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Building a better methane generation model: Validating models with methane recovery rates from 35 Canadian landfills

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ABSTRACT

The German EPER, TNO, Belgium, LandGEM, and Scholl Canyon models for estimating methane production were compared to methane recovery rates for 35 Canadian landfills, assuming that 20% of emissions were not recovered. Two different fractions of degradable organic carbon (DOC_f) were applied in all models. Most models performed better when the DOC_f was 0.5 compared to 0.77. The Belgium, Scholl Canyon, and LandGEM version 2.01 models produced the best results of the existing models with respective mean absolute errors compared to methane generation rates (recovery rates + 20%) of 91%, 71%, and 89% at 0.50 DOC_f and 171%, 115%, and 81% at 0.77 DOC_f. The Scholl Canyon model typically overestimated methane recovery rates and the LandGEM version 2.01 model, which modifies the Scholl Canyon model by dividing waste by 10, consistently underestimated methane recovery rates; this comparison suggested that modifying the divisor for waste in the Scholl Canyon model between one and ten could improve its accuracy. At 0.50 DOC_f and 0.77 DOC_f the modified model had the lowest absolute mean error when divided by 1.5 yielding 63 ± 45% and 2.3 yielding 57 ± 47%, respectively. These modified models reduced error and variability substantially and both have a strong correlation of $r = 0.92$.

1. Introduction

Atmospheric methane concentrations have increased by 30% in the last 25 years (IPCC, 2007) and multiplied by a factor of 2–3 since the 1700s due to human activities. This methane addition has increased radiative forcing by 0.47 W m^{-2} (IPCC, 2007, 2006). Approximately 70% of methane emissions are anthropogenic (e.g., agriculture, natural gas activities, landfills, etc) and 19% (70 Tg/year) of these are attributed to landfill gas generation (Lay et al., 1996; Czepiel et al., 2003). Landfill gas is typically 40–60% methane (Senior, 1990), with methane having 25 times the global warming potential of carbon dioxide (CO_2) over a hundred year period (IPCC, 2007).

Landfills are estimated to be the largest source of anthropogenic methane. In the 1990s, landfill emissions amounted to 37% of United States' emissions, 48% of United Kingdom's, and 31% of the European Union's (Hilger and Humer, 2003). However, new regulations and programs have resulted in diverting organic waste from landfills in the EU and enhanced gas recovery in the US. Technologies and management programs to reduce methane production or recover methane from landfills are relatively inexpensive compared to similar carbon dioxide equivalent (eCO_2) reductions (Reilly et al., 1999). Since methane is produced only during the anaerobic decay of organic matter, and not during aerobic decay, the diversion of organic waste from landfills to composting reduces methane production (Thompson and Tanapat, 2005). Also, landfill gas can be collected to heat nearby industrial or agricultural operations or to produce electricity, which can be sold to the power grid. Landfill gas utilization provides a source of revenue, replaces fossil fuel use, and reduces greenhouse gas emissions (Thompson and Tanapat, 2005).

However, most provinces in Canada, as well as many other countries in the world have not begun to consider regulations that either ban organics from landfills or require landfill gas recovery. Landfill gas comprises about 3% of Canada's greenhouse gas (GHG) emissions, or 0.83 tonnes eCO_2 per capita (Environment Canada, 2006a,b). From 1990 to 2006, GHG releases from the waste sector increased by about 2.8 Mt, or 15.2% due to increasing amounts of waste being generated and sent to landfills (Environment Canada, 2008). This GHG increase would have been larger had landfill gas recovery projects and waste diversion programs (composting and recycling) not been implemented in Canada (Environment Canada, 2009). Fifty-two landfills in Canada either recovered methane to produce electric power or heat or alternatively flared the landfill gas to reduce methane to CO_2 (Thompson et al., 2006, 2007b, 2008). For example, the 25 MW electricity generating plant at the Centre de Tri et d'Élimination des Déchets powered 8200 single detached houses at an initial cost of CAD $37 million with a payback period of only 5 years (EDIE, 2008). Recently the Ontario government required new and existing landfills to install a system to capture methane if the landfill releases more than 1.5 million cubic

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metres annually in order to reduce GHG emissions provincially by over 4 million tonnes annually (EDIE, 2008). Other provinces have reduced organics going to landfills. Two small provinces, Prince Edward Island (PEI) and Nova Scotia (NS), have banned organics in all landfills to increase waste diversion of organics to composting facilities. In NS, 70% of people have curb-side collection of source separated organics (Thompson et al., 2008).

