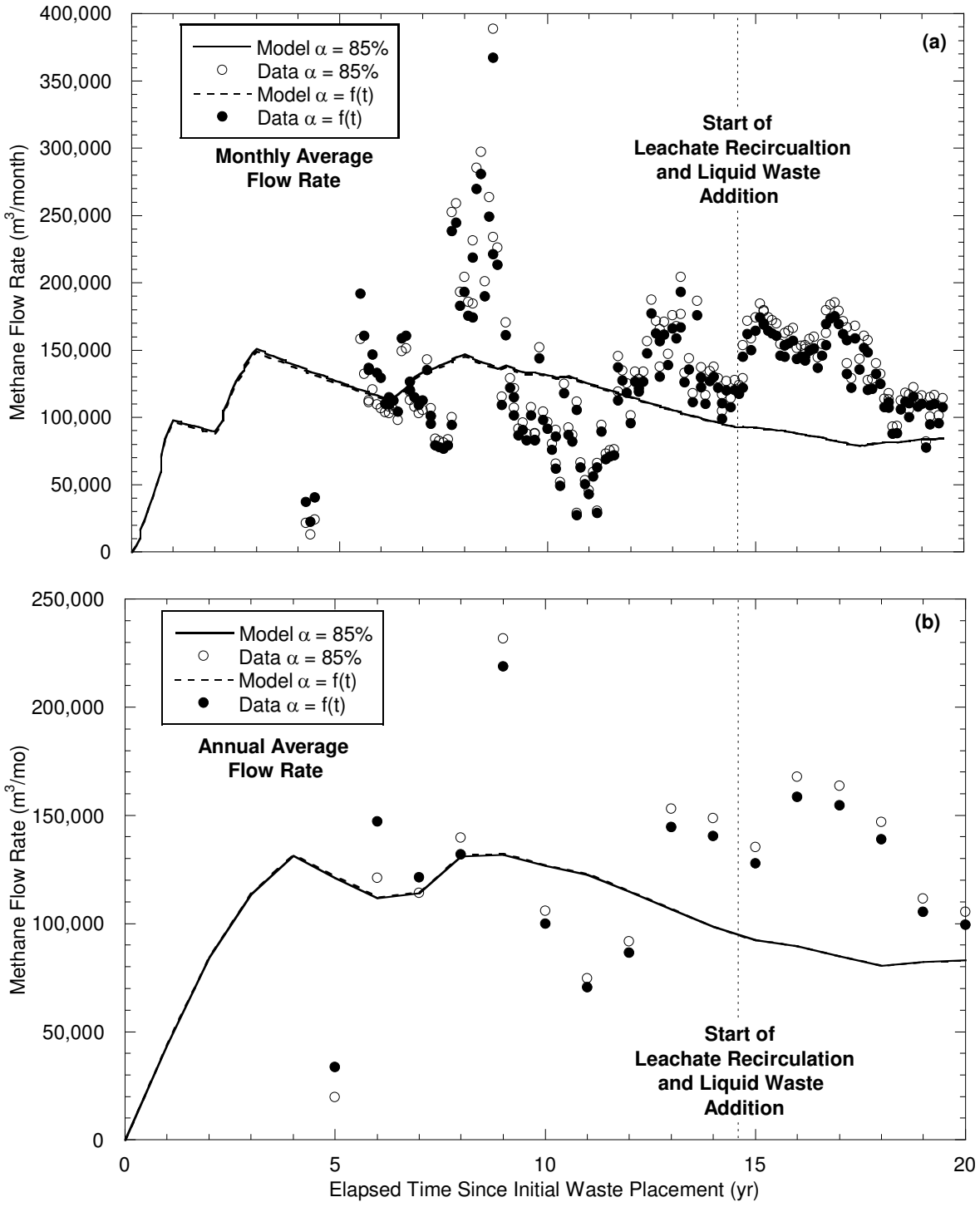

Fig. 19. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 1B & 2B in Scenario I. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

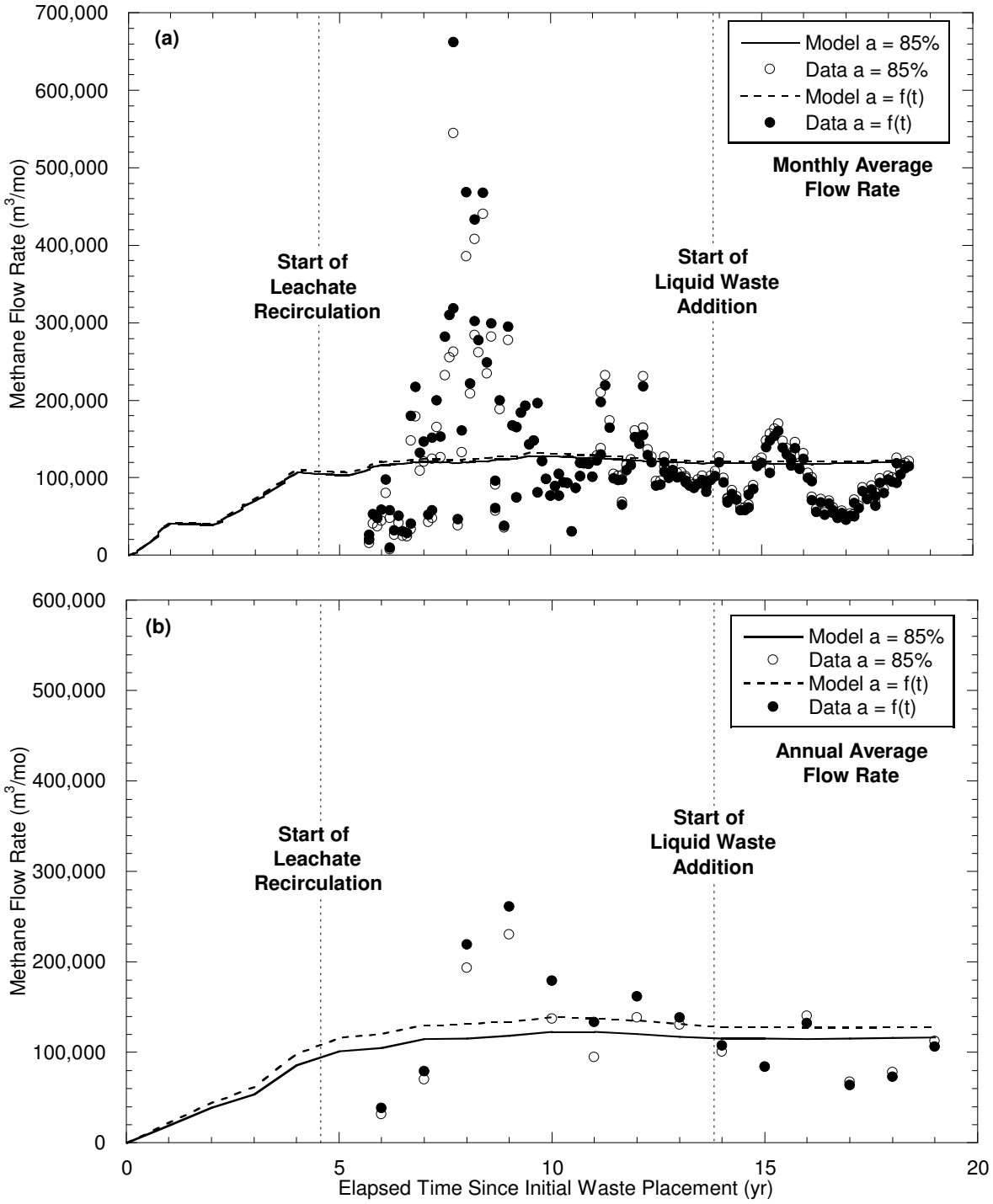

Fig. 20. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 3 & 4 in Scenario I. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

