Canadian Landfill Gas Production:

Improving the Model to Estimate Present and Future Methane Production

By
Jennifer Sawyer

A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF ENVIRONMENT

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ABSTRACT

Landfill gas, consisting primarily of methane and carbon dioxide, negatively affects human and environmental health. Its production and ultimate release into the atmosphere contribute to greenhouse gases and global warming. Accurate portrayals of current and future Canadian landfill-gas production guide appropriate methods for its mitigation. Without adequate knowledge regarding how the landfill environment operates, it is difficult to employ an environmentally friendly and cost effective management strategy. Modeled projections can provide insight to guide current and future policy decisions regarding the control and prevention of methane production.

This thesis improves current and future Canadian landfill methane production models, thereby advancing the knowledge used to select waste management and reduction strategies. Other objectives achieved include: 1) choosing a landfill gas model that best predicts methane production, 2) advancing the science of model inputs, and 3) predicting future methane production based on current and prospective waste diversion practices.

The German EPER, TNO, Belgium, LandGEM, and Scholl Canyon models were tested for their suitability to model methane production for 35 Canadian landfills. A modified Scholl Canyon/LandGEM model, the "Sawyer Model" best calculated methane production, initially yielding a relative percent error of 19% and $p=0.2501$. Inputs for this model, decay rate (k) and methane generation potential (Lo), were reevaluated to best fit the measured data. Decay rates were trended with annual precipitation, improving the methodology used to calculate site-specific values. Methane generation potentials were assessed using site-specific and provincial waste composition data. Their calculated

values were determined to be 10% less than that required to mimic Canadian landfill conditions successfully. Using these modified/improved inputs, the "Sawyer Model" yielded a median of -2% and $p=0.5538$. Although this change in Lo increased the percent error, the likeness between the measured and modeled data changed from moderate to high. Other variables not currently included in the "Sawyer Model" were assessed for their relationship/contribution to methane production. Current waste-in-place amounts (>10 Mt of waste versus <10 Mt of waste) and landfill operating status (closed versus operating landfills) were found to have significant relationships with methane production and should be considered when modeling landfills. Finally, four landfills were modeled to the year 2025 under five different waste diversion scenarios, illustrating that methane recovery projects are viable under a variety of waste diversion scenarios and in conjunction with recycling/composting initiatives.

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ABBREVIATIONS

Alta. - Alberta
ANOVA – Analysis of Variance
atm - Atmosphere
B.C. – British Columbia
BTU – British Thermal Units
CH_4 - Methane
CO_2 – Carbon Dioxide
D – Collection Efficiency Factor
DOC - Degradable Organic Carbon
DOC_f – Fraction of Assimilated Degradable Organic Carbon
EC – Environment Canada
F – Fraction of Methane Converted to Landfill Gas
ft – Feet
ft^3 – Cubic Feet
GWP - Global Warming Potential
IPCC - Intergovernmental Panel on Climate Change
k - Decay Rate
kg - Kilogram
kt - Kilotonne
KWh – Kilowatt-hour
Lo - Methane Generation Potential
M – Waste Landfilled
m - Meters
m^3 – Cubic Meters
MCF – Methane Correction Factor
mm - Millimeters
MMO – Methane Mono-Oxygenase
MSW – Municipal Solid Waste
Mt - Megatonne
n – Sample Size
NMOC - Non-Methane Organic Compound
NREL – National Renewable Energy Laboratory
Ont. - Ontario
Q – Methane Production
Que. - Quebec
S – Stoichiometric Factor
scf – Standard Cubic Feet
$t_{1/2}$ - Half-life
Tg - Teragram
UNFCCC - United Nations Framework Convention on Climate Change
US EPA – United States Environmental Protection Agency

CHAPTER 1: INTRODUCTION

Landfill gas is typically 95% methane and carbon dioxide, which are both powerful greenhouse gases contributing to global warming (Senior, 1990). Methane, the most abundant and stable hydrocarbon in the atmosphere, has a global warming potential (GWP) 23 times that of carbon dioxide (mole basis, 100 year timeframe) (Spokas, 2006). Over the past two centuries, the atmospheric methane burden has more than doubled and the tropospheric methane concentration has increased at an approximate rate of 1% per year. This increase briefly stabilized in the 1990's, but has since continued its increase (Czepiel et. al, 2003). Methane has a tropospheric lifetime of nine years; therefore, a reduction in methane emissions would cause a rapid decrease in atmospheric levels. Each year, human activity contributes approximately 60% of the 600 Tg emitted to the atmosphere (Mosher, Czepiel, and Harriss, 1999).

Landfills are large methane producers, contributing 10-19% (20-70 Tg/yr) of total yearly global anthropogenic emissions (Czepiel et al., 2003; Lay, Li, and Noike, 1996). Landfill gas production can continue for 40 years after the final waste is deposited (Qin, Egolfopoulos, and Tsotsis, 2001) making landfills an important infrastructure to study pre- and post-closure. Current Canadian landfill-gas production data is uncertain and incomplete; this thesis better quantifies present and future Canadian landfill-gas methane production, contributing to the science and understanding of landfill gas generation.

1.1 Landfilling

Landfill gas negatively affects the global atmosphere, local environment, and human health (Attenborough et al., 2002). If it is not properly collected and utilized, landfill gas can be a significant source of atmospheric and groundwater pollution. In the atmosphere, landfill gas causes ozone depletion and global warming, while gas odor, potential flammability, and vegetative stress (leading to plant destruction) affect the local environment. Additionally, potentially toxic trace concentrations of landfill gas components and combustion products, as well as a poor air quality impact human health (Kim, 2003; Attenborough et al., 2002).

Landfilling is the most commonly used method of waste disposal worldwide. Municipal solid waste (MSW) generation is an inevitable product of human activity, resulting in increased attention towards management practices. With over 85% of North American MSW landfilled (Borjesson et al., 2000), waste management has both large economical and environmental impacts. Technological advancements in collection, transport, recycling, composting, combustion, and landfilling help minimize potential impacts to human health and the environment (Weitz et al., 2002).

1.2 Landfill Gas Production

Current Canadian landfill-gas production knowledge must be improved for several reasons. First, Annex 1 countries (including Canada) under the Kyoto protocol must monitor and report their greenhouse gas emissions to the United Nations Framework Convention on Climate Change (Jacobs and Scharff, 2001). This requires comprehensive information regarding methane formation, oxidation, production, and emission. Recovery and processing of the organic waste fraction are essential if landfill diversion objectives set by the Canadian government (provincial and federal) will be met (Otten, 2001).

Second, the design and operation of landfill gas extraction and utilization projects requires reliable methane production forecasts for project feasibility (Oonk and Boom, 1995). Both short and long-term production projections are required for control, energy recovery, and to meet environmental compliance objectives (Huitric and Soni, 1997). Existing technologies and management programs can stabilize and reduce landfill methane production and subsequent emissions. A 10-20% decrease of anthropogenic methane emissions would stabilize atmospheric methane concentrations to 1990 levels (Mosher, Czepiel, and Harriss, 1999). However, municipalities and provinces are reluctant to invest in recovery projects due to the limited ability to predict landfill-gas generation rates and total gas yield, particularly when some methane recovery projects have yielded 10% of that estimated by models (Goldstein, 2007).

1.3 Objectives

The objective of this thesis is to improve current and future Canadian landfill methane production models, thereby advancing the knowledge used to select waste management and reduction strategies. The sub-objectives include: 1) choosing a landfill gas model that best predicts methane production, 2) advancing the science of model inputs, and 3) predicting future methane production based on current and prospective waste diversion practices.

1.4 Significance

The significance of this work lies in its potential to aide in the reduction of greenhouse gases and improve landfill management practices. Accurate portrayals of current and future landfill-gas production will guide an appropriate method for its mitigation. Without adequate knowledge regarding how the landfill environment operates, it is difficult to employ an environmentally friendly and cost effective management strategy. Modeled projections can provide insight to guide future policy decisions regarding the control and prevention of methane production, which ultimately leads to atmospheric landfill-gas release.

1.5 Thesis Layout

This thesis consists of six chapters. The first chapter introduced the issues surrounding landfill-gas production, as well as project scope. Chapter 2, a literature review, examines previous work pertaining to methane modeling, environmental influences on methane production, and management alternatives. Chapter 3 describes the methodology used to meet objectives outlined in Chapter 1. Chapter 4 presents the study results and Chapter 5 discusses them in detail. Finally, Chapter 6 summarizes the findings and their relevance.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Serious environmental consequences can arise from poor waste management practices, including leachate groundwater pollution, methane gas production, and atmospheric pollution from incinerators. Waste goals set at the 1992 Earth Summit in Rio include minimizing waste, stabilizing waste production, quantifying waste flows, maximizing waste reuse and recycling, developing national programs for waste management research and practice, raising public awareness, and promoting environmentally sound waste disposal (Read, Phillips, and Robinson, 1998).

Landfill gas composition is over 95% methane and carbon dioxide, with the methane content typically ranging from 40-60% (Senior, 1990). Non-methane compounds such as nitrogen, oxygen, hydrogen sulfide, disulfides, and volatile organic carbons are present in trace amounts (DeWalle et al., 1978). Canadian waste reduction initiatives aim to reduce the dependence upon landfilling, which is the most common Canadian waste management strategy. There are an estimated 10,000 landfills/dumps in Canada and while the majority are small, approximately 115 are major landfills (Sawell, Hetherington, and Chandler, 1996).

The following section describes landfill-gas modeling techniques, modeling inputs, and methane utilization, all of which influence methane gas estimates and its subsequent mitigation. The presented theory examines landfills and the challenges of modeling such systems.

2.2 Landfill-Gas Modeling

Quantifying landfill methane-gas production is desirable for several reasons. First, methane recovery produced alternative energy, which has potential economic value, but this project is only considered if methane is quantified as economical. Second, waste-reduction government policy requires information regarding gas production quantity to assess appropriate mitigation strategies and to fulfill Kyoto reporting requirements. Landfill-gas models act as tools to provide an estimate of generated methane or total landfill gas over time from a particular waste source. They describe in simple terms the complex changes occurring during landfill decomposition.

Landfill gas models are based on practical descriptions of gas formation previously observed either in laboratory experiments or in full-scale recovery projects. Landfill gas emission models generally describe methane production according to Darcy's Law, physical characteristics (climate, refuse mass, and age), substrate utilization, biokinetic characteristics, and environmental factors (moisture content, sulfate, and volatile solids) (Lay, Li, and Noike, 1996). Landfill gas production is highly variable due to the heterogeneity of the landfill composition, making it difficult to characterize landfill systems on a general scale.

2.2.1 Landfill-Gas Formation

In landfill systems, the conversion of organic matter to landfill gas requires microorganism groups working in concert, producing reactions in series and parallel to one another. A web of interacting anaerobes is required to convert organic matter into methane; therefore, the amount of gas produced varies depending on the presence of other microorganisms and their environmental interaction in the landfill. Over many years deposited waste covers other, previously deposited waste. Therefore, vertical and spatial landfill zones simultaneously exist in different decomposition phases. The heterogeneous environment (with respect to moisture content, waste density, and nutrient availability) affects the duration and character of each phase.

Hydrolytic and fermentative bacteria, acetogenic bacteria, and methanogenic bacteria are the three main bacterial groups involved in landfill methane production. These bacteria convert degradable organic carbon (DOC) into landfill gas in three major steps: 1) hydrolysis, 2) syntrophic association, and 3) methanogenesis (Lay, Li, and Noike, 1996).

1) Hydrolysis

The first decomposition step hydrolyses large compounds such as carbohydrates, proteins, and fats into soluble sugars, amino acids, long chain carboxylic acids, and glycerol (Equation 2.1). As polymer transport across microbial cell membranes is difficult, biological polymer hydrolysis is mediated by the production of extracellular enzymes from landfill microorganisms. Fermentative microorganisms then break down the hydrolyzed products into short chain carboxylic acids, ammonia, carbon dioxide, hydrogen, and acetic acid (Equation 2.2; Kim, 2003).

$$C_6H_{10}O_6 + H_20 \rightarrow C_6H_{12}O_6 + 2H_2 \qquad \text{Equation 2.1}$$

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O \qquad \text{Equation 2.2}$$

2) Syntrophic Association

In the second syntrophic step, obligate proton-reducing acetogens oxidize the fermentation products (propionate and butyrate) to yield acetate, carbon dioxide, and hydrogen (Equations 2.3, 2.4, and 2.5). This process is only thermodynamically favorable under low hydrogen concentrations ($10^{-5} – 10^{-4}$ atm), consequently, obligate proton reducing acetogens can only work in syntrophic association with hydrogen scavengers such as methanogens or sulfate reducers, who maintain such conditions (Kim, 2003).

$$CH_3CH_2COO^- + 3H_2O \rightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \quad \text{Equation 2.3}$$

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad \text{Equation 2.4}$$

$$2HCO_3^- + 4H_2 + H^+ \rightarrow CH_3COO^- + 4H_2O \quad \text{Equation 2.5}$$

3) Methanogenesis

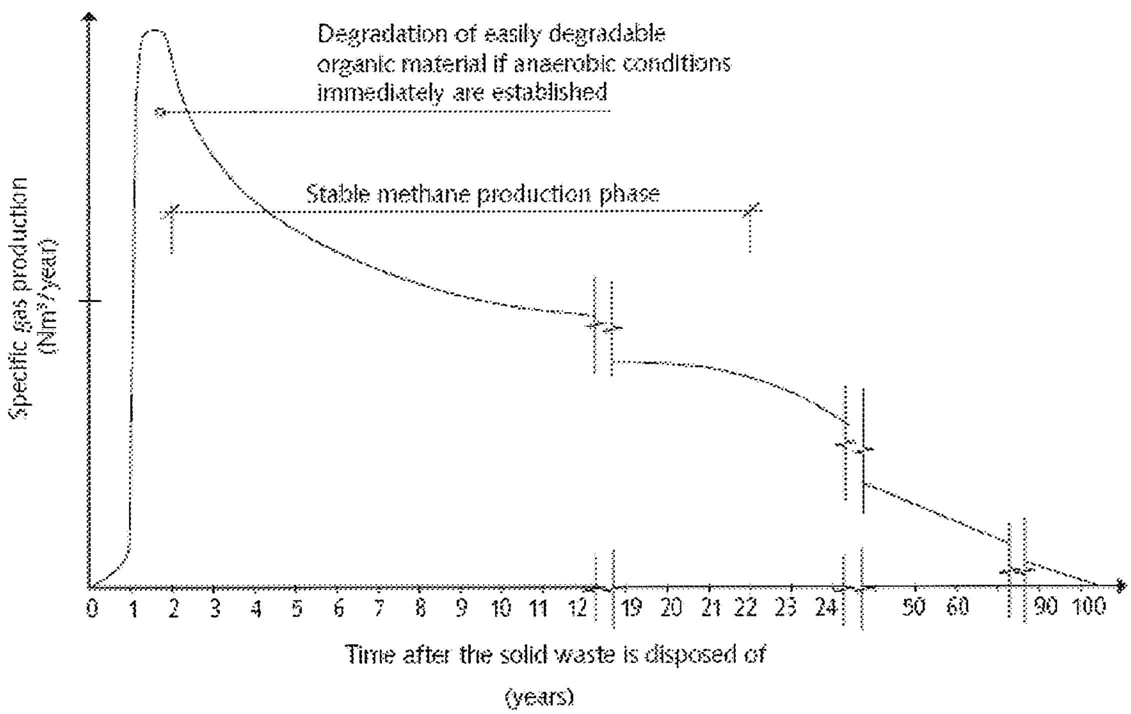
In the final step, methanogens utilize hydrogen and carbon dioxide (or formate and acetate) as substrates to produce equal parts of methane (methanogenesis) and carbon dioxide (Equation 2.6; Huitric and Soni, 1997). Methanogens, belonging to the kingdom Archaea, are oxygen sensitive, fastidious anaerobes. Their consumptive habits are limited to a small number of simple compounds, most only containing one carbon (Kim, 2003). A steady rate of gas production is generally reached in landfills after about 80-500 days and is maintained for 10-20 years (Borjesson et al., 2000).

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad \text{Equation 2.6}$$

2.2.2 Landfill Gas Production Models

Landfill gas production tends to follow a three-step process, ideally mimicking the bacterial progression occurring within the landfill. During the period of initial waste placement, there is a rapid increase in methane yield. This is followed by a peak disposal rate that is sustained for a period comparable to the gas generation period and total site yield peaks. The third, and final stage, is characterized by a rapid decline and a tailing off of the gas yield following landfill closure (Figure 2.1; Huitric and Soni, 1997).

Figure 2.1. Model Representation of Landfill Degradation (Jensen & Pipatti, 2003).

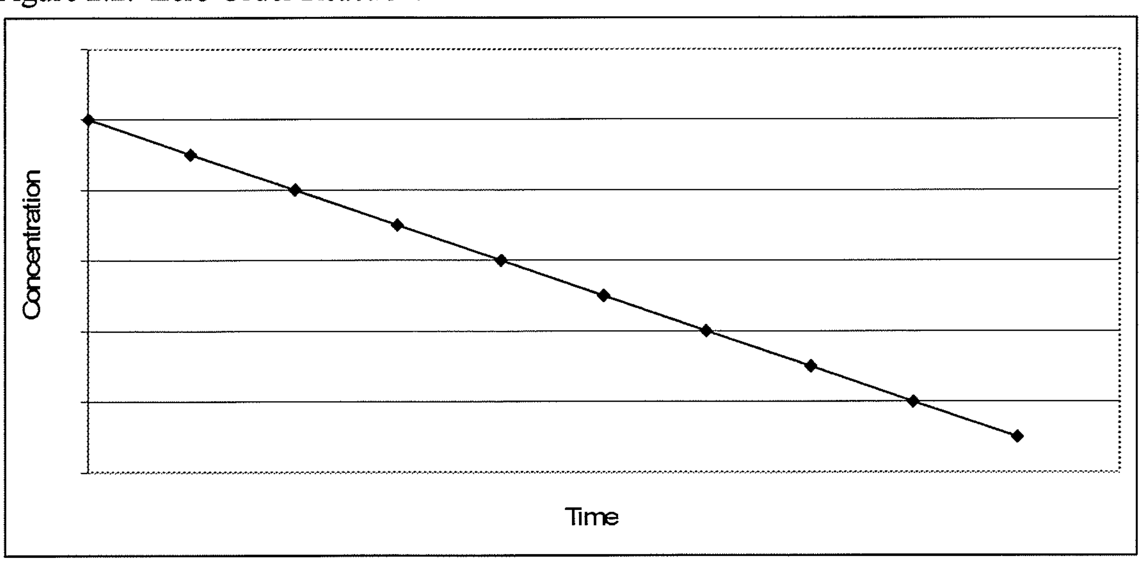


Landfill-gas production models have traditionally followed zero, first, or multi-phase models to quantify methane production in all three of its stages. Currently, the single-phase or multi-phase first order kinetic models are most popular (Jacobs and Scharff, 2001).

2.2.2.1 Zero Order Model

Zero order models do not account for changes occurring over time (Figure 2.2). A zero order model, such as the German EPER Model, generates the rate of methane production independent of the amount of substrate remaining or of the amount of biogases already produced. Zero order models predict an extreme decline in methane production towards the end of the landfill lifespan. This type of sharp decline is not generally observed in landfills, making a zero order model an unlikely choice for modeling landfill gas production (Huitric and Soni, 1997). Zero order models may be good for approximating operational landfills; however, after a landfill closure, gas production decreases a phenomenon that is not reflected in this model type (Jacobs and Scharff, 2001). This model is only suitable for landfills with domestic and residential waste that are currently undergoing waste deposition. This type of model works well for estimating national and global gas emissions provided that there are no major changes in the waste composition and amounts of waste landfilled over time (EPER, 2003).

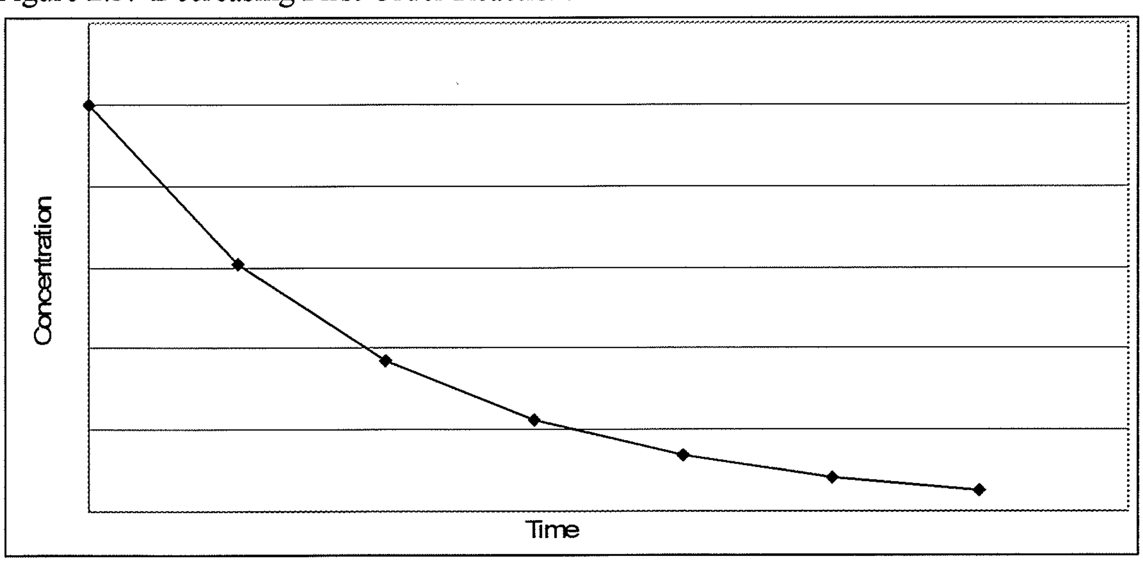
Figure 2.2. Zero Order Reaction.



2.2.2.2 First Order Model

Evaluation of appropriate landfill-gas production models began in the 1970's, when it was established that landfill decomposition follows a decreasing first order model (Huitric and Soni, 1997); however, a definitive formula has yet to be defined. A substance exhibiting a first-order disappearance, as with landfill gas, will show an exponential decrease in concentration over time (Figure 2.3) (Jensen, 2003). It is assumed that gas production is proportional to the degradation of organic matter along first order kinetics (Borjesson et al., 2000) with a gradual decline in landfill gas occurring post closure. First order models including the TNO, Belgium, LandGEM, and Scholl Canyon models are currently used by Denmark, Norway, the Netherlands, and the United States (EPER, 2003). Environment Canada (2006) currently advocates using the first order, Scholl Canyon Model for calculating methane production.

Figure 2.3. Decreasing First Order Reaction.



First order models are criticized because they have difficulty mimicking gas production for initial waste placement, as they lack an initial rising branch describing the early, increasing stages of methanogenesis (Findikakis et al., 1988). Additionally, departures from this type of model were observed in landfills after episodes of long-term wet or dry cycles (Huitric and Soni, 1997), thereby periodically yielding unreliable methane production estimates.

2.2.2.3 Multi-Phase Model

Multi-phase models, such as the Afvalzorg or GasSim models, separately consider different waste types and their respective fractions and degradation characteristics. The multi-phase model best represents what actually occurs in the landfill because it compartmentalizes the heterogeneous environment down into its most similar parts. This model is advantageous because typical waste composition can be taken into account since all waste contains typical fractions of the three phases of degradable materials (Coops et al., 1995). However, this type of model has been heavily criticized because of the difficulty to divide waste into distinct categories with appropriate modeling kinetics (Huitric and Soni, 1997), as this amount of detailed information is often unknown and unrecorded at landfill sites.

2.2.3 Model Outputs

The different gas production models have shown widespread variation in calculated production outputs. In a Netherlands study conduced by Jacobs and Scharff (2001), the first order Scholl Canyon Model greatly overestimated methane production. The zero order German EPER model and the multi-phase Afvalzorg model yielded similar results to each other, noteworthy due to previous studies showing that zero order models when compared to first order and multi-phase models show a large relative error (approximately 44%). However, this study was only conducted for one landfill site and therefore its scientific value is limited as the results might not be indicative of landfills in general (Jacobs and Scharff, 2001). In a separate study, Coops (1995) found no significant difference in different first order models. A National Renewable Energy Laboratory (NREL) study (Huitric and Soni, 1997) found that no difference between zero and first order models exists, while Huitric (1997) concluded that zero order models were unrealistic in predicting landfill gas production. It is apparent that landfill model results fluctuate greatly and a global standard has yet to be found.

2.2.4 Gas Transport Model

Following landfill gas production, the gas migrates to its surrounding environment outside of the landfill. A transport model determines how much of the produced gas quantity releases into the atmosphere. Specifically, a gas transport model calculates the time development of the pressure and gas concentration profiles in the landfill cell to determine flows and movement (El-Fadel, Findikakis, and Leckie, 1996). Models that simulate gas transport are considered analogous to contaminant transport through ground water, as past models have adapted traditional groundwater equations for groundwater/contaminant transport to describe gas flow (Metcalfe and Farquhar, 1987).

Several assumptions are commonly made when modeling gas transport regarding composition, movement, and boundary conditions. In the majority of transport models, the gas is treated as a single species, not distinguishing between the different landfill gas components. When gas collection systems are present, advection is the dominant transport mechanism, while dispersion is not notably influential, allowing the model to only consider the vertical direction. Most models assume that the landfill gas performs as an ideal gas and that the system is isothermic (Copty, Ergene, and Onay, 2004). Finally, most models consider the landfill bottom and sides to be impermeable, thereby only considering gas flow across the top surface of the system (El-Fadel, Findikakis, and Leckie, 1996).

2.2.5 Modeling Difficulties

Estimates of the speed and quantity of landfill gas production can be extremely inaccurate and highly variable, making it difficult to predict landfill gas on a large scale. A single method suitable for registering all landfill production cases would be advantageous, preventing confusion and inconsistencies between reporting countries. Unfortunately, this may not be realistic due to a lack of reliable landfill gas production, emission, and modeling data (Borjesson et al., 2000).

High uncertainty surrounds methane production estimates because of limited available landfill-wide production data. When available, data is uncertain due to problematic measurements originating from the large area that the landfill occupies as well as its heterogeneous environment (Mosher, Czepiel, and Harriss, 1999). Uncertainty also can arise from the efficiency of the gas collection system due to factors such as site-specific climatic conditions, degree of waste saturation, waste and soil-cover gas permeability, landfill design, and operational variances (Copty, Ergene, and Onay, 2004).