Countries in the developing world have methane rates that are generally lower than in developed countries due to lower per capita waste generation and open waste pits. As sanitation imperatives are changing waste disposal practices from open waste pits to landfills, anaerobic decay will result in greater methane production (Hilger and Humer, 2003), unless waste diversion and/or methane recovery programs and regulations are implemented.

To evaluate appropriate methane reduction strategies, landfill gas production rates must be accurately quantified. The design and operation of landfill gas extraction and utilization projects require reliable emission forecasts for project feasibility and to ensure environmental compliance (Huitric and Soni, 1997; Oonk and Boom, 1995). Municipalities and companies are reluctant to invest in methane recovery projects due to the high uncertainty in estimating gas production rates and total gas yield, which are needed to accurately determine payback periods for the capital and operational costs of any project. Some methane recovery projects have yielded only 10% of that estimated by methane generation models (Goldstein, 2007). Landfill gas models continue to receive criticism due to their poor accuracy and insufficient validation: most model results have not been evaluated against methane recovery data (Barlaz et al., 2004; Borjesson et al., 2000; Bogner and Matthews, 2003; Mosher et al., 1999). A few studies (Spokas et al., 2006; Barlaz et al., 2004; Bogner and Matthews, 2003; SCS Engineers, 1997) have compared methane recovery data to estimates of methane generation from models, but only for a few landfills. This limited approach is inadequate to validate the model for a wide, rather than site-specific, application. Despite the Intergovernmental Panel on Climate Change's (IPCC, 2006, 1996) attempt to establish a suitable universal method, countries still use different methods for collecting and reporting their methane production due to lack of validation of models and no model being accurate over a range of conditions. A validated model is needed to facilitate a standardized methodology. This paper profiles the different models and the current understanding of their inputs before evaluating the accuracy of six models' estimates against methane recovery rates.

2. Methane generation models

Landfill gas models describe in simple terms the complex changes occurring during landfill decomposition to estimate methane generation over time. See Table 1 for formulas for all the models evaluated including one zero order model, four existing first order models and one modified first order model. The zero order model, EPER model, generates the rate of methane production independent of the amount of substrate remaining or of the amount of biogases already produced (Scharff, 2005; Scharff and Jacobs, 2006). The German EPER model roughly approximates methane generation from operational landfills but not closed landfills. Although complete anaerobic decay of organic waste in landfills requires many years EPER only considers the last year's waste input to estimate methane generation (Scharff, 2005; Scharff and Jacobs, 2006; SCS Engineers, 1997).

Table 1
The formulas for five existing and one modified landfill gas generation models.

	Model formula	Symbol index
German EPER model	$Q = (M)(\mathrm{DOC})(\mathrm{DOC}_f)(F)(D)$	Q = methane production (kt/yr) M = waste generation (Mt/yr) DOC = degradable organic carbon (kg/tonne) DOC_f = fraction assimilated DOC F = fraction of methane in landfill gas D = collection efficiency factor
TNO model	$Q = (\mathrm{DOC}_f)(1.87)(M)(\mathrm{DOC})(k)e^{-(kt)}$	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	$Q = (M)(\mathrm{DOC})(k)(\mathrm{DOC}_f)\ \exp^{-(kt)}$	Q = methane production (kt/yr) M = waste generation (Mt/yr) DOC = degradable organic carbon (kg/tonne) k = decay rate (yr^{-1}) DOC_f = fraction Assimilated DOC t = time of waste disposal (yr)
Scholl Canyon	$Q = (M)(k)(\mathrm{Lo})\ \exp^{-(kt)}$	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 version 2.01	$Q = \left(\frac{M}{10}\right)(k)(Lo)\exp^{-(kt)}$	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)
Modified model	$Q = \left(\frac{M}{10}\right)(k)(Lo)\exp^{-(kt)}$	Q = Methane production (kt/yr) M = Waste generation (Mt/yr) k = Decay rate (yr^{-1}) L_0 = Methane generation potential (kg/tonne) x = divisor of waste between 1 and 10 t = time of waste disposal (yr)

Methane generation at landfills is generally modeled using a first order kinetic equation (Blaha et al., 1991; Bogner and Matthews, 2003; Thompson et al., 2006, 2008) based on waste amounts over time, waste composition, and other factors. In first order models, methane production is assumed to be in a steady, linear decrease over time proportional to the degradation of organic matter in any given year and the remaining fraction of organic matter from previous years (Borjesson et al., 2000). Each year's waste follows a decreasing exponential trend in gas production until it is completely degraded (Huitric and Soni, 1997). Thus, according to these model assumptions, a gradual decline in landfill gas would occur post-closure. First order models, including TNO, Belgium, and LandGEM, are currently used by Denmark, the Netherlands, and the United States, respectively (Thompson et al., 2006, 2008). Environment Canada (2006a,b) and the IPCC (1996) advocate using the Scholl Canyon model for calculating methane production. Although these four first order models have the same basic components with slight differences, their outputs vary considerably.

