# *MODELING LANDFILL GAS GENERATION TO DETERMINE TARGETS AND STRATEGIES TO REDUCE GREENHOUSE GASES FROM LANDFILLS*

**Shirley Thompson[1], Jennifer Sawyer[2], Rathan Kumar Bonam[1], and Stephen Smith[1]**

[1] Natural Resources Institute, University of Manitoba
70 Dysart Road, Winnipeg, Manitoba, CANADA R3T 2N2
Phone: 204-474-7170; Fax: 204-261-0038, Email: s thompson@umanitoba.ca

[2] Faculty of Environment, Earth and Resources, University of Manitoba
440 Wallace Building, Winnipeg, Manitoba, CANADA R3T 2N2
Phone: 204-474-7170; Fax: 204-261-0038, Email: jenmsawyer@gmail.com

## ABSTRACT

The future impact of different waste management policies on greenhouse gas (GHG) emissions from landfills was estimated using the Scholl Canyon methane generation model. This scenario modeling provided a useful decision-making tool to determine appropriate targets for reductions in emissions and strategies to reach feasible goals. At low rates of 25% total waste diversion in Canada, the GHG emissions continue to rise due to historical organic waste emitting methane for 30 years to 50 years following landfill closure at higher rates than is reduced by organic diversion. At diversion rates of 50%, which is less than that already occurring in Prince Edward Island, GHG emissions decreased slightly. If 75% of total waste is diverted, which occurs in most European Union countries, a 30% reduction of GHG would result after 25 years. Waste diversion has a gradual impact on GHG: composting, recycling and extending producer responsibility provide the long-term solution to reduce GHG production and waste generation. However, diversion does not prevent emissions from waste already in place. End-of-pipe methane recovery technology burns methane from historical waste, decreasing GHG to create alternative energy, preferably, or by simply flaring the methane. Both methane recovery and waste diversion should be pursued to maximize GHG reduction.

**Keywords:** Scholl Canyon model, Greenhouse Gas, Methane, Waste Diversion, Composting, Landfills

## INTRODUCTION

Anthropogenic methane should be controlled to reduce global climate change (Hilger and Humer, 2003; IPCC, 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 (Mosher, Czepiel, and Harriss, 1999). Landfill gas is typically 40%-60% methane (Senior, 1990), which has 23 times the global warming potential of carbon dioxide ($CO_2$) over a hundred year period (IPCC, 2001)[1]. Approximately 70% of methane originates from anthropogenic sources and

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[1] *Although the IPCC updated its estimates of methane s GWP from 21 (IPCC, 1996) to 23 (IPCC, 2001), the Conference of the Parties decided that 21 would be used to convert GHG emissions into comparable* $eC0_2$. *To comply with this decision, 21 is used for conversions in this document.*

of that amount, as much as 19% (70 Tg/year) is attributed to landfill emissions (IPCC, 1996). Landfills are estimated to be the largest source of anthropogenic methane emissions in the United States (37%), United Kingdom (48%) and the European Union (31%) with the developing world contributing less. However, in many parts of the globe, improved sanitation will likely increase methane emission rates, as covering waste with soil to prevent odour and disease vectors will cause anaerobic decay of waste to methane (Hilger and Humer, 2003). A 10%-20% decrease of anthropogenic methane emissions would stabilize atmospheric methane concentrations to 1990 levels (Mosher, Czepiel, and Harriss, 1999) and could be accomplished by landfill gas reduction. To reduce GHG emissions, specifically from municipal solid waste landfills, waste management strategies could either: 1) reduce the organic waste entering landfills, where it decomposes anaerobically to create methane, and/or 2) collect methane from landfills for energy recovery or flaring (Thompson and Tanapat, 2005). But which of these waste management strategies is the best and what is a feasible reduction for these strategies to target?