Accurate landfill gas predictions require data for waste quantity, age, and composition, factors that are often unknown (Scharff et al., 2002). Several difficult to quantify factors influence landfill-gas production rates, including waste composition, moisture availability, waste interaction, internal percolating moisture, microbial activity, and stage of landfill stabilization. Additionally, there are problems associated with using recorded data including data quality and sparseness, missing data periods, inappropriate data application, varying geographic/climatic conditions, and factors specific to each landfill design such as depth, liner, and leachate recirculation.

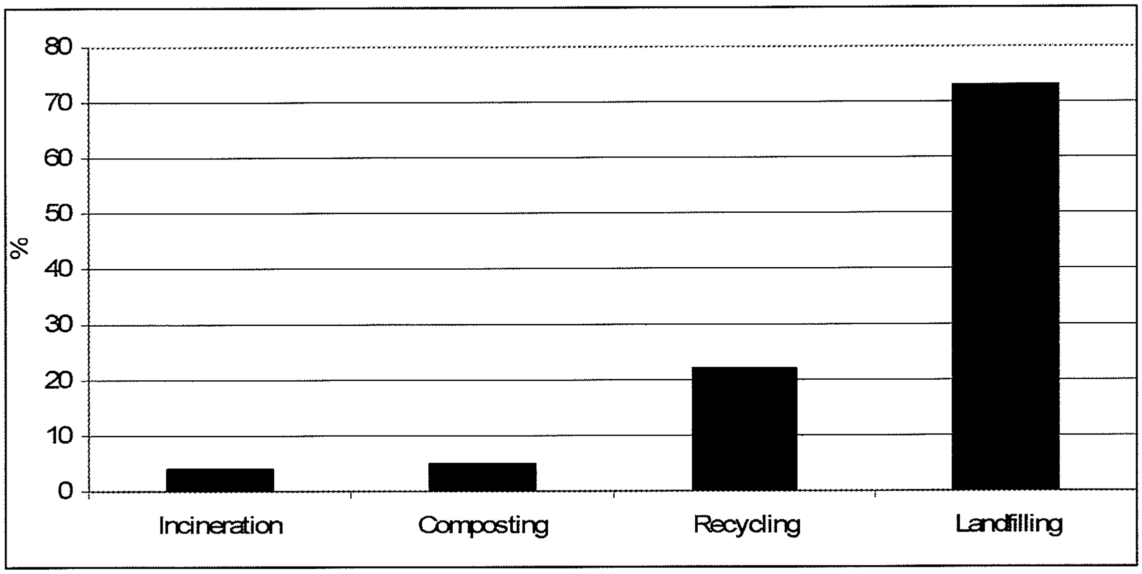
2.3 Model Inputs

Regardless of which landfill-gas production model is used, several inputs are consistently required for calculating methane production. The models typically require inputs regarding the landfill waste, decay rate, and organic content. The methodology involved in calculating these inputs can vary and different approaches are advocated by various reputable sources, making their calculation difficult and uncertain.

2.3.1 Waste

Landfills are the most commonly used method of disposing municipal solid waste in Canada (Figure 2.4). Municipal solid waste landfills contain all waste produced by society except industrial waste, agricultural waste, and sewage sludge (Freudenrich, 2005). Landfill gas production is directly dependant on the amount of waste present in the landfill; therefore, waste data is required in all landfill-gas generation models. It is necessary to distinguish between the amounts of waste generated by society as opposed to landfilled waste because diversion techniques such as recycling and composting have decreased the total landfilled waste. Waste data inputs are required to be reflective of landfilled waste quantities, as opposed to generated waste quantities.

Figure 2.4. Municipal Solid Waste Disposal Methods in Canada (Statistics Canada, 2005).



2.3.2 Decay Rate (k)

The decay rate (k) represents the rate of decomposition occurring within a landfill system. In a first order model, the decay rate is the fractional part of the remaining methane potential released per year (Equation 2.7). The remaining potential changes over time; therefore, the fractional part released in any year will be less than the original "k" value. For example, if $k=0.05\ yr^{-1}$, then the annual release for the first and second years following waste disposal will equal 4.9% and 4.6% (respectively) of the original k-value.

$$k = \frac{d[CH_4]}{dt}$$ Equation 2.7

Where:
k = Decay rate (yr^{-1})
[CH_4] = Concentration of methane gas

The half-life value is the time required for half of the degradable organic carbon to be degraded. In a first order model, when k=0.05 yr^{-1}, the decay rate can be expressed in terms of half-life (Equation 2.8), which in this example, equals approximately 14 years (Huitric and Soni, 1997; IPCC, 2006). In a landfill, the half-life of organic matter typically ranges from five to twenty-five years, depending on waste composition (Reindl, 2002).

$$t_{1/2} = \frac{\ln(2)}{k}$$ Equation 2.8

Where:
k = Decay rate (yr^{-1})
$t_{1/2}$ = Half-life (yr)

Landfill decay rates are extremely difficult to quantify accurately because many environmental conditions act upon this process. Past quantification methods include lab simulations (Harries et al., 2001), samples excavated from landfills (Gardner et al., 2003; Rodriguez et al. 2002; Baldwin, Stinson, and Ham, 1998) and test cells designed to simulate real world conditions (Mehta et al, 2002) to study decomposition. In-field excavation studies have encountered several problems, including the inability to locate all samples after they have been landfilled, sample contamination making weight measurements difficult, variability in landfill conditions, and short sample burial time relative to the period required for complete decomposition (Barlaz, 2004; Baldwin, Stinson, and Ham, 1998). Attempting studies with longer assessment periods are imperative to produce better results with lower uncertainty, although the possibility exists that even after a 10-20 year study, the waste might not be fully decomposed and modeling will be required (Barlaz, 2004).

2.3.2.1 Canadian Decay Rates

The currently used Environment Canada (2004) provincial decay rates were obtained by matching equivalent climatic data to United States state data with the exceptions of the Canadian territories of Nunavut, Northwest Territories and the Yukon (Levelton, 1991). Subsequently, Canadian provinces have the same decay rates as their United States counterpart, except for the three territories. The current provincial decay rates range from 0.003-0.0280 yr^{-1} (Table 2.1). Although not explicitly stated in Levelton (1991), the Northwest Territories, Nunavut, and Yukon presumably have decay values that fall below 0.006 yr^{-1} due to their exceptionally dry climatic conditions. This particular approach was taken due to a lack of information regarding decay rates in Canadian landfills.

With these current decay rate values, Alberta, Saskatchewan, Manitoba, Northwest Territories, Nunavut, and Yukon have half-lives of landfilled material exceeding 100 years (Table 2.1). This suggests that current Canadian decay values are far too low to be reflective of actual landfill decomposition conditions, highlighting a discrepancy between Levelton (1991) and scientific findings.

Table 2.1. Provincial Decay Rates and Corresponding Half-Lives.

Province	Kinetic Rate Constant k (yr^{-1}) (Levelton, 1991)	Half-Life (yr^{-1})
British Columbia	0.028	24.8
Alberta	0.006	115.5
Saskatchewan	0.006	115.5
Manitoba	0.006	115.5
Ontario	0.024	28.9
Quebec	0.024	28.9
New Brunswick	0.011	63.0
Prince Edward Island	0.011	63.0
Nova Scotia	0.011	63.0
Newfoundland	0.011	63.0
Northwest Territories	0.003	231.0
Nunavut	0.003	231.0
Yukon	0.003	231.0

2.3.2.2 Intergovernmental Panel on Climate Change (IPCC) Guidelines

The IPCC guidelines (2006) recommend that decay rates range from 0.03-0.2 yr^{-1}, with a default value of 0.05 yr^{-1}, based on values obtained from measurements of municipal solid waste sites in the United States, the United Kingdom, and the Netherlands. A decay rate of 0.2 yr^{-1} (a half-life of approximately 3 years) is associated with high moisture content and rapidly decaying materials. A slower decay rate of 0.03 yr^{-1} (a half-life of approximately 23 years) is associated with dry conditions and slowly degradable materials. Presently, the provincial decay rates range from 0.003-0.028 yr^{-1}, which is significantly lower than the IPCC recommendation. Current decay rates suggest that no Canadian landfills have high moisture, quick decay waste systems. The Northwest Territories, Nunavut, and Yukon have a decay rate that is ten times lower than what the IPCC would recommend for low moisture, slow decay systems (IPCC, 2006).

A major criticism of landfill operators currently using the first order Scholl Canyon Model is that it considerably overestimates methane production from landfills, making its estimates inaccurate and unreliable (BFI Canada, 2006). However, overestimations may result from poor input choices rather than an improper model formula. Many landfill operators use a default decay rate value ranging from 0.04-0.05 yr^{-1}, which are much higher than most of the rates previously selected for Canadian landfills. Using default values can result in overestimated production estimates relied upon for making gas management decisions. When gas estimates do not accurately reflect landfill production, improper strategies may be used to mitigate the situation as policy makers often rely heavily on modeled predictions.

2.3.3 Degradable Organic Carbon (DOC) and Methane Generation Potential (Lo)

The degradable organic carbon (DOC) input appears in the modeling equation on its own or is integrated into the methane generation potential (Lo) input. The degradable organic content, derived from the biodegradable portion of the waste (Equation 2.9), contributes to the methane generation potential (Lo) equation (Equation 2.10; IPCC, 2006). Small variations in the DOC can result in large variations in the methane production estimates because methane production is directly dependent upon the chemical nature of the degradable waste components (IPCC, 1996; Lay, Li, and Noike, 1996).

$$DOC = (0.4 \times A) + (0.17 \times B) + (0.15 \times C) + (0.3 \times D) \qquad \text{Equation 2.9}$$

Where:
DOC = Degradable organic carbon (kg carbon/tonne waste)
A = Fraction of MSW that is paper and textiles
B = Fraction of MSW that is garden or park waste
C = Fraction of MSW that is food waste
D = Fraction of MSW that is wood or straw

$$Lo = MCF \times DOC \times DOC_F \times F \times 16/12 \qquad \text{Equation 2.10}$$

Where:
Lo = Methane generation potential (kg carbon/tonne waste)
MCF = Methane correction factor (fraction; default=1.0)
DOC = Degradable organic carbon (kg carbon/tonne waste)
DOC_F = Fraction of assimilated DOC (default=0.77)
F = Fraction of methane in landfill gas (default=0.50)
16/12 = Stoichiometric factor

The degradable organic carbon (DOC) content of the waste is required in all landfill-gas production models as it represents the waste portion available for microbial degradation to landfill gas. Steel and aluminum cans, glass containers, and HDPE, LDPE, and PET plastic are inert in landfills; therefore, their methane production is negligible. Organic waste products such as paper, wood, food, and garden waste are degraded, contributing to methane production. Degradable organic carbon constitutes a significant portion (70-80%) of the municipal solid waste (Preen and Murphy, 2001). The organic content of municipal solid waste (MSW) is comprised of cellulose (40-50%), lignin (10-15%), hemicellulose (12%), and protein (4%). Cellulose and hemicellulose are readily biodegradable under anaerobic conditions; however, lignin (found in wood and newspaper) is not (Kim, 2003).

The methane generation potential (Lo) represents the potential amount of methane produced per tonne of waste landfilled. Waste density, composition, and shredding greatly influence the Lo. The density can affect the methane generation potential at any stage of production. The compaction is inversely proportional to gas production rate; as compaction increases, gas production decreases because of decreased surface area exposure to enzymatic hydrolysis and decreased liquid mobility (Von Felde and Doedens, 1999). Shredding enhances the decomposability of the waste material and increases the density by about 15% as compared with unprocessed refuse (Preen and Murphy, 2001).

The DOC/Lo value is generally considered constant, as waste composition does not differ considerably from year to year, unless considerable measures have been taken to alter the organic waste composition such as recycling or composting (Huitric and Soni, 1997).

2.3.3.1 Canadian Parameters

Currently, the methane generation potential numbers employed by Environment Canada (2003) are 165 kg/tonne of waste from 1941-1989 and 117 kg/tonne of waste from 1990-present. The latter value reflects a significant reduction in the organic content of waste landfilled due to recycling initiatives beginning around 1990. Recycling products such as paper decrease the amount of degradable organic carbon (DOC) available to microbes, thus decreasing the waste's methane generation potential.

The Lo value from 1941-1989 (165 kg/t of waste) was obtained from the US EPA's guidelines, while the post 1990 value (117 kg/t of waste) was calculated using Equation 2.11 (Environment Canada, 2003).

$$Lo = \frac{M_c F_b S}{2} \qquad \text{Equation 2.11}$$

Where:
Lo = Methane generation potential (kg/tonne)
M_c = Kilogram of carbon per tonne of waste landfilled (kg/tonne)
F_b = Biodegradable fraction
S = Stoichiometric factor

Environment Canada (2003) calculated the biodegradable fraction (F_b) by dividing the biodegradable carbon by the total carbon. The M_c calculation is the carbon content in the waste (on a dry basis) determined as a percentage of the waste disposed. The carbon content consisted of two categories, biodegradable carbon and refractory carbon. Biodegradable carbon is easily degraded carbon, while refractory carbon is slowly degraded carbon, unavailable for greenhouse gas production. The stoichiometric factor for methane to carbon is 16/12. The entire equation was divided by a factor of two because 50% of the gas produced is methane while the other half is carbon dioxide.

2.3.4 Oxidation

Total methane production does not necessarily equal the methane released into the atmosphere due to methane oxidizing methanotrophs. Methanotrophs thrive in systems such as soil, sediment, landfills, groundwater, seawater, peat bogs, hot springs, plant rhizosphere, and salt reservoirs, where an overlap occurs in the methane and oxygen profiles. Methanotrophs are aerobic bacteria, unable to survive without the presence of oxygen. Methanogens oxidize methane as a carbon and energy source, utilizing the enzyme methane monooxygenase (MMO), and thereby producing methanol (Equation 2.12). Degradation continues until the material is converted to formic acid (Equations 2.13 and 2.14; Hanson and Hanson, 1996).

$$CH_4 + O_2 + H_2 \xrightarrow{MMO} CH_3OH + H_2O \qquad \text{Equation 2.12}$$

$$CH_3OH + H_2O \rightarrow HCOOH + 3/2H_2 \qquad \text{Equation 2.13}$$

$$HCOOH \rightarrow CO_2 + H_2 \qquad \text{Equation 2.14}$$

It is debatable whether oxidation plays a significant role in landfill systems. Dense landfill compaction is not conducive for a methane-oxygen interface, suggesting that oxidation may not substantially occur under high-level density conditions (Parsons, 2002). Historically, US EPA models have not considered methane oxidation, potentially over-estimating landfill methane emissions (Bogner, Spokas, and Burton, 1997). However, consideration of the oxidizing top landfill layer may be required when calculating landfill-gas emissions (Jacobs and Scharff, 2001), as a 10-20% methane oxidation rate has more recently been observed (Oonk, 1996; Czepiel et al., 2003; IPCC 2002).

Oxidation should only be considered when calculating methane emission and not methane production because the majority of the oxidation occurs in the daily and final cover, not when it is initially produced. When comparing model outputs to measured values taken from methane recovery units, the landfill gas has not yet had time to migrate to the surface of the landfill in order to be oxidized. Therefore, the measured values would not have an oxidation reduction accounted for in its values.

2.3.5. Collection Efficiency

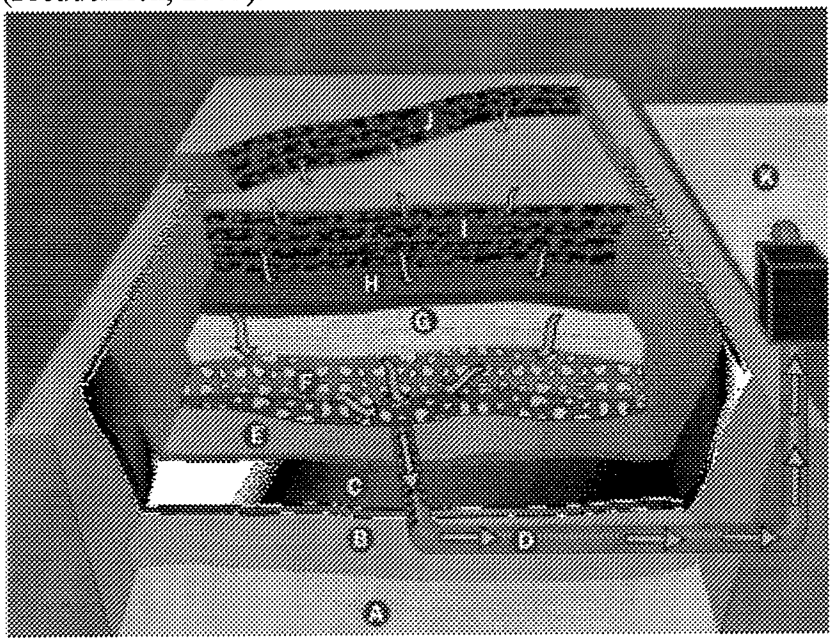
The collection efficiency is the amount of landfill gas collected in the recovery system as compared to the amount generated. The collection efficiency is greatly influenced by the cover type (daily, intermediate, or final) and type of collection system (active or passive system, air quality control, and landfill gas migration control) (Alberta Research Council, 2007). The efficiency rates used for modeling landfill gas are typically derived from previous modeling studies, calculated by dividing the measured gas extraction rates by the modeled gas extraction rates, and tend to range from 50% to 75%, prior to better efficiency rates noted by Spokas et al (2006). However, these values may not reflect actual efficiency, as when calculated in this manner they are highly dependant on the accuracy of the landfill gas model used. Other methods used to calculate/estimate the efficiency include flux chamber and tracer gas measurement, although they are criticized for being highly uncertain (Huitric and Kong, 2007).

Currently, the US EPA (2004) recommends using a collection efficiency default value of 75% based on survey responses of industry estimates. However, Spookas et al. (2006) and Huitric and Kong (2007) suggest that the US EPA's data is inaccurate and unreliable. Both studies claim that the efficiency is higher, ranging between 85% to around 98% based on emission estimates.

2.4 Landfill Environmental Impacts

A landfill is a carefully designed structure built into or on top of the ground to ensure refuse isolation from its surrounding environment. Its design and operation acts to minimize public health and environmental impacts. Most engineered MSW landfills have six basic components: 1) a bottom liner system, 2) cells (old and new), 3) storm-water drainage system, 4) leachate collection system, 5) methane collection system, and 6) a covering or cap (Figure 2.5; Freudenrich, 2005). Although these structural advances are not explicitly mentioned in the landfill-gas production models, their construction can promote or thwart methane production.

Figure 2.5. Landfill Design Cross Section. Arrows Indicate Leachate Flow Direction (Freudenrich, 2005).



A. Groundwater
B. Compacted Clay
C. Plastic Liner
D. Leachate Collection Pipe
E. Geotextile Mat
F. Gravel
G. Drainage Layer
H. Soil Layer
I. Old Cells
J. New Cells
K. Leachate Pond

1) Bottom Liner

The liner system, constructed from a durable, puncture-resistant synthetic plastic such as polyethylene, high-density polyethylene, or polyvinylchloride, is the landfill base. A compacted clay soil may be combined with the plastic liner as an additional liner to prevent the movement of leachate and landfill gases (Kim, 2003). A fabric, geotextile mat may surround the plastic liner on either side to prevent tearing or puncturing of the liner from nearby rock and gravel layers (Freudenrich, 2005).

2) Cells

Refuse is compacted daily by tractors, bulldozers, rollers, and graders into different cell areas to allow for maximum landfill capacity. Typical waste compaction ranges from 700-1500 kg/m^3, depending on the type of compacting equipment used (Preen and Murphy, 2001). Once the cell is completed, it is covered with six inches of soil and then further compacted (Freudenrich, 2005).

3) Storm-Water Drainage System

A storm-water drainage system controls rainwater infiltration in order to prevent increased leachate production. Plastic drainage pipes and storm liners collect water from areas throughout the landfill and channel it to concrete or gravel–lined drainage ditches surrounding the landfill's base. The ditches carry the water to collection ponds located beside the landfill for chemical testing prior to being pumped off-site (Freudenrich, 2005).

4) Leachate Collection/Recirculation System

The storm-water drainage system is imperfect and may occasionally allow water to permeate through the landfill cells. As the water percolates, it reacts with contaminants including organic and inorganic chemicals, metals, and biological waste products of decomposition, producing acidic leachate. Perforated pipes running throughout the landfill drain the leachate into a leachate pipe and transport it to a leachate collection pond. The leachate undergoes testing for biological and chemical oxygen demand, organic chemicals, pH, calcium, magnesium, iron, sulfate and chloride levels, after which it is treated in a similar manner to sewage/wastewater before its release (Freudenrich, 2005).

Leachate recirculation systems, a relatively new management technique, collect landfill-generated leachate from the base of the site and reintroduce it into the cells by surface irrigation, sub-surface irrigation, or injection (Lawson, 1997). Leachate recirculation can optimize landfill environmental conditions, provide enhanced landfill stabilization, and treat leachate moving through the fill. Accelerated gas production rates and the return of organic material to the landfill can enhance landfill gas production by up to a factor of two, a desirable outcome if the landfill gas is managed properly (Reinhart and Al-Yousfi, 1996).

5) Methane Collection System

Landfill gas, containing primarily methane and carbon dioxide, escapes from the landfill passively or is pumped by an active collection system. In passive systems, the pressure of the generated gas provides the driving force to move the methane through the collection system. This method works well for smaller landfills, producing small gas quantities, while larger landfills producing large gas quantities require active collection systems. In an active system, the gas flow is vacuum controlled, collected, transported to a processing station, and then managed according to individual landfill policy (Guo and Song, 1996).

6) Landfill Cover

There are two types of landfill covers, daily and final covers. The daily cover controls disease vectors, litter dispersion, odors, moisture infiltration, and fire risks (Preen and Murphy, 2001). Cells are covered daily with six inches of compacted soil, thereby preventing pests such as birds, rats, mice, and flying insects from rummaging through the refuse (Freudenrich, 2005). A polyethylene cap, followed by a two-foot layer of compacted soil, permanently covers a finished landfill section (Freudenrich, 2005). This final, more extensive cover minimizes rain and snow infiltration, mitigates the release of landfill gases, controls the proliferation of disease vectors, limits the risk of fire, and allows for future site use (Kim, 2003; Department of Health and Human Services, 2001).

2.4.1 Landfill Moisture Content

Moisture content, considered the most important parameter in organic waste decomposition and landfill-gas production, is proportional to gas production. At higher water contents, contact among microorganisms, nutrients, and degradable substrates improve and microbial metabolism accelerates (Bogner and Spokas, 1993). The waste's initial moisture, the moisture entering from the surface and groundwater, and the moisture produced during decomposition all influence landfill moisture content. The moisture content can show a significant increase after a heavy rain or snowfall event, effecting decomposition rates (EMCON Associates, 1980; Thompson and Tanapat, 2005).

The great depth, impermeable bottom liner, and closure with an impermeable cap limit moisture from entering the landfill. Without moisture present, the landfill serves as a storage unit for the waste with minimal decomposition activity (Reinhart and Al-Yousfi, 1996), although a moisture rich environment can be created through leachate recirculation. Regardless, the moisture level required by methanogenic bacteria is very low, thereby facilitating gas production under low moisture conditions. Laboratory experiments found that moisture content greater than 55% could lead to amplified methane production, while systems with less than 35% moisture content produced methane erratically, reducing methane output. Additionally, the lag-time between waste placement and methane production decreased with increased moisture levels (Lay, Li, and Noike, 1996). In situ experiments show that high moisture content (within the 60-80% range) favors maximum decomposition. Landfill moisture conditions generally range between 15-40%, which although not optimal, is sufficient for microbial activity (Warith, 2003). In Canada, the moisture content ranges from 23.8% to 25.3%, with an average of 24.4% (Levelton, 1991), all below the level of moisture needed to produce methane consistently according to Levelton, but sufficient for microbial activity.

2.4.2 Temperature

When considering model parameters, particularly the decay rate, it is debated whether ambient temperature impacts landfill gas generation rates. This is of particular interest in Canada where temperatures fluctuate throughout the country over a year. Although existing Canadian studies have not explored temperature effects on landfill gas formation at great lengths, other countries with similar climatic conditions have.

Temperature variations can influence microbial activity, subsequently affecting their ability to decompose matter (Maurice and Lagerkvist, 1997). In many parts of Canada, sub-zero conditions exist for up to seven months of the year, with temperatures dropping below -30°C (Environment Canada Weather Office Environment Canada, 2004). Despite fluctuations, evidence suggests that ambient temperature does not affect landfill decay rates (Thompson and Tanapat, 2005) due to landfill "hot-spots"; areas of increased microbial activity reflective of sections rich in substrate availability. Microbial activity produces heat, as seen in landfill gas samples where increased temperatures correlate with increased biological activity. These "hot-spots" can have temperatures exceeding 70°C, thereby offsetting any negative microbial effect that a colder ambient temperature may have (EMCON Associates, 1980). Subsequently, the uniform temperature within a landfill generally ranges between 25-45°C (Department of Health and Human Services, 2001) with optimum landfill-gas production temperature being around 40°C (Lay, Li, and Noike, 1996).

2.4.2.1 Seasonal Variations

Northern Scandinavia and Canada have similar climatic conditions, with both countries experiencing six-month long winters and temperatures dropping to -35°C. Northern Scandinavian studies have shown that although climatic variations can cause temperature changes in the landfill top cover, the bioactive surface is rarely below 0°C. Seasonal temperature variations in the waste were minimal when compared with atmospheric temperature variations. Although shallow landfills may exhibit nearfreezing temperatures during cold weather, landfills at least 15 m in depth are relatively unaffected by ambient temperature (Maurice and Lagerkvist, 1997).

In Lulea, North Sweden, researchers examined gas production fluctuations in a landfill exposed to sub-arctic climate conditions. In Lulea, the winter extends from October until April, during which the soil is frozen down to several decimeters and a snow layer of several decimeters covers the surface. Their summers typically last for two months, with temperatures reaching 30°C. The study demonstrated that the waste and soil at the deepest parts of the landfill maintained a steady temperature throughout the year. For landfill depths between 3-6 m, the waste temperature remained relatively constant at 5±1°C throughout the year. Temperature variations ranging between 0°C and 25°C existed in the top cover and in the waste located near the top cover (depth between 0-3 m), concluding that seasonal variations may influence the decomposition of wastes down to 3 m but are inconsequential at greater depths (Maurice and Lagerkvist, 1997).