In reviewing the model formulas in Table 1 some models have only slight differences. For example, the LandGEM model version (v.) 2.01 uses the same calculations as the Scholl Canyon model but divides the waste by ten (Alexander et al., 2005). The equation used in LandGEM v. 2.01 integrates methane generation over each year, similar to Scholl Canyon. However, the revised equation in LandGEM v. 3.02 integrates methane generation over a 0.1 year time increment, producing slightly lower emission estimates than previous versions for typical *k* values (Alexander et al., 2005). A modified model is created that divides the waste in the Scholl Canyon model by numbers between one and ten to explore if it is possible to build a better methane generation model.

To determine the accuracy of the models, estimates by the models must be compared to the methane recovery rate at specific landfills, while taking into consideration a factor to account for storage and losses. Total methane generated in landfills is a sum of many activities (Eq. (1)), including the methane recovered, emitted into the atmosphere, oxidized by methanotrophs, that has laterally migrated, and that has been internally stored in the landfill volume (Bogner and Spokas, 1993).

$$\begin{aligned}\mathrm{CH_4\ generation\ rate} &= \mathrm{CH_4\ emitted} + \mathrm{CH_4\ oxidized}\\ &\quad + \mathrm{CH_4\ recovered(flared)} + \mathrm{CH_4\ migrated}\\ &\quad + \mathrm{CH_4\ storage[all\ units = mass\text{-}time^{-1}]}\end{aligned} \tag{1}$$

2.1. Considering gas recovery efficiencies in the models

Modeled results need to be compared to methane recovery rates, taking into consideration gas recovery efficiency, to ensure accuracy (Spokas et al., 2006). Gas recovery efficiencies are typically estimated to be in the range of 60–90%, based on measured gas extraction rates divided by modeled gas generation rates (Alexander et al., 2005; Visse, 2004). As a result of the mass balance work done by Spokas et al. (2006), the French environment agency adopted the default percent recovery values of 35% for an operating cell with an active landfill gas (LFG) recovery system, 65% for a temporary covered cell with an active LFG recovery system, 85% for a cell with clay final cover and active LFG recovery, and 90% for a cell with a geomembrane final cover and active LFG recovery. The US EPA (2004) applies a default gas recovery rate of 75%.

2.2. Model Inputs

All landfill gas models calculate methane yield based on three key inputs. The three necessary inputs are: (1) waste amounts deposited in landfill over all the years that the landfill has been opened (except EPER model inputs waste only for the one year of interest), (2) degradable organic content (DOC), and (3) decay rate (k). In addition to those inputs, LandGEM and Scholl Canyon have a methane generation potential (Lo) that is the percentage of methane in the landfill gas multiplied by DOC and other factors.

2.2.1. Degradable organic content (DOC)

The DOC of the waste is required in all landfill gas generation models as it represents the waste portion available for microbial degradation into landfill gas (Kim, 2003). The organic fraction of each type of organic waste is considered as all have different decay rates. Celluloses and hemicelluloses, found in food and yard waste, are readily biodegradable under anaerobic conditions, while lignin, found in wood and newspaper, is not (Kim, 2003). Few landfill waste composition studies have been undertaken to quantify DOC accurately (IPCC, 2006). In developed countries, the largest portion of municipal solid waste is biodegradable accounting for 60–75% wet weight (w/w) of the total landfilled with a DOC of approximately 15–25% kg/tonne of waste (Bingemer and Crutzen, 1987). This DOC, all reported in w/w, contains cellulose (40–50%), lignin (10–15%), hemicellulose (12%), and protein (4%), according to Preen and Murphy (2001). Thompson et al. (2007a) study of 17 Canadian landfills' waste audits differ slightly with 62% of MSW being biodegradable but with a higher proportion of lignin waste (29%) and a lesser proportion of hemicellulose and cellulose (12% garden and non-food waste and 21% food waste). As waste composition in landfills fluctuate widely based on recycling and organic waste diversion programs (e.g., availability of organic curb-side collection, pay per bag), the regulatory environment (e.g., ban on organics in landfills), and social/economic factors, it is ideal to apply site-specific DOC based on the landfill's waste composition study. If a site-specific DOC is not available, a waste composition from the same regional or provincial jurisdiction is preferred as they typically have more similar social/economic and, regulatory factors, although programming usually differs by municipality. In our model estimates, a provincial DOC and both IPCC (1996, 2006) default values for the fraction of degradable organic carbon assimilated (DOC_f). IPCC (1996) guidelines recommended 0.77 DOC_f with an error value of ±10% but the IPCC (2006) amended this value to a default of 0.50, assigning an error of ±20%.