With many unknowns regarding landfill gas production under different scenarios, modeled projections provide a useful decision-making tool to determine appropriate targets for reduction in methane at the national or provincial level or site-specific targets, as well as the best strategy to meet the identified goal (Thompson and Tanapat, 2005). In the absence of a specific target for GHG reduction for landfills in many countries including Canada, this paper considers whether Canada s Kyoto target (6% below 1990 GHG emission levels for all sources and sinks) is appropriate to apply to Canadian landfills. In this way, Scholl Canyon s utility in goal-setting and for determining effective management strategies is explored. As methane has an atmospheric lifetime of nine years, a reduction in methane emissions would cause a rapid decrease in atmospheric levels. Although landfill gas is a mixture including $CO_2$ as well as small amounts of hydrogen, oxygen, nitrogen, hydrogen sulphide, non-organic compounds and volatile organic compounds, methane is the central concern from landfills for GHG (Gardner et al., 1993; Schumacher, 1983). Carbon dioxide emissions from landfills are not included in the National Inventory Reports as they are of biogenic origin. The $CO_2$ produced from burning methane collected from a landfill for flaring or energy recovery or generated from aerobic or anaerobic decomposition of biomass, when composted, is deemed a sustainable cycle, unlike methane. Carbon in $CO_2$ is sequestered temporarily in vegetation when the biomass regenerates (Environment Canada, 2006a).

Canada ratified the Kyoto Protocol promising to reduce greenhouse gas (GHG) emissions to 6% below 1990 levels between 2008 and 2012 for the st abilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 2003: 1). The United Nations Framework Convention on Climate Change (UNFCCC) sets an overall framework for intergovernmental efforts to address climate change, recognizing that the climate system is a shared resource whose stability is being impacted by industrial and other emissions of $CO_2$ and other GHGs. This international obligation applies to Canada s GHG emission sources and sinks as a whole, which increased by 25% from 1990 to 2005 (Environment Canada, 2006a). This agreement did not require any reduction for individual sectors, like waste, or for individual industries or landfills (Environment Canada, 2006a). Environment Canada lacked sector specific mandatory targets until recently when the *Regulatory Framework for Air Emissions* set a 2010 implementation date for major industrial sectors requiring an absolute reduction of 150 megatonnes by 2020 (Environment Canada, 2007a, 2007b). However, this framework does not presently include goals for the waste sector. Methane from landfills accounts for 4% of the GHG in Canada and have increased by 22% between 1990 to 2005 (Environment Canada, 2006a).

## WASTE MANAGEMENT POLICIES TO REDUCE GREENHOUSE GASES

A number of different approaches to waste management could be adopted to reduce GHG emissions significantly. Preventing and diverting waste would reduce GHG. Requirements for methane recovery would reduce the amount of GHG being emitted to the atmosphere. Also, to maximize GHG reduction, both reducing waste and recovering methane should be required. Policies encouraging, rather than requiring, diversion could be coupled by strong requirements for methane recovery from all medium and large landfills. Strong requirements for diversion could reduce GHG such that only large landfills need to recover methane. For example, Ontario s proposed regulation requires landfills larger than 1.5 million cubic metres to install a system to capture methane (Ontario government, 2007). This proposed regulation could be coupled with requirements for source separating organic collection and/or landfill ban of organics to significantly reduce GHG from landfills.

### Reducing waste entering landfills

Since organic waste decaying anaerobically produces methane, diverting and reducing waste going to landfill reduces GHG. To project the potential impact of diversion on GHG, the quantity and composition of Canadian waste and the existing diversion programs must be considered. Canadians produce more waste per person than most other countries in the world (IPCC, 2006). In 2002, Canadians produced almost one tonne/person/year (i.e., 971 kg/person/year) of waste or 2.66 kg/person/day, of which 2.08 kg/day (i.e., 760 kg/person/year or 23.8 million tonnes) is disposed of in landfills or incinerators (Statistics Canada, 2002). This includes 0.26 kg/person/day of construction waste. The waste going to landfills has continued to rise in Canada despite a growing number of diversion programs, since it appears that consumption of disposable products is growing at a higher rate than diversion programs. Overall in 2002, Canadians diverted 12% of all the waste generated; approximately 60% of these diverted materials were organics (Statistics Canada, 2002; Thompson and Bonam, 2007). Recycling programs started at the municipal level in the mid to late 1980s in Ontario and in the early 1990s in other provinces (Statistics Canada, 2002; Thompson, Sawyer, Bonam and Smith, 2006).

Only recently, in early and mid 2000s, have source separated organics municipal programs started to become popular across Canada (van der Werf and Cant, 2006a). A national survey of composting in Canada found that 135 municipalities have curbside composting programs, reaching 17 million people (van der Werf and Cant, 2006a, b). All of these 135 municipalities have yard waste composting and 40% of these have source separated organic programs. In Prince Edward Island, Nova Scotia and Ontario, over 80% of the population have access to curbside composting and in British Columbia, it is about 60%, with lower access for the prairies (van der Werf and Cant, 2006a, b). van der Werf and Cant (2006a, b) considered that it was feasible to divert 50% of Canada s organic waste or 2.9 million tonnes/year through composting.