2.5 Landfilling Alternatives and Methane End-Uses

Landfill-gas production can be reduced by eliminating organic waste prior to it entering the landfill through alternatives such as composting, which decrease the landfill's overall methane generation potential. Alternatively, collecting landfill gas for beneficial purposes as opposed to it escaping or flared, decreases odors and improves surrounding community air quality. One tonne of municipal solid waste can produce up to 300 m^3 of landfill gas (US EPA, 2006). Much of this gas can be collected and utilized instead of emitted, as recovered landfill gas can be flared, used for energy, or both.

2.5.1 Composting

Composting prevents methane production by diverting a significant portion of waste material that would otherwise go to the landfill. Composting the organic fraction and recycling other waste results in a relatively inert residual waste stream; consequently, the landfill requires less daily cover, equipment and labor during operation, and post closure monitoring. Additionally, it reduces the toxicity and acidity of leachate and the organics in leachate. Composting is one of the least expensive alternative methods of dealing with organic waste (Pickin, Yuen, and Hennings, 2002) and can assist in achieving waste reduction objectives.

Aerobic composting is a self-heating, thermophilic, aerobic, biological process in which complex organic compounds are partially oxidized while releasing heat, water vapor, carbon dioxide, ammonia, and trace amounts of other gases. The non-mineralized component is humidified to form a stable end-product. Anaerobic digestion takes place in sealed vessels in order to produce, recover, and use biogas. Anaerobic digestion is not yet widely used to treat municipal solid waste in North America; however, it is common in Europe.

Compost has many beneficial properties and uses. It can be used as a biofilter for leachate drainage systems and as material for daily, temporary, and final cover. Composting can perform partial degradation of organic compounds in leachate and act as a buffering material enhancing waste biostabilization, as it removes heavy metals from leachate due to adsorption or complexation phenomena. Finally, compost can be sold for revenue to landscapers and developers (Otten, 2001).

Composting organic materials is an attractive alternative to landfilling; however, the end uses of municipal solid waste compost are generally limited to agricultural or land reclamation uses. This is due to the compost's chemical characteristics resulting from the material generally found in municipal solid waste. Additionally, plastics and glass have posed contamination problems in compost resulting from improper separation. Subsequently, the role of compost as a diversion mechanism has decreased over the past decade (Preen and Murphy, 2001).

2.5.2 Combustion

Combustion (also referred to as flaring or thermal destruction), uses flares, incinerators, boilers, gas turbines, and internal combustion engines to thermally destroy landfill gas compounds. Combustion is a management practice used on the full spectrum of materials found in the solid waste stream (Freed and Choate, 1999). The landfill gases are combusted in the presence of oxygen, ensuring the effective destruction of volatile organic carbons, achieving over 98% organic compound destruction (Kim, 2003). Combustion's appeal is its disposal capabilities, waste pathogen destruction, and electrical energy recovery.

Incineration development has been limited due to the close proximity in which landfills are situated to communities. Although combustion converts the methane to carbon dioxide (a greenhouse gas with a lower global warming potential), this process creates oxides of nitrogen, sulfur dioxide, and particulate matter, which are harmful to the environment and human health (Department of Health and Human Services, 2001). Incineration also creates large quantities of ash, does not incorporate the 3 R's (reuse, reduce, recycle) and is inconsistent with the pollution prevention strategy (Sawell, Hetherington, and Chandler, 1996).

2.5.3 Recovery Projects

Landfill gas was not considered an exploitable fuel source until the late 1980's. Today landfill gas is commonly recovered and utilized, providing a cost effective way to decrease methane emissions. Landfill-gas recovery projects capture approximately 60-90% of the produced methane depending on the system design and effectiveness. Landfill gas utilization potentially provides a source of revenue, reduces fossil fuel use, and advocates environmental protection. There are presently over 300 landfill-to-energy projects producing energy or steam in the United States (Weitz et al., 2002), compared with 52 in Canada (Thompson et al., 2006; Environment Canada, 2006).

Landfill-gas recovery feasibility is dependant on the landfill having at least one million tonnes of waste. The waste must be greater than 35 ft deep with an area greater than 35 acres. An estimate of the quantity of landfill gas formation and recoverable landfill gas is required to ensure the project's feasibility. The landfill must be composed of waste that can generate high amounts of landfill gas with greater than 35% methane composition. The recovery project will be economically viable at landfills with gas generation rates of one million ft^3/day. In an operating landfill, active recovery operation can continue through the landfill's lifespan, however for a closed landfill, the recovery project will be economically sound for no more than a few years post closure (Department of Health and Human Services, 2001).

2.5.4 Energy Utilization

Landfill-gas is a reliable and renewable fuel option that remains largely untapped despite its many benefits as a cost efficient method of reducing greenhouse gas emissions from landfills. Major developments in non-combustion methods such as energy recovery techniques and gas-to-product conversion technologies occurred in the 1990's. Energy recovery technologies directly use landfill gas for energy production, electricity, and heat. The gas-to-product conversion technology converts landfill gas to commercial products such as compressed natural gas, methanol, purified carbon dioxide and methane, and liquefied natural gas (Department of Health and Human Services, 2001).

Generated landfill gas is either burned or collected and distilled. The collected/distilled gas is upgraded to pipeline quality or directly used. The directly used landfill gas is utilized for industrial uses or for dual fuel electric engines. The gas upgraded to pipeline quality is used for automobile fuel or electricity generation (Yedla and Parikh, 2001). Landfill gas used for electricity production consists of mostly methane and carbon dioxide, with smaller amounts of oxygen and nitrogen, and trace amounts of halogenerated and organosulfur compounds. The trace compounds are often removed from the landfill-gas before it enters the combustion chamber because they can corrode the equipment (Qin, Egolfopoulos, and Tsotsis, 2001). Landfill gas is a relatively cost effective way to provide renewable energy producing 400-500 BTU/scf of energy (Kim, 2003). Landfill gas has a lower heating value than natural gas (1,000 BTU/scf) due to its carbon dioxide and nitrogen content present prior to upgrading (Blanchet and Staff, 1977).

2.5.5 Costs and Benefits

Various costs and benefits are associated with landfill gas recovery. The benefits include that landfill gas collection decreases the risk of explosions, provides financial benefits for the community, conserves other energy sources, and decreases the risk of global climate change (Department of Health and Human Services, 2001). Landfill-gas recovery projects generate revenue from gas sales while creating jobs associated with the design, construction, and operation of the energy recovery system through the involvement of engineers, construction firms, equipment vendors, and utilities or end-users of the produced power. Its use increases environmental protection, improves waste management practices, and advocates for responsible community planning (US EPA, 2006).

Burning landfill gas to produce energy destroys almost all of the non-methane organic compounds (NMOC) present in the landfill gas, thereby decreasing potential health risks from these substances (US EPA, 2006). However, characteristic of all combustion devices, burning landfill gas generates some nitrogen oxide emissions, contributing to local ozone and smog formation. Despite this, the total environmental impact is lessened due to significant reductions in methane emissions, hazardous air pollutant reductions, and avoidance of using non-renewable energy resources more polluting than landfill-gas (US EPA, 2006). Other potential costs include landfill preparation, management, waste collection, transportation and dumping, energy conversion and distribution, and administration.

2.6 Summary

This chapter examined the many issues that surround, contribute to, and influence landfill gas production. This information contributed to researching and meeting the thesis objectives in chapter 1. Landfill management, typical landfill gas production, methane end uses and quantification, modeling inputs, and environmental impacts all affect the ability to model Canadian landfill gas production accurately. Landfill methane gas is potentially harmful when released into the atmosphere; however, if properly harnessed, it has the potential to be economically viable and less damaging. Successful landfill gas quantification will lead to the implementation of better management strategies, thus reducing the negative environmental impact. Chapter 3 describes, in detail, the methodology employed to quantify present and future landfill-gas production for Canadian landfills.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The following section describes the methodology used to meet the objectives outlined in Chapter 1, namely:

1. Determine a model to estimate methane production that best fits the measured recovery data.
2. Evaluate current and potential model inputs.
3. Analyze how changes in waste inputs affect future methane production.

The methodology, outlined below, quantifies landfill gas production for present and future conditions in landfills located in British Columbia, Ontario, Alberta, Nova Scotia, and Quebec. This method has eight main steps:

1. Analyze survey data for landfill selection.
2. Input waste, decay rates based on annual precipitation, and degradable organic carbon/methane generation potential (using defaults or if available composition data) into standard models to arrive at an estimated methane production for each landfill.
3. Subtract 25% of modeled production to account for lack of efficiency of collection for each landfill based on the US EPA (2004) default value, which is then compared with measured data.
4. Select a model based on smallest percent error compared to measured data.
5. Revise model to better match measured data.
6. Improve inputs (decay rates, methane generation potential) to better match measured data.

7. Consider additional factors potentially influencing the landfill model through the statistical analysis of landfill size, depth, density, temperature, precipitation, years of operation, and well type (horizontal and vertical).
8. Use the revised model for selected landfills to determine future production under five different waste management scenarios.

3.2 Data Collection

3.2.1 Survey

In September 2006, a nationwide survey (Appendix A) was conducted to create a landfill database for small, medium, and large landfills throughout Canada. Dr. Shirley Thompson wrote the survey, which received approval from the Joint-Faculty Research Ethics Board of the University of Manitoba, Canada. Rathan Bonam conducted the survey through mail, telephone, and internet/email with 300 active and recently closed Canadian municipal solid waste, construction, demolition, and hazardous waste landfill operators. The response rate was 44% (n=130). As the focus of this research is on methane recovery it is important to note that all (n=52) of the 52 landfills that recovered methane provided surveys, although not all were complete.

The survey obtained information required to evaluate landfill gas production (specifically methane) from Canadian landfills with responses from British Columbia, Ontario, Alberta, Nova Scotia, and Quebec. The relevant survey information included questions regarding waste placement, waste composition, landfill gas composition, and landfill-gas capture rates as they were used to calibrate the landfill-gas models and calculate current and future methane production from landfills.

3.2.2 Landfill Selection

The landfills modeled were selected based on: 1) willingness to participate in additional landfill questions, and 2) those that measure methane production. Site-specific model calibration is feasible and accuracy is best achieved for landfills with complete gas systems, quality long-term waste disposal, and extensive gas collection histories (Huitric and Soni, 1997).

Thirty-seven landfills had methane production measurements from 2005, which were initially used (n=37) to test how well the models performed for that year. Two of the 37 landfills (St. Cecile De Milton, Quebec and Coquitlam, British Columbia) were outliers (section 4.2 Model Results), reducing the sample size to 35 (n=35). Fifteen of the 52 landfills currently recovering methane were not modeled because they did not provide any past landfilled waste data (Appendix B). Previous studies (Spokas, 2006; Barlaz et. al, 2004; Bogner and Matthews, 2003; SCS Engineers, 1997) have examined the appropriateness of using models to predict landfill gas production; however, none has used as many landfill sites in one study.

Six landfills (the Vancouver and Cache Creek landfills in British Columbia, the Toronto landfill in Ontario, the Edmonton landfill in Alberta, and the Cowansville and Sherbrooke landfills in Quebec) provided methane production measurements for multiple years and were used to further calibrate and validate the models and their inputs. These landfills met most of the above criteria for landfill modeling selection, with the exception that some of the landfills are closing shortly and could not be used for modeling future methane production. Of the 35, four landfills (the Vancouver landfill in British

Columbia, the Cowansville landfill in Quebec, the Waterloo landfill in Ontario, and the Halifax landfill in Nova Scotia) were modeled for future methane production until 2025.

3.3 Model Output

Landfill-gas models calculate methane yield considering the decaying portion of waste deposited each year since the landfill's opening. Each year's waste follows a decreasing exponential trend in gas production until it is completely degraded (Huitric and Soni, 1997). Methane production values were assessed for their trend outputs from their opening until 2005.

3.3.1 Model Selection

The German EPER, TNO, Belgium, Scholl Canyon and LandGEM models (Table 3.1) were selected to calculate landfill gas production from 35 Canadian landfills. Several modified Scholl Canyon/LandGEM models were tested, using the Scholl Canyon Model's equation but dividing the waste value by factors of 1.5, 2.0, 2.5, and 3.0 instead of by 10 as done in the LandGEM Model. These particular models were chosen because they are all simple, zero or first order models, require (relatively) accessible and comprehensible data, and are commonly used amongst landfill operators worldwide. Each model was analyzed on Excel (2002) spreadsheets, as it is easy to use, compatible spreadsheet program, lacking the faults embedded within existing programs.

Table 3.1. Model Formulas and Inputs (Thompson, et. al, 2006).

Model	Formula	Symbol Index
German EPER Model	$Q=(M)(DOC)(DOC_f)(F)(D)$	Q = Methane production (kt/yr) M = Waste generation (Mt/yr) DOC = Degradable organic carbon (kg/tonne) DOC_f = Fraction of assimilated DOC F = Fraction of methane converted to landfill gas D = Collection efficiency factor
TNO Model	$Q=(DOC_f)(1.87)(M)(DOC)(k)e^{-(kt)}$	Q = Methane production (kt/yr) DOC_f = Fraction of assimilated DOC M = Waste generation (Mt/yr) DOC = Degradable organic carbon (kg/tonne) k = Decay rate (yr^{-1}) t = Time of waste disposal (yr)
Belgium Model	$Q=(M)(DOC)(k)(DOC_f)\exp^{(-kt)}$	Q = Methane production (kt/yr) M = Waste generation (Mt/yr) DOC = Degradable organic carbon (kg/tonne) k = Decay rate (yr^{-1}) DOC_f = Fraction of Assimilated DOC t = Time of waste disposal (yr)
Scholl Canyon	$Q=(M)(k)(L_0)\exp^{-(kt)}$	Q = Methane production (kt/yr) M = Waste generation (Mt/yr) k = Decay rate (yr^{-1}) Lo = Methane generation potential (kg/tonne) t = Time of waste disposal (yr)
LandGEM	$Q=(\frac{M}{10})(k)(L_0)\exp^{-(kt)}$	Q = Methane production (kt/yr) M = Waste generation (Mt/yr) k = Decay rate (yr^{-1}) Lo = Methane generation potential (kg/tonne) t = Time of waste disposal (yr)

3.3.2 Present Output

To determine which model formula best suits Canadian landfills, the German EPER, Belgium, TNO, Scholl Canyon, LandGEM, and modified Scholl Canyon/LandGEM models were each run under site-specific landfill inputs, which included: i) yearly waste quantity, ii) decay rate, and iii) degradable organic carbon/methane generation potential. When available, site specific, survey data was inputted; when data was missing or unavailable, the models used theoretical constants. All required calculations followed the 1996/2006 IPCC guidelines.

The model values were compared with site-specific landfill gas capture data to test which model best mathematically describes landfill methane production, as previously done by Spokas (2006), and Sheeper and Van Zanten (1994). Outputs were calculated and compared with the measured methane data for 35 landfills across Canada (Appendix B) for 2005. Outputs for additional years were examined for the six Canadian landfills that provided additional yearly methane production data (Table 3.2). On average, the gas capture units have a 75% efficiency rate (US EPA, 2004; Visse, 2004); therefore, all model calculations were reduced by 25% prior to comparing the results with the measured data in order to convert the modeled methane production data to modeled methane recovery data equivalents.

Table 3.2. Measured Methane Recovery Values.

Year	Vancouver, B.C. (kt/yr)	Cache Creek, B.C. (kt/yr)	Cowansville, Que. (kt/yr)	Sherbrooke, Que. (kt/yr)	Edmonton, Alta. (kt/yr)	Toronto, Ont. (kt/yr)
1988	NA	NA	NA	NA	NA	9.5563
1989	NA	NA	NA	NA	NA	9.5230
1990	NA	NA	NA	NA	NA	13.2000
1991	NA	NA	NA	NA	NA	14.4510
1992	NA	NA	NA	NA	NA	28.5595
1993	NA	NA	NA	NA	NA	32.0747
1994	NA	NA	NA	NA	NA	37.3166
1995	NA	NA	NA	NA	NA	39.3620
1996	NA	NA	NA	NA	NA	49.6366
1997	NA	NA	NA	NA	NA	63.4834
1998	NA	1.8050	NA	NA	17.3680	65.5003
1999	NA	1.7921	NA	NA	15.0297	69.5340
2000	NA	2.0628	NA	NA	17.4231	72.5878
2001	11.5616	2.2885	NA	NA	16.8602	69.6815
2002	10.3772	2.4819	1.2614	2.3988	NA	69.8575
2003	8.8454	2.4174	1.3263	1.9373	NA	66.7894
2004	14.9925	2.5141	0.9010	1.9940	11.2419	57.2236
2005	19.5785	2.1595	1.0467	2.2807	10.3917	49.2751
2006	16.1471	2.2562	1.5904	1.8739	13.6875	44.0427

*NA- Unavailable information or the landfill was not collecting methane at that time.

3.3.2.1. Model Inputs

i) Waste Quantity and Disposal Time

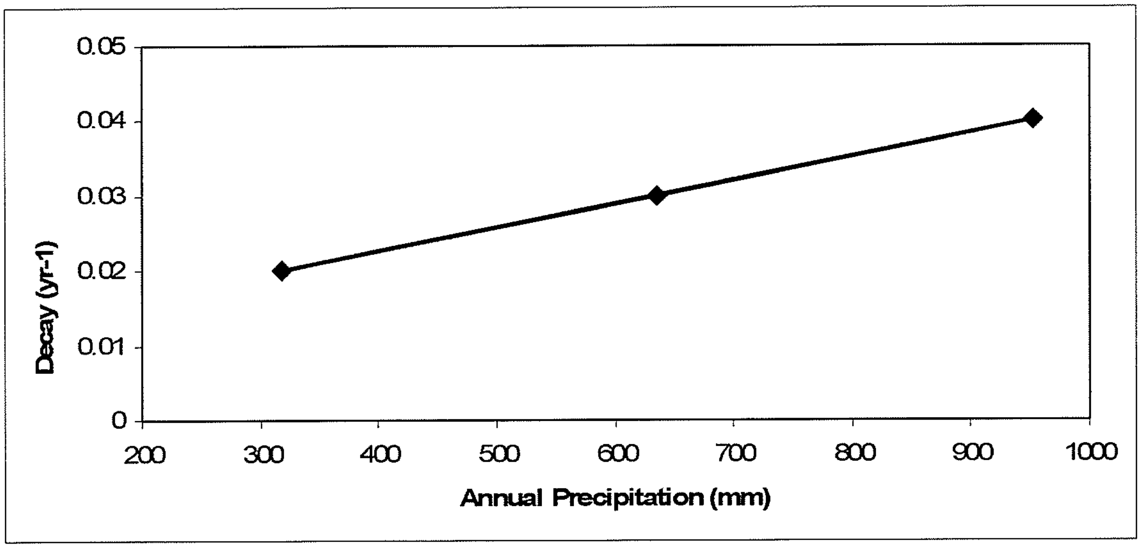
The 35 landfill operators provided the waste and disposal times, inputted without modification or variation into the models as this is a measured value. Waste disposal and gas generation are time dependant; therefore, model time-steps must be small enough for gas rates to be considered constant. Time-steps of one year are considered small enough for municipal solid waste data and were used for all of the landfill gas production models.

ii) Decay Rate (k)

Landfills are heterogeneous systems; therefore, using a general decay rate constant may result in a poor fit when modeling a variety of different landfills (Huitric and Soni, 1997). No landfill provided site-specific decay rate information; therefore, an adaptation of United States Environmental Protection Agency (US EPA, 2004) data was used to calculate province-specific decay rates.

The US EPA (2004) assigns a default decay value of 0.02 yr^{-1} to areas with an annual precipitation less than 25 inches (635 mm) and 0.04 yr^{-1} to areas with an annual precipitation greater than 25 inches. As the junction at 25 inches does not provide a metered rationale approach to precipitation change to assign a 100% increase in decay values, a more balanced linear approach was taken with the assumption of a 1:1 relationship between precipitation and decay. Using 25 inches (635 mm) as the midpoint and averaging the decay values 0.02 and 0.04 yr^{-1} yields a point of 0.03 yr^{-1}, for the average at the 25 inches point. To obtain further points around the midpoint, 635 mm (25 inches) was halved, giving 317.5 mm (corresponding to 0.02 yr^{-1}) and increased by 50%, giving 952.5 mm (corresponding to 0.04 yr^{-1}). Graphing these three values provides a linear relationship between annual precipitation and decay (Figure 3.1; Equation 3.1) upon which individual decay rates (y) could be determined for 37 landfills using city/region specific annual average precipitation (x) from 1971-2006 (Environment Canada Weather Office, 2006). A linear relationship between moisture and decay rate has been observed in other in field and laboratory studies, including McDougall and Pyrah (1999) and Chian and DeWalle (1979).

Figure 3.1. Decay as a Function of Annual Precipitation.



$$y = 3.2x10^{-5}(x) + 0.01$$ Equation 3.1

iii) Degradable Organic Carbon (DOC)/Methane Generation Rate (Lo)

Site-specific degradable organic carbon (DOC) and methane generation potential (Lo) constants were calculated as using general, national values result in a poor fit (Huitric and Soni, 1997). The German EPER, Belgium, and TNO models use degradable organic carbon (DOC) as their model input, while the Scholl Canyon and LandGEM models incorporate the DOC within the methane generation potential (Lo) input, which considers additional factors discussed below.

The 1996 IPCC guidelines identify the DOC as four different fractions: 1) paper and textiles; 2) garden and park waste; 3) food waste; and 4) wood and straw. As widespread Canadian waste diversion initiatives began in 1990, this altered the organic portion of the waste stream significantly. To account for the changing waste composition, two different DOC values (and subsequently two different Lo values) were calculated, one prior to 1990 and the other post 1990.

The survey requested that landfill operators provide the fraction of each type of waste landfilled to calculate the present total DOC content (Equation 2.6), for the post 1990 value. Of the 35 landfills modeled, nine provided site-specific waste composition data (Table 3.3) used to calculate their DOC and Lo values. The waste compositions varied considerably between the different landfills. The paper and textiles fraction ranged from 10.0% (Montreal, Que.) to 42.9% (Surrey, B.C.), the garden and yard fraction from 2.0% (Montreal, Que.), to 38.4% (Kelowna, B.C.), the food fraction from 0.5% (Montreal, Que.) to 45.0% (Kirkland, Que.), and the wood and straw fraction from 0.0% (Edmonton, Albt.) to 22% (Kirkland, Que.). The remaining 25 landfills used the general, provincial waste fraction proportions (Appendix C) to calculate the DOC/Lo values. For provinces where waste audit data was not available for the entire province, but rather for the capital city, it was assumed that the capital city data was indicative of the provincial waste composition.

Table 3.3. Waste Composition Data for Nine of the Thirty-Five Landfills.

	Paper and Textiles (%)	Garden and Yard (%)	Food (%)	Wood and Straw (%)
Edmonton, Albt.	19.3	37.9	23.3	0.0
Kelowna, B.C.	16.6	38.4	13.3	5.4
Surrey, B.C.	42.9	7.3	17.4	5.2
Nanaimo, B.C.	15.0	7.0	23.0	5.0
Vancouver, B.C.	20.0	20.0	12.0	13.0
Waterloo, Ont.	17.8	2.1	35.8	2.0
London, Ont.	23.0	22.0	21.0	2.0
Kirkland, Que.	18.0	15.0	45.0	22.0
Montreal, Que.	10.0	2.0	0.5	30.0

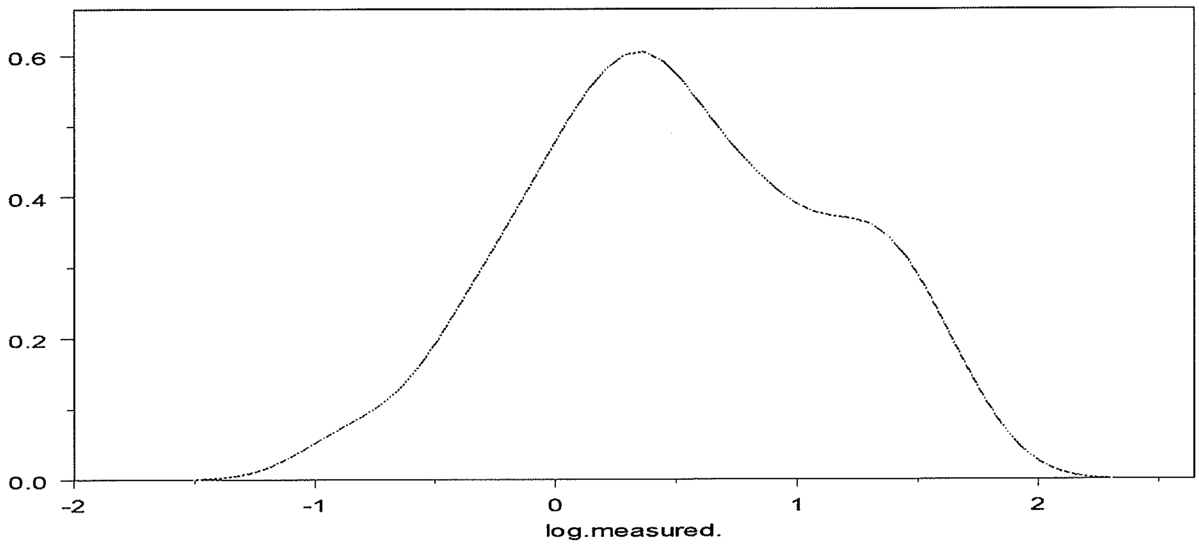
When calculating the site-specific DOC and Lo inputs prior to 1990, survey diversion information was used to estimate the percentage of diverted organic materials for each landfill. The calculated values post 1990 were increased by the percentage currently diverted in order to estimate the DOC and Lo prior to 1990.

3.3.3 Model Analysis

Several statistical analyses assessing for model competency (correlation, relative and absolute percent difference, t-test) were conducted to compare the measured and modeled data to determine which model performed best using Microsoft Excel (2002). The correlation (r) measures the direction and strength of the linear relationship between two quantitative variables. This value ranges between -1 and +1, with -1 indicating a negative correlation and +1 a positive correlation. A value of 0 indicates no relationship between the two variables (Garson, 2006). The relative percent error measures the difference between the observed and expected (measured versus modeled) values, taking into account the direction of the value. Alternatively, the absolute error measures the difference; however, it does not consider the direction of the value, instead taking the absolute value of the error (Craw, 2003).

A paired t-test was chosen, as it is a high powered, robust statistical test used to test two sets of data in a comparative study (Moore, 2003). The measured data followed a lognormal distribution (Figure 3.2) when all 35 data points were considered (a normal distribution is required prior to performing a paired t-test) using S-Plus (2006); therefore, the measured and modeled results were adjusted to a log scale prior to calculating their significance. The null hypothesis (H_0; rejected when $p<0.05$) considers the measured data to equal the modeled data. The alternative hypothesis (H_A; accepted when the null hypothesis is rejected) considers the modeled data to be significantly different from the measured data.