The methane generation potential (Lo) represents the amount of methane produced per tonne of waste landfilled. The Lo, shown in Eq. (3), multiplies DOC and DOC_f, to the fraction of methane in the landfill gas and other factors. The IPCC (1996) recommended a methane generation potential (Lo) between 100–200 kg of methane/tonne of waste. As recycling and composting programs in the 1990s reduced organics going to landfills, Environment Canada (2006a,b) applied a higher Lo before 1990 at 165 kg of methane/tonne of waste and after 1990 at 117 kg/tonne. However, provincial waste diversion programs differ, thereby making nation-wide constants unsuitable.

2.2.2. Decay rates

The decay rate (k) is the biodegradation half-life in years^{-1} for organic material in a landfill. The IPCC (2006) recognizes the high uncertainty and error associated with k. The decay rates range from one to 50 years and even longer in landfills located in dry, cold climates. Decay rates have been determined by a number of methods: laboratory simulations (Harries et al., 2001), samples excavated from landfills (Gardner et al., 2003; Rodriguez et al, 2001; Baldwin et al., 1998), and test cells designed to simulate real world conditions (Mehta et al., 2002). Although many different environment conditions act upon decay, typically only precipitation is considered to have an effect on k (US EPA, 2004; Maurice and Lagerkvist, 1997; Lay et al., 1996). Moisture is essential for bacterial growth, metabolism, and nutrient transport. The US EPA (2004) offers a binary choice for default decay rates of either 0.02 year^{-1} below 25 inches (635 mm) of precipitation or 0.04 year^{-1} above 25 inches. Thompson et al. (2006) and Environment Canada (2006a,b) define a linear relationship between decay and annual precipitation to scale k with location-specific moisture levels based on the US EPA (2004) defaults. A linear relationship between moisture and decay rate has been observed in other field and laboratory studies (McDougall and Pyrah, 1999; Chian and DeWalle, 1979).

3. Method

The methane generation estimates from five existing models and a modified Scholl Canyon model were compared to methane recovery rates for 35 landfills, adding a 20% loss factor, to determine the accuracy of the models. To undertake this analysis the following steps were undertaken:

1. Conducted a national survey that captured 52 of the 52 Canadian landfills recovering methane (100% return rate), obtaining necessary model inputs, and methane recovery rates for landfills in 2005 (Thompson et al., 2007b). All 52 landfills had recovery data; however, due to insufficient waste data and outliers, only 35 landfills were considered to calibrate the landfill gas models. The 35 landfills operated in five provinces, namely, Alberta, British Columbia, Ontario, Nova Scotia, and Quebec.
2. Estimated methane generation for 35 landfills for six models using the equations listed in Table 1. The German EPER, Belgium, TNO, Scholl Canyon, LandGEM, and a modified Scholl Canyon model (dividing the waste by numbers between one and ten) were all run in Excel 2002 with the following three factors:
    (i) Waste amounts. The site-specific yearly waste quantity from the opening of the landfill to year 2005 were applied to all models except the EPER model, which only considered the 2005 waste amount (Sawyer and Thompson, 2007).
    (ii) Degradable organic carbon (DOC) and Methane Generation Potential. Waste composition data shown in Table 2 were plugged into Eq. (2).

$$\begin{aligned}\mathrm{DOC} = {} & (0.4 \times A) + (0.17 \times B) + (0.15 \times C) \\ & + (0.30 \times D)[\text{all units wet weight}(w/w)\text{of} \\ & \text{kg carbon/kg waste}]\end{aligned} \tag{2}$$

where DOC = degradable organic carbon A = fraction of municipal solid waste (MSW) that is paper and textiles waste 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 waste. The current audit composition was modified for the pre-recycling and composting period, as presented in Table 2 by subtracting the organic waste diverted from the DOC available in Statistics Canada (2002, 2004).