Composting success stories include the Cleanit Greenit Composting System in Edmonton, Alberta, which has significantly reduced GHG emissions (Castro-Wunsch and Ng-Grondin, 2001). This state-of-the-art composting and landfill gas recovery facility is operated by TransAlta for $62/tonne, which is lower than the tipping fee for many landfills in Canada (Goldstein, 2000). The compost is sold to remediate nearby industrial, mining and oil contaminated sites, since the compost process degrades wood preservatives, pesticides, and both chlorinated and non-chlorinated hydrocarbons, and binds heavy metals to prevent their migration to water resources or absorption in plants (Goldstein, 2000). In addition, compost is a highly valued garden input as it reduces the need for water, fertilizers, and pesticides. Another composting success story is Nova Scotia s landfill ban on organics. This resulted in Nova Scotia reducing its waste disposal rate to half that of other provinces, with an overall 56% diversion rate from landfills (Betts, 2007). Halifax Regional Municipality has rates of organic diversion at 68%. This almost reaches rates in the EU, which are above 80% for Austria, Belgium (Flanders), Germany, Switzerland, Luxembourg, Italy, Spain (Catalonia), Sweden and the Netherlands (ECN, 2007). These countries all have country-wide policies that require source separation of organics. Austria s diversion of 87% reduced municipal landfill and collection costs as a large number of people compost at home (ECN, 2007).

On average, 63% of landfilled waste is organic waste according to the results of 17 composition studies at Canadian landfills conducted in 2005/2006 (Thompson and Bonam, 2007). This 63% of biodegradable material includes: 21% food, 20% paper and textiles, 12% garden and non-food organic waste, and 10% wood (Thompson, and Bonam, 2007). Both Nova Scotia and Prince Edward Island have a ban on organics from landfills. As 30% of organics going to landfills are papers, textiles or wood, these organic materials biodegrade but might not be included in a source separated organics program. Thus, to divert high rates (e.g., 75%) of organics, requires improved recycling and prevention of waste (e.g., extended producer responsibility), as well as source separated organics collection program and/or a ban on organics from landfills. The GHG reduction from paper recycling and composting over landfilling is 50 kg $eCO_2$ to 280 kg $eCO_2$ depending on the efficiency with which the landfill controls landfill gas emissions (Smith et al., 2001).

## Methane Collection for Flaring or Recovery

Another way to manage GHG in landfills is by the systematic recovery of landfill gas, which can then be flared or used as an alternative renewable source of energy to replace fossil fuel use (Pembina Institute, 2003; Smith et al., 2001). One tonne of household waste has a methane gas production potential of 180 to 250 cubic meters during the 30 year to 50 year period that waste takes to decompose. Methane recovered from one tonne of waste produces approximately 1000 kilowatt hours (kWh) as one cubic metre ($m^3$/yr) of methane gas has an energy value of four kWh to five kWh (Pembina Institute, 2003). Fifty-two landfill gas collection systems capture slightly over one billion cubic meters per year of landfill gas with half (526 million $m^3$/year) producing energy and the remainder being flared to reduce methane to $CO_2$ (Thompson and Bonam, 2007). There was an increase in the total amount of methane captured from 312 kt of methane (6.56 Mt of $eCO_2$) in 2003 to 314 kt methane (6.69 Mt of $eCO_2$) in 2005. This slight increase was a result of nine landfills starting methane recovery (Thompson and Bonam, 2007) and the decline in several major closed landfills. The Keele Valley Landfill site declined from 62 kt of methane in 2003 to 47 kt in 2005. Montreal s Complexe Environnemental de Saint-Michel CESM landfill site decreased from 48 kt to 28 kt during the same time period (Thompson and Bonam, 2007).