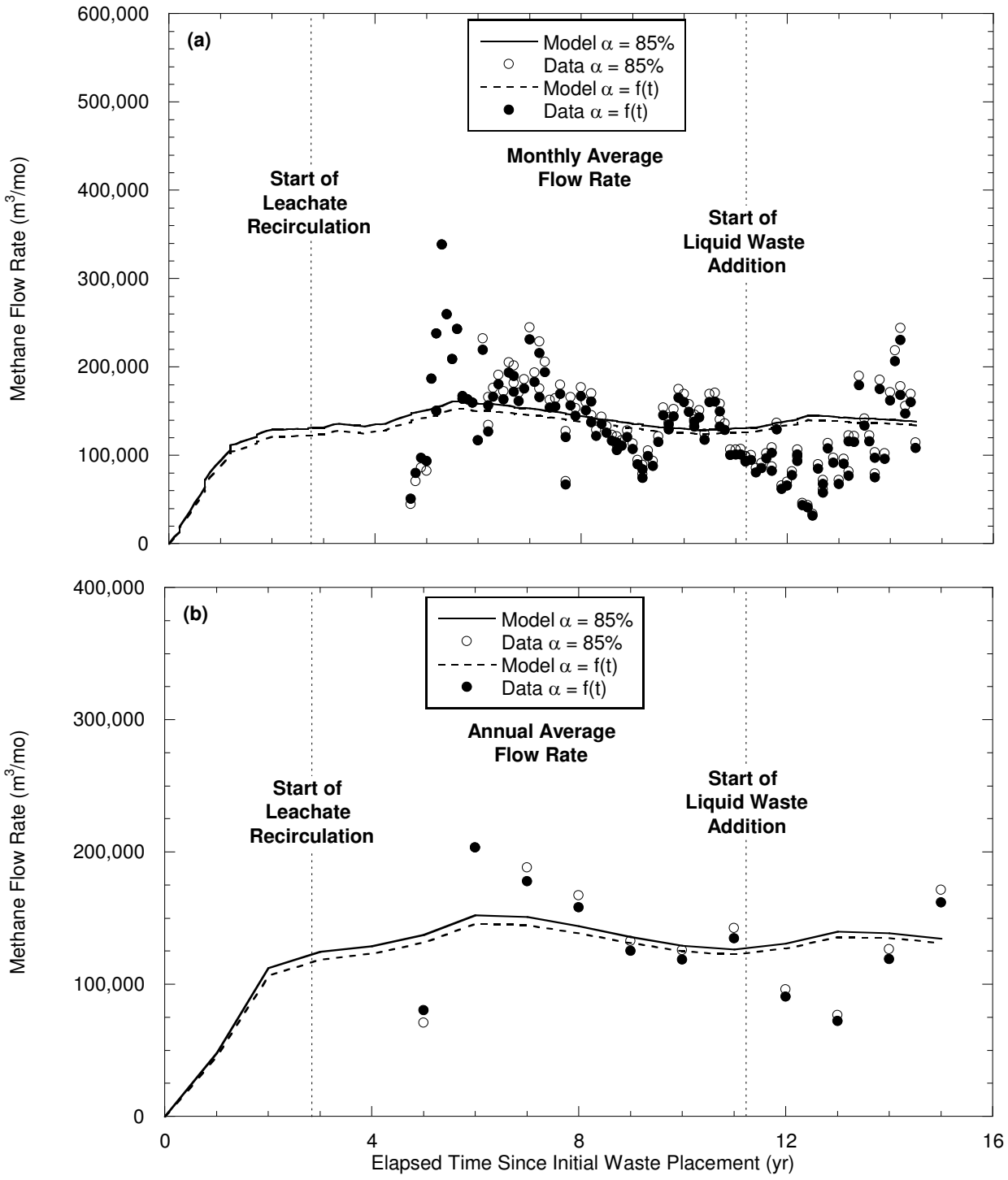

Fig. 21. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 5 in Scenario I. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

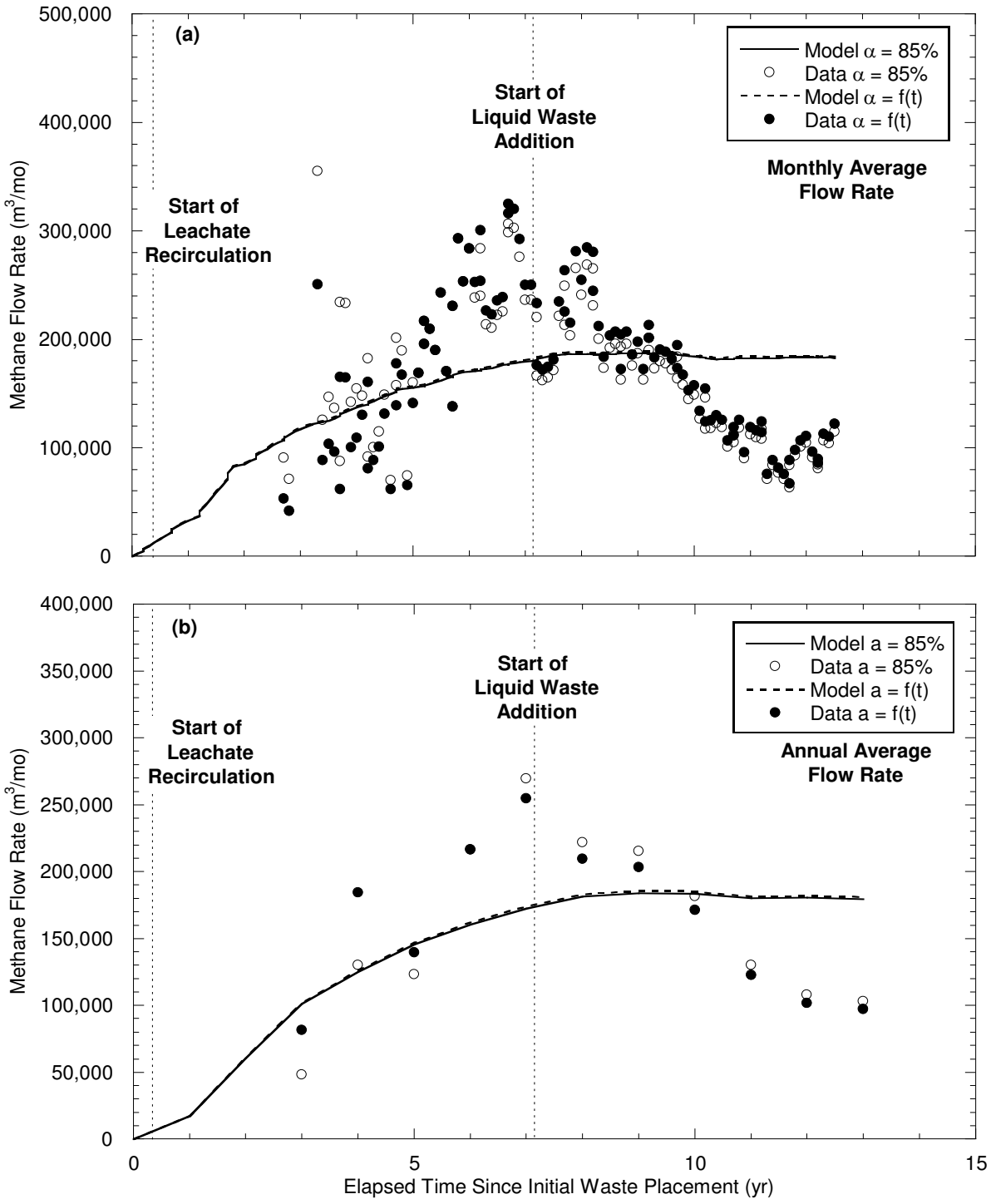

Fig. 22. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 6 in Scenario I. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

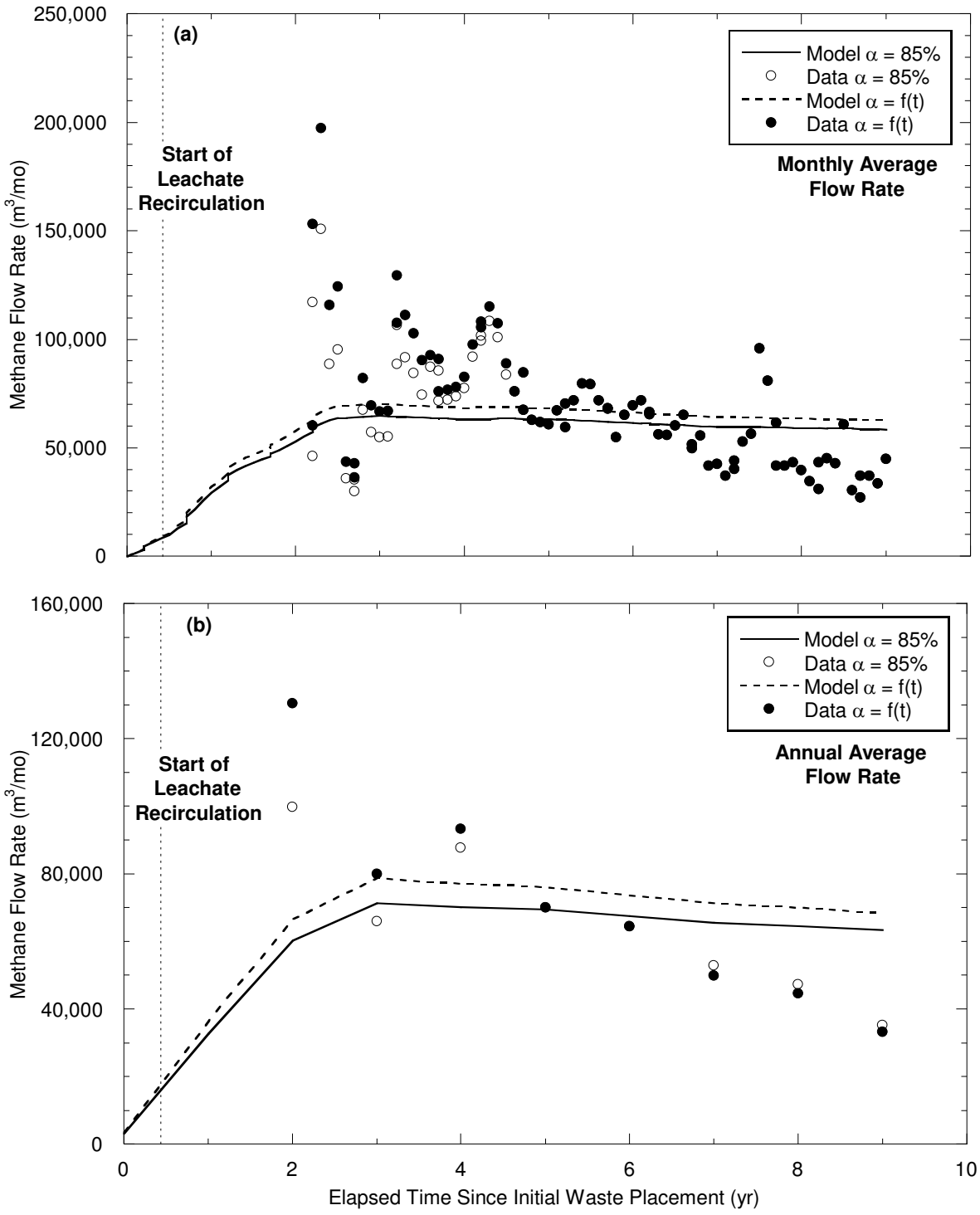

Fig. 23. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 7 in Scenario I. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