In the Scholl Canyon, LandGEM, and modified models, the DOC is entered into Eq. (3) to yield the methane generation potential (Lo):

$$\mathrm{Lo} = F \times \mathrm{DOC} \times \mathrm{DOC}_f \times 16/12 \times \mathrm{MCF} \tag{3}$$

where Lo = Methane generation potential (kg/tonne) MCF = Methane correction factor (fraction; default = 1.0) DOC = Degradable organic carbon (kg/tonne) DOC_f = Fraction of assimilated DOC (IPCC, 1996 default = 0.77; IPCC, 2006 default = 0.50); F = Fraction of methane in landfill gas (0.5 default) 16/12 = Stoichiometric factor.

Table 3

Decay rates derived from precipitation for each province.

Province	Mean precipitation (mm)*	Decay rate (year $^{-1}$)	Half-life (year)
British Columbia	1281	0.048	20.8
Alberta	445	0.023	43.5
Ontario	902	0.037	27.0
Quebec	1070	0.042	23.9
Nova Scotia	1452	0.056	17.9

* Environment Canada (2006b).

    (iii) Decay rates are determined based on precipitation rates in Table 3 by the following equation based on US EPA (2004) defaults of k

$$k = 3.2 \times 10^{-5}(x) + 0.01 \tag{4}$$

where: k = decay rate (year^{-1}); and x = annual average precipitation from 1971 to 2006 for province where the landfill is (Environment Canada Weather Office, 2006).

3. Added 20% to the methane recovery rates to get “methane generation rates” as the midpoint of 80% between the US EPA (2004) default of 75% and the Spokas et al. (2006) default of 85% for clay final covers.
4. Compared the methane generation rate to the estimates for the 35 landfills for each of the five established models and the modified Scholl Canyon model. The absolute mean and median percent error and Pearson correlation were calculated. The absolute percent error measures the percent difference between the observed and modeled values. The Pearson correlation (r) measures the direction and strength of the linear relationship between two quantitative variables (Sweet and Grace-Martin, 2003).

4. Results and discussion

Table 4 compares methane generation estimates of six models compared to recovery rates considering a loss factor, for 35 landfills for both a DOC_f of 0.50 and 0.77. No model perfectly matches the methane recovery data but some models fare better than others. The LandGEM model consistently underestimated methane generation, but all other models typically overestimated methane generation. Using the smaller fraction for DOC_f of 0.5, rather than 0.77, reduces the estimate for methane generation error by almost half for the EPER (from 589% to 332%) and for the TNO model (from 376% to 201%). The German EPER and TNO models consistently pro-

Table 2

Degradable organic content and methane generation potential (Lo) values derived.

Province	Ontario[a]	Nova Scotia[b]	Quebec[c]	Alberta[d]	British Columbia[d]
Paper and textiles (% w/w)	27.0	27.7	59.0	35.0	40.6
Garden and Park waste	13.0	15.4	NA	11.0	17.5
Food Waste	25.0	25.3	2.7	12.0	11.7
Wood and	2.9	NA	2.9	6.0	0.3
Straw waste (w/w)					
DOC (% w/w)	17.6	17.5	24.9	19.5	21.2
DOC post-recycling (kg/tonne)	176	175	249	195	212
DOC (pre-recycling, kg/tonne)	205	227	283	228	261
Lo (post-recycling, kg/tonne)	90	90	128	100	109
Lo (pre-recycling, kg/tone)	105	105	145	117	134

NA – Unavailable categorical information.

[a] Ontario Ministry of the Environment (2004).

[b] Government of Nova Scotia (2003).

[c] Government of Quebec (2002).

[d] Thompson et al. (2007a).

Table 4
Model results for the 35 landfills compared to methane recovery rates with loss factor.