Figure 3.2. Measured Data Lognormal Distribution.



For the 35 landfills, the modeled 2005 results were compared to the 2005 measured data (Appendix B), yielding 35 data points for each of the five models under each analysis. For the six landfills with additional measured data, Vancouver yielded 6 data points, Cache Creek 9, Cowansville 5, Sherbrooke 5, Edmonton 7, and Toronto 19 data points.

3.4 Revising Model Inputs

Initially, the model inputs were determined using survey data for site-specific inputs and literature review information. Model input evaluation was separately and individually based for each landfill. Slight variations in the applied kinetic rate constant values can greatly influence the calculated production (Jacobs and Scharff, 2001); therefore it is necessary to ensure high data quality.

3.4.1 Uncertainty of Decay Rate, Degradable Organic Carbon (DOC), and Methane Generation Potential (Lo) Inputs

Currently, no widely accepted methodology for calculating decay rates exists, causing a substantial amount of uncertainty when determining their value. Additionally, it remains unclear if the DOC/Lo equations reflect actual Canadian landfill conditions. To improve upon the methodology used in section "3.3.2.1 Model Inputs", the original k and Lo inputs were modified by increasing and decreasing increments of 10%, 20%, and 30% and run in whichever model best represented the methane production for the 35 landfills, as similarly executed by SCS Engineers (2006). The six landfills with additional measured data were used to further test the model inputs and their effect on those landfills using the chosen model. First, the incremental decay rate changes were inputted into the model while the methane generation potentials remained constant as their initial value(s). Second, the methane generation rates were changed, while the decay rate remained constant as its initial value. Statistical analyses including relative percent error, absolute percent error, correlation, and t-tests were performed to determine which input combinations yielded the best model results when compared to the measured data.

3.4.2 Other Factors Potentially Influencing Methane Production

The currently used methane production models only consider waste quantity, organic content, and decay rate in their model formula. Potentially, a relationship exists between the landfill methane production and variables such as landfill waste-in-place, depth, density, years in operation, temperature, precipitation, and well type (horizontal and vertical). The measured data from the 35 landfills was tested for a correlation and underwent an ANOVA analysis with each of these factors to observe if a relationship potentially influencing future model equations exists. The analysis of variance (ANOVA) test compares the variation due to specific sources with the variation among individuals who should be similar. The ANOVA test was used to test whether several populations have the same mean by comparing how far apart the sample means are with how much variation there is within the samples (Moore, 2003). Additionally, the model's percent error was tested against these same variables for a correlation, in the event that one or several of the variables contribute to the error.

3.5 Future Output

Once a suitable model and model inputs were identified, the methane production was calculated to the year 2025 for the Vancouver (British Columbia), Cowansville (Quebec), Waterloo (Ontario), and Halifax (Nova Scotia) landfills. Future waste generation was calculated and extrapolated based on the landfills' waste disposal trends from 2000-2005 (Equations 3.2, 3.3, 3.4, and 3.5), assuming that current recycling initiatives, population growth, and consumption habits will remain stable (Bogner and Matthews, 2003).

$y = 0.0409x - 81.571$ Equation 3.2 (Vancouver Landfill)

$y = 0.0020x - 4.014$ Equation 3.3 (Cowansville Landfill)

$y = 0.0339x - 67.639$ Equation 3.4 (Waterloo Landfill)

$y = 0.0091x - 18.038$ Equation 3.5 (Halifax Landfill)

Future methane production was calculated under the following scenarios for the four landfills (Appendix D):

1) Current waste diversion trends remain steady
2) Current waste diversion trends increase by 20%
3) Current waste diversion trends increase by 40%
4) Current waste diversion trends increase by 60%
5) Current waste diversion trends increase by 80%

The yearly future waste inputs (under each scenario) were used to calculate the methane production of the four landfills until 2025. The other model inputs (decay rate, methane generation potential) remained constant, as they were considered independent of the changing waste stream. The model inputs used were those deemed most appropriate in sections 3.3 and 3.4.

It is advantageous to have a baseline year to compare gas production to; therefore, the future modeled values were compared against the 1990 and 2006 levels for the Vancouver and Waterloo landfills and 2006 levels for the Cowansville and Halifax landfills. The Cowansville and Halifax landfill were not compared against 1990 production levels because they did not open until 2000 and 1999, respectively.

3.6 Research History

The interest in landfill gas modeling began in the 1970's, when research teams such as Farquhar and Rovers (1973) and De Walle et al. (1978) began characterizing landfill decomposition and the impacting environmental factors. They began researching the general landfill decomposition trend in order to model methane production, a question that currently remains. Recent studies including Findikakis (1988), Jacobs and Scharff (2001), and Jensen and Pipatti (2003) have continued to examine landfill gas production stages and the methane generation curve. Many studies (Coops, 1995; Huitric and Soni, 1997; Huitric, 1997; Jacbos and Scharff, 2001; Bogner and Matthews, 2003; Barlaz et al, 2004) have tested different model types; however, results have varied drastically regarding which reaction order and model is best.

As landfill gas quantification grew in popularity, the environmental impacts effecting methane production became more widely studied. EMCON Associates (1980) observed that ambient temperature does not affect the landfill temperature, making a strong case against its inclusion when modeling decay rates. The US EPA (2004) recommends using annual precipitation when assigning high and low decay rates; however both Barlaz (2004) and the IPCC (2007) recognize the uncertainty surrounding landfill decay rates and the difficulty in calculating reflective values. Recently, studies have focused on landfill efficiency (Spokas, 2006; Huitric and Kong, 2007; Alberta Research Council, 2007), as this is a potentially significant source of error when modeling landfill gas production.

This research builds upon previous work pertaining to which model is best, specifically when modeling Canadian landfills systems. A criticism of past model comparison work is the lack of data and landfill sites used for modeling (Borjesson et al., 2000; Bogner and Matthews, 2003; Barlaz et al., 2004). This study was unique as it looked at 35 Canadian landfills with data from 2005, while previous studies have only looked at a few landfills at a time. Regarding model inputs, this study builds on Levelton's 1991 Canadian landfill report, addressing inconsistencies in the previously used methodology. Similar to a SCS Engineering (2006) study, this study varied the decay rate and methane generation potential inputs by different percentages to test the accuracy of the input calculation methodology. Additionally, this study tested potential environmental factors effecting landfill gas models, building on research (Lay, Li, and Noike, 1996) that identified these factors but did not consider their inclusion in landfill gas models. Finally, this study mimics Bogner and Matthews (2003), calculating future methane production from landfills to quantify how different waste diversion scenarios affect future production.

3.7 Summary

This chapter outlined the methodology used to improve current Canadian landfill knowledge and methodology regarding landfill-gas model selection, currently used model inputs (waste landfilled, decay rate, DOC, and Lo), other factors potentially affecting methane production, and calculating future methane production. By comparing measured data from landfills to modeled data, I hope to improve the method to determine landfill generation estimates.

CHAPTER 4: RESULTS

4.1 Introduction

Thirty-five Canadian landfills were examined, modeling their current methane production and improving model inputs, with six of these monitored for methane over their lifespan. As well, modeling future methane production was done for four landfills. The first section illustrates the methane-production model outputs as calculated by the German EPER, TNO, Belgium, LandGEM, Scholl Canyon, and modified models, ultimately recommending a model that best suits Canadian landfills. The second section illustrates current model input (decay rate (k) and methane generation potential (Lo)) modifications as well as potential additional model inputs. The final section examines possible future methane production (until 2025) for four landfills under five different waste reduction scenarios.

4.2 Model Results

The methane production was calculated using the German EPER, Belgium, TNO, LandGEM, Scholl Canyon, and modified models utilizing two different landfill groupings for: 1) 37 Canadian landfills with measured methane collection data for 2005, and 2) six Canadian landfills over multiple production years. When the model results were examined for the 37 landfills, the St. Cecile-de-Milton (Quebec) and Coquitlam (British Columbia) landfills consistently produced errors drastically larger than the other landfills (Appendix E). These two landfills were considered outliers and the statistical analysis sample size was reduced from 37 to 35.

The TNO and German EPER models were disregarded because their methane production calculations consistently produced much higher values than the measured values. The results were poor when used for the 35 landfills in 2005; the TNO Model produced an average relative error of 337% with a correlation of r=0.8785 (Figure 4.1), and the German EPER Model an average relative error of 536% with a correlation of r=0.8589 (Figure 4.2). Similarly, when compared against the six individual landfills, neither of the models produced percent error below 140%.

Figure 4.1. The TNO Model Results as Compared with the Measured Results for 35 Canadian Landfills in 2005.

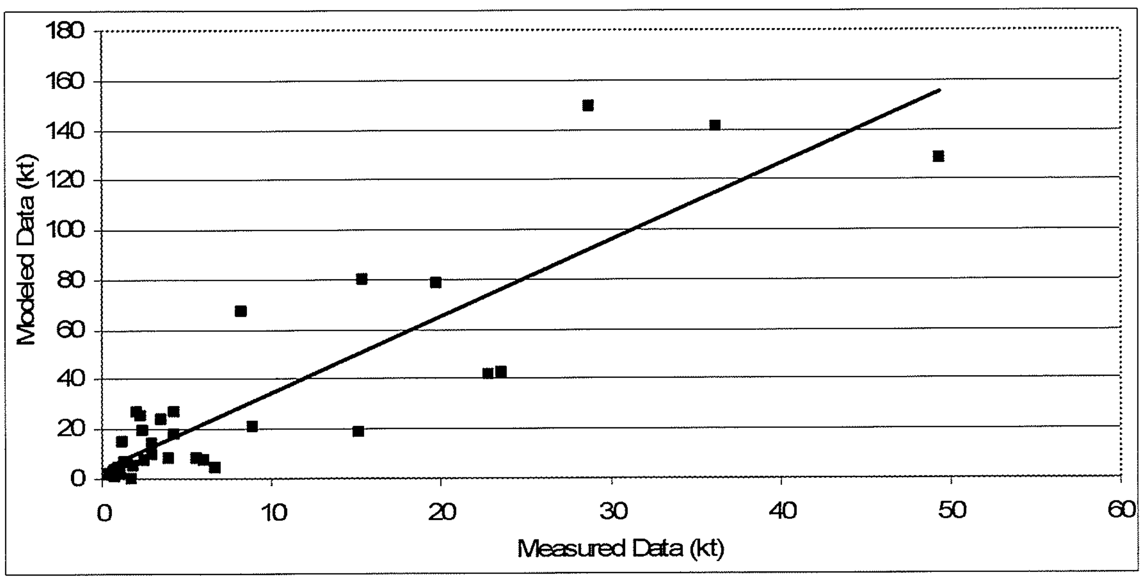
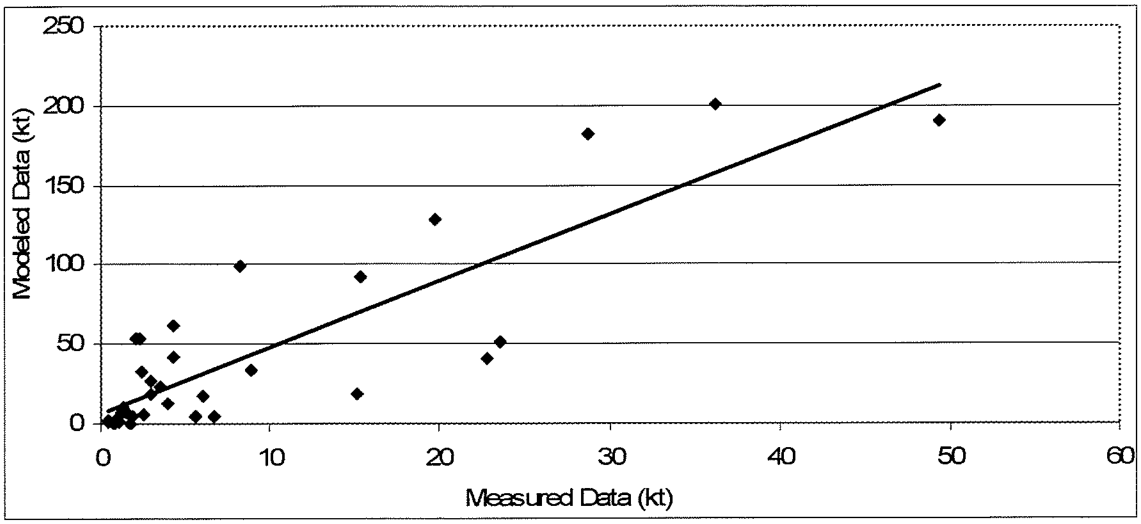
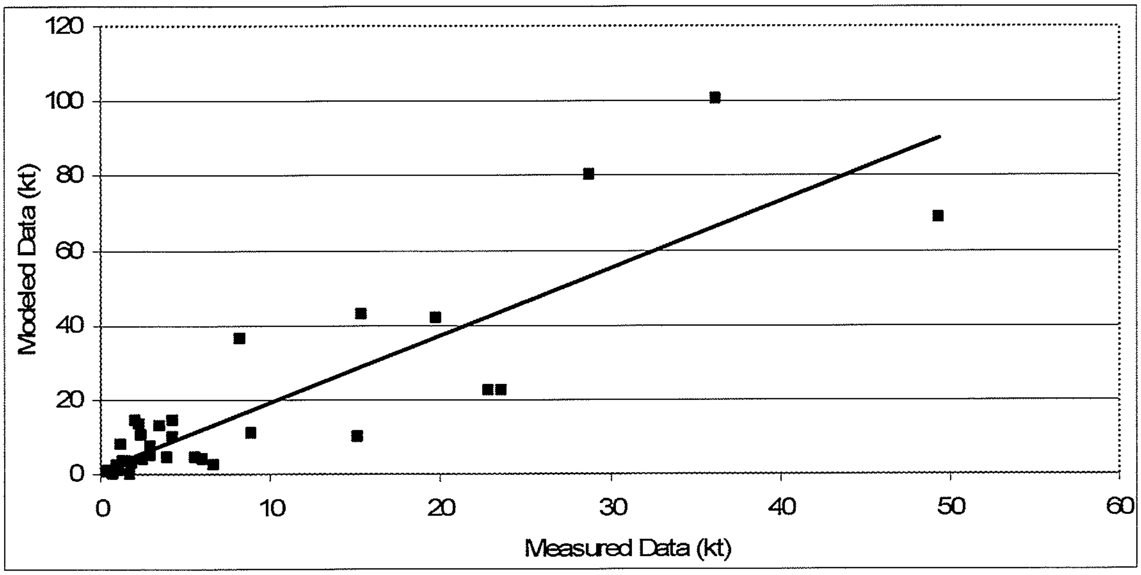


Figure 4.2. The German EPER Model Results as Compared with the Measured Results for 35 Canadian Landfills in 2005.



Using the Belgium Model, the 35 landfills produced an average relative error of 136% and a correlation of r=0.8674 (Figure 4.3). This model yielded high error values with four of the six landfills. The Toronto and Cowansville landfills produced relatively low error values (32% and 50%, respectively); however, the remaining four landfills each had errors exceeding 100%. Due to high error values and a correlation that was lower than the TNO Model, this model was not considered a good fit for Canadian landfills.

Figure 4.3. The Belgium Model Results as Compared with the Measured Results for 35 Canadian Landfills in 2005.



The Scholl Canyon and LandGEM models both yielded reasonable results when compared to the other models. When used to calculate the 2005 methane production from the 35 landfills, the Scholl Canyon Model's relative percent error was 81% with a correlation of r=0.9159 (Figure 4.4). The model produced percent errors below 100% for the Vancouver, Cowansville, Edmonton, and Toronto landfills; however, its' results were 155% and 208% for the Sherbrooke and Cache Creek landfills, respectively. The LandGEM Model was the only model that consistently produced percent errors below 100%, although its equation always underestimated methane production. In the 35 landfills, the average relative percent error was -82% with a correlation of r=0.9164 (Figure 4.5), while for the six landfills, the model's percent error ranged from -69% (Cache Creek) to -91% (Toronto).

Figure 4.4. The Scholl Canyon Model Results as Compared with the Measured Results for 35 Canadian Landfills in 2005.

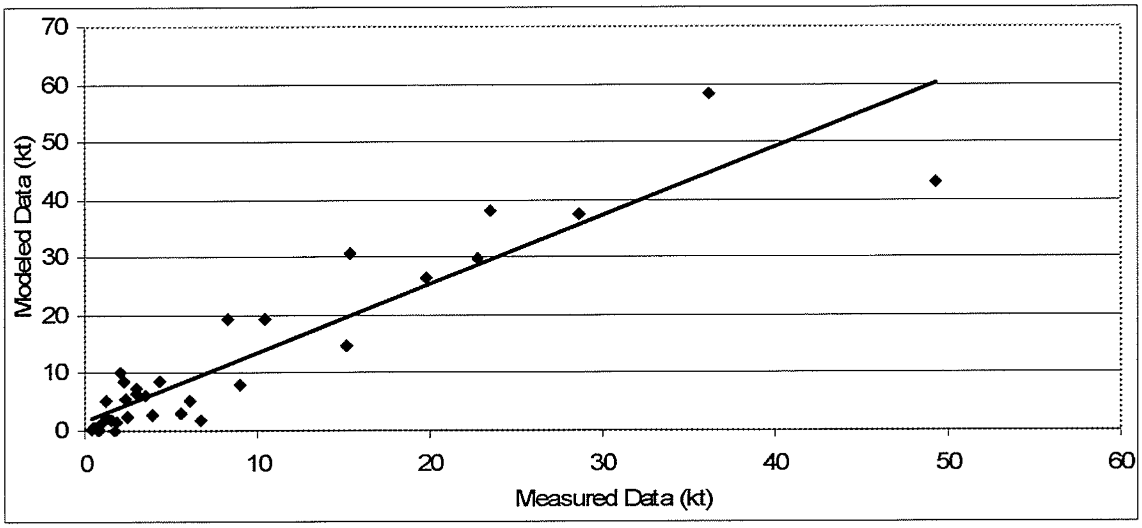
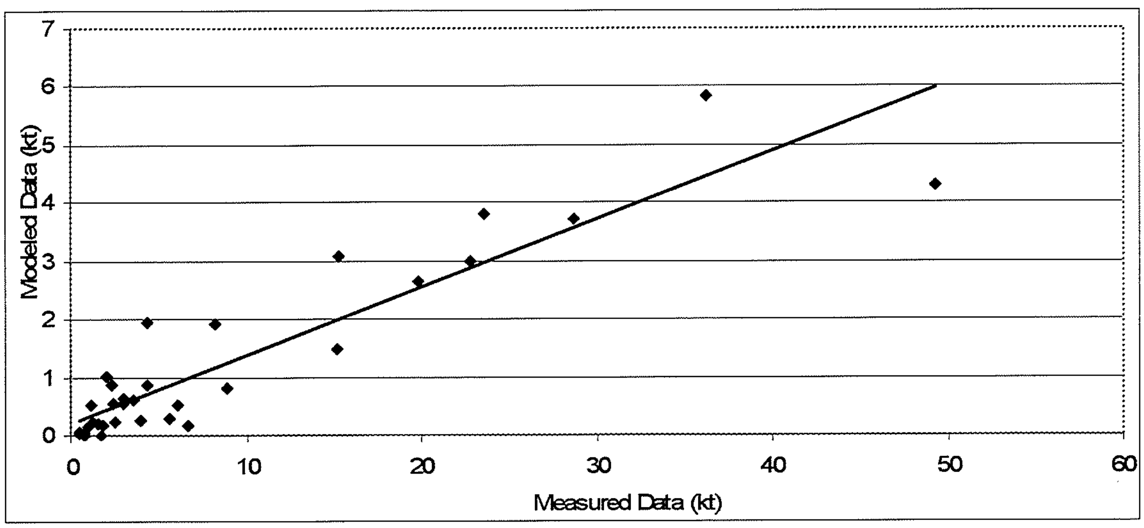


Figure 4.5. The LandGEM Model Results as Compared with the Measured Results for 35 Canadian Landfills in 2005.



The average relative error, average absolute error, correlation, significance (using a paired t-test), and error median were calculated for the 35 landfills under each of the five models (Table 4.1). Of the five models, the Scholl Canyon Model had the lowest average relative error, the lowest error median, and was the only model to not reject the null hypothesis (H_0: the measured data equals the modeled data). The LandGEM Model had a lower average absolute error and a slightly higher correlation than the Scholl Canyon Model.

Table 4.1. Statistical Analyses for the 35 Landfills under each of the 5 Models.

	Mean Relative Error	Mean Absolute Error	Median Error	Correlation (r)	Significance (p)
German EPER Model	536%	548%	341%	0.8589	2.98×10^{-8}
TNO Model	337%	348%	289%	0.8785	4.89×10^{-8}
Belgium Model	136%	158%	111%	0.8674	0.0037
Scholl Canyon Model	81%	108%	34%	0.9159	0.1999
LandGEM Model	-82%	82%	-87%	0.9164	2.52×10^{-14}

The Scholl Canyon model's best fit for the 35 landfills occurred when the waste value was divided by 1.5, 2.0, or 2.5, corresponding to relative percent errors of 19%, -11% and -28%, respectively (Table 4.2).

Table 4.2. Statistical Analyses using the Modified Scholl Canyon/LandGEM Model with A 1.5, 2.0, and 2.5 Denominator.

	Average Relative Error	Average Absolute Error	Error Median	Correlation (r)	Significance (p)
1.5 Denominator	19%	66%	-11%	0.9180	0.2501
2.0 Denominator	-11%	57%	-33%	0.9180	0.0065
2.5 Denominator	-28%	58%	-38%	0.9180	0.0039

The 1.5, 2.0 and 2.5 modified models each reported correlations of 0.9180 for the 35 landfills. A paired t-test was performed on each set of this data, illustrating that under

a 2.0 or 2.5 denominator the null hypothesis was rejected as the p-values were less than 0.05. When the model used the 1.5 denominator, the p-value was greater than 0.05 and the null hypothesis was not rejected (Table 4.3). Since the modified Scholl Canyon/LandGEM Model yielded the best statistical results when the denominator was 1.5, this "Sawyer Model" was used to further test model inputs and calculate future methane production (Table 4.3; sections 4.3 and 4.4).

Table 4.3. Paired T-Test using the "Sawyer Model".

	Variable 1	Variable 2
Mean	0.482643737	0.567293238
Variance	0.517363867	0.321576277
Observations	35	35
Pearson Correlation	0.80389497	
Hypothesized Mean Difference	0	
df	34	
t Stat	-1.170207735	
P(T<=t) one-tail	0.125027416	
t Critical one-tail	1.690923455	
P(T<=t) two-tail	0.250054833	
t Critical two-tail	2.032243174	

The results from the German EPER, Belgium, TNO, LandGEM, Scholl Canyon, and "Sawyer" models were compared with the six Canadian landfills that provided measured methane data over multiple years giving a general perspective of the models and their respective trends (Figures 4.6, 4.7, 4.8, 4.9, 4.10 and 4.11). This data explores how the measured trends compare to the models. By looking at individual landfills we are able to see the responsiveness of the model to change over time and the different accuracy in different stages of the landfills (e.g., closed with the Toronto landfill, new with the Cowansville landfill, and steady-state with the Vancouver, Cache Creek, Sherbrooke, and Edmonton landfills).

Figure 4.6. Vancouver Landfill (British Columbia) Model Results as compared with the Measured Results.

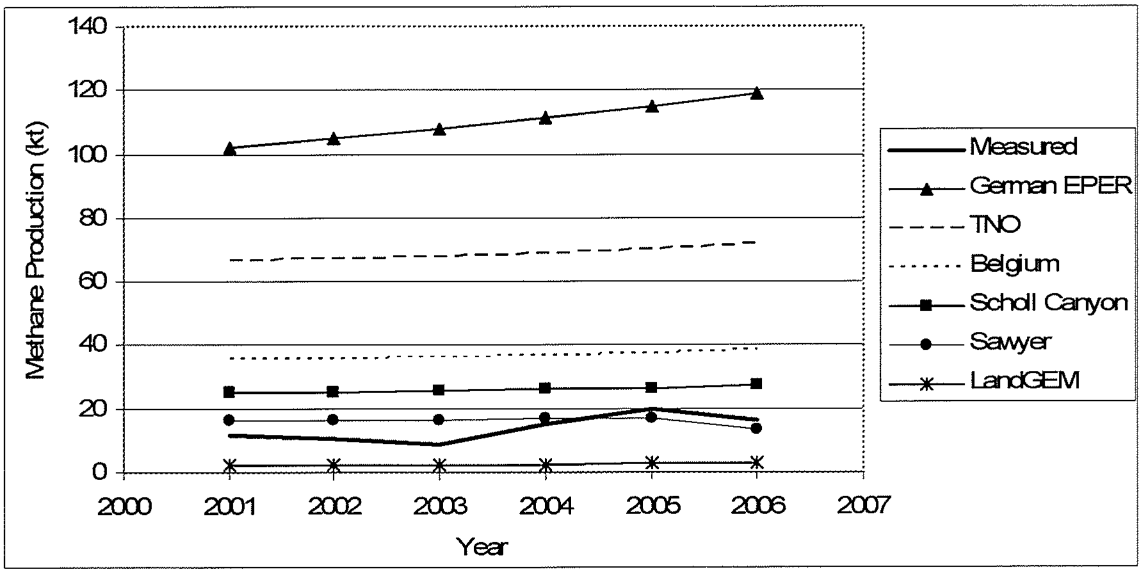


Figure 4.7. Cache Creek Landfill (British Columbia) Model Results as compared with the Measured Results.