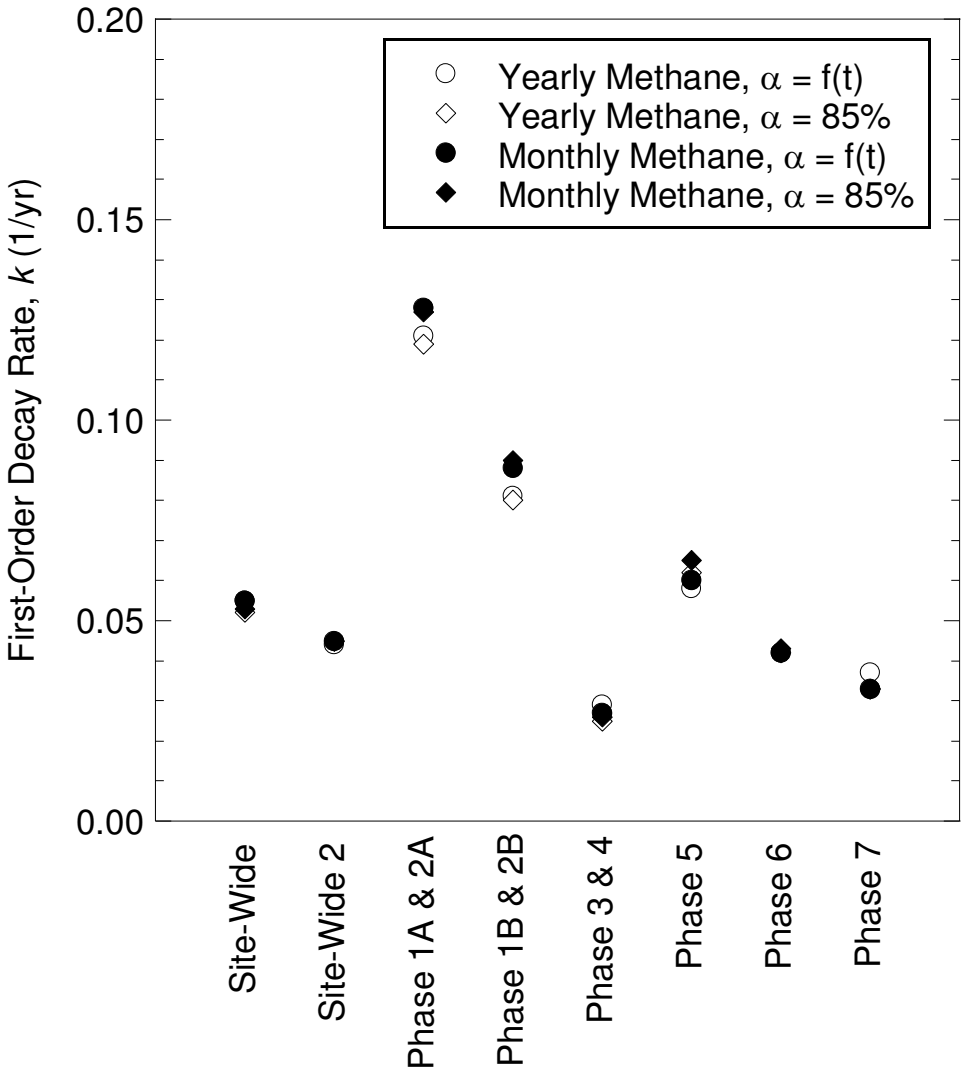

Fig. 24. Graphical summary of optimized first-order decay rates for all gas analyses conducted in Scenario I.

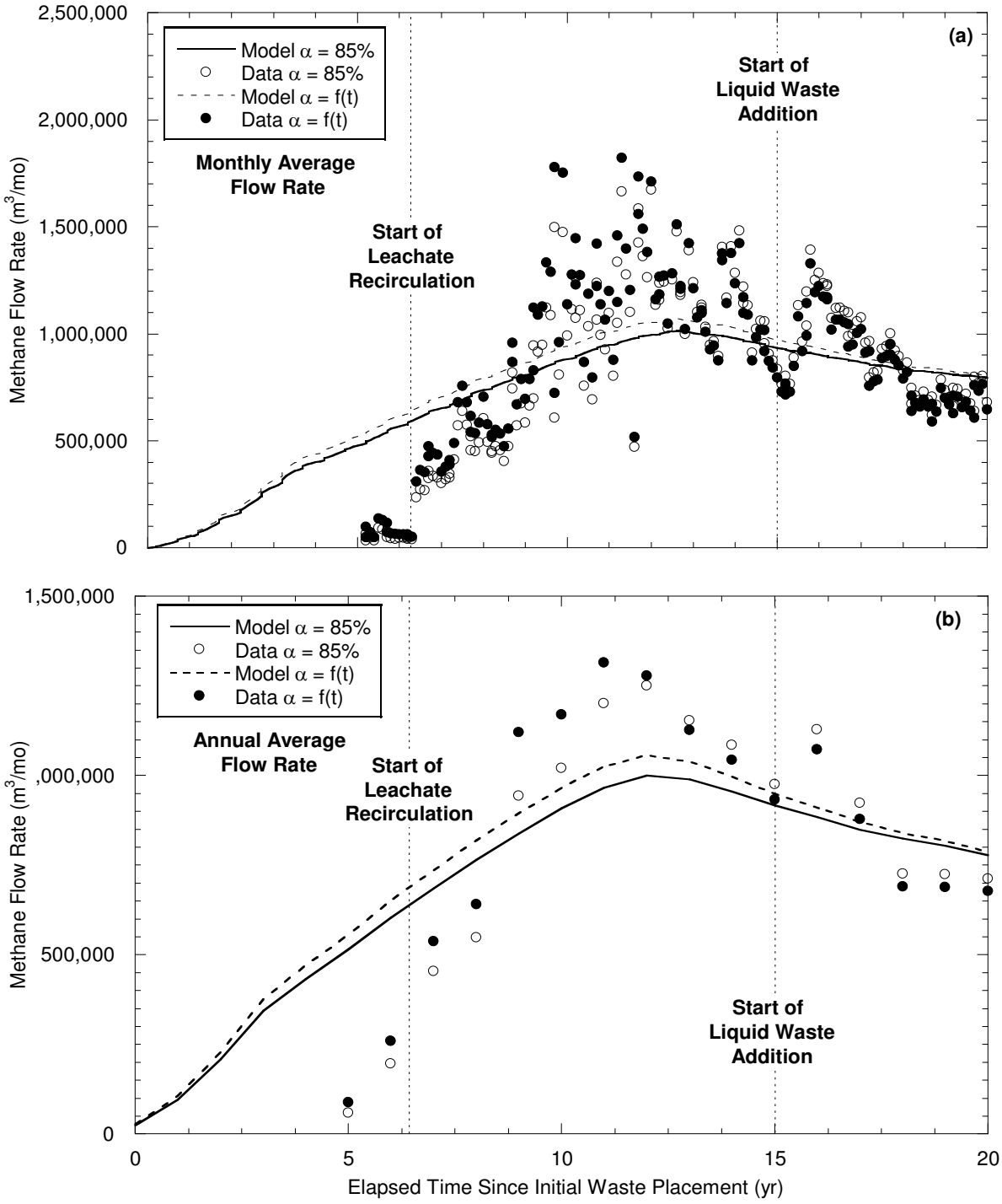

Fig. 25. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for the entire landfill (i.e., site-wide analysis) in Scenario II. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

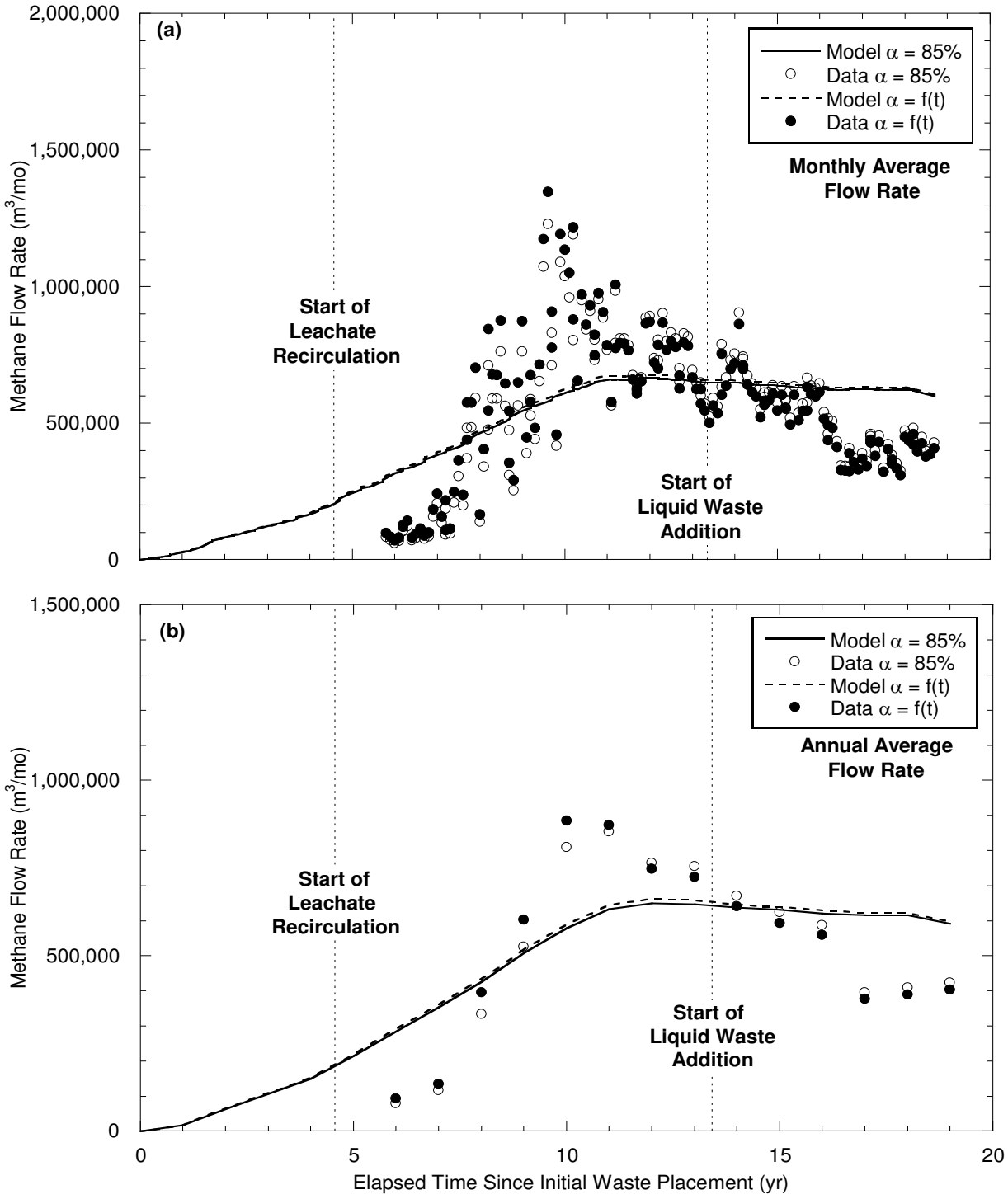

Fig. 26. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for a site-wide analysis excluding Phase 1A & 2A and Phase 1B & 2B in Scenario II. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