Methane recovery of landfill gas represents one of the most cost effective means to reduce GHG emissions due to both fuel sales and credits from GHG reduction. Environment Canada (1999) reported that the price of GHG reduction (e.g. GHG credits) is between $1.00 and $2.00 (CAD value based on 1999) per tonne of $eCO_2$ reduced. In addition, the capture and use or flaring of landfill gas provides the ancillary benefits of limiting odours, controlling damage to vegetation, minimizing owner liability, reducing risk from explosions, fires and asphyxiation, and reducing smog while providing a potential source of revenue and profit (Smith et al., 2001).

The removal of methane is considered the more critical goal for climate change than energy production: 95% of the benefit is related to methane reduction and 5% from the energy gain of methane replacing fossil fuels (CEC, 1996). When energy use is not economically feasible, flaring or biotic methane removal systems is recommended (Hilger and Hummer, 2003). Biotic methane removal systems offer the same methane conversion as flaring (Hilger and Hummer, 2003). Despite its many benefits, methane recovery is essentially an end of pipe s olution, which does not actively address the root cause of waste generation, unlike composting.

This paper considers the future impact of different levels of waste diversion on GHG emissions from all landfills in Canada using the Scholl Canyon methane generation model. This simple model is widely used in the landfill gas industry in Canada and the United States, particularly for landfills with greater than one million tonnes of waste in place (Environment Canada, 2003; US EPA, 1996, 2001). However, this model has never before been used as a decision-making tool to determine strategies to reduce GHG production. The Scholl Canyon model is consistent with IPCC climate change protocols for calculating GHG emissions, and is the model that Environment Canada applied to estimate emissions as required by the UNFCCC secretariat. The Scholl Canyon model assumes that after a lag time of negligible duration, during which anaerobic conditions are established and the microbial biomass are built up and stabilized, the gas production rate is at its peak (Schumacher, 1983). This model is an exponential decay model dependent on factors that affect biodegradation rates (e.g., age of waste, moisture content, etc.) used to estimate methane generation from landfills but has the ability to compare options for waste management (IPCC, 1996). Gas generation is modelled over an extended period (1941 to 2030) to better understand how methane emissions relate to waste quantities accumulating in the landfill over time.

## METHODOLOGY

Methane emissions were estimated for Canada s waste according to the following steps:

1. Compiled quantities of waste landfilled for each year from 1941 to 2004 for each province and territory from a variety of sources. Waste estimates for Canada were available by province from Levelton and Associates (1991) for 1941 to 1990, Statistics Canada (1994, 1996, 1998, 2000, 2002) and Resource Integration Systems Ltd (1996). To determine waste amounts entering all Canadian landfills for the missing years (i.e., 1991, 1993, 1995, 1997, 1999, 2001, 2003 and 2004), waste amounts were linearly extrapolated from neighbouring points. Since the territories lacked any estimates of waste quantities, the estimates were extrapolated from other Canadian provinces based on population.
2. Projected total waste (organics and non-organics) amounts from 2005 to 2030 for four different waste diversion strategies, namely: 1) business as usual (considering that recycling initiatives, population growth, and consumption would continue at the same rate); 2) 25% of business as usual rate; 3) 50% of business as usual rate; and 4) 75% of business as usual rate.
3. Inputted waste amounts for every year from 1940 to 2030 into the Scholl Canyon model to estimate methane emissions for that period.

$$dL/dt = kLo\ ?\ r_i\, e_i^{\ k\,ti} \qquad (1)$$

where:

- L is the amount of gas generated per unit weight of waste ($m^3$ methane/tonne of waste or standard cubic feet per minute (SCFM);
- Lo is the methane generation potential ($m^3$ methane/tonne of waste) determined specific for each province;
- n is the number of years considered from 1941 to 2030;
- $t_i$ is the time from placement year 1941 to 2030 (years);
- k is the decay rate constant each year, applying province-specific constants (Thompson et al, 2006; Environment Canada, 2007a);
- $r_i$ is a ratio of the tonnage of all previous years accumulated to the landfill s maximum capacity of landfill.

Each province specific Lo is determined by (IPCC, 1996; Environment Canada, 2007a):

$$Lo = F \times DOC \times DOC_F \times 16/12 \qquad (2)$$

where:

- F is the fraction of $CH_4$ in landfill gas (50% $CH_4$ measured in biogas).
- DOC is degradable organic carbon (fraction),
- $DOC_F$ is the fraction degradable organic carbon assimilated (0.77) (IPPCC default).

The emissions from each province were added to determine a national GHG emission for each year.

