Understanding Waste from a Climate Change Perspective: Municipal Solid Waste Management in Canada

By

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Of Master of Natural Resources Management (M.N.R.M)

Abstract

This thesis analyses the current solid waste management situation in Canada to determine the most effective methods of managing solid waste. To arrive at best practices for sustainable waste management, the relationships between waste composition, diversion efforts, management methods and landfill characteristics were explored for 97 Canadian landfills. Municipal solid waste undergoes biological decomposition to generate landfill gas, a potent greenhouse gas that contributes to global warming. In addition I developed: 1) a statistical analysis of operations and their impact on methane generation, and 2) waste management guidance to reduce emissions from the solid waste sector.

Landfill space is in short supply with many landfills reaching their capacity. In order to save landfill space and prevent further harm to the atmosphere, best practices in waste management have to be embraced by landfill sites across Canada. Based on the limited capacity of landfills in many regions of Canada and growing waste generation per capita a shortage of landfill space is expected in the next twenty years, which increases the pressure for sustainable waste management practices.

Best practices for managing landfills and waste include increased depth, greater compaction, waste diversion and landfill gas capture. These could control pollution and conserve landfill space. Higher disposal fees are significantly statistically related to better waste management practices, such as greater compaction rates (i.e., higher density) and greater depth, as well as more diversion. The average depth of a Canadian landfill is 20 meters with the deepest being 50 meters. If the national average depth was doubled, this action would double the average life of Canadian landfills. The survey showed that the average density of waste is about 750 kg/cubic meter, varying from 125 to 1380 kg/cubic meter. If the national average for waste compaction is increased to 1380 kg/metre, this

would have the overall effect of nearly doubling the amount of waste that can be placed into the same landfill space. In addition, higher disposal fees are correlated with lower per capita waste production.

Methane recovery is only occurring at 52 landfills but should be carried out at all landfills above a minimum size to reduce greenhouse gases (GHG). Currently, many provinces have targeted landfill gas recovery as part of their greenhouse gas mitigation strategy. Major questions remain with respect to actual methane production in landfill sites. Therefore, to see if operational factors impact emissions production, recovered methane emissions were statistically analyzed. The average absolute error between the statistically modeled and recovered methane from the 29 landfills is 44%. In addition, the linear regression model with an $R^2 = 0.832$, showed that landfill emissions are positively correlated with landfill depth, density and organic waste and negatively correlated with waste diversion.

In 2005, only a small portion of the waste stream was recovered or composted. Finally, waste diverted in 2005 from 97 active landfills produced a net decrease of approximately three million tonnes of GHG emissions. Considering all the benefits of waste diversion and its impact on GHG emissions, all municipalities should adopt curbside composting and recycling programs as part of the waste solution to reduce greenhouse gas production and waste generation.

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Dedication

This thesis is dedicated to my guru Sri Sadguru Sainath. I also dedicate this thesis to my parents and to my wife for their support.

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CHAPTER 1: INTRODUCTION

1.1 Background

Until our society stops viewing material as disposable and sees it as cyclical and a valuable resource, energy and material are wasted. A sense of urgency to change this perspective is emerging for solid waste managers in OECD countries, because in these nations municipal solid waste increased by 40% between 1980 and 1997 and is predicted to increase by a further 40% by 2020 (King et al., 2006). Total amount of waste generated in Canada increased by 17% between 1980 and 1997, and became the worst performer on this indicator (Boyd, 2001). Within 16 year, from 1990 to 2006, Canada increased its waste disposal in landfills by 24%, tarnishing Canada's already poor environmental track record even more (Environment Canada, 2009). Further, many of Canada's existing waste disposal facilities are close to capacity and receiving approvals for new disposal sites is a very expensive and politically difficult endeavour (McDavid and Laliberte, 1998).