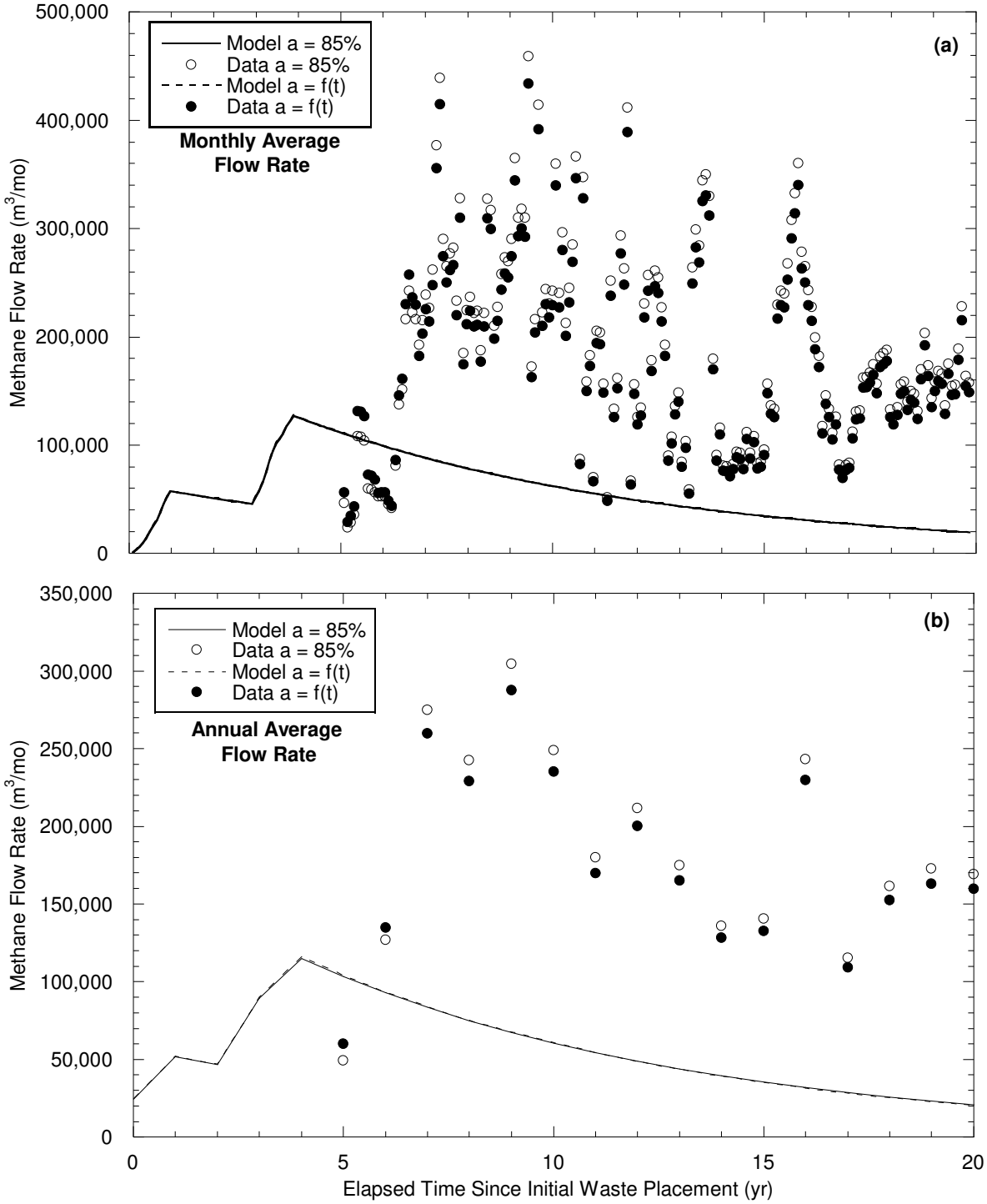

Fig. 27. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 1A & 2A in Scenario II. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

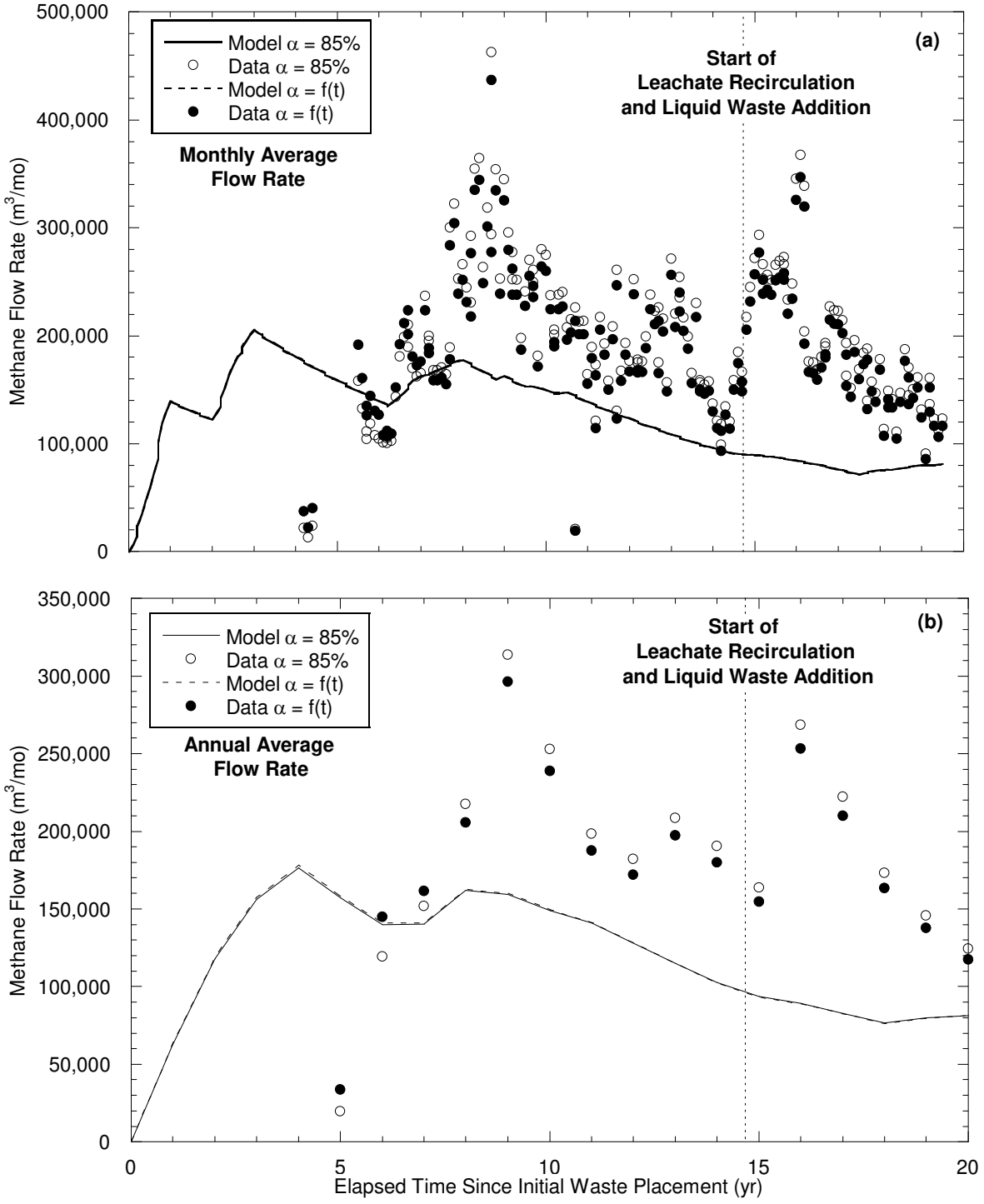

Fig. 28. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 1B & 2B in Scenario II. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