Model type	Mean absolute error and standard error (%)	Error median	Correlation (r)	Mean relative error (%)
Prexisting models				
German EPER model				
with $DOC_f = 0.5$	332 ± 396	238	0.8589	312
with $DOC_f = 0.77$	589 ± 666	371	0.8589	578
TNO model				
with $DOC_f = 0.5$	201 ± 207	153	0.88	131
with $DOC_f = 0.77$	376 ± 356	322	0.8785	289
Belgium model				
with $DOC_f = 0.5$	91 ± 92	30	0.8674	22
with $DOC_f = 0.77$	171 ± 177	125	0.8674	111
Scholl Canyon model				
with $DOC_f = 0.5$	71 ± 86	−28	0.9210	13
with $DOC_f = 0.77$	115 ± 152	43	0.9164	91
LandGEM model				
with $DOC_f = 0.5$	89 ± 11	−93	0.9210	−89
with $DOC_f = 0.77$	81 ± 17	−86	0.9164	−81
Modified Scholl Canyon model				
Dividing waste by 1.5-with $DOC_f = 0.5$	63 ± 45	−52	0.9210	−25
Dividing waste by 2.3-with $DOC_f = 0.77$	57 ± 48	−38	0.9164	−17

duced much higher estimates than the methane generation rates with very large standard errors. The German EPER model provided the largest average error of 332 ± 396% at 0.5 DOC_f and 589 ± 666% at 0.77 DOC_f, but with a strong correlation at $r = 0.86$. This poor accuracy is not surprising as the model considers only methane generation from the 2005 year's waste. However, the first order TNO Model was not much better – it produced a mean error of 201 ± 207% at 0.5 DOC_f and 376 ± 356% at 0.77 DOC_f, with a correlation of $r = 0.88$. The overestimation by the TNO model was consistent with the findings of Oonk and Boom (1995) and Scharff (2005).

Other models estimated rates closer to the actual methane generation rates. The Belgium model fared better at 0.5 DOC_f than at 0.77 DOC_f, with an average absolute error of 91 ± 92% and 171 ± 177% with a correlation of $r = 0.87$ for both. The model estimates by the LandGEM and Scholl Canyon models were closest to the actual methane generation rates than the other existing models. The Scholl Canyon model's mean absolute error was 71 ± 86% at $DOC_f = 0.50$ and 115 ± 152% at $DOC_f = 0.77$ with a very strong correlation of $r = 0.92$. At $DOC_f = 0.50$ most methane generation estimates were underestimated by Scholl Canyon, resulting in a median of −28%, but at $DOC_f = 0.77$ were overestimated with a median of 43.

The LandGEM model was the only model that consistently produced estimates lower than the recovery rate, with the absolute mean percent error of 89 ± 11% at 0.5 DOC_f and 81 ± 17% at 0.77 DOC_f. That the LandGEM's estimates are so much smaller than the generation rates (relative absolute error of −89 ± 11% at 0.5 DOC_f and −81 ± 17% at 0.77 DOC_f) results in the small standard error.

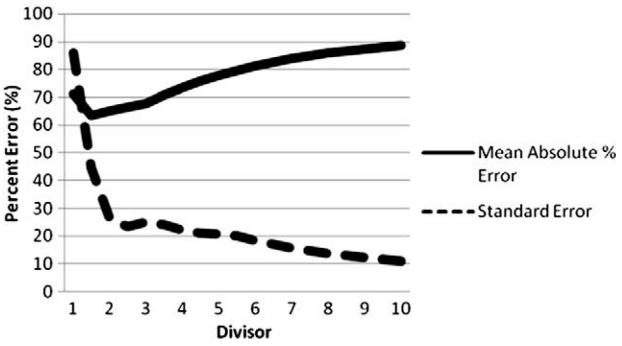

Fig. 1. Error rates when different divisors are applied to waste in a Modified Scholl Canyon Model ($DOC_f = 0.50$).

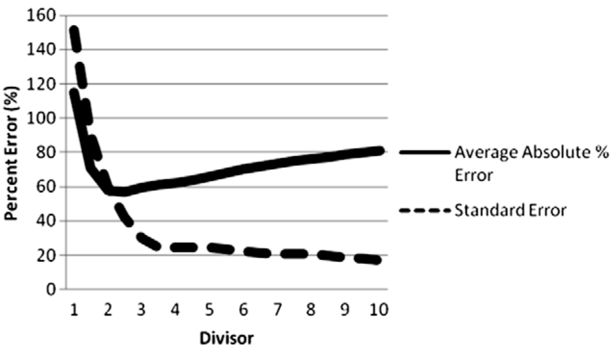

Fig. 2. Error rates when different divisors are applied to waste amounts in a Modified Scholl Canyon Model ($DOC_f = 0.77$).