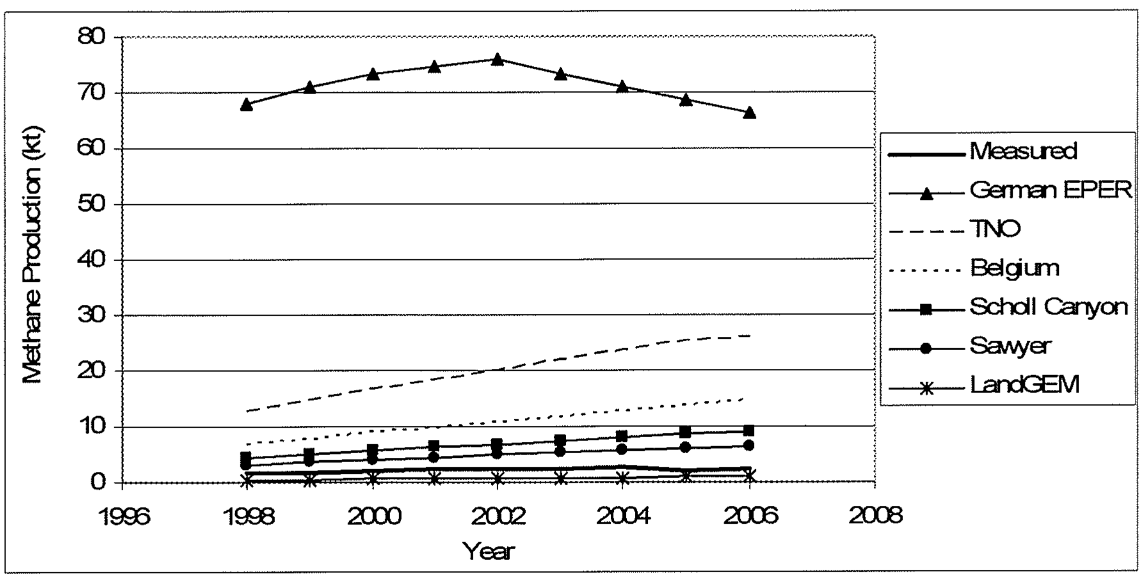


Figure 4.8. Cowansville Landfill (Quebec) Model Results as compared with the Measured Results.

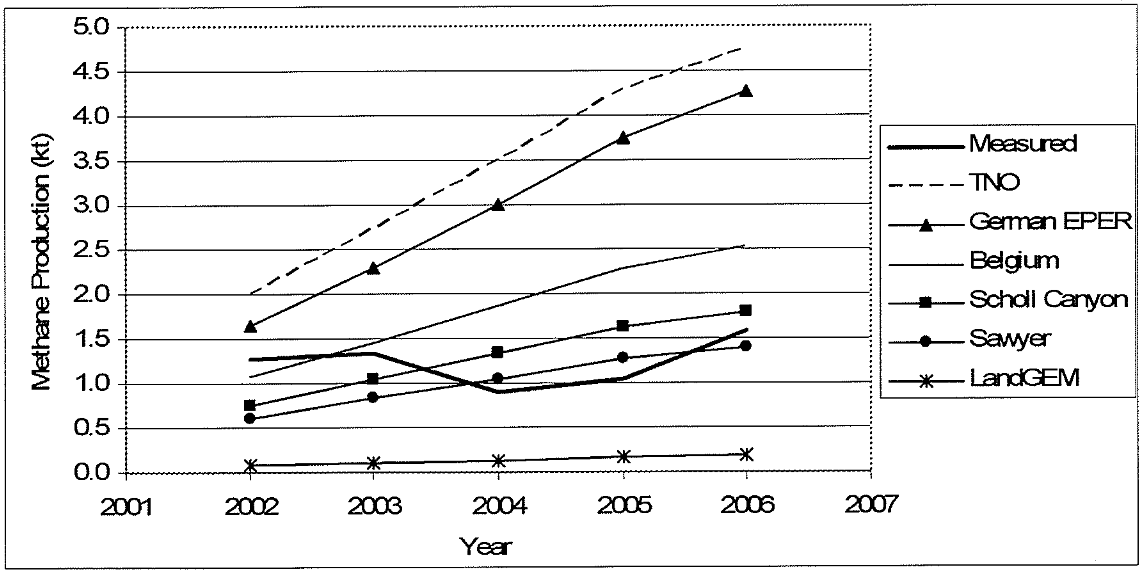


Figure 4.9. Sherbrooke Landfill (Quebec) Model Results as compared with the Measured Results.

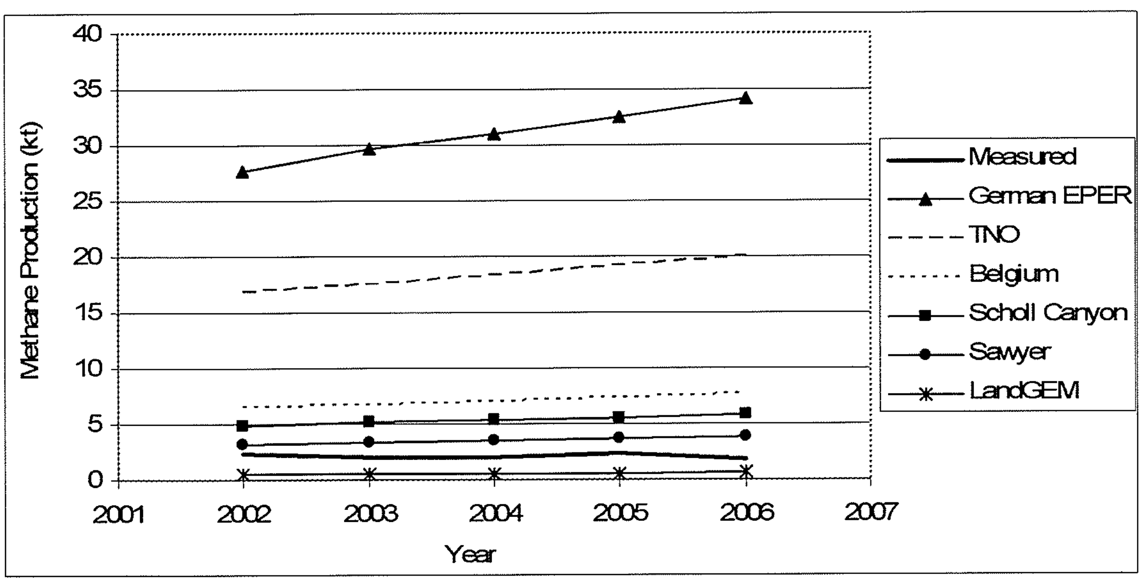


Figure 4.10. Toronto Landfill (Ontario) Model Results as compared with the Measured Results.

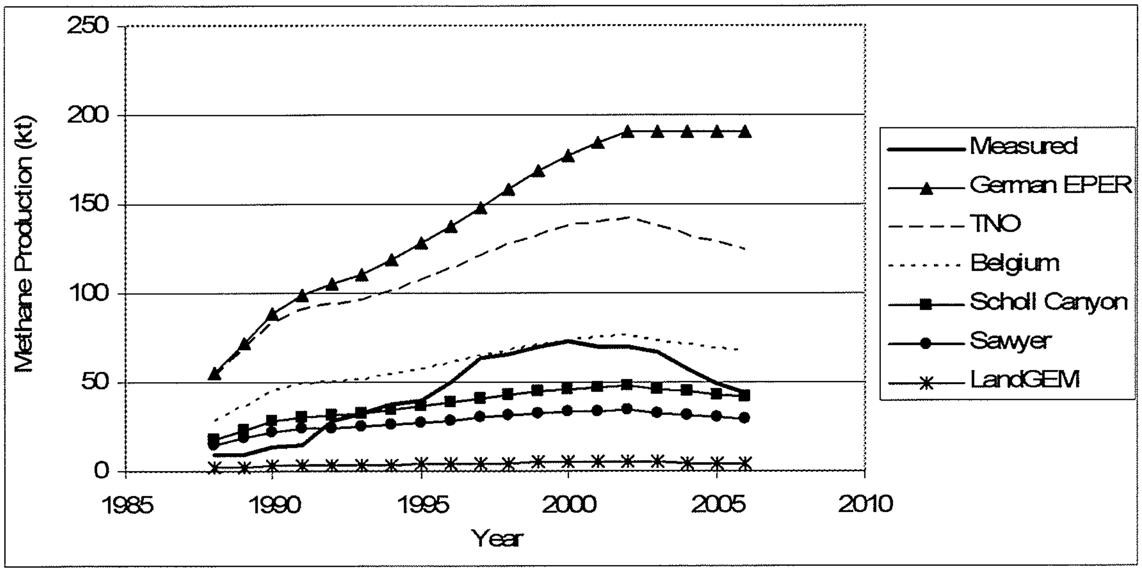
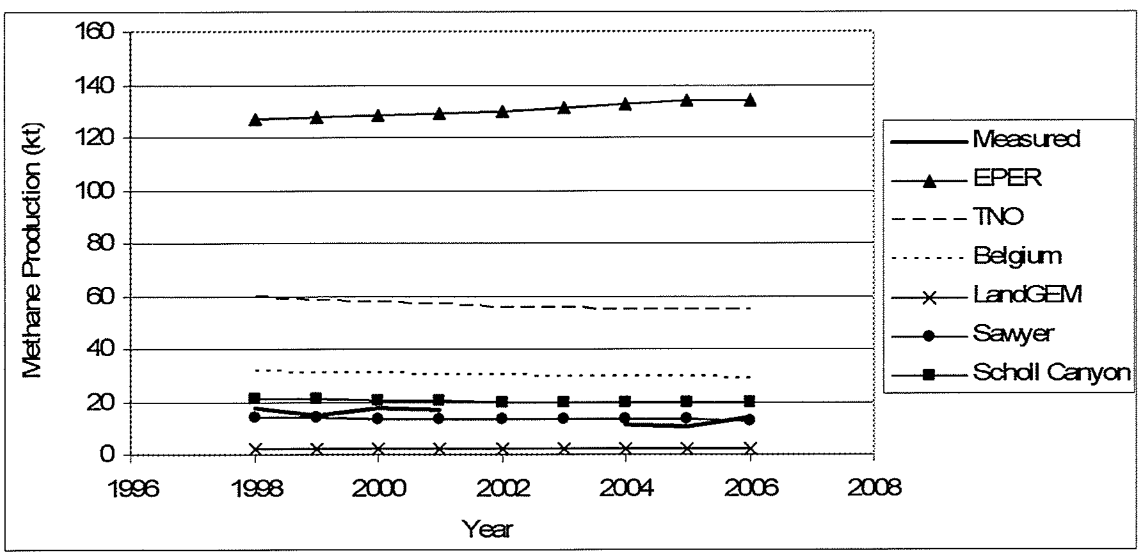


Figure 4.11. Edmonton Landfill (Alberta) Model Results as compared with the Measured Results.



**The Edmonton Landfill's methane recovery system was not in service from 2002-2003.

4.3 Model Inputs

This section presents the site-specific, model values tested for the landfills to improve the methodology for calculating the decay rate (k) and methane generation potential (Lo) values. All possible variable combinations were tested against each other using the "Sawyer Model". The data from the 35 landfills was used to test for potential relationships between the measured methane and landfill temperature, precipitation, size, depth, density, years in operation, and well type.

4.3.1 "Sawyer Model" Inputs

The originally inputted decay rates and methane generation potentials were increased and decreased by 10%, 20%, and 30% for each of the 35 landfills (Ste. Cecile-de Milton and Coquitlam were outliers, Appendix E) and inputted into the "Sawyer Model" . A relative percent error, absolute percent error, correlation, median, and significance (paired t-test) were calculated for each potential output (Tables 4.4 and 4.5).

Table 4.4. The Percent Error and Paired t-Test Results for the 35 Landfills using the "Sawyer Model" under Changing Decay Rates (k) and Standard Methane Generation Potential (Lo) Inputs.

	Mean Relative Error	Mean Absolute Error	Median Error	Correlation (r)	Significance (p)
No Change	19%	66%	-11%	0.9180	0.2501
+10%	26%	69%	-7%	0.9157	0.4202
+20%	32%	72%	-1%	0.9156	0.6194
+30%	41%	75%	25%	0.9142	0.9925
-10%	12%	64%	-15%	0.9169	0.1258
-20%	4%	62%	-19%	0.9140	0.0487
-30%	-5%	60%	-25%	0.9151	0.0141

Table 4.5. The Percent Error and Paired t-Test Results for the 35 Landfills using the "Sawyer Model" under Changing Methane Generation Potentials (Lo) and Standard Decay Rate (k) Inputs.

	Mean Relative Error	Mean Absolute Error	Median Error	Correlation (r)	Significance (p)
No Change	19%	66%	-11%	0.9180	0.2501
+10%	31%	73%	-2%	0.9164	0.5538
+20%	43%	80%	7%	0.9164	0.9402
+30%	59%	90%	34%	0.9164	0.6878
-10%	7%	61%	-20%	0.9164	0.0803
-20%	-4%	58%	-29%	0.9162	0.0178
-30%	-16%	57%	-38%	0.9164	0.0022

Using both initial inputs, the "Sawyer Model" yielded a relative percent error of 19%, an absolute percent error of 66%, a median of -11%, and a p=0.2501 (which did not reject the null hypothesis). When the Lo value remained constant, the best model output occurred when the k-value was increased by 10%, giving a median of -7% and p=0.4202. When the k-value remained constant, the best model output occurred when the Lo value was increased by 10%, yielding a median of -2% and p=0.5538. When the Lo and k-values were crossed with each other, no value produced as successful results as when the k-value remained constant and the Lo was increased by 10%.

4.3.2 Additional Inputs

The measured data from the 35 landfills was trended against the annual precipitation, average yearly temperature (Environment Canada, 2006), density, current waste-in-place, depth, years in operation, and well type (horizontal versus vertical wells) variables. Of these, only the current waste-in-place variable with a correlation of r=0.6881 (Figure 4.12) had a strong correlation, while all other variables had weak correlations ($r \leq 0.2980$). An analysis of variance (ANOVA) test was performed, thereby accepting the null hypothesis for all variables ($p \geq 0.4045$ in each case) except the current waste-in-place variable ($p=7.64 \times 10^{-6}$; Table 4.6) which did not reject the null hypothesis when the landfills were differentiated by size (small (<10 Mt) and large (>10 Mt) landfills). The widest range in error was observed for the small as compared to the large landfills (Figure 4.13).

Figure 4.12. Measured 2005 Methane Production Compared with the Current Sizes of the 35 Landfills.

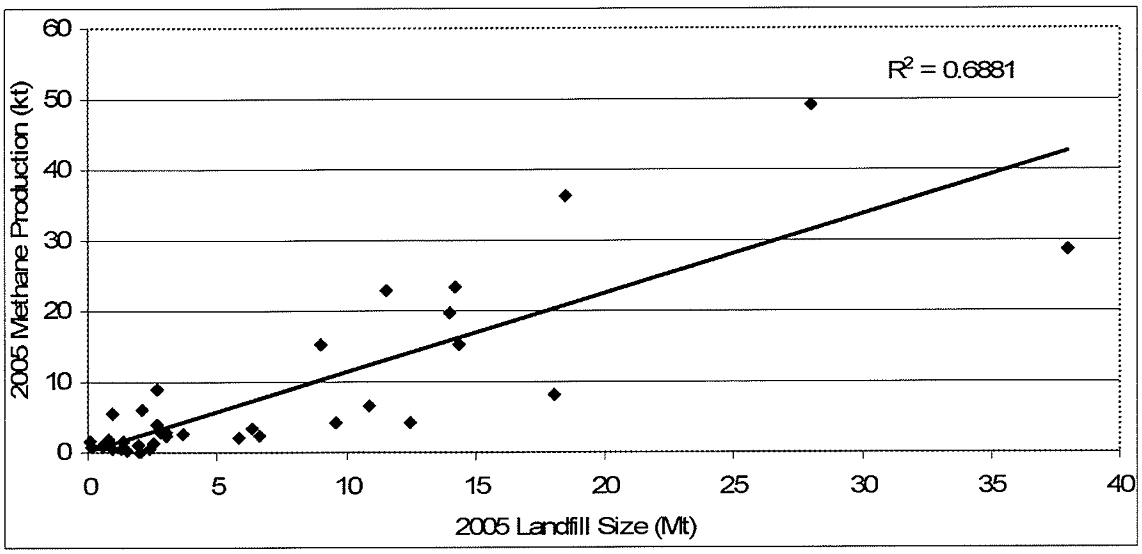


Table 4.6. Statistical Results for the Percent Error compared with Large (>10 Mt) and Small (<10 Mt) Landfills.

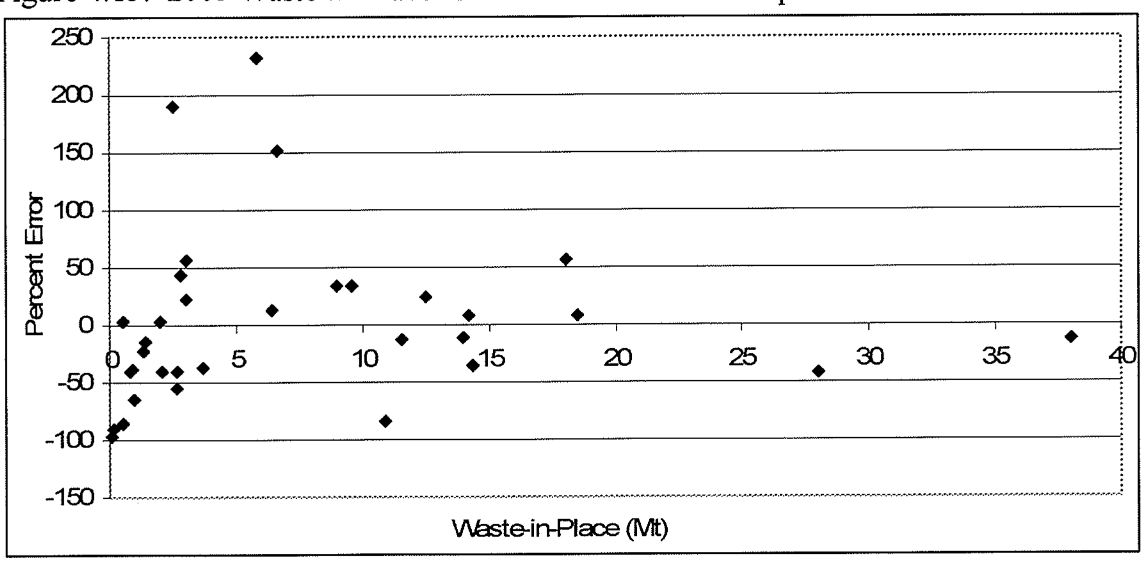
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
% Error	31	- 924.4380565	-29.82058247	2257.901
Small Landfill	31	40	1.290322581	0.212903
Big Landfill	31	53	1.709677419	0.212903

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	20276.28945	2	10138.14473	13.46769	7.64E-06	3.097696322
Within Groups	67749.80386	90	752.7755984			
Total	88026.09331	92				

Figure 4.13. 2005 Waste-in-Place for the 35 landfills as compared with the Percent Error.



After determining that the current waste-in-place amount had an effect on methane production, the relationship between the methane production measured separately from small and large landfills and precipitation, temperature, density, depth, years in operation and well type (horizontal and vertical) was examined. The majority of the variables had weak correlations ($r \leq 0.0800$); however, the density, depth, and well type each had slightly stronger correlations with at least one of the landfill size groups. The large landfills displayed some correlation with the density, depth, and horizontal wells ($r=0.1983$, 0.1413, and 0.1622, respectively), while the small landfills showed a correlation with the vertical wells ($r=0.7517$). Although typically a notable correlation is reserved for $r \geq 0.5000$, in this case lower r-values were considered as a multitude of variables can contribute to methane production in landfills. None were statistically significant ($p<0.05$), except the size.

4.3.2.1 Operating Status

Using the "Sawyer Model" the majority of the error was located on the closed landfills as opposed to the operating ones. Of the 35 landfills, those currently operating ($n=29$) carried 2% of the percent error, while those that were closed ($n=6$) carried 35% of the percent error. When the closed landfills used a modified model with a denominator of 2.0, the error from the closed landfills dropped to 1%. However, a t-test showed that the null hypothesis could only not be rejected when the denominator was 1.5 as opposed to 2.0. The "Sawyer Model" performed consistently well with landfills that are both operating and closed. An ANOVA test showed that the difference between the operating and closed landfills was significant (Table 4.7), thereby rejecting the null hypothesis.

Table 4.7. Statistical Results for the Measured Data compared with Operating and Closed Landfills.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Measured	32	280.8146	8.775456	140.8754
Closed	32	58	1.8125	0.157258
Opened	32	38	1.1875	0.157258

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1135.472	2	567.7358	12.06323	2.198E-05	3.094343
Within Groups	4376.889	93	47.06332			
Total	5512.36	95				

4.4 Future Model Projections

The "Sawyer Model" was used to predict future methane production to 2025 under different waste diversion scenarios for the Vancouver, Cowansville, Waterloo, and Halifax landfills. In 2025, the potential methane production at the Vancouver landfill ranged from 13.56 kt under 80% waste reduction to 36.85 kt under no waste reduction (Figure 4.14). At the Cowansville landfill, the potential methane production ranged from 1.47 kt under 80% waste reduction to 5.53 kt under no waste reduction (Figure 4.15). The Waterloo landfill's methane production ranged from 6.06 kt under 80% reduction to 19.01 kt under no reduction (Figure 4.16), while the Halifax landfill ranged from 1.47 kt to 10.38 kt under the same respective waste diversions (Figure 4.17).

Figure 4.14. Future Vancouver Methane Production using the "Sawyer Model" According to Five Waste Strategies.

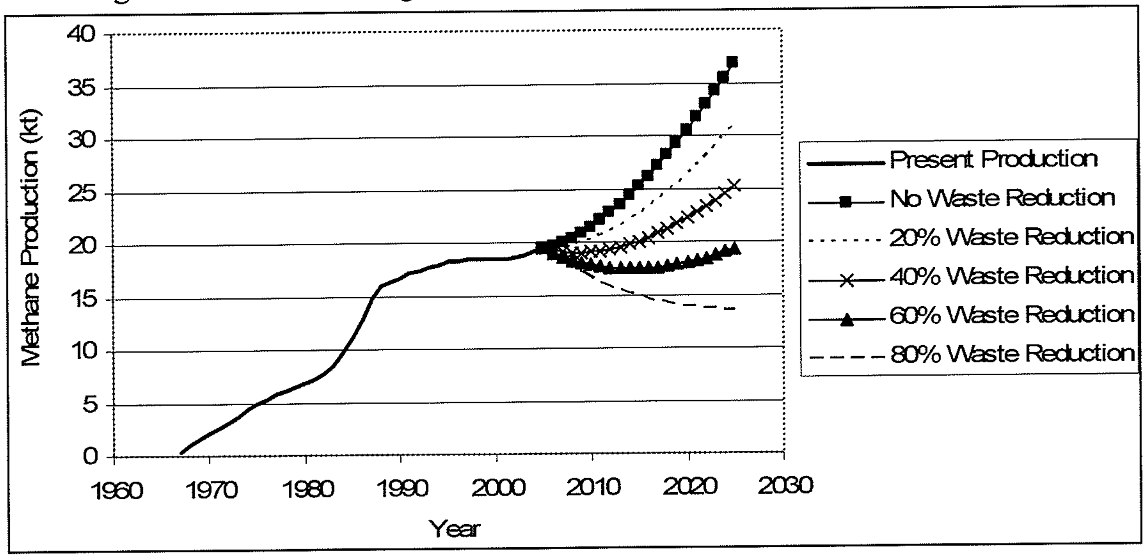


Figure 4.15. Future Cowansville Methane Production using the "Sawyer Model" According to Five Waste Strategies.

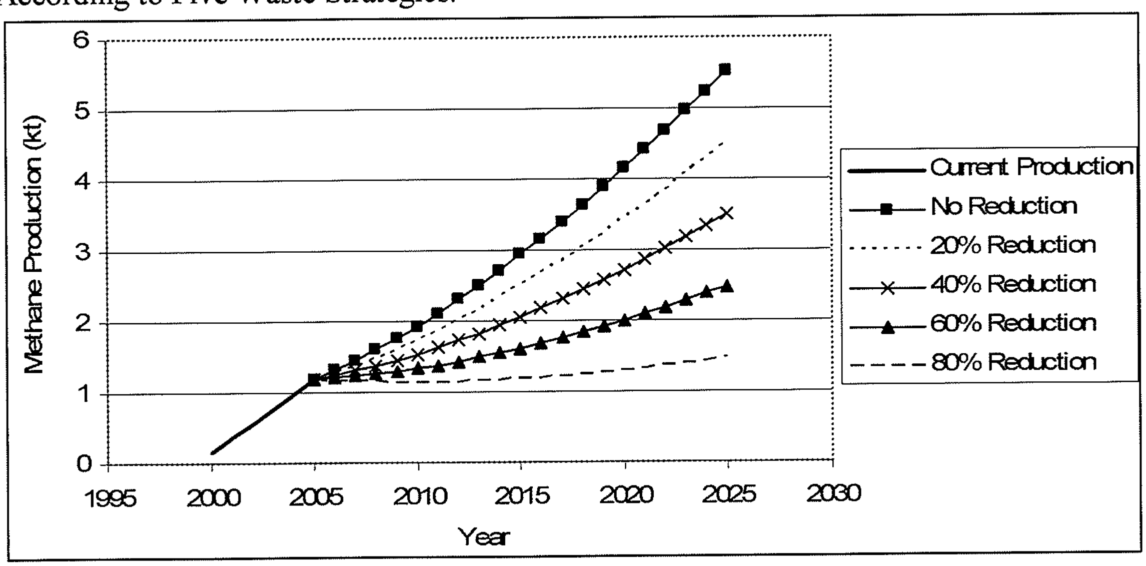


Figure 4.16. Future Waterloo Methane Production using the "Sawyer Model" According to Five Waste Strategies.