That current waste management practices are unsustainable requires that we look for alternative waste management practices to help us stop and, eventually, reverse the steady increase in our waste production. Although usable materials are now being salvaged from landfills in many locations, there are easier ways to cycle resources (Van der Zee et al., 2004). Significant environmental pressures are currently resulting from our rising waste generation levels and our improper disposal of waste; these behaviours lead to the unsustainable consumption of natural resources and energy, and contribute to the pollution of air, land, and water. In awareness of these environmental risks, Canada adopted a 50% waste reduction target from 1988 levels by 2000 to increase waste diversion (i.e., recycling, composting, etc.) (PWGSC, 2005). However, contrary to this goal, the amount of waste disposed in landfills in Canada actually increased by 25%

between 1990 and 2000 (Thompson et al., 2006). An average person in Canada currently generates about 2.66 kg of waste each day and most of it ends up in a landfill (Thompson et al., 2006).

Municipal solid waste is the waste stream that includes wastes from the residential, commercial, and institutional sectors, as well as waste from construction and demolition activities. A recent study showed that between 2000 and 2002, total municipal solid waste (MSW) generated increased by 4%, from 29.3 to 30.4 million tonnes (Mt) (Environment Canada, 2005). The study also showed that the total amount of MSW disposed of in landfills in Canada also increased by 3% during the same period (Environment Canada, 2005). These findings suggest that as waste generation increases, the amount of waste entering landfills increases, as well. Over the past few decades, waste management practices in Canada have largely concentrated on how to collect and bury waste efficiently. Now, however, there is a greater emphasis on techniques and approaches that avoid or minimize the need for waste disposal in landfills through diversion (Maclaren, 1995).

The management of solid waste is the "supervised handling of waste materials from their source through recovery processes to disposal" (EPA, 2006). As Canada does not rely much on waste incineration for volume reduction and energy production, MSW is disposed of in landfill sites in bulk quantities (Environment Canada, 2005). Therefore, Canadian solid waste management systems should employ volume reduction techniques and move in the direction of waste minimization through recycling and composting programs. Unfortunately, landfilling still remains the dominant waste management practice for waste generated in Canada despite releasing methane emissions into the atmosphere (Thompson et al., 2006; Sawell et al., 1996). As much as 60% of waste in landfills is organic matter which undergoes biological decomposition to produce landfill gas, which is largely a mixture of methane and carbon dioxide, with traces of other constituents (Weitz et al., 2002). Methane is a potent greenhouse gas (GHG) that has a global warming potential 25 times greater than that of carbon dioxide (IPCC, 2007). In order to help prevent further atmospheric emissions, stringent landfill regulations must come into effect for landfill sites across Canada (Brown & Maunder, 1994). However, to achieve significant landfill gas (LFG) emission reductions, the amount of waste entering landfills must be reduced, instead of focusing solely on reducing the GHG emissions from landfills. To better manage the amount of waste entering landfills, regional and provincial governments need to implement waste management strategies that can reduce waste production and promote the sustainable use of materials. Recent studies have shown that the MSW currently flowing into Canadian landfills consists of approximately one-third of each of the following three components: 1) recyclables including organics like paper, 2) other organics, and 3) residual materials (Environment Canada, 2005).

Landfill gas composition depends on a number of site specific conditions, such as the composition, density, and age of the landfill waste. However, the quantity and composition of MSW determines the total production of LFG emissions (IPCC, 1996). Since organic waste, including kitchen and yard waste, paper, and wood, is the main component of MSW that produces landfill gas, one of the best methods to control LFG emissions is to have source separation of waste. Source separation of waste is accomplished when recyclable and compostable materials are taken out of the waste stream heading to landfills to reuse these resources. Good solid waste management should first consider ways to reduce waste and then should prioritize the recovery of waste materials where minimization is not possible (Sakai et al., 1996).

By signing the Kyoto Protocol in April 1998, Canada agreed to reduce its greenhouse gas emissions by 6% below 1990 levels by 2012 or about 20% from today's emissions (Environment Canada, 2002). However, Canadian landfill emissions increased between 1990 and 1999. Landfill emissions are estimated to have been 24 Mt carbon dioxide equivalent (eCO_2) in 1999, accounting for 3.4% of the national greenhouse gas emissions at the time, a slight increase from 3.3% in 1990 (Government of Canada, 2004). In addition, an increase in the quantity of waste buried in landfills has resulted in a 22% increase in GHG emissions from landfills between 1990 and 2000 (Olsen et al., 2002). If the present trend in waste generation and disposal continues, Canadian landfills will account for 4% of the national greenhouse gas emission total by 2010 (Boire, 2002), up from 3.1%.