Across all different diversion rates, LO and DOC are held constant to better observe the impact of overall diversion rates. Waste diversion is assumed in this paper to decrease a variety of waste types, impacting the absolute quantity but not the ratio of waste materials.

## RESULTS AND DISCUSSION

Figure 1 shows that the amount of waste being landfilled has steadily increased over time even after the beginning of municipal recycling programs in the mid to late 1980s in Ontario and early 1990s in other provinces. Recycling did not decrease waste amounts. Waste landfilled or incinerated rapidly increased in the late 1990s and 2000s to surpass previous levels. Increasing waste, with organics, results in higher methane emissions. To reduce 6% below 1990 levels from Canadian landfills requires curtailing methane production or emissions to 1034 kt methane or 22 Mt $eCO_2$, eliminating 459 kt (9.6 Mt $eCO_2$). The methane generation estimates shown in Figure 2, obtained from the Scholl Canyon model with Canadian-wide waste data, were in agreement for 1990 at 22 Mt eC02 with Environment Canada s national inventory report. Slight differences between these two estimates occur in later years due to Environment Canada s (2006b) National Inventory Report for 2005 subtracting methane recovered from that emitted prior to reporting, while this paper reports the methane generated directly without subtracting the methane recovered. Thus, Environment Canada s methane is lower at 27 Mt $eCO_2$ than this research s finding of 30.5 Mt $eCO_2$ in 2002, which includes methane generation that is recovered. Also, slight variances in modeled results are expected from different methods to estimate waste from territories and provinces in the absence of any data available regarding waste quantities.

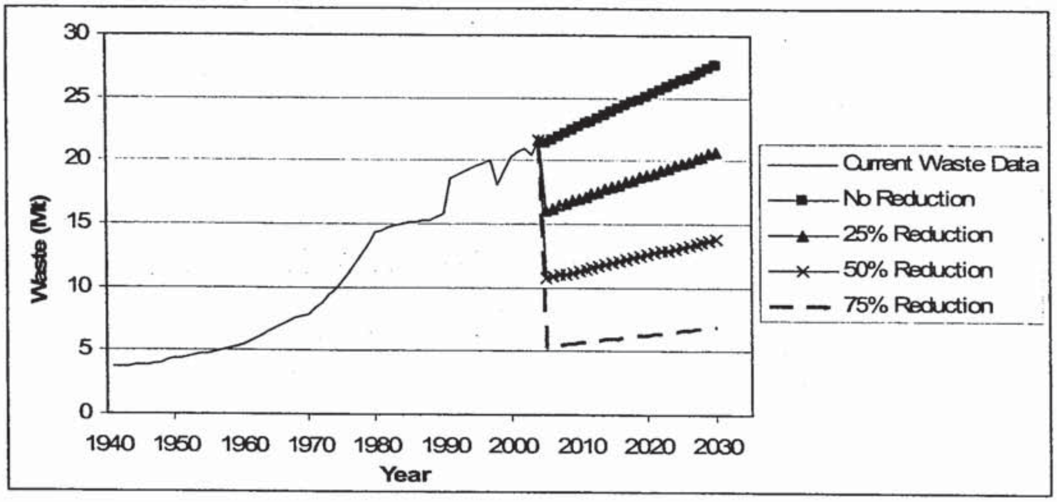

**FIGURE 1**
**Waste Disposal based on historical data and projections for different waste diversion rates (0 to 75%) starting in 2005**