As the only difference between the LandGEM (v. 2.01) model and the Scholl Canyon model is a divisor for waste of ten, the waste divisor was varied between one (Scholl Canyon) and ten (LandGEM) to create a modified model. At $DOC_f = 0.5$ the modified model's mean absolute error is lowest at 63 ± 45%, which occurs when waste is divided by 1.5. See Fig. 1 to show that a divisor of 1.5 has the lowest mean absolute error but not the smallest standard error. At $DOC_f = 0.77$ the modified model's lowest mean absolute percent error was at 57 ± 47%, having a correlation of 0.92. See Fig. 2 to show that 2.3 has the lowest mean absolute error but not the smallest standard error. At both DOC_f defaults the modified model had a strong correlation at 0.92.

5. Conclusion

This study is the first to compare modeled methane generation to methane generation recovery rates for a statistical sample of landfills. Clearly, this type of model validation is needed to develop a more accurate model so that estimated yield can effectively determine the viability of landfill projects, the sizing of equipment (e.g., generators, boilers, etc.), and the need for organic waste diversion. Existing models are all strongly correlated with the methane generation rate; however, not all the models are accurate. In particular, the German EPER and TNO models were wildly inaccurate in modeling the actual methane generation rates in Canada. The Belgium, Scholl Canyon, and LandGEM v. 2.01 models produced the best results of the existing models: their respective mean absolute percent errors with methane generation rates were out by 91%, 71%, and 89% at $DOC_f = 0.50$ and 171%, 115% and 81% at $DOC_f = 0.77$. The Scholl Canyon and Belgium median error of −27% and 30%, respectively, shows that a number of high overestimates pulled the mean of these models up and that these models may provide more accurate estimates in a normal distribution. Most models had better accuracy with 0.5 DOC_f, which is the default recommended by IPCC (2006).

The Scholl Canyon model errors were on average too high (particularly at 0.77 DOC_f) and the LandGEM estimates were consistently too low; this suggested that a Scholl Canyon model with a waste divisor between one and ten would yield more accurate results. At 0.50 DOC_f and 0.77 DOC_f the modified model had the lowest absolute mean error of 63 ± 45% when divided by 1.5 and 57 ± 47% when divided by 2.3, respectively. These modified models reduced error and variability substantially and both had a strong correlation of $r = 0.92$. This decrease in absolute error of the modified model from Scholl Canyon is 8 ± 41% for 0.5 DOC_f and 58 ± 104% for 0.77 DOC_f. This improved model may allow more municipalities to adopt methane recovery and consider the importance of implementing organic diversion by yielding credible data. These modified models are the best option available for first order models at present. As LandGEM, v. 3.01 produces lower estimates than LandGEM 2.01, LandGEM v. 3.01would not have produced more accurate results.

Ideally a model would be within 10–25% of the recovery data, with limited variability across different landfill conditions. However, considering that defaults or provincial rates were applied for landfill gas concentration, decay rates and DOC, rather than site-specific data, the results for Belgium, Scholl Canyon, LandGEM, and the modified models are fairly good. Applying provincial rates or other defaults add additional errors that site-specific inputs and measured decay rates and DOC would not.

While this analysis presumes that existing models consider all the important factors in determining methane generation, other factors could be impacting methane generation, including depth of landfills, temperature, and waste density (Thompson et al., 2007a). As well as the model itself, inputs to the model require more research to reduce error in model estimates. This paper clearly shows the difference that inputs make. Applying the IPCC change from DOC_f of 0.77 (IPCC, 1996) to 0.5 (IPCC, 2006) had a huge impact on the accuracy of estimates, decreasing error by halve for a number of models. Decay rates hold much uncertainty and need further research work. As well, most landfills have not conducted a waste composition study required to calculate site-specific DOC. Waste composition fluctuates widely within Canada, making it inaccurate to assign national DOC values. The provincial values assigned are slightly better but do not account for differences in municipal programming. In the future, this input may become better documented when municipalities examine the impact of diversion initiatives by doing waste audits.

To reduce the impact of landfills on GHG, composting and/or methane recovery is required. Few provinces or municipalities in Canada ban organic materials in landfills or provide curb-side collection of organics to divert from landfills to composting facilities. As well, recycling rates have to improve to reduce methane generation. That a higher lignin value was found for the recent Canadian waste composition audit (Thompson et al., 2006) compared to other studies suggests Canada needs to both adopt wood waste diversion programs and have targets for municipalities to reach high recycling rate targets for paper.

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