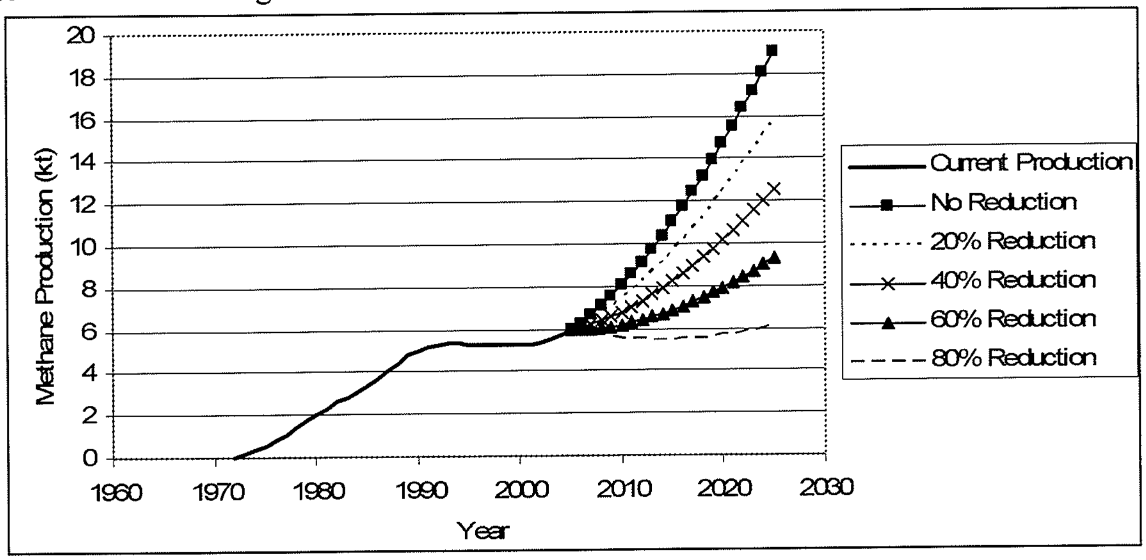
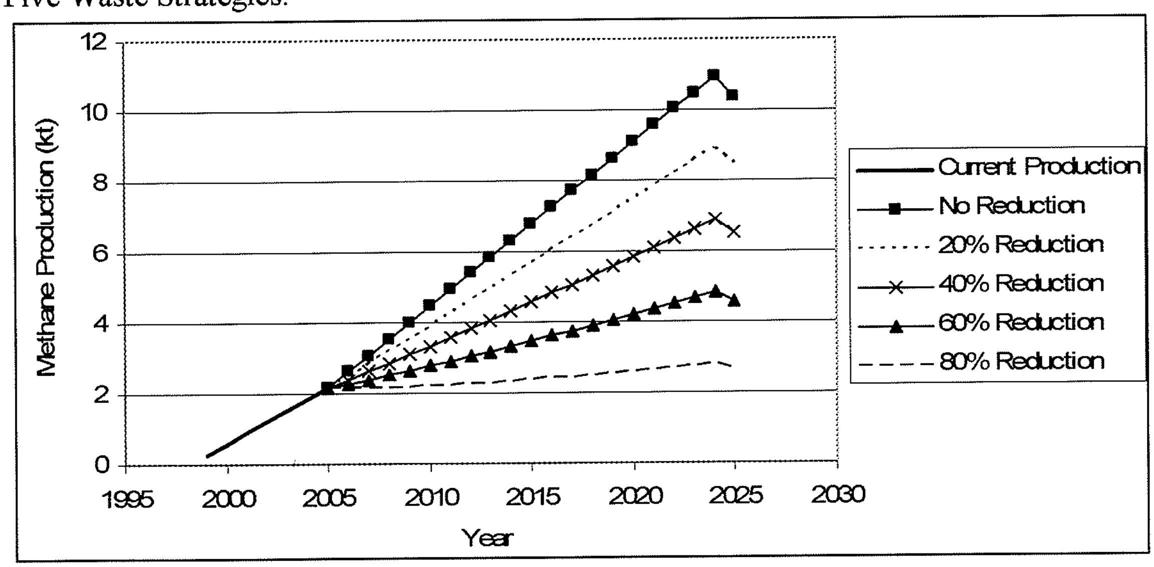


Figure 4.17. Future Halifax Methane Production using the "Sawyer Model" According to Five Waste Strategies.



4.5 Summary

The available methane production model and its inputs had average relative percent errors of 536% for the German EPER, 3337% for TNO, 136% for Belgium, 81% for Scholl Canyon, and -82% for the LandGEM models that could be improved upon for Canadian landfills. The results concluded that a modified Scholl Canyon/LandGEM Model with a denominator of 1.5, named "Sawyer Model" is best for calculating landfill methane production. An examination of the decay rate and methane generation potential proved that the best results occur when the k-values are trended with annual precipitation and the Lo is increased by 10%. Landfill waste-in-place amount and operating status were shown to cause potential modeling difficulties and should be considered when modeling landfills. Future methane production was calculated under five different potential waste scenarios for the Vancouver, Cowansville, Waterloo, and Halifax landfills, illustrating prospective trends. The following chapter discusses these results and their relevance to landfill operators and policy makers.

CHAPTER 5: DISCUSSION

5.1 Introduction

The results and their relevance are considered in this chapter. The methane production models are evaluated for their strengths and weaknesses when calculating landfill-gas production with the recommended "Sawyer Model". Improvements on the decay rate and methane generation potential are discussed, while other variables such as waste-in-place and operating status are considered for future models. Finally, the future methane production for four landfills is reviewed, evaluating composting/recycling versus energy use options.

5.2 Model Selection

It is difficult to choose an accurate model to calculate landfill methane production due to the paucity of validation of available models, which have different and conflicting methodologies but are currently used and accepted by different countries worldwide. The IPCC (2006) has attempted to establish a suitable universal method; however, because landfill conditions vary drastically, not all countries have found the IPCC's method appropriate for their landfills. Countries use different methods for collecting and reporting their methane production/emission, making it impossible to compare their results, thereby rendering global standardization impossible. A single accepted method would be advantageous, allowing for standardization within the reporting process and the establishment of emission standards, mitigation methods, and future targets. For this to occur, the model has to be validated using reliable measured data under appropriate conditions.

Used worldwide, the German EPER, TNO, LandGEM, Belgium, and Scholl Canyon models were tested for their ability to predict methane production from 35 landfills for 2005 and from 6 specific landfills that provided additional measured methane data. The new "Sawyer Model" is similar to the LandGEM in that both modify only one aspect of the Scholl Canyon, the waste factor: LandGEM by 10 and the "Sawyer Model" by 1.5. Each model is discussed individually regarding its applicability and usefulness in modeling methane production from Canadian landfills under the original inputs.

5.2.1 German EPER Model

The German EPER Model is a zero order model. It disregards the effect of time on methane production during and after landfilling activity, consequently receiving criticism for poorly portraying landfill conditions and degradational activity. This critique held true for the 35 landfills as well as the Vancouver, Toronto, Cache Creek, Cowansville, Edmonton, and Sherbrooke landfills, as in each case this zero order model produced greater error than any of the first order models examined. Clearly, this type of model is not suited for calculating methane production, as its relative percent error for the 35 landfills was 536%.

In particular, zero order models are notoriously recognized for their inability to accurately depict methane production in a post-closure landfill situation (SCS Engineers, 1997; Oonk et. al., 1994; Scharff and Afvalzorg, 2005). Landfills such as the Toronto landfill, which closed in 2002, continue producing methane post-closure. Since zero order models do not consider organic waste decay as a function of time, the model calculates no methane production immediately after waste acceptance stops (Scharff and Afvalzorg, 2005).

All landfills eventually close; thereby limiting the usefulness of the model and raising suspicion regarding the authenticity of a zero order to represent natural landfill processes, particularly in those landfills that had low percent error values such as the St. Catherine's (Ontario), Kingston (Ontario), and Otter Lake (Nova Scotia) landfills, where the model underestimated methane production. However, it only yielded good results for landfills having low waste-in-place values or a short operating period, further illustrating that this model is inconsistent and inappropriate to use for Canadian landfills.

5.2.2 TNO Model

Similar to most first order models, the TNO model (commonly used in the Netherlands) considers the degradable organic matter, the decay rate, and the waste landfilled in its model. This model is unique in that it includes a dissimilation factor in its equation (IPCC (1996) recommends 0.77) and assumes that the municipal solid waste's organic fraction is primarily cellulose, thereby including a conversion factor of 1.87 (Scharff and Afvalzorg, 2005).

In the 35 landfills, the TNO model overestimated methane production (relative percent error=337%), which is consistent with the six specific landfills and other study findings by Oonk and Boom (1995) and Scharff and Afvalzorg (2005). Although the 1.87 conversion factor is considered appropriate for municipal solid waste landfills because they typically have a large organic waste content (Scharff and Jacobs, 2004), this yields unreliably high model outputs. This factor is far too high, making the model unsuitable and a poor choice for modeling methane production relative to the other first order models examined.

5.2.3 Belgium Model

For the 35 landfills, the Belgium Model produced a relative percent error of 136%, which although low when compared to the TNO and German EPER models, was high relative to the Scholl Canyon and LandGEM models. The model rarely underestimated methane production, instead overestimating it by over 100% in 17 of the 35 landfills. Regarding the six individual landfills, the Belgium Model overestimated the methane production in the Vancouver, Sherbrooke, Edmonton, and Cache Creek landfills but yielded good methane production outputs for the Cowansville and Toronto landfills when compared to the measured data. Other than the Scholl Canyon Model, no other models were able to achieve good results for the Cowansville and Toronto landfills. Although the Belgium Model successfully calculated the methane production for some landfills, it was unable to do so for most, rendering it inconsistent in its performance.

Two hypotheses could explain why the Belgium Model calculated some of the landfill's methane production well, but not others. The first hypothesis is regarding landfill waste-in-place. For the 35 landfills, 64% of the landfills that the Belgium Model calculated well (percent error that were less than ±50%) were landfills containing less than 2.5 Mt of waste, while the model was inconsistent when calculating large landfills. The majority of the gross overestimations (percent error >200%) were observed in landfills containing over 6 Mt of waste.

The second hypothesis relates to the landfill's operation lifespan. The model only calculated two of the seven closed landfills well, while the remaining five had percent errors exceeding 150%. For landfills operating less than 15 years, the Belgium Model performed consistently well, yielding percent errors that were less than ±50%, which suggests that the model is far superior at modeling new landfills than closed ones. A similar trend was observed with the six specific landfills; Cowansville, the newest landfill of the six, performed well under this model with a percent error of 50%. Alternatively, the other four landfills that have been operating over 10 years did poorly under this model. However, for the closed Toronto landfill the model performed very well yielding a relative percent error of 32%, illustrating that this model has some success with modeling post-closure sites.

Both hypotheses limit the model's applicability for modeling a wide range of landfills. A good model is consistent and reliable in its predictions, unlike the Belgium Model. It is desirable to calculate methane gas at all stages of waste input and all stages of gas production, which the Belgium Model could not do. The Belgium Model was inconsistent with its model outputs and was disregarded as a viable model option for calculating methane production from Canadian landfills.

5.2.4 LandGEM Model

The LandGEM Model always underestimated methane production, yielding an relative error of -82% for the 35 landfills. Although this model produced the smallest range of all the models, its average error was more substantial than the Scholl Canyon Model's. Of the six landfills, this model calculated the Vancouver, Cache Creek, and Sherbrooke landfills statistically well, although it underestimated the methane production values in each case. The underestimated was more pronounced for the Toronto and

Cowansville landfills, as the dividing factor was too great and the LandGEM Model could not be considered a good fit in their cases.

The US EPA (2004) recommends the LandGEM Model (it is available free of charge on their website), to estimate methane production in landfills. Its equation is divided by a factor of ten to address concerns that the Scholl Canyon equation overestimates methane production. The US EPA (2005) recommends default inputs for the decay rate (k) and the methane generation potential (Lo) in the LandGEM Model based on the EPA's "Compilation of Air Pollutant Emissions Factors" (AP-42) and Clean Air Act (CAA; US EPA, 2005). The default inputs are considerably higher than those calculated in this study, as it was determined that the (higher) inputs were not appropriate for the examined landfills. The possibility exists that the EPA's (2005) default inputs could yield statistically valid results using the LandGEM Model, as higher model inputs cause higher model outputs; however, this would be misleading, not truly reflecting the landfill's actual state according to scientific knowledge.

5.2.5 Scholl Canyon Model

Of the five models, the Scholl Canyon Model equation produced the best relative percent error (81%) for the 35 landfills. It yielded the best results for the Toronto and Cowansville landfills when compared to their measured gas productions and the second best results for the Vancouver, Cache Creek, and Sherbrooke landfills (the LandGEM Model was the best predictor for those landfills). Environment Canada (2006), SCS Engineers (1997), and Korea (Kim, Park, and Lee, 2005) promote using the Scholl

Canyon Model, as they have found it to be quite successful for a wide range of landfill conditions.

Many Canadian landfill operators expressed skepticism regarding the Scholl Canyon Model's ability to calculate methane production from experiences with model overestimation (particularly with landfills containing less than 10 Mt of waste), as observed in this study with the Vancouver, Cache Creek, and Sherbrooke landfills. As a result, many operators declined to participate in this study, fearing that the model would misrepresent their landfill's gas production. This study found that under the appropriate model inputs, the Scholl Canyon Model can produce reasonable, reliable results, reflective of Canadian landfill conditions; however, its tendency to overestimate methane production, particularly when many site-specific model inputs are uncertain, is problematic and a valid concern.

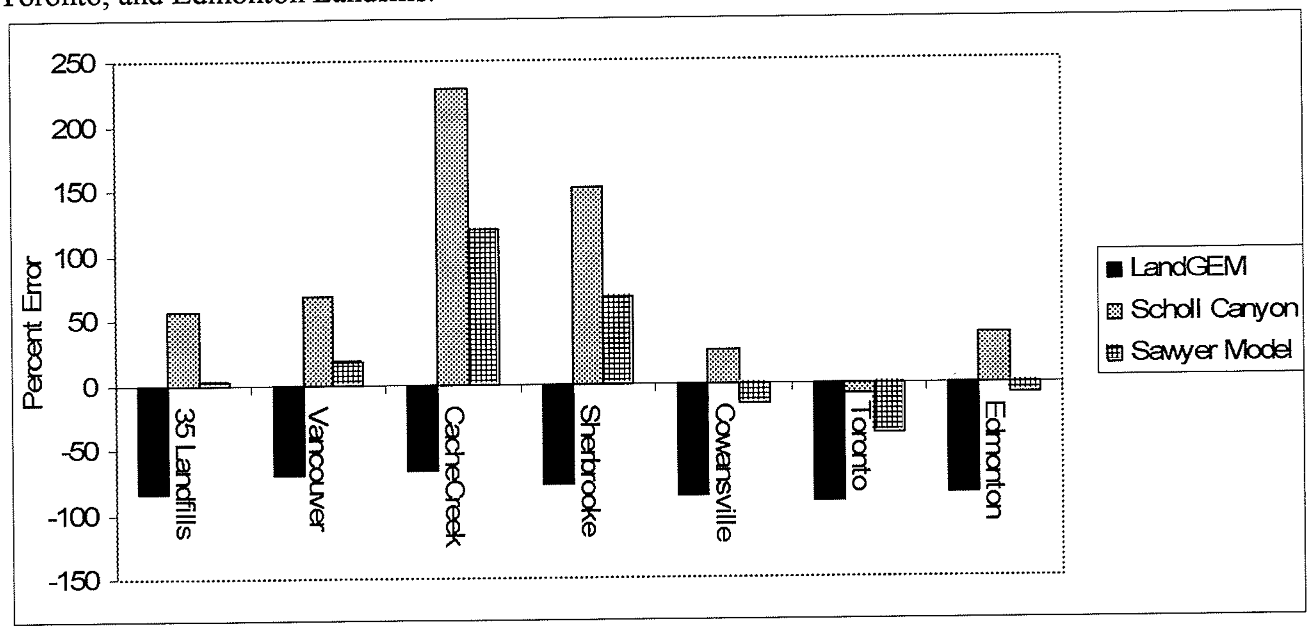
5.2.6 "Sawyer Model"

Of the five models tested, the Scholl Canyon and LandGEM models produced values that were the closest to the measured values. However, both models had problems with either over or underestimating methane production and were inconsistent in successfully calculating all landfills. The landfills that were compatible with the Scholl Canyon Model found that the LandGEM Model grossly underestimated their gas production, while the landfills that were compatible with the LandGEM Model found that the Scholl Canyon Model grossly overestimated their gas production.

Since the Scholl Canyon and LandGEM models share the same core equation, this was maintained when determining a model that could be used for all landfills. The

LandGEM Model's devisor was too large for most landfills, while a dividing factor of 1.5 provided the lowest percent error compared with any of the other previously tested models (Figure 5.1). The "Sawyer Model" was considered the best model for calculating Canadian landfill methane production and is recommended for future use.

Figure 5.1. Relative Percent Error of the LandGEM, Scholl Canyon, and "Sawyer Model" for the 35 Landfills, Vancouver, Cache Creek, Sherbrooke, Cowansville, Toronto, and Edmonton Landfills.



5.2.7 Data Limitation

The number of potential Canadian landfills suitable for modeling is limited because only 52 landfills (out of an estimated 144 major landfills; Environment Canada, 2006) currently collect methane gas thereby recording the production quantity. Of the 52, only 37 landfills provided survey data that was complete enough to use for this study. Of the 37 landfills, two were omitted from the data because they were outliers, shrinking the sample size to 35. For these landfills, only the 2005 measured methane data was collected, limiting the number of data points available for establishing a relationship between the model, its inputs, and the measured data. Only six landfills (Vancouver, Cache Creek, Sherbrooke, Cowansville, Edmonton, and Toronto) released their methane collection data for multiple years, thus greatly limiting the validity of obtaining a relationship suitable for extrapolation to other Canadian landfills from this data.

The six landfills have only been collecting landfill gas for 5-7 years (except Toronto whose data dated back to 1998), a short period for observing and fitting general landfill production trends, particularly when determining if gas fluctuations are regularly occurring or not. The more data points available to compare the modeled and measured data, the better, as this reduces the uncertainty surrounding the observed trends (Jorgensen and Bendoricchio, 2006). When fewer data points are available, it becomes difficult to determine if an irregular data point is an anomaly or alternatively, if it is regularly occurring thus requiring a model adjustment.

5.2.8 Modeling Error

Numerous sources of error are associated with methane production models that stem from model inputs and equations, as many of the contributing production factors are unknown or difficult to define. When errors occur in the model input equations, they propagate through the entire model equation making it desirable to minimize the error at all stages of modeling. When choosing which model would best reflect the landfills' gas production, the methodology for the model inputs was kept consistent in order to avoid introducing any additional, unnecessary error. Regardless, the methodology used for both inputs is uncertain, creating error.

The decay rate's cause and effect relationship within the landfill's environment (precipitation, temperature, and waste composition) are not yet clearly defined, making it difficult to assign an appropriate input for modeling purposes. Although a relationship based solely on annual precipitation was used based on previous studies (Lay, Li, and Noike 1996; Maurice and Lagerkvist, 1997; US EPA, 2004), the relationship between decay and the landfill environment remains ambiguous and uncertain. The IPCC (2006) recognizes the high uncertainty and error associated with decay rates, as they are the least well-defined input in landfill methane modeling.

Most landfills have not conducted waste composition studies, which prohibits calculating a site-specific degradable organic carbon (DOC) input that accurately reflects the landfill's waste composition. Waste composition fluctuates widely between and within Canadian provinces (as seen in Table 3.3), making it difficult to assign national or provincial DOC values. In the future, this input may become better documented as municipalities focus on diversion initiatives in order to meet waste diversion targets. Additionally, the breakdown within the DOC category can be ambiguous, as paper, food, garden, and wood waste do not necessarily have constant DOC values. There have been few landfill degradable organic carbon studies making it difficult to quantify their values accurately (IPCC, 2006). The IPCC (2006) suggests an error value of ±10% on the DOC input.

The methane generation potential (Lo) input carries its own uncertainty, building on that already present in the DOC value. The default value for the fraction of degradable organic carbon (DOC_f) in the 1996 IPCC guidelines was 0.77; however, as of 2006, the IPCC amended this value to a default of 0.50, assigning an error of ±20%. This study used the original 1996 value, which yielded good results for the Canadian landfills and carries an error of ±10%. The methane correction factor (MCF) which equaled a default value of 1 as the landfills used in this study are characterized as managed landfills, carries an error of -10%, 0%.

5.3 Model Inputs

Although the process can be uncertain, calculating reflective decay rates (k), and the degradable organic carbon (DOC)/methane generation potential (Lo) inputs is required for model success. As both inputs are highly variable and difficult to determine, accurate model representation is essential in obtaining realistic and reflective methane production quantities from landfills. Additional factors not considered in the model may contribute to methane production. Factors including current waste-in-place and operating status were examined for their relationship with methane production and their potential model impact.

5.3.1 Decay Rate (k)

Moisture, a significant factor in determining waste decomposition and subsequent methane production, is essential for bacterial growth, metabolism, and nutrient transport. Landfill moisture content is influenced by initial waste moisture, surface and groundwater precipitation, and decomposition (EMCON Associates, 1980). Laboratory experiments and field observation have not clearly defined the relationship between ambient temperature and decay (Maurice and Lagerkvist, 1997; Lay, Li, and Noike 1996; EMCON Associates, 1980); therefore this study only considered precipitation when calculating and reevaluating decay rates which proved successful. In the cases of the 35 landfills, the best fitting rates occurred when the originally proposed equation (Equation 3.1) linking precipitation to decay was used. The decay rates ranged between and within the provinces (Table 5.1), from 0.019 yr^{-1} in the Cache Creek (British Columbia) landfill to 0.054 yr^{-1} in the Halifax (Nova Scotia) landfill, corresponding to half-lives of 36.5 and 12.8 years, respectively.

Past Environment Canada provincial decay rates ranged from 0.003-0.028 yr^{-1} (nationally), with British Columbia, Ontario, Quebec, Alberta, and Nova Scotia assigned rates of 0.028, 0.024, 0.024, 0.006, and 0.011 yr^{-1} respectively (Levelton, 1991). Environment Canada provincial decay rates were recently revised using Equation 3.1, increasing British Columbia, Ontario, Quebec, Alberta, and Nova Scotia to 0.048, 0.037, 0.042, 0.023, and 0.056 yr^{-1} respectively (half-lives of 14.3, 18.7, 16.5, 30.1, and 12.4 years) (Environment Canada, 2006). The revised Environment Canada (2006) data, adopted from Thompson, Sawyer, and Bonam (2006) was based solely on average annual provincial precipitation (Table 5.1) (US EPA, 2004), as opposed to individual landfill location annual precipitation.

Table 5.1. Revised Environment Canada (2006) Provincial Decay Rates as compared with this Study's Provincial Decay Rate Ranges.

	Revised EC Provincial Decay Rates (yr^{-1})	Study's Provincial Decay Rate Ranges (yr^{-1})
Nova Scotia	0.056	0.054
Quebec	0.042	0.041-0.048
Ontario	0.037	0.034-0.041
Alberta	0.023	0.022-0.024
British Columbia	0.048	0.019-0.052

Environment Canada (2006) advocates using provincial wide decay rate constants when calculating methane production from landfills. However, upon observing the radical difference in decay rates between the Environment Canada (2006) value for British Columbia and the range exhibited by this study, provincial decay rates seem inadequate when calculating landfill methane production.

Several landfills may reside in the same province but their geographical locations differ such that their average annual precipitation differs drastically; therefore, their decay rates and subsequently methane production should also differ drastically. Assigning a single, provincial-wide decay rate constant is not an effective way of calculating methane production from Canadian landfills, consistent with findings from landfills in different areas of the United States (Bentley, Smith, and Schrauf, 2004). Instead, a simple, user friendly, formula linking city or regional precipitation (available from Environment Canada's weather website) to site-specific decay rates is advantageous because it allows operators to calculate their landfill's rate with relative ease and increased precision over generalized, provincial rates unreflective of their landfill's conditions.

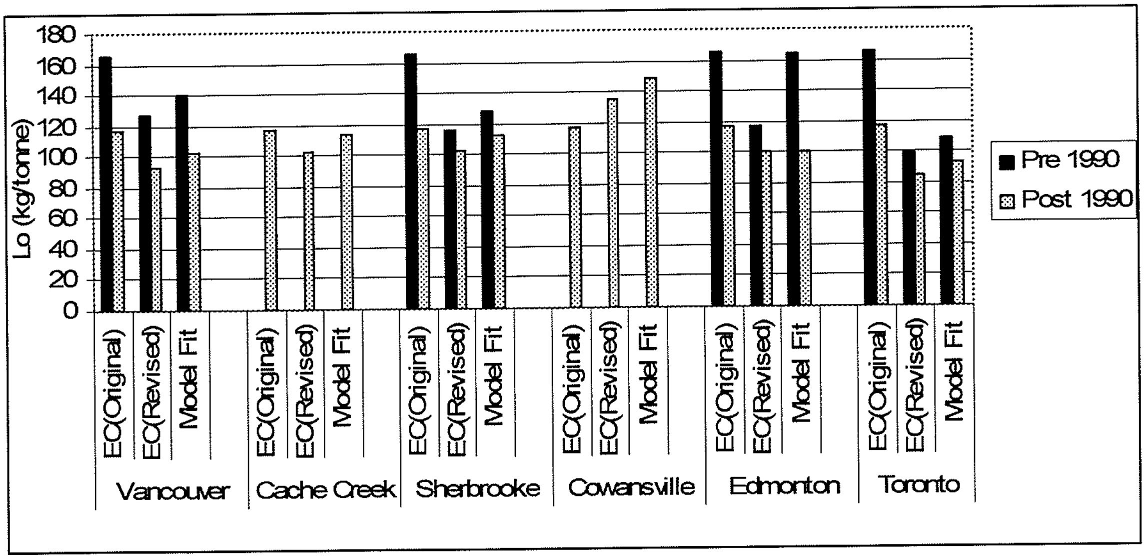
5.3.2 Degradable Organic Carbon (DOC)/Methane Generation Rate (Lo)

Degradable organic carbon (DOC), the waste portion available for microbial degradation to methane gas, is a fundamental factor for determining landfill methane generation potential. Recycling paper, cardboard, and more recently, programs collecting food wastes for composting reduces the organic component. Small DOC changes impact the methane generation potential (Lo), and can result in large methane estimate variations as methane production directly depends on the degradable waste composition (IPCC, 1996; Lay et al., 1996). In this study, only nine of the 35 landfills provided site-specific waste audit data; because the other landfills did not, generic provincial data was used (Appendix C). The 35 landfills yielded the best fit with the "Sawyer Model" when the Lo (pre and post 1990 recycling initiatives) was increased by 10% of its original values.

The IPCC (1996) recommends a methane generation potential (Lo) between 100-200 kg/tonne of waste. Until recently, the nation-wide Lo's utilized by Environment Canada were: i) 165 kg/tonne of waste from 1941-1989; and ii) 117 kg/tonne of waste from 1990-2003. These values did not consider that provincial waste diversion programs differ from one another, thereby making nation-wide constants unsuitable. The Environment Canada DOC and Lo's were reexamined and recalculated according to specific provincial information (Appendix C; Thompson, Sawyer, and Bonam, 2006), in an attempt to reflect different provincial waste diversion policies.

When the six landfills were examined using Lo values that were 10% higher than their original values, in five of the six landfill the original Environment Canada values were higher than those fit under the "Sawyer Model". The Cowansville landfill, the newest landfill of the five, was the only landfill having a best model fit that was higher than the original Environment Canada data. When compared with the revised Environment Canada data, the Vancouver, Cache Creek, Cowansville, Sherbrooke, Edmonton, and Toronto landfills all produced best model fits that were comparable or higher than the revised values (Figure 5.2).

Figure 5.2. Environment Canada Methane Generation Potential Values Compared to the Model Fit Methane Generation Potential Values.