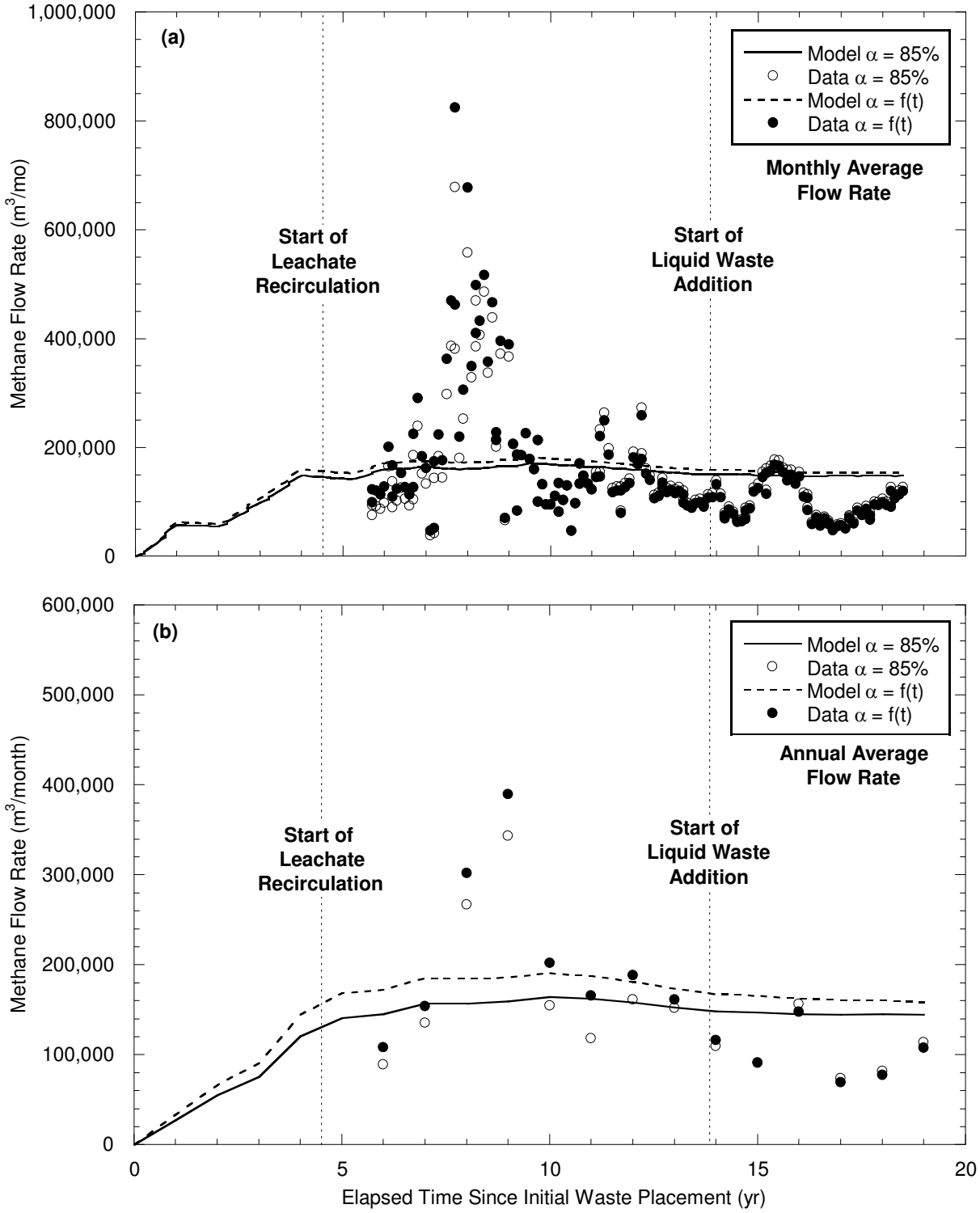

Fig. 29. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 3 & 4 in Scenario II. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

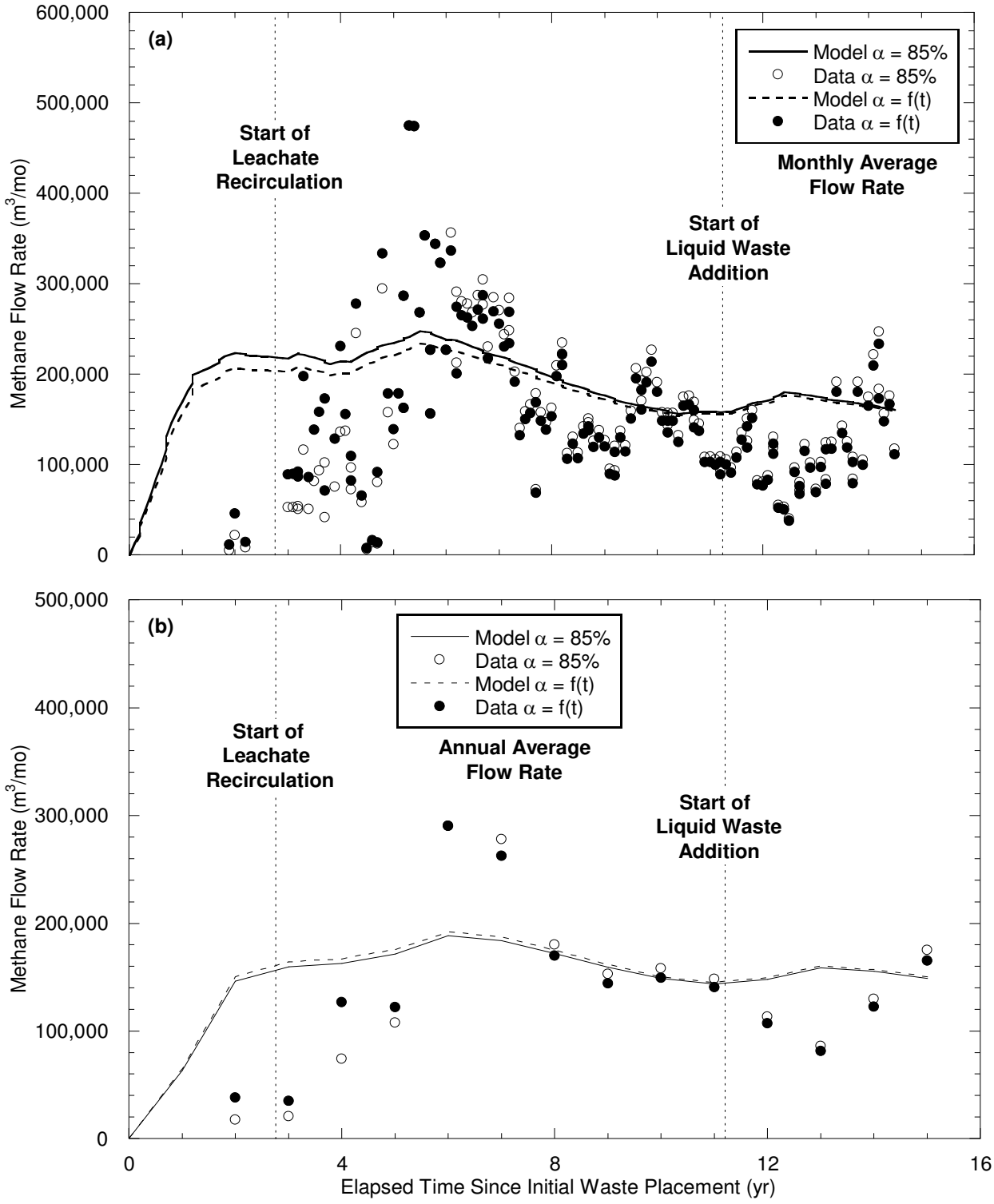

Fig. 30. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 5 in Scenario II. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

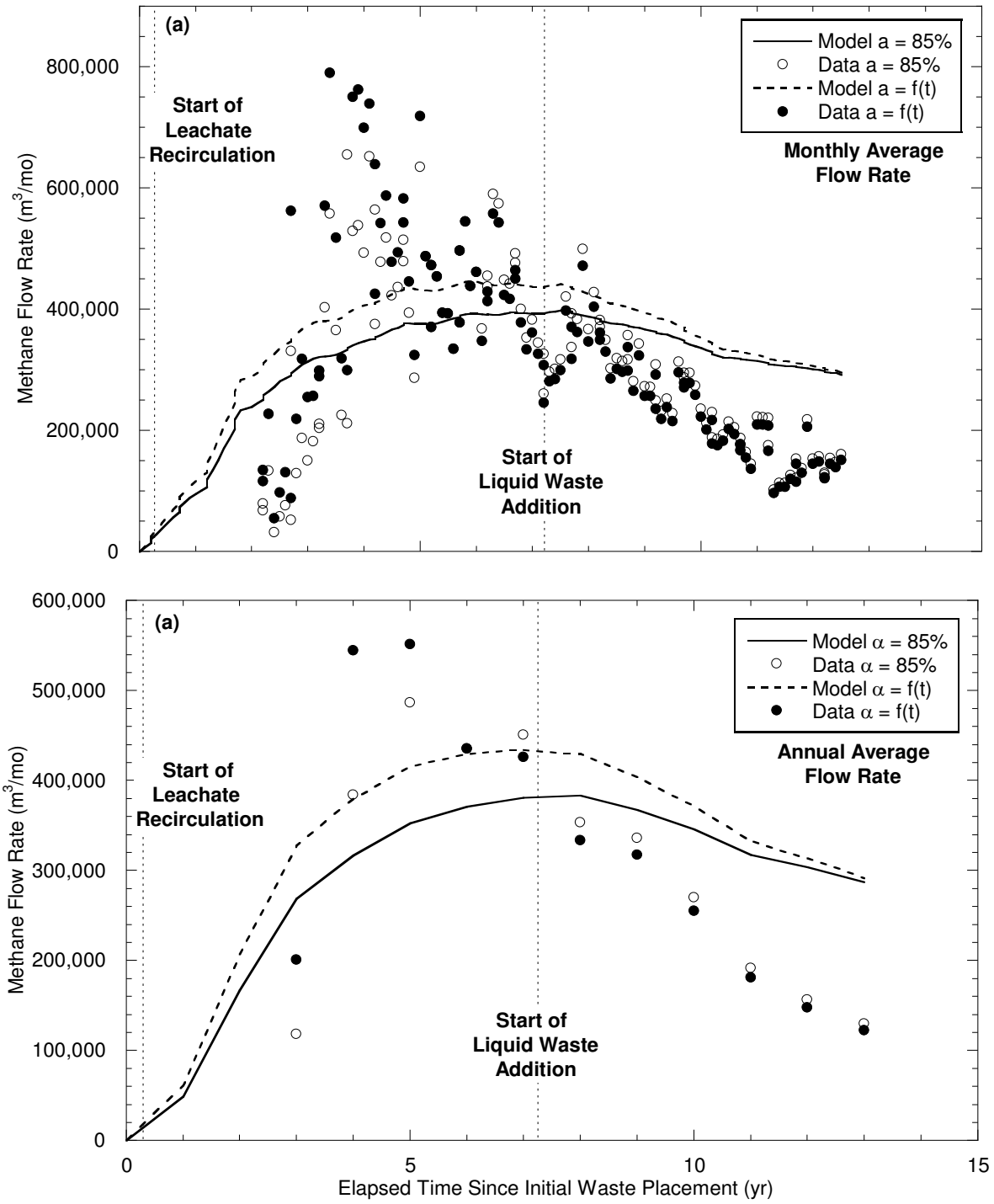

Fig. 31. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 6 in Scenario II. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