Landfill gas production rates and volumes largely depend upon site-specific characteristics of waste, including the composition and density of the refuse (IPCC, 1996). The waste composition is one of the main factors influencing both the volume of methane produced and the rate of methane production within a specific landfill. The methane generation rate depends significantly on the biodegradability of the waste components. For example, food waste degrades readily, while paper waste degrades at a more moderate rate (Garg et al., 2006). The average residential waste composition of several municipalities across Canada is dominated by paper and organic waste (Maclaren, 1995). Along with the composition, refuse compaction also affects the gas production rate. As the density of the waste placed in a landfill increases, the gas production decreases because of a decrease in the surface area exposed to enzymatic hydrolysis, decreasing decomposition rates (Levelton, 1991). This study will try to better our understanding of different waste streams to identify where our efforts should be primarily focused in order to achieve the greatest greenhouse gas emission reductions. Understanding the composition of waste is also essential in determining the best waste management practices for managing our municipal solid waste. This study will focus on small, medium, and large landfills within Canada that are active and that accept municipal solid waste. The survey concerns only waste that is managed off-site, and does not cover any waste that is directly managed by the generator (i.e. industrial waste) or illegal dumping.

1.2 Purpose

The purpose of the research is to estimate greenhouse gas emissions from MSW disposed of at landfills and to assess the effectiveness of various waste management options to reduce greenhouse gas emissions from MSW.

1.3 Objectives

- To identify best practices for sustainable waste management by studying the relationships between waste composition, diversion, waste capacity, and landfill management methods.
- To determine the effect of waste diversion, landfill depth, disposal fees, MSW composition and the density of solid waste on greenhouse gas emissions from 97 landfills across Canada.
- To identify which waste management options can contribute to reducing emissions from the solid waste sector.

1.4 Significance

The way we choose to manage MSW has a direct impact on the generation of greenhouse gases. Even though Canada has some encouraging waste minimization programs/services in place (e.g. Blue Box, Green Bin, composting initiatives etc.), Canada has not realized a reduction in the amount of waste buried at landfills. There is a need to revolutionize our perspective on waste. In order for that to happen, the current waste scenario, as well as best management practices, must be studied to inform policy-makers and waste managers. With MSW piling up at landfills across the nation, a study that shows the magnitude of the waste problem, along with recommendations to overcome it, can help Canadians make wise waste management decisions to achieve waste reduction/diversion targets in the near future.

This research will help MSW managers to design efficient processing and disposal alternatives by illustrating how solid waste management may contribute to the mitigation of climate change by reducing the sector's GHG emissions. With its rigorous data collection and analysis at the national level, this study can fill in data gaps (such as non-uniform reporting on waste) and mitigate GHG emissions in the waste sector. Importantly, this study can help in the decision-making process by developing a preferred waste management strategy from a large pool of alternatives. Today, when many communities and companies are announcing plans to achieve zero waste reduction targets (e.g. Toronto wants to achieve zero waste by 2010), this research can assist in achieving these goals.

CHAPTER 2: LITERATURE REVIEW

This literature review will examine a number of issues related to waste management, specifically waste generation, diversion and disposal, as well as best practices for waste management. Although the description of what we consider waste is dynamic because waste flow and composition are constantly changing (Read et al., 1998), the standard definition of waste is static: waste is the unwanted materials produced through human activity (OEA, 1998). The management of solid waste is an essential service for improving the health and well-being of people.