*EC= Environment Canada
**All "model fit" data is with respect to the "Sawyer Model"

5.3.2.1 Error

The majority of the error associated with the DOC/Lo calculation in this study most likely originates from the DOC portion of the equation due to a lack of site-specific waste composition data. Provincial legislation differs greatly across Canada regarding waste management and diversion practices. In addition, these same policies and practices differ within provinces. This was noted by the nine landfills that provided site-specific waste composition data, as landfills within the same province differed greatly with their landfilled organic waste volumes (Table 3.1). This calculation becomes increasingly important when calculating potential future methane production as the landfilled organic fraction may change due to alterations in provincial waste diversion policy (Section 5.3).

5.3.3 Additional Inputs

The 35 landfills showed a good correlation when the measured methane data was compared to the amount of current landfilled waste-in-place, indicating that the larger landfills produce more methane than the smaller landfills. This was not surprising, as it would be expected that landfills with more waste-in-place would produce more gas than those with less. When the percent error was trended with the current waste-in-place for the 35 landfills, the majority of the fluctuating error was located in the small landfills, particularly those containing less than 5 Mt of waste. In several cases, the model grossly overestimated the small landfill's methane production, yielding unreliable results. This was more likely to occur in situations where the landfill had not been operating for less than 20 years as observed with the Cache Creek, Halifax, Cornwall and Kingston landfills. It is recommended that landfill operators exercise caution when modeling smaller landfill sites, as the model may overestimate production. In such cases a model denominator larger than 1.5 should be considered.

Although not very strong, the large landfills did show a slight positive correlation with the density, depth, and horizontal well type, the small landfills showed a slight correlation with the vertical well type, further demonstrating that small and large landfills have different modeling needs. However, these correlations were not strong enough to definitively comment on whether those variables should be considered in future models, particularly for the large landfills who, in this study, had a very small sample size (sample size=9).

5.3.4 Operating Status

Post-closure, landfills demonstrate a decreasing methane production trend as new waste is no longer entering the system. This post-closure trend is quite different from the increasing or stabilized methane production trend observed from operating landfills. This was apparent from the ANOVA analysis, as the results from the closed and open landfills were statistically significant. Although the majority of the error was located in the closed landfills, the t-test proved that the difference was insignificant between the measured and modeled data. However, the sample size for the closed landfills was only seven, thereby yielding inconclusive results.

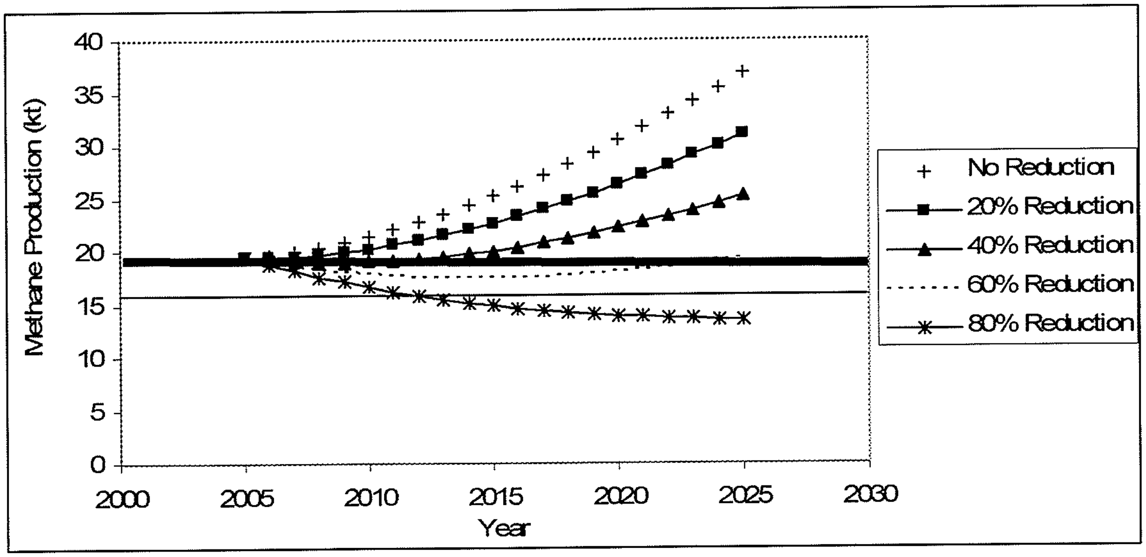
5.4 Future Methane Production

Although Canada ratified the Kyoto Protocol (2002), its targets address sinks and sources as a whole, not individual sectors. As such, the waste sector is not committed to reducing its methane production to 6% below 1990 levels by 2012 and should not be expected to do so (Palmer, 2007).

5.4.1 Future Trends

Due to rapid growth, the Vancouver landfill's methane production only falls below the 1990 production level (16.73 kt) under an 80% waste reduction, while all other waste diversion scenarios result in higher production levels. Under an 80% reduction, the methane production drops to 16.64 kt in 2010 and remains below this level through to 2025. Under a no reduction or a 20% reduction scenario, the methane production is not effected and continues to grow steadily until 2025. A 40% waste reduction causes the methane production to remain relatively stable until 2011 when it begins to increase, while under a 60% reduction the production decreases until 2014 before it regains its upward trend (Figure 5.3).

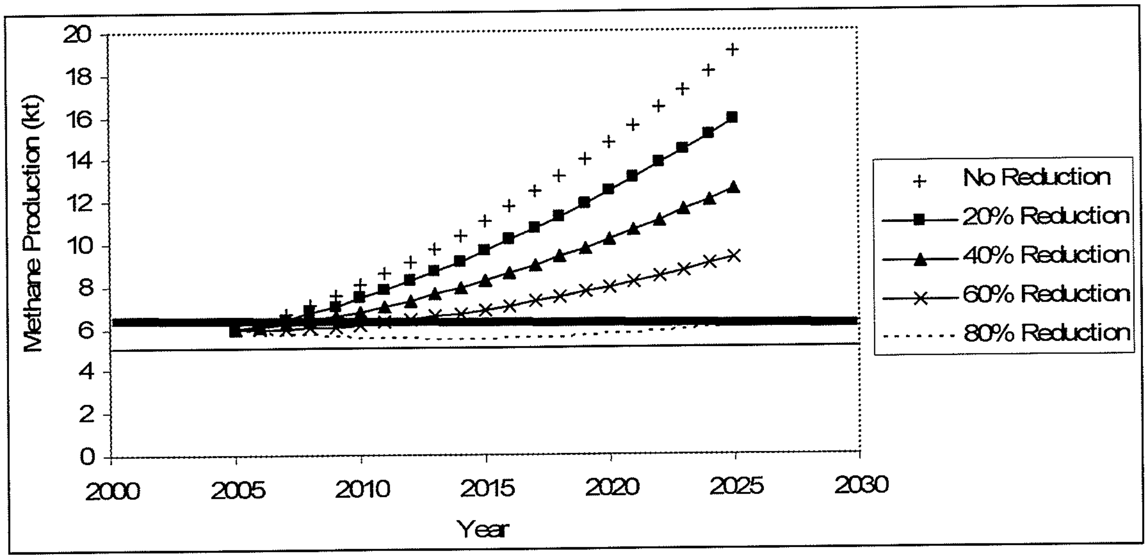
Figure 5.3. Vancouver Landfill Future Methane Production as compared to 1990 and 2006 Levels.



** Indicates 1990 Level
Indicates 2006 Level

A similar trajectory occurs for the Waterloo landfill; however, none of the waste diversion scenarios yield methane production levels below the 1990 value (5.03 kt). Similar to Vancouver, the Waterloo landfill never reaches the 2006 methane production (6.28 kt) under an 80% diversion policy. With 60% diversion, the production does not exceed the 2006 value until 2011, while under no reduction, 20% and 40% reduction the methane production surpasses the 2006 level almost immediately (Figure 5.4).

Figure 5.4. Waterloo Landfill Future Methane Production as compared to 1990 and 2006 Levels.



** —— Indicates 1990 Level
▬▬ Indicates 2006 Level

A similar, yet slightly different trend was observed with the Cowansville and Halifax landfills, most likely because they are newer landfills (both are roughly 6 years old) and have yet to reach their maximum methane production potential. In contrast, the Vancouver and Waterloo landfills have been operating for over 30 years and have stabilized environments. The Cowansville and Halifax landfills are in the process of reaching their stable, constant systems; therefore, the diversion scenarios did not have as great of an impact on their future methane production (Micales and Skog, 1996).

The Cowansville and Halifax landfills followed identical trajectories from 2006-2025. Excluding the 80% and 60% diversion rates, all other diversion scenarios immediately exceeded the 2006 methane production levels for the Cowansville and Halifax landfills. For both landfills, the 80% and 60% diversion rates exceeded the 2006 rate by 2020 and 2009, respectively.

When the future methane production was calculated for all four landfills, the total waste composition was assumed to remain constant. Only changing the total amount of future waste landfilled assumes that the proportion of non-methane producing materials to methane producing materials remains stable; therefore, the methane generation potential/degradable organic carbon (Lo/DOC) calculation remained constant post 2006. However, if any of the four landfills become more aggressive with organic waste diversion relative the overall waste composition, then the Lo/DOC model input would be lower than currently used. Subsequently, the waste diversion scenarios would have a greater impact on reducing methane gas production from landfills, and future methane production would be less than what was projected.

5.4.2 Recycling and Composting

Recycling and composting initiatives throughout Canada have been gaining popularity and widespread acceptance since they began over 17 years ago. By diverting organic material, the landfill's methane producing capacity is reduced thereby mitigating its negative effects as a greenhouse gas contributor (Farquhar and Rovers, 1973). However, not all recycled materials contribute to methane gas production, as diverted materials including glass, plastic, and metal are not organic compounds and therefore do not contribute (Hudgins and Harper, 1999). Although diverting these materials has positive benefits with respect to other waste management and production concerns, it does not help mitigate methane production.

Current trends suggest that recycling and composting efforts across Canada are on the rise; however, the total amount of waste disposed also continues to rise (Thompson et al., 2006). From 2000 to 2002, waste generation in Canada rose by 4%, and increased by 3.5% from 2002 to 2004 (Statistics Canada, 2002; 2004), while the recycling/composting rate increased by 15% from 2000 to 2002 and 22% from 2002 to 2004 (Statistics Canada, 2002; 2004). Although recycling and composting help divert materials from landfills, landfilling continues to be the most common form of waste disposal in Canada. For a major impact to be felt, recycling and composting initiatives must be significantly increased, with a simultaneous effort devoted to reducing waste production at the source.

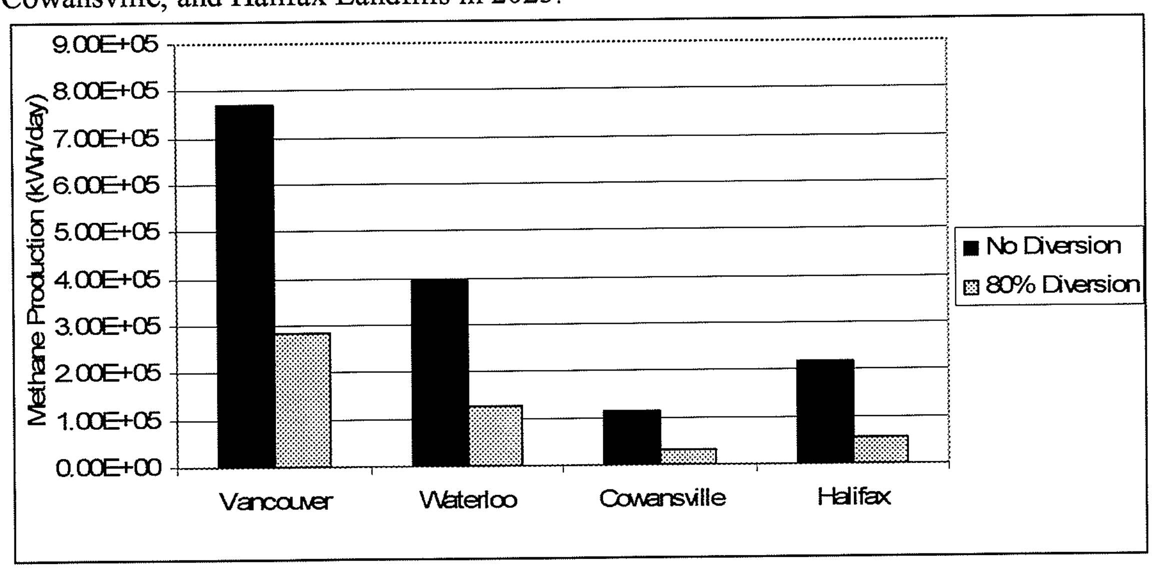
5.4.3 Methane Recovery and Energy Utilization

As recycling and composting initiatives gain popularity, the total amount of landfilled organic content will be reduced, thus decreasing the quantity of methane gas production. When landfills such as Vancouver, Waterloo, Halifax, and Cowansville install methane recovery systems for energy utilization, maximum gas production will be required to yield the greatest profit. If large quantities of organic material are no longer landfilled, then the recovery system may no longer be economically viable in the future. However, with historic waste where a lot of waste-in-place is present producing methane for 30 to 50 years, there should be ten to twenty years of sizable production post-closure or reduced organics.

Under the different waste scenarios, in 2025 the Vancouver landfill could potentially produce between 13.56 kt of methane (80% waste diversion) and 36.85 kt of methane (no waste diversion) annually, the equivalent of between $2.83\text{x}10^5$ and $7.69\text{x}10^5$ kWh/day. On average, 20 kWh/day are required to heat a house (Revelle, 2003), allowing the Vancouver landfill to heat between 14,150 and 38,450 homes per day depending on the waste diversion option. In 2025, the Waterloo landfill could produce between 6.06 kt and 19.01 kt of methane (80% waste diversion and no waste diversion respectively). This is the equivalent of between 1.26×10^5 and 3.96×10^5 kWh/day, which heats between 6,300 and 19,824 homes per day (Figure 5.8).

As the Cowansville and Halifax landfills are smaller, their methane gas potential is less that the Vancouver and Waterloo landfills. In 2025, the Cowansville landfill could produce between 1.47 kt and 5.53 kt of methane (3.07×10^4 kWh/day and 1.15×10^5 kWh/day, respectively) under 80% reduction and no reduction scenarios, potentially heating between 1,535 and 5,750 homes per day. The Halifax landfills, produces more gas, potentially yielding between 2.66 kt and 10.38 kt in 2005 under 80% reduction and no reduction waste scenarios. This produces between 5.55×10^4 kWh/day and 2.16×10^5 kWh/day, potentially heating 2,775 to 10,800 homes per day (Figure 5.5).

Figure 5.5. Potential Energy Output Highs and Lows from the Vancouver, Waterloo, Cowansville, and Halifax Landfills in 2025.



The beneficial value of installing a methane recovery system into a landfill is potentially quite large, regardless of the chosen waste diversion scenario. It is clear that composting and recycling programs can successfully coexist with methane recovery systems as the profitability of the recovery system does not have to suffer due to external diversion programs. However, the flexibility for the two programs to coexist is much greater when the landfill is larger, as it produces gas on a much greater scale.

5.5 Summary

Modelling methane production should be improved as current models' error provides inaccurate information to base decisions on. The "Sawyer Model" yields the least error compared to the measured methane generation (after subtracting 25% of modeled production to account for lack of efficiency of collection) when compared with the German EPER, TNO, LandGEM, Belgium, and Scholl Canyon models. Additionally, the model inputs (decay rate, degradable organic carbon and methane generation potential) were evaluated regarding their appropriate methodology and value for each landfill. The decay rates were trended successfully with precipitation, yielding results that reflected Canadian landfill conditions, while the methane generation potentials required an increase of 10% relative to their initial values. Trends were examined between measured data and other landfill variables including the amount of waste-in-place and operating status. Finally, the Vancouver, Cowansville, Waterloo, and Halifax landfills' future methane production was examined under different waste diversion scenarios, revealing that recycling/composting and energy use options can coexist.

CHAPTER SIX: CONCLUSION

With a global warming potential 23 times that of carbon dioxide (100 year timeframe) (Spokas, 2006), methane is a powerful greenhouse gas. In Canada, landfilling is one of the greatest anthropogenic contributors to atmospheric methane emissions giving importance to mitigating and controlling its release. However, when the methane emission or (prior to its atmospheric release) production quantity is unknown, it is difficult to select a proper landfill management strategy for any given site. Landfill-gas models aid in quantifying current and future methane production to allow thoughtful, justifiable decision making regarding waste diversion initiatives and landfill management practices.

This thesis was successful in improving current and future Canadian landfill methane production models, thereby advancing the knowledge used to select waste management and reduction strategies. The study was able to: 1) choose a landfill gas model that best predicts methane production 2) advance the science of provincial and site-specific model inputs; and 3) predict future methane production based on current and prospective waste diversion practices.

Several recommendations, based on the above objectives, for modeling landfill methane production include:

1. Use the "Sawyer Model", a modified Scholl Canyon Model, to calculate methane production from Canadian landfills.
2. Use a linear relationship between annual precipitation (x) and landfill decay (y) to calculate site-specific decay rate model inputs: $y = 3.2x10^{-5}(x) + 0.01$

3. Increase methane generation potential inputs by 10% of their calculated value to achieve optimal modeling results.
4. Caution should be exercised when using the model for small landfills with less than 5 Mt of waste-in-place as the model tends to over-predict such cases.
5. Recovery projects and recycling/composting programs can successfully coexist with one another to reduce landfill-gas.

The first recommendation arose from examining five pre-existing landfill-gas production models. Although the Scholl Canyon and LandGEM models satisfactorily mimicked landfill conditions their respective percent errors with measured data were large. Thus, an improved "Sawyer Model" was developed, combining the best aspects of the two models to lower the error and increase the similarity between the measured and modeled data sets. The "Sawyer Model" minimized the percent error, maintained a strong correlation, and produced statistically similar results between the measured and modeled data. It is recommended that landfill operators and policy makers utilize this new and improved model when calculating methane production from Canadian landfills.

The second recommendation pertains to the decay rate (k) and degradable organic carbon/methane generation potential (DOC/Lo) inputs used in the "Sawyer Model". Decay rates were successfully trended with annual precipitation, yielding an easy to use, comprehensible, linear formula that can calculate any landfill's decay rate. Using this linear formula increases the input's reliability as compared to using a default value, which was generally larger (indicating a slower decay) than what is appropriate for Canadian landfill conditions. The DOC/Lo input for each landfill was calculated using the IPCC's (1996) recommended formula. This formula produced values that were 10%

lower than necessary to reflect landfill conditions adequately; however, had site-specific waste composition data been available for all landfills, this may not have been the case. When possible, it is always best to use site-specific values as opposed to provincial or national values when modeling.

The third recommendation brings attention to evaluating other potential variables that could influence gas production but are not presently considered in the model. Current waste-in-place quantity proved to have a strong correlation with the measured data. In particular, small landfills (<5 Mt waste-in-place) contributed to a wide range of the observed model error. It is recommended that caution be taken when modeling new landfills with small amounts of waste-in-place, as the modeled values tended to overestimate methane production. A second potential factor examined was operating versus closed landfills, as a statistically significant difference existed between those two types of landfills. However, due to a lack of closed landfill data, no conclusive recommendation can be given at this time.

Finally, methane production was modeled to the year 2025 for four landfills, two small and two large. Through five different waste diversion strategies, the landfills demonstrated varying amounts of methane gas that could be produced in the future. The outputs showed that methane recovery units could coexist with recycling/composting initiatives in an effective manner due to the substantial amounts of produced gas at almost every level of waste diversion. It is recommended that these two waste management strategies be used in tandem to achieve maximal methane reduction from landfills.

The five recommended changes are intended to improve methane production modeling for Canadian landfills. The above recommendations are advantageous as they can be implemented by any user in a relatively easy manner and do not require excessive amounts of additional information to obtain a good model result. Past landfill modeling approaches used data that did not reflect Canadian conditions, consequently not providing a substantial basis for waste policy. Implementing these model recommendations yield results that are reliable and consistent for calculating Canadian landfill production, allowing sound waste management decision-making.

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APPENDIX A: Landfill Survey

SECTION: I

Contact Information

Name of present owner of Landfill:

Name of Landfill Operator (if different from owner):

Name of landfill:

Landfill Site Address:

Contact name:

Phone number:

Fax Number:

E-mail address:

Postal Address of contact person (if different from site address):

Web Site:

Names of communities served:

Approximate diameter of the landfill catchment area (service area): km.

Approximate population of the landfill service area:

(i) In first year of operation:

(ii) In last year or 2005 if still operating:

Landfill Information

Date when landfill began operations[1]:

Landfill closure or expected closure date[2]:

Present quantity of waste in landfill: m^3 (or) tonnes

If known, please provide the estimated density of the waste placed in the landfill – taking into account if the waste is non-compacted, compacted by a landfill compaction vehicle or compacted by a hydraulic compaction unit: (tonnes /m^3)

Landfill design waste capacity: m^3 (or)
tonnes
Average Depth of Waste (m):

Design Landfill Area (area designated for waste placement only) (hectares)[3]:
Does the Landfill facility have a scale? ☐ ☐ Yes ☐ ☐ No

If no, please describe the method by which the quantity of waste placed in the landfill is estimated:

Waste acceptance rate in 2005 (tonnes):

Disposal fees or Cost per tonne of waste disposed ($):

Landfill tax, if any ($):

---

[1] This date refers to when the landfill began operations not the date of excavation of specific cells.
[2] If no other date available, can use date provided in Certificate of Approval, Ministerial Directive, or other provincial or municipal operating permit
[3] Strictly waste placement area – excluding berms, buffer areas, access roads, run-off or leachate collection ponds, etc.

How many refrigerators, freezers, or other halocarbon (e.g., CFCs) containing appliances (i.e. air conditioners, dehumidifiers, water coolers, heat pumps etc) are received at your landfill/transfer station on weekly basis for this region?

What percentage of these refrigerators, freezers, or other halocarbon containing appliances are improperly decommissioned (i.e. the halocarbon refrigerant has been vented into the atmosphere) when they arrive at your landfill or transfer station?

Does your waste disposal ground or transfer station charge a disposal fee for refrigerators, freezers, or other halocarbon containing appliances at the point of disposal? And if so, would this fee cover the cost for the proper removal of the halocarbon refrigerant from the unit?

Estimate the total waste for each year accepted annually from 1941 or initial year of operation, whichever is most recent, to 2005: ☐ Measured ☐ Estimated

(Please indicate the units of measurement by checking one of the following boxes):

☐ Tons ☐ Tonnes ☐ Cubic Yards ☐ Cubic Meters

2005		2004		2003	
2002		2001		2000	
1999		1998		1997	
1996		1995		1994	
1993		1992		1991	

1990		1989		1988	
1987		1986		1985	
1984		1983		1982	
1981		1980		1979	
1978		1977		1976	
1975		1974		1973	
1972		1971		1970	
1969		1968		1967	
1966		1965		1964	
1963		1962		1961	
1960		1959		1958	
1957		1956		1955	
1954		1953		1952	
1951		1950		1949	
1948		1947		1946	
1945		1944		1943	
1942		1941		1940	

Type and Proportion of waste accepted currently:

Residential		%	Institutional		%
Industrial		%	Hazardous		%
Commercial		% ☐	Wood		%
Construction & Demolition		% ☐			

☐

Other (specify):

If a waste composition audit has been performed, please provide the waste composition breakdown as follows:

i. Year of the composition audit:

ii. Percent of waste that is paper and textiles:

iii. Percent of waste that is garden waste, park waste or other non-food organic putrescibles:

iv. Percent of waste that is food waste:

v. Percent of waste that is wood or straw:

vi. Percentage of recyclables (e.g. aluminium cans):

vii. Other (Percent of Non- biodegradable waste):

Estimates of surface methane emissions released to the atmosphere (if available)[4]:

t CH_4/year

Is there monitoring of greenhouse gas emissions (check appropriate box or boxes)?

☐☐ CH_4
☐
☐ CO_2
☐
☐ N_2O
☐
☐ Other
☐
☐ None

[4] This is an estimate of methane emissions not captured by landfill gas control systems. If no landfill gas control systems are in place then this is simply an estimate of the total methane emissions.

If yes, please provide the emission rates of the corresponding greenhouse gases and the frequency of monitoring:

Are greenhouse gas emissions currently calculated? If yes, how are they calculated (i.e. via emission factors and waste input data?)

What emissions factors are used in calculating greenhouse gas emissions?

Please provide the following parameters:

i. Methane generation rate constant (k, yr^{-1}):

ii. Methane generation potential (L_o, kg CH_4/ t refuse):

Current waste management practices (Please check appropriate practices and provide a brief description):

☐ ☐ Landfill cover (daily, intermediate and/or final):

☐ ☐ Landfill capping:

☐ ☐ Leachate collection:

☐ ☐ Leachate recirculation:

☐ Compaction:

☐ ☐ Bioreactor:

☐ ☐ Other (please describe):

Current waste diversion activities and rates for each (please check and complete where applicable):

☐ Composting Rate: ________ (tonnes / year)

☐ Recycling Rate: ________ (tonnes / year)

☐ Household Hazardous Waste Collection Rate: ________ (tonnes / year)

☐ Other (please describe):

Are there any waste diversion activities being considered for implementation within the next five years (e.g. composting, anaerobic digestion of organics, household hazardous waste collection and recycling programs)?