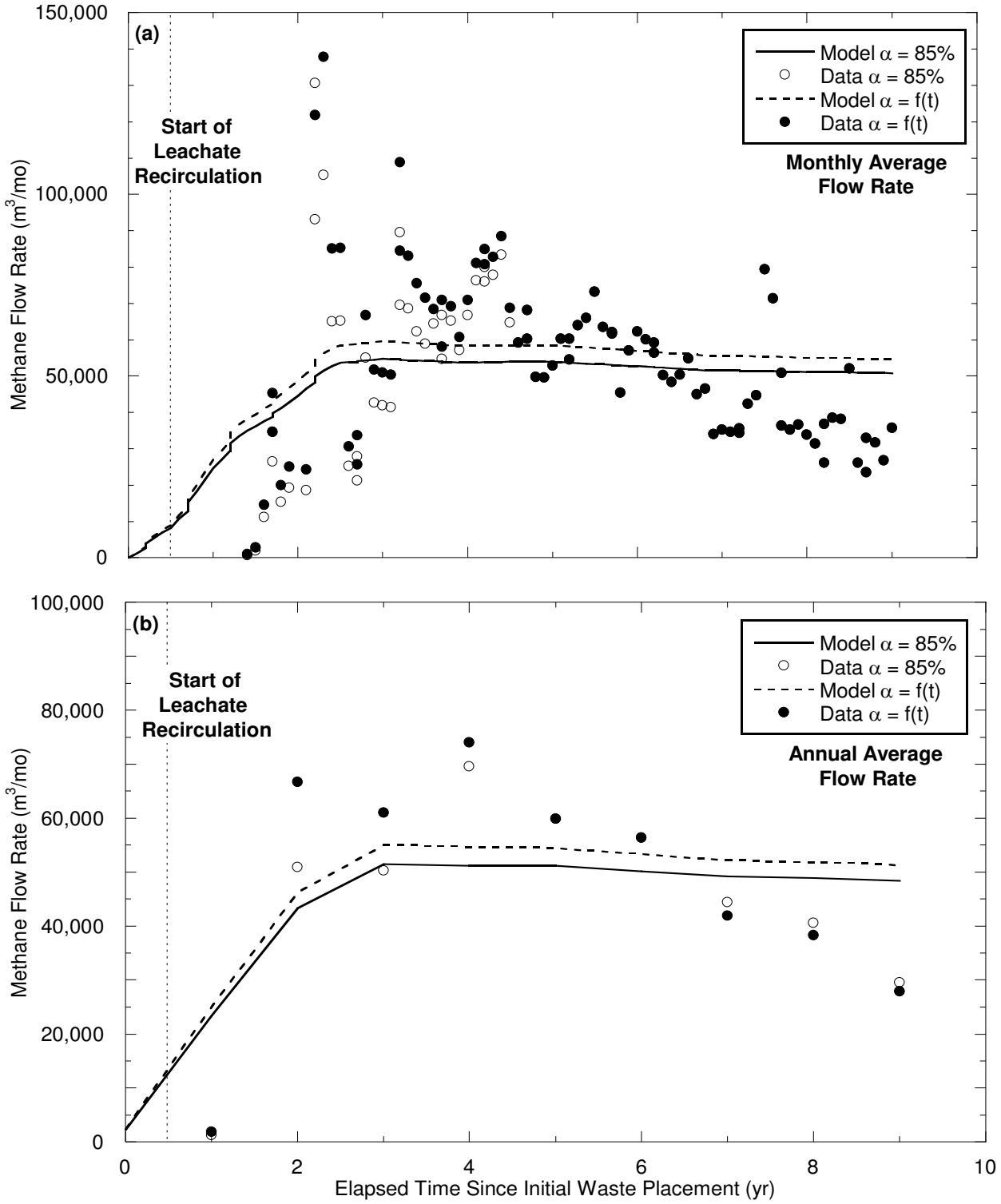

Fig. 32. Temporal trends of (a) monthly average methane flow rate and (b) annual average monthly methane flow rate for Phase 7 in Scenario II. LandGEM simulations were conducted based on an assumed gas collection efficiency of 85% (α = 85%) and temporally varying gas collection efficiency [α = f(t)].

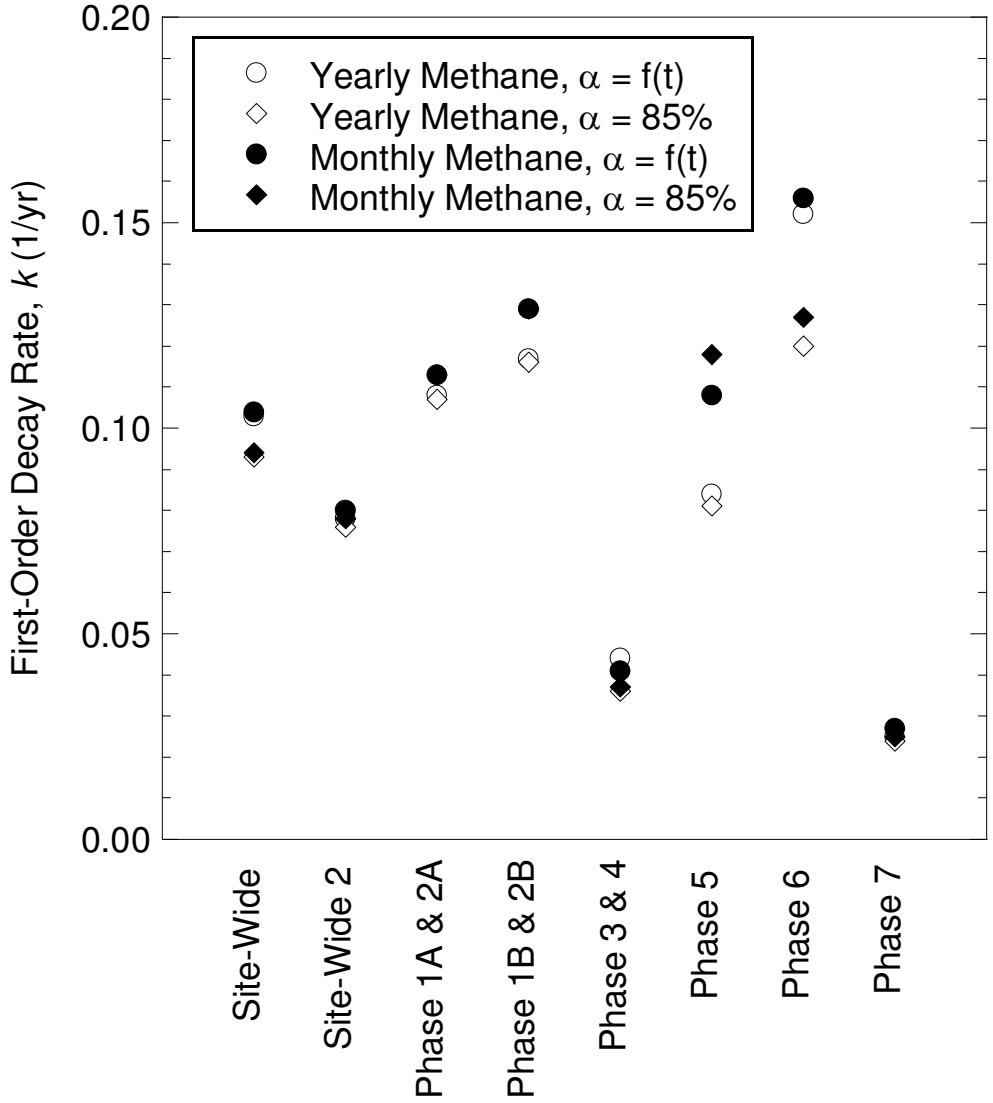

Fig. 33. Graphical summary of optimized first-order decay rates for all gas analyses conducted in Scenario II.