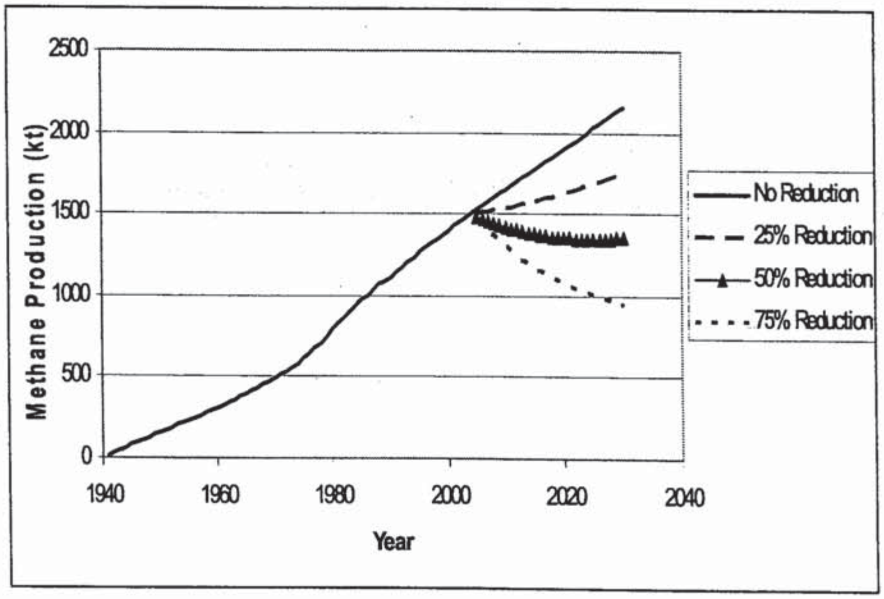

**FIGURE 2**
**Methane Emissions (1941-2030) from Canadian Landfills estimated by the Scholl Canyon Model for different waste diversion rates (0 to 75%) starting in 2005**

Figure 2 shows the methane generation estimates determined by the Scholl Canyon Model for four different rates of diversion. Business as usual results in 63% higher methane emissions in 2012 at 1701 kt (35.7 Mt $eCO_2$) than in 1990. To reach the proposed target at this rate, methane recovery would have to more than double (208%) from 314 kt methane (6.6 Mt $eCO_2$) to 667 kt. Similarly, with diversion rates of 25% total waste, the GHG emissions continue to increase to 1550 kt methane (32.5 Mt $eCO_2$). Due to historical waste emitting methane at higher rates than that reduced from diversion, a 60% increase in methane recovery is required to reach the 1034 kt goal. Fifty percent diversion would decrease GHG emissions to 1399 kt methane (29.4 Mt $eCO_2$). This comes very close to meeting the target. This diversion rate considers that 314 kt is presently recovered, so that only a 13% increase in methane recovery is needed. At 75% total diversion, the target for reduction would be surpassed without additional methane recovery. Figure 3 shows that 75% organic diversion reduces methane enough (253 kt methane or 26.2 Mt $eCO_2$) with the current levels of methane recovery to reach the target at present levels of methane recovery by 2008.

## CONCLUSION

The Scholl Canyon model was a useful tool to show the effectiveness of different waste diversion programs at reducing GHG. The model clearly demonstrated that to reduce GHG significantly, in the short term, methane recovery is necessary to address the problem of historical waste releasing methane emissions for 30 years to 50 years following waste deposition. The most sustainable waste management strategies would be to both 1) increase methane recovery to prevent methane emissions from historic waste, and 2) divert a high rate of organic waste to prevent any future potential for methane emissions. However, it should be noted that waste diversion would probably decrease methane more that this model shows as the degradable organic fraction could decrease considerably with a composting program.

The model demonstrated that a number of strategies could be employed to reach the target. A weak policy on diversion might result in only 25% total diversion, which would slow but not decrease methane emissions. This would require a strong policy on methane recovery to reach target. If methane recovery doubled and municipal composting and recycling programs increased slightly above present levels, Canada would easily reduce emissions by one-third and meet the proposed target. Alternatively, a 75% waste diversion effort would achieve the target with the present-day amount of methane recovery. For this to occur provincial requirements for separate source organics and/or landfill bans on organics would be required.

Waste diversion from landfills provides the long-term solution to prevent methane generation. However, a long lead time is required for waste diversion to result in a significant reduction in methane emissions, due to historical waste emitting waste for 30 to 50 years. Significant waste diversion requires strong government regulation to ban organics from landfills in each province across Canada as was done in Nova Scotia and Prince Edward Island. Another approach is to require source separation and collection of organics at the municipal level, which has resulted in 80% or higher diversion rates in European countries. This 80% diversion could be achieved if each province requires its municipalities to provide separate source organic collection and recycling collection. Currently, a small number (135) of municipalities offer some type of composting program, most of them limited to collecting yard waste with many in northern Canada, currently lacking any composting or recycling programs. Grants to fully cover initial set-up costs and develop markets may be necessary to assist municipalities, particularly in less populated or isolated Northern areas. As well, incentives, such as carbon credits, should be offered for composting and recycling programs as they reduce methane emissions from landfills. Carbon credits are presently dispensed for methane re-