List the barriers that prevent more waste diversion activities:

List the barriers that prevent methane recovery activities:

Site characteristics (please check the applicable boxes for the description that best describes the landfill):

☐ ☐ Managed Landfill Site (i.e. controlled placement of waste with some degree of control of scavenging and a degree of control of fires and will include some of the following: cover material, mechanical compacting or levelling of waste)

☐ ☐ Unmanaged Landfill Site (≥ 5 m waste)

☐ ☐ Unmanaged Landfill Site (< 5 m waste)

☐ ☐ Landfill Final Cover - please provide a type description of the layers (eg. vegetative layer, geomembranes, geonet, drainage layers, bentonite, and geosynthetic clay) and thickness of each used from top to waste level:

Bottom Liner - please provide a description of the layers (geomembranes, geonet, drainage layers, bentonite, geosynthetic clay, leachate collection layers etc.) and thickness of each used in sequence from waste level to natural soil):

SECTION: II

LANDFILL GAS COLLECTION FOR 2005

Where landfill gas (LFG) has been or is being captured the following additional information is required:

Name of present operator:

Phone number:

Fax Number:

E-mail address:

Web Site:

Gas collection system start up date:

Specific treatment for recovered gas, if any (i.e. H_2S removal, moisture removal, CO_2 separation, conditioning & liquefaction with start-up date):

LFG composition: (% CH_4)

LFG capture rate in 2005: cfm (or) m^3/yr

Methane captured in 2005: m^3/year and tonnes /yr

In order to convert the captured methane from volume units to mass units we require the pressure and temperature for which the flowmeter is calibrated (eg. A landfill gas flowmeter may be calibrated to provide a readout based on a standard pressure and temperature of 1 atmosphere and 0 °C):

Pressure: (Atm)

Temperature: (°C)

Quantity of LFG vented, flared and/or utilized for energy recovery or other purposes in 2005 (Please check the appropriate box):

Vented ☐ [ ] (m^3/yr) [ ] (t/yr); ☐ Measured ☐ Estimated

Flared ☐ [ ] (m^3/yr) [ ] (t/yr); ☐ Measured ☐ Estimated

Total Utilized ☐ [ ] (m^3/yr) [ ] (t/yr); ☐ Measured ☐ Estimated

a) For electricity generation: ☐ [ ] (m^3/yr) [ ] (t/yr); ☐ Measured ☐ Estimated

b) For space heating: [ ] (m^3/yr) [ ] (t/yr); ☐ Measured ☐ Estimated

c) Other (specify): [ ] (m^3/yr) [ ] (t/yr); ☐ Measured ☐ Estimated

Average higher heating value (if available): [ ] (MJ/m^3)

Specification of flare: please check box: ☐ open ☐ enclosed

Flare Efficiency (if available): [ ]

Start-up date of flare: [ ]

Start-up date of LFG recovery unit: [ ]

Number of vertical wells in 2005: [ ]

Number of horizontal wells in 2005: [ ]

If LFG was recovered in 2005 for energy purposes, please fill out the following table:

Type of Recovery Unit (i.e. gas turbine, steam turbine, electrical production, heat production etc.)	Manufacturer	Rating (MW or BTU)		Output (MW or BTU)		Efficiency (%)	Quantity of LFG utilized	
		MW	BTU	MW	BTU		m^3/y	t/yr

Buyer of electricity:

Buyer of thermal energy:

Please describe the gas measurement/estimation methodology used by landfill operator throughout the operational life of the gas collection system (i.e. manual monitoring, automated monitoring, other):

Do you have any reports that you could e-mail or send us related to landfill gas generation, combustion, and/or utilization at your facility?

Would you be willing to help us again by participating in a future landfill survey?

Do you have any further comments?

Thank you for your assistance.
This study has been approved by the Joint-Faculty Research Ethics Board of the University of Manitoba.

APPENDIX B: Canadian Landfill Information

Table B.1. Modeled Landfills

	2005 Measured CH4 (kt)	ppt (mm)	Temperature (0C)	Density (tonne/m^3)	2005 Size (Mt)	Depth (m)	Operating Years	Horizontal Well	Vertical Well
Nova Scotia									
Otter Lake	5.5903	1452.2	6.3	0.780	0.9257	20.0	6	0	75
Quebec									
Montreal	28.6980	1064.6	5.0	1.100	38.0000	50.0	37	2	361
Cowansville	1.0467	1266.7	5.3	0.700	0.5480	20.0	5	0	17
Kirkland	3.0144	1064.6	5.0	NA	3.0000	66.0	25	0	33
Lachute	15.1919	1132.7	5.4	0.900	14.4000	52.0	29	22	13
Sherbrooke	2.3827	1144.1	4.1	0.600	3.0000	NA	51	3	72
Ste. Cecile De Milton	0.2434	1232.6	5.9	0.800	1.5223	28.0	51	NA	NA
St. Nicephore	22.7866	1125.0	5.9	1.100	11.5386	23.0	21	26	54
St. Sophie	23.5360	1064.6	5.0	1.250	14.2500	26.0	41	83	72
Lachenaie	36.2102	1064.6	5.0	0.850	18.5000	9.0	37	0	250
St. Thomas	15.3126	1033.3	5.6	1.000	9.0000	15.0	27	0	220
St. Lambert-De-Lauzon	0.4913	1126.3	4.3	0.950	1.3000	0.5	31	0	9
Ontario									
Ottawa	6.6841	943.5	6.0	1.380	10.9351	26.0	45	6	52
Toronto	49.3075	792.7	7.5	0.670	28.0000	NA	22	50	50
Waterloo	8.9359	907.9	6.7	0.593	2.6690	40.0	33	6	103
Cambridge	3.9649	907.9	6.7	0.593	2.6690	40.0	32	5	62
Napanee	2.5065	960.1	7.6	1.304	3.6602	23.0	51	0	44
Scarborough	4.3295	837.9	7.4	0.900	9.6000	46.0	37	0	88
Pickering	8.2144	877.9	7.7	0.950	18.0500	NA	30	21	110
Kingston	1.7090	960.1	7.6	NA	0.0530	3.5	22	0	18
Napean	3.5446	943.5	6.0	0.750	6.3750	NA	25	0	50

Nanticoke	1.8719	1022.6	7.5	0.700	0.8021	26.4	13	0	27
Cornwall	0.7890	1002.0	7.2	NA	0.5500	11.0	20	0	30
Peterborough	1.5419	855.5	6.9	0.620	1.3976	NA	24	0	17
London	2.0488	987.1	7.5	1.000	5.8157	12.0	28	0	12
St. Catherines	0.7894	970.1	8.9	0.700	0.1624	10.0	10	35	35
Lasalle	6.0724	846.8	8.1	1.060	2.0690	25.0	12	39	0
Green Lane	3.0078	987.1	7.5	0.900	2.7970	30.0	27	0	23
Alberta									
Edmonton	10.3917	476.9	3.9	0.850	12.5000	43.0	30	0	70
Calgary	1.2659	412.6	4.1	1.200	NA	17.0	45	0	60
British Columbia									
Fort George	0.4700	600.8	4.0	0.900	2.3880	NA	29	0	12
Surrey	1.1983	1409.2	10.2	NA	2.5000	35.0	36	0	110
Coquitlam	0.1312	1924.0	8.6	0.695	2.0386	11.0	30	0	80
Nanaimo	0.9958	1162.7	9.8	0.690	1.9800	NA	59	1	30
Vancouver	19.7975	1199.0	10.1	1.000	14.0000	15.0	39	10	200
Cache Creek	2.2780	286.2	9.2	0.900	6.6200	NA	16	0	42
Kelowna	0.4557	380.5	7.7	0.700	0.9100	20.0	43	NA	NA

Table B.2. Canadian Landfills Recovering Methane but with Insufficient Modeling Information.

Nova Scotia Landfills	Quebec Landfills	Ontario Landfills	British Columbia Landfills
Upper Sackville	Gatineau	Niagara Falls	Richmond
	Magog	Peel	Langley
		Guelph	North Vancouver
		Aurora	Abbotsford
		Mississauga	Maple Ridge
			Victoria
			Burnaby

APPENDIX C: Methane Generation Potential

Table C.1. Canadian Methane Generation Potential (Lo) Values Derived from Waste Audit Data (1990-2003).

Location	Paper and Textiles (% by wet weight)	Garden and Park Waste (% by wet weight)	Food Waste (% by wet weight)	Wood and Straw Waste (% by wet weight)	Degradable Organic Carbon (% by wet weight)	Methane Generation Potential (kg /tonne)
Vancouver, British Columbia	40.6	17.5	11.7	0.3	21.2	108.8
Alberta	35.0	11.0	12.0	6.0	19.5	100.0
Regina, Saskatchewan	33.2	17.0	30.7	NA*	20.8	106.8
Winnipeg, Manitoba	31.0	6.6	26.1	2.3	18.1	92.4
Ontario	27.0	13.0	25.0	2.9	17.6	90.3
Quebec	59.0	NA*	2.7	2.9	24.9	127.8
New Brunswick	----	----	----	----	----	----
Prince Edward Island	----	----	----	----	----	----
Nova Scotia	27.7	15.4	25.3	NA*	17.5	89.8
Newfoundland	37.0	NA*	30.0	NA*	19.9	102.2
Northwest Territories and Nunavut	----	----	----	----	----	----
Yukon	----	----	----	----	----	----

*NA- Unavailable categorical information

---- Unavailable provincial data

(CG&S 2000, ; City of Vancouver 1995, ; City of Winnipeg 1998, ; Clifton Associates Ltd 2002, ; Government of Nova Scotia 2003, ; Government of Quebec 2002, ; Newfoundland and Labrador Department of Environment 2002, ; Ontario Ministry of the Environment 2004,)

APPENDIX D: Future Waste Trends

Figure D.1. Future Vancouver Waste Production under Different Waste Reduction Scenarios.

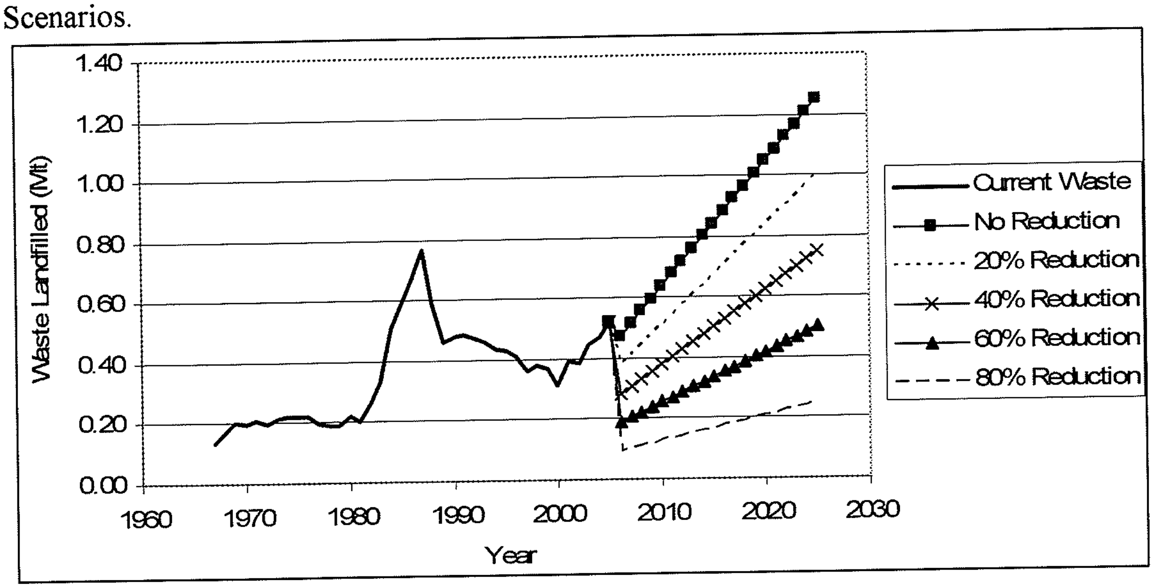


Figure D.2. Future Cowansville Waste Production under Different Waste Reduction Scenarios.

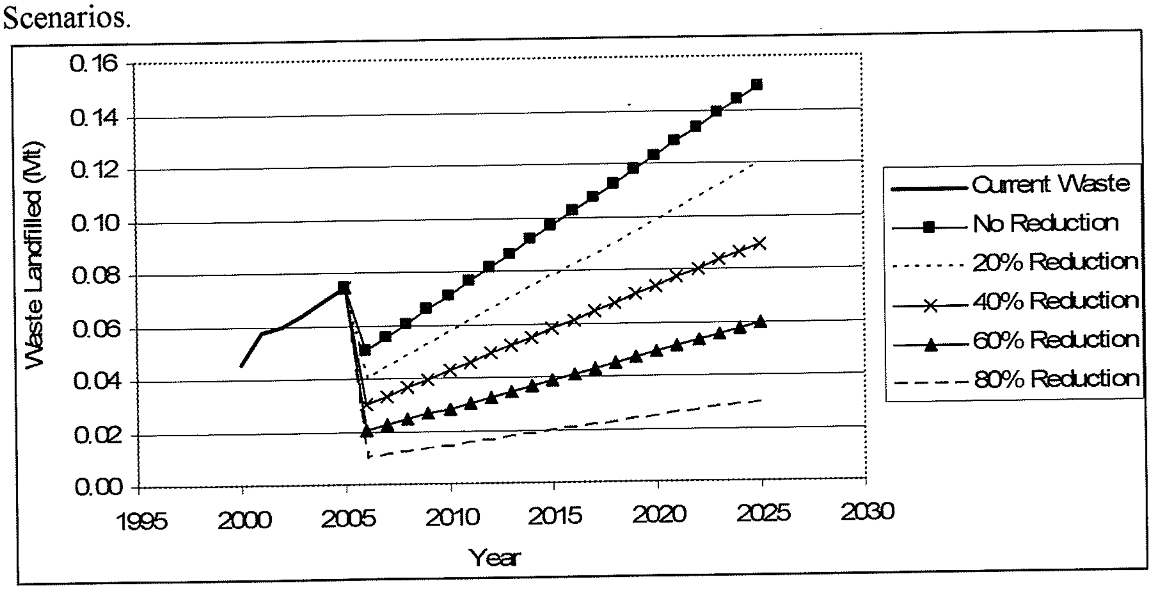


Figure D.3. Future Waterloo Waste Production under Different Waste Reduction Scenarios.

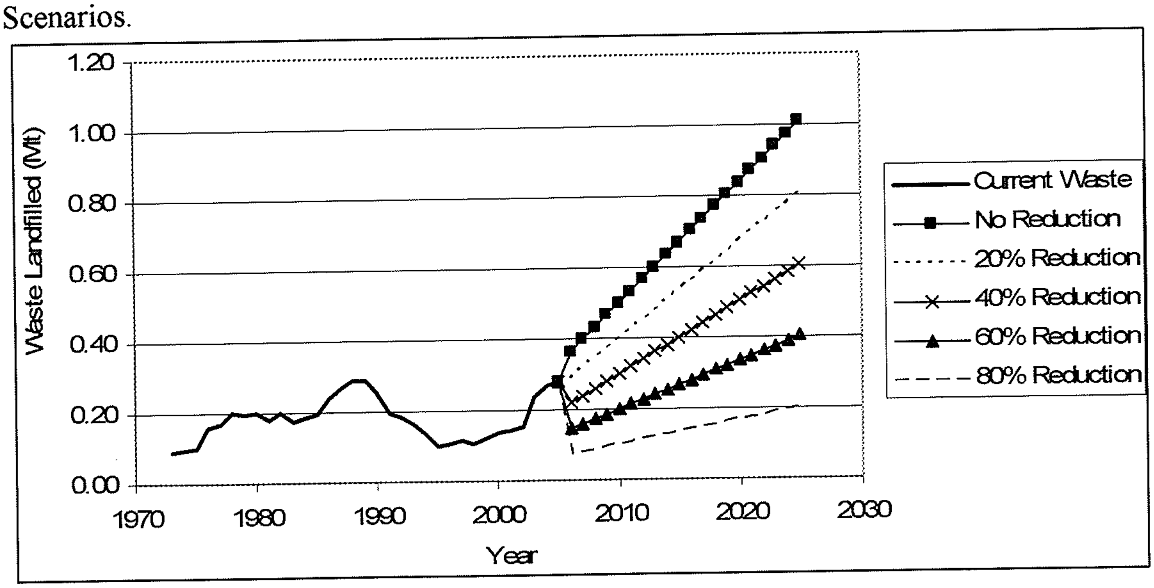
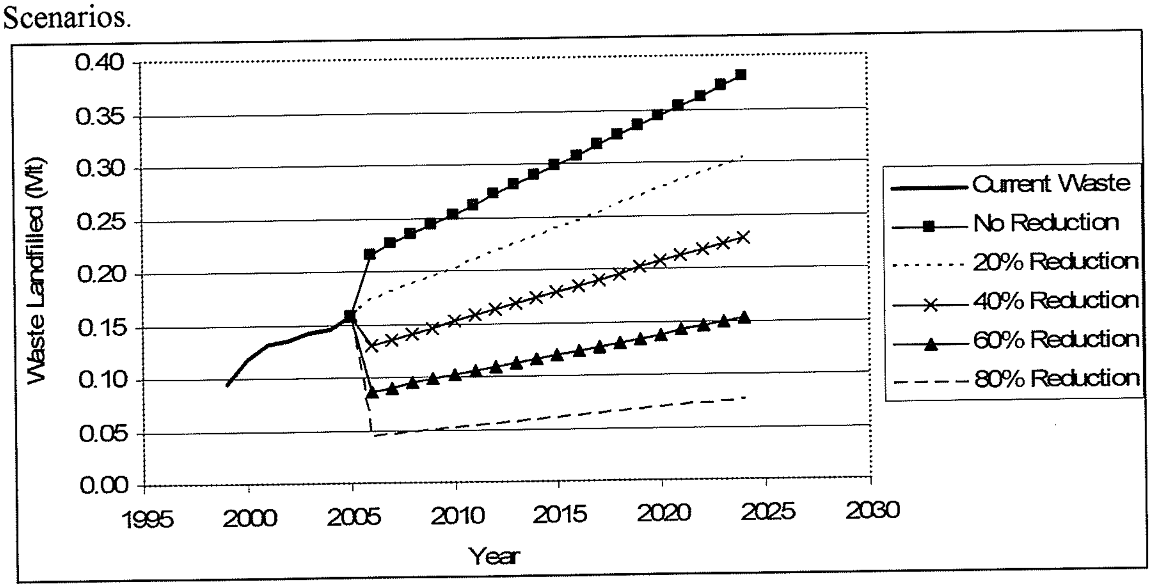


Figure D.4. Future Halifax Waste Production under Different Waste Reduction Scenarios.



APPENDIX E: Model Percent Error

In each of the figures (E.1 to E.5) the outliers with the highest percent error for each model are St. Cecile-de-Milton and Coquitlam.

Figure E.1. Percent Error for the 37 Landfills using the German EPER Model.

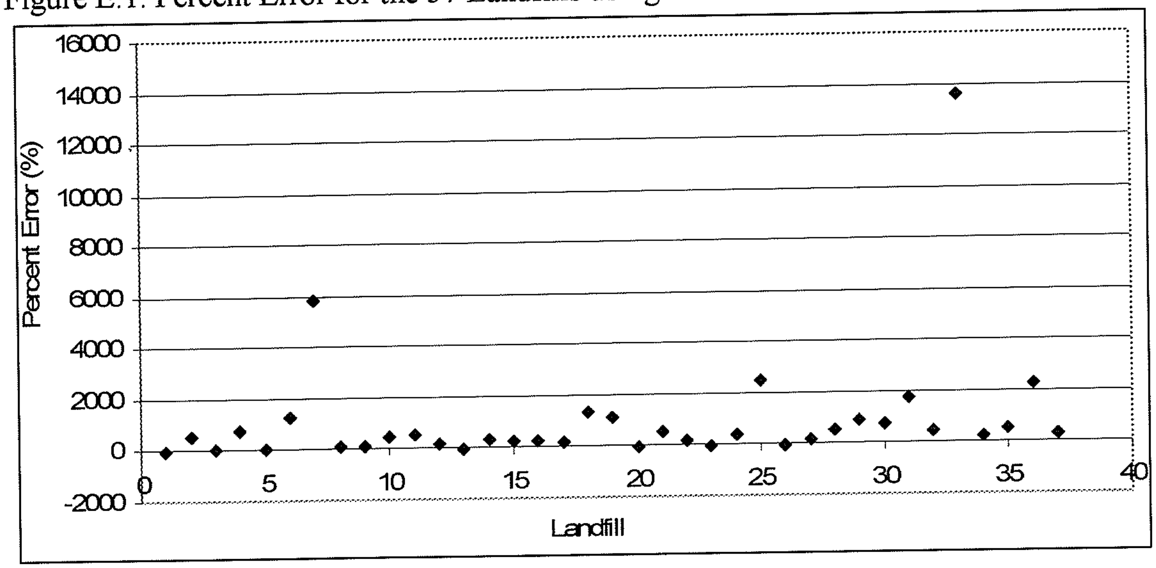


Figure E.2. Percent Error for the 37 Landfills using the TNO Model.

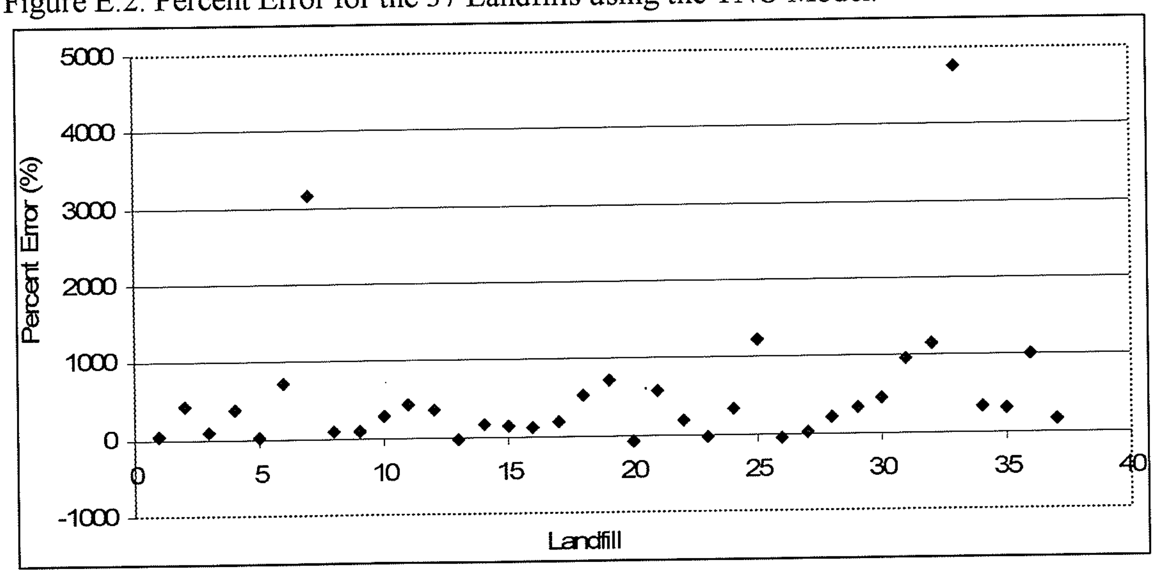


Figure E.3. Percent Error for the 37 Landfills using the Belgium Model.

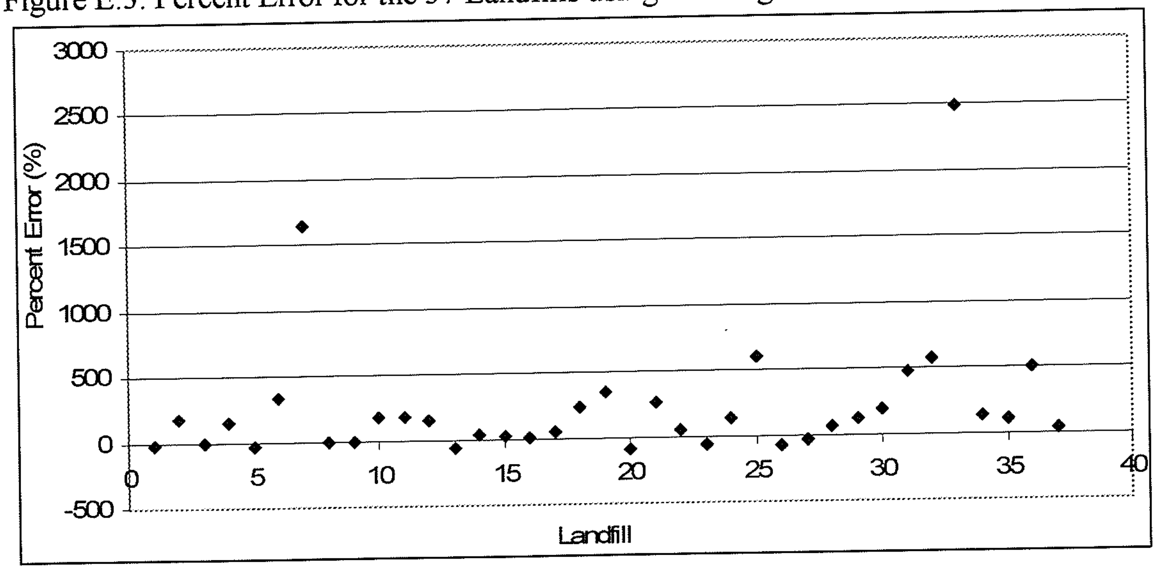


Figure E.4. Percent Error for the 37 Landfills using the Scholl Canyon Model.

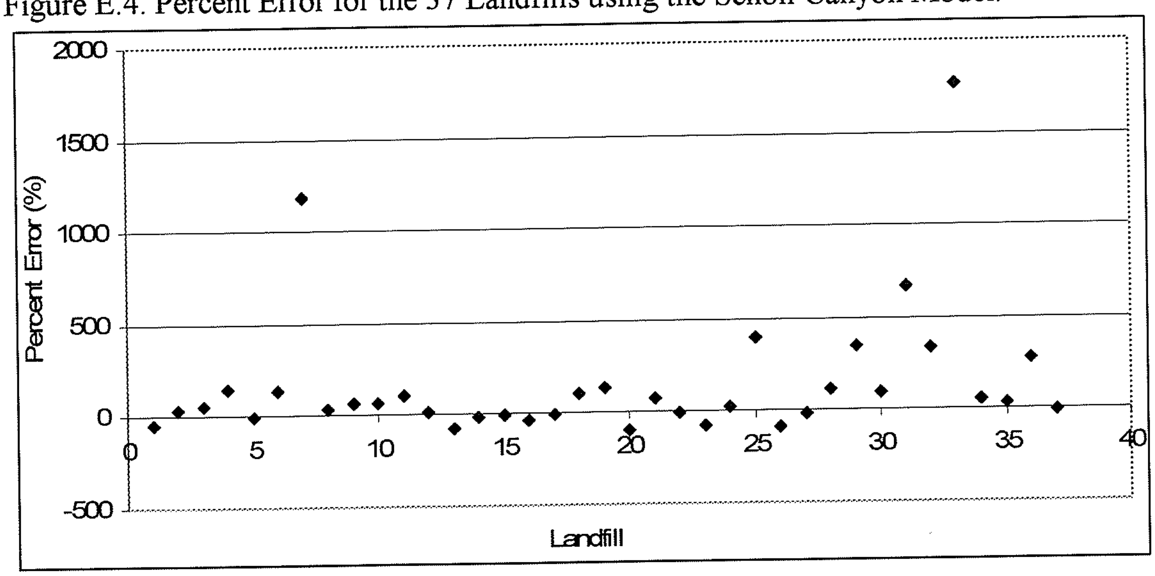


Figure E.5. Percent Error for the 37 Landfills using the LandGEM Model.