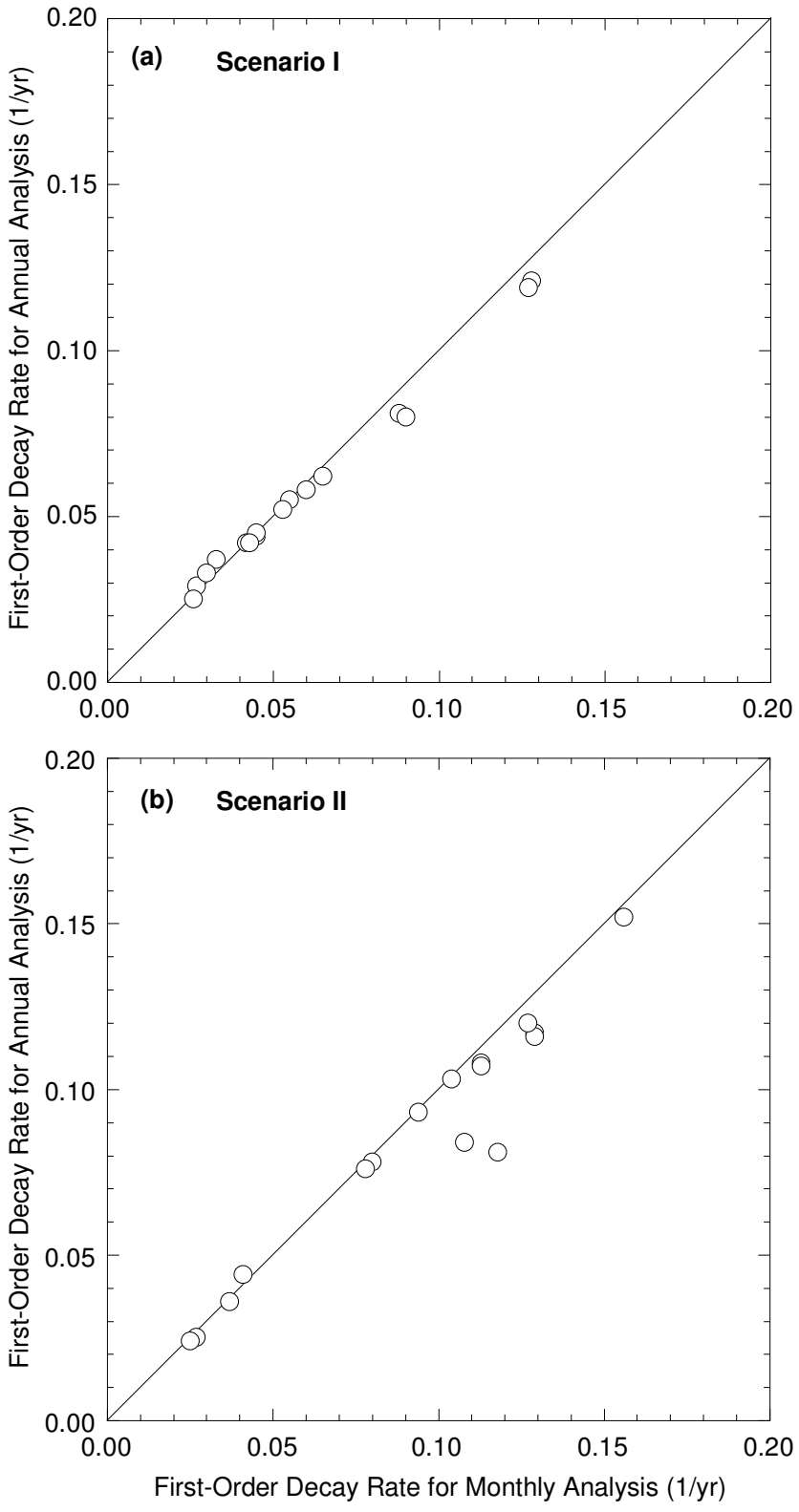

Fig. 34. Comparison between optimized first-order decay rates from annual versus monthly methane flow rate analyses performed for (a) Scenario I and (b) Scenario II.

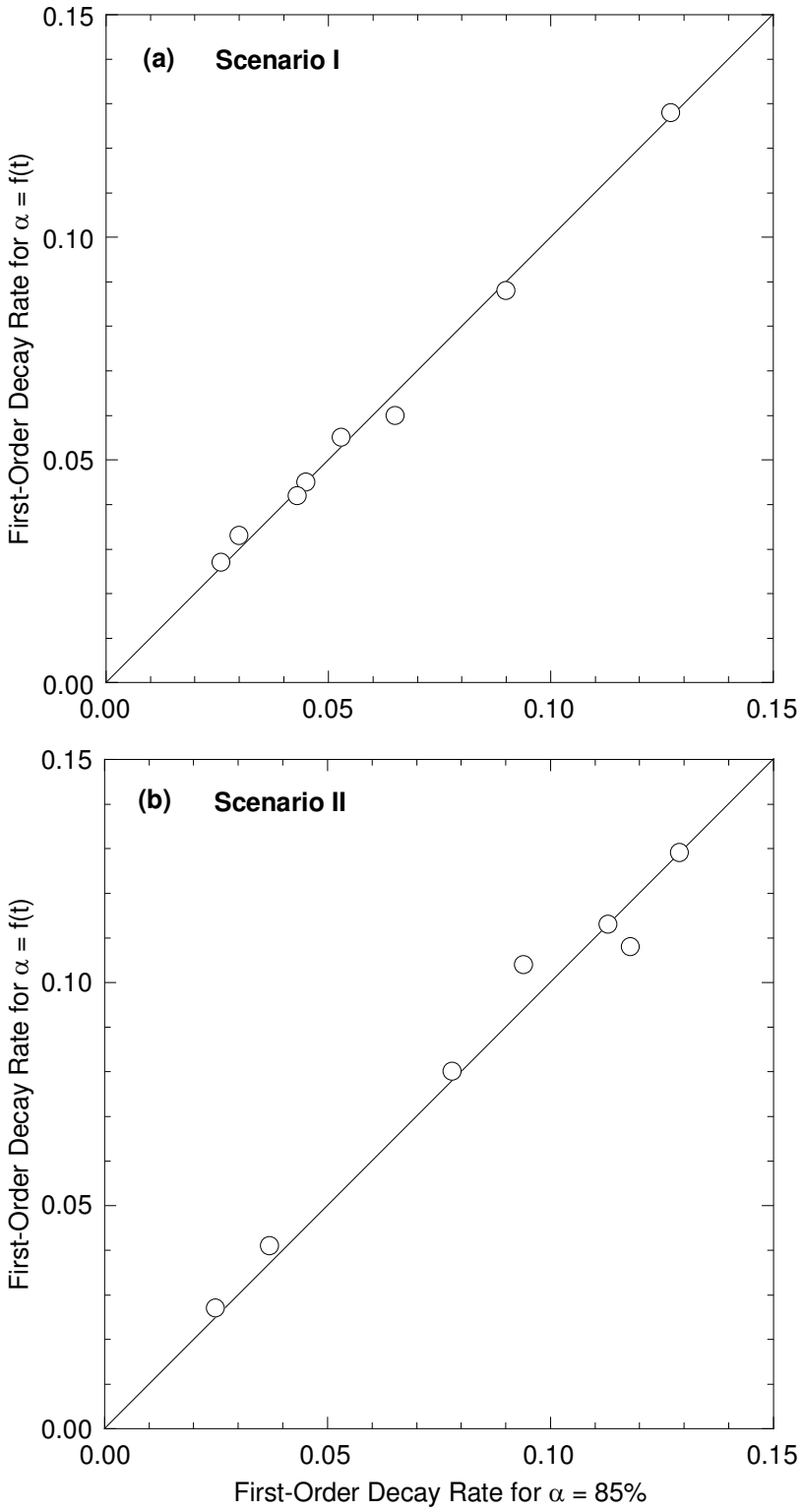

Fig. 35. Comparison between first-order decay rates optimized for monthly average methane flow rates using monthly and annual temporally varying collection efficiency [α = f(t)] versus a constant gas collection efficiency of α = 85% in (a) Scenario I and (b) Scenario II.