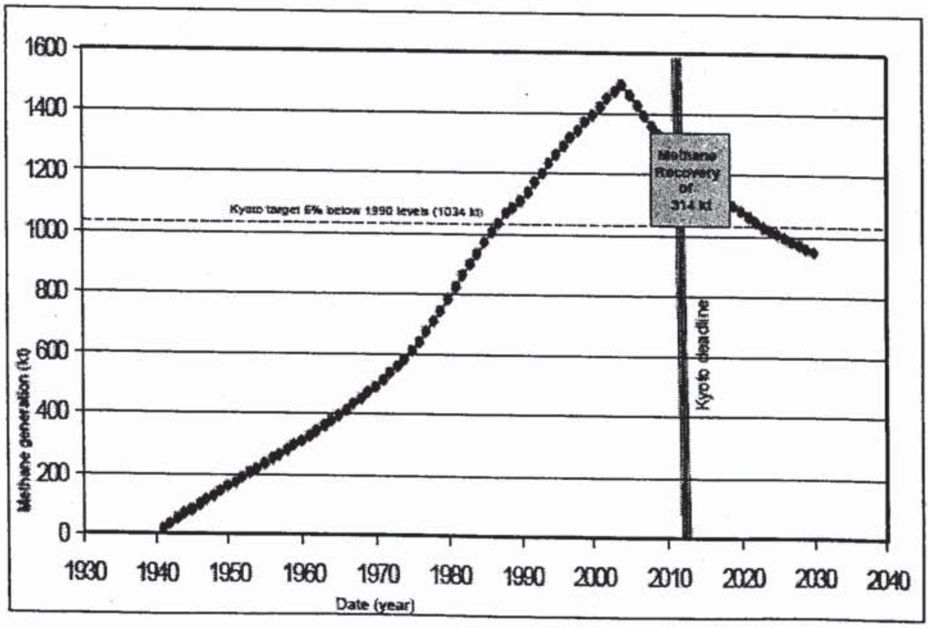

**FIGURE 3**
**75% percent waste diversion s impact on Methane Generation**

covery, which is an end-of-pipe solution, but not organic diversion, where the latter is a control at the source strategy.

Methane recovery is needed to address emissions from historical waste. Currently, less than half of the large active and closed landfills in Canada recover methane. To increase methane recovery by municipalities, incentives to fund some of the capital costs of installing gas pipes for collection and/or regulation that prevents methane release without flaring or recovery for energy use may be necessary. As well, the revenue from utilizing the gas energy and from carbon credits provides additional incentive to pursue this approach. Ontario s proposed legislation will require large landfills to recover methane for use as renewable energy, according to Environment Minister Laurel Broten: This initiative would have dual benefits - by capturing the methane operators can sell that power to the electricity grid for profit, while limiting the amount of greenhouse gases we emit into the atmosphere (Ontario Government, 2007).

Other policies to prevent waste entering landfills should be adopted immediately as required in Europe, including the extended producer responsibility (EPR) for packaging and other products. EPR requires producers to take-back and recycle or reuse paper, cardboard and other products, usually at target rates of 75% or higher. This encourages producers to reduce packaging and waste at source by redesigning packaging and products, thereby preventing paper production of disposable or one-use packaging.

Anthropogenic methane should be controlled to mitigate global climate change and landfills are the key component (Hilger and Humer, 2003; IPCC, 2006). Landfills could reduce GHG by waste diversion and methane recovery. Landfill gas curtailed through these achievable methods could reduce anthropogenic methane emissions by the 10% to 12% required to stabilize atmospheric methane emissions. Nineteen percent (70 Tg/year) of anthropogenic emissions is attributed to landfill emissions (IPCC, 1996) and a 10%-20% decrease of anthropogenic methane emissions (Mosher, Czepiel, and Harriss, 1999) is expected to stabilize atmospheric methane concentrations to 1990 levels. As methane has an atmospheric lifetime of nine years, a reduction in methane emissions would cause a rapid decrease in atmospheric levels.

## ACKNOWLEDGEMENTS

Sincere thanks to Craig Palmer for his insightful and very detailed review of this paper, improving it greatly. Both Craig Palmer and Paula Critchley provided invaluable assistance with this research. Acknowledgement is also given to Environment Canada for their funding support of this research. Thanks to David Smith for his encouragement, guidance and editing.

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