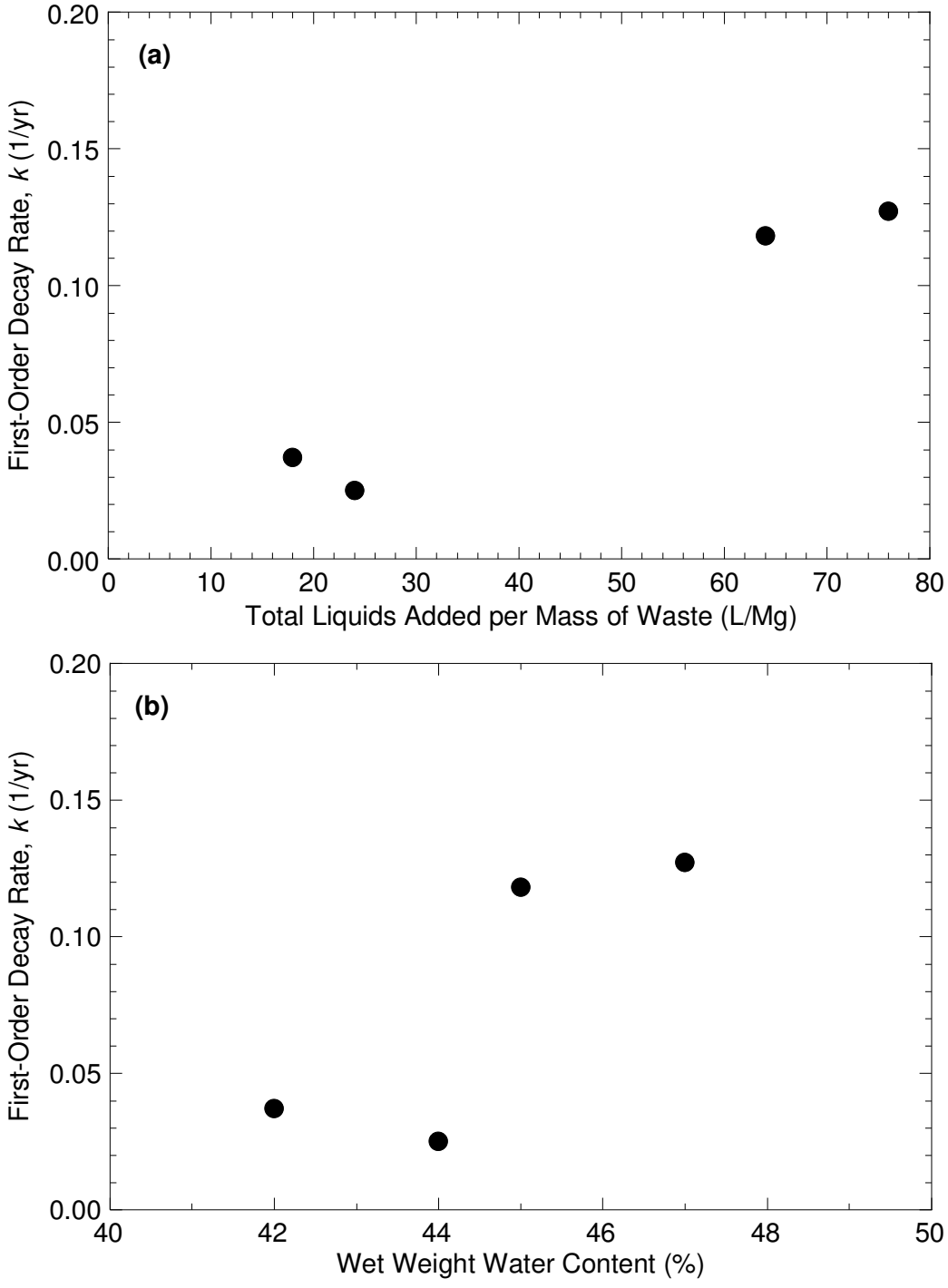

Fig. 36. Relationships between optimized first order decay rates versus (a) total liquid added per waste and (b) wet weight water content.

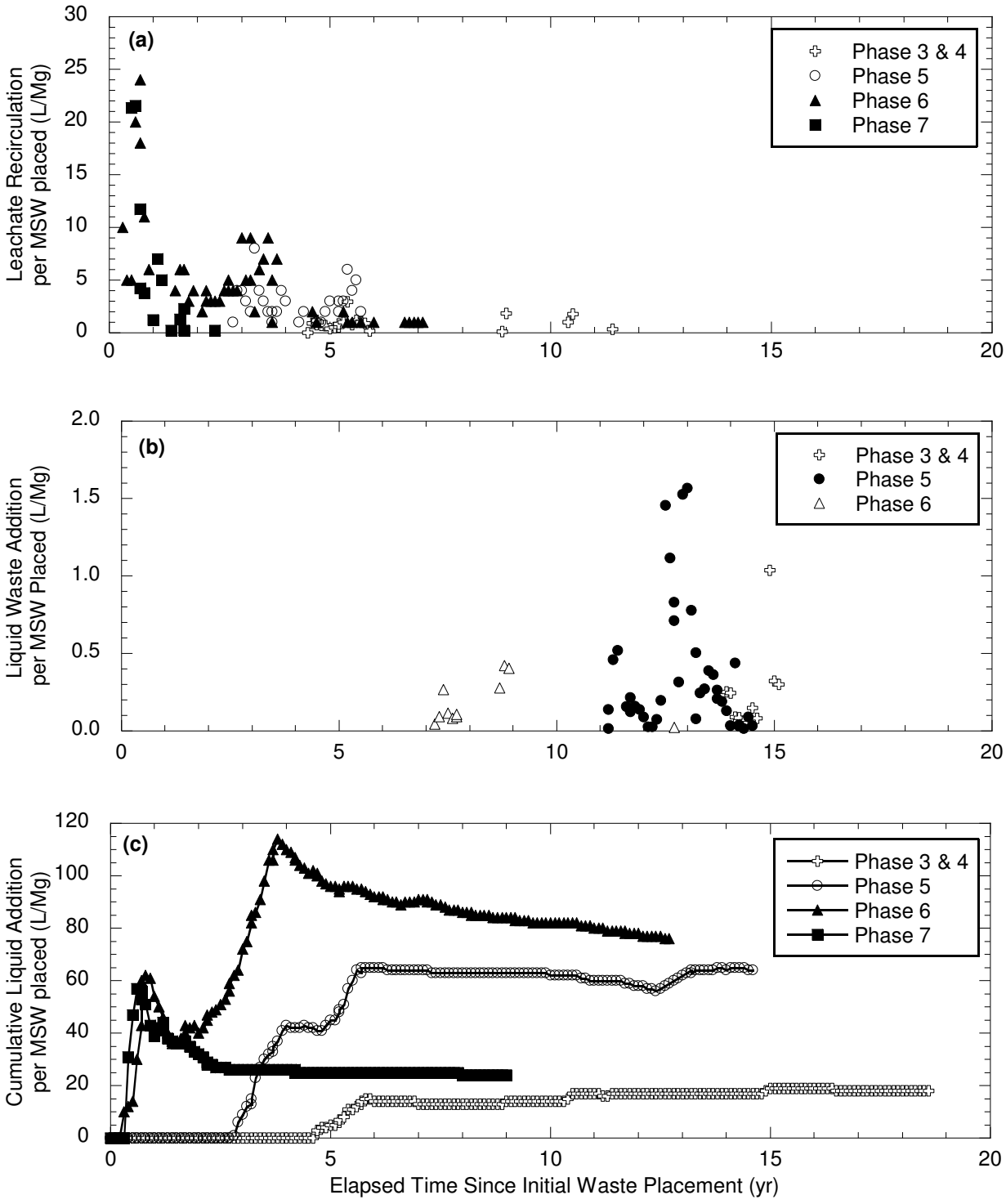

Fig. 37. Temporal trends of (a) leachate recirculation per total municipal solid waste (MSW) placed (b) liquid waste addition per total MSW placed and (c) cumulative liquid addition per total MSW placed in Phases 3 & 4, 5, 6 and 7.

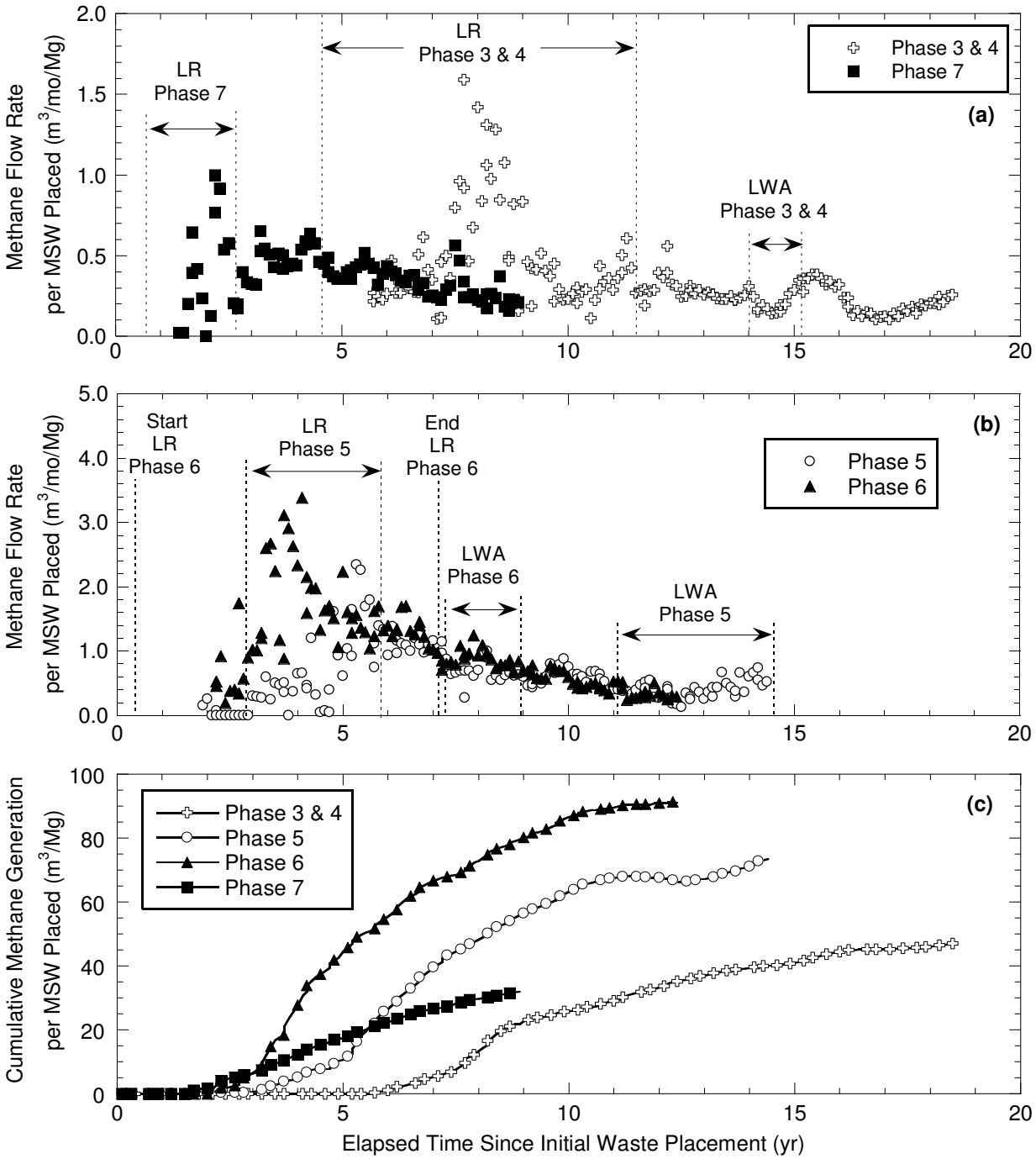

Fig. 38. Temporal trends of (a) methane flow rate per total mass of municipal solid waste (MSW) laced in Phases 3 & 4 and 7, (b) methane flow rate per mass of total MSW placed in Phases 5 and 6, and (c) cumulative methane generation per total MSW placed in Phases 3 & 4, 5, 6, and 7. Notes: LR = leachate recirculation; LWA = liquid waste addition.

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.