There are many concerns regarding the current solid waste management systems in Canada, like the high costs associated with the diversion of waste in some municipalities: it costs approximately $124 for solid waste diversion per tonne and an average of $37 for solid waste disposal in Ontario per tonne (Ontario Municipal Benchmarking Initiative, 2005). Waste is difficult to divert (i.e., recycle, reuse, compost, etc.) as it is typically a mixture of different components, needing separation and sometimes remanufacturing. Although landfilling waste is cheaper than waste diversion, in general, sending waste to landfills is problematic: resources are lost, there are serious difficulties with siting the large land base required for the construction of new landfills, and pollution is produced, including GHGs and leachate (Strathman et al., 1995). So, while landfilling waste is still the dominant waste management method employed by the waste disposal authorities in Canada, this practice needs to change. This study will make recommendations to promote alternative solid waste management strategies.

2.1 Size of the Problem

Canadian households and businesses generated over 30 million tonnes (Mt) of waste in 2002 and only 6.6 Mt were processed for recycling (Statistics Canada, 2005). Even though the diversion rate increased from 5.98 Mt in 1996 to 6.6 Mt in 2002, an increase in the total waste generated in Canada over that time period resulted in no change in the overall proportion of waste being recycled (Statistics Canada, 2005). This over-reliance on landfills will push Canada towards a landfill crisis.

2.2 Solid Waste Characterization

Solid waste can be classified by source (e.g., residential, commercial, industrial, etc.) or by composition (e.g., organic, paper, glass, etc.). Accurate information about solid waste by source and composition is necessary in order to control existing waste management systems and to make regulatory decisions. In this study, MSW is characterized as having a residential, commercial, institutional, construction or industrial source and includes newspaper, durable and nondurable goods, wood, containers and packaging, food waste and yard trimmings, and miscellaneous inorganic wastes (EPA, 1995).

2.3 Waste Generation

Having knowledge of waste generation rates and waste composition is essential for good waste management planning: this knowledge can provide guidance when determining how to *change* waste generation rates (Maclaren, 1995). Understanding the factors that influence waste generation can help save Canada millions of dollars and promote greenhouse gas mitigation (Statistics Canada, 2005). It is important for Canadians to determine the sources of waste and why such large quantities of waste are produced each year. In 2002, over 30.4 Mt of MSW was generated. The amount of MSW generated by each sector was distributed as follows (Table 1): 40% Residential, 49% Institutional, Commercial, and Industrial (IC&I), and 11% Construction and Demolition (C&D) (Environment Canada, 2005). The amount of MSW generated per capita increased from 952 kg/person to 971 kg/person between 2000 and 2002 (Statistics Canada, 2005). Even though people have become increasingly aware and concerned about waste generation in the last decade, this has had seemingly little or no effect on actual waste generation. Widespread campaigns, such as the “reduce and reuse” initiative, have obviously failed to end the increasing solid waste generation trend in Canada. Canadian households generated more than 12 Mt of residential waste in 2002 (Table 1), which is about 383kg/person/year and an increase of more than 4.9% from 2000 (Statistics Canada, 2002).

Table 1: Generation of Waste, by Source and by Province and Territory (2000 and 2002)

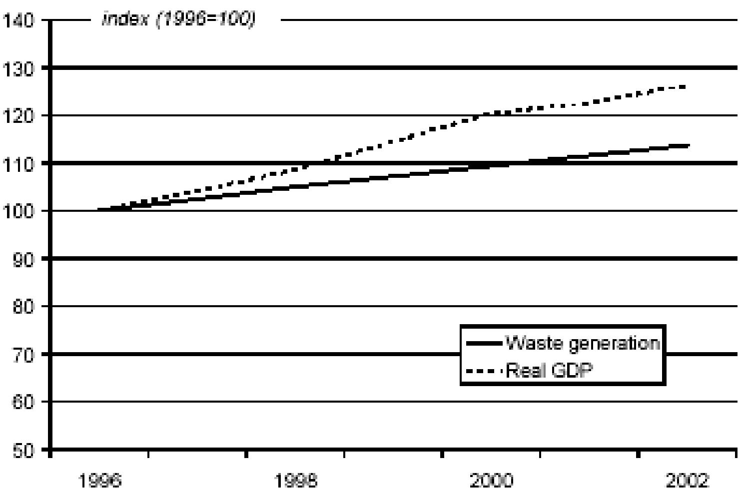
	Residential sources		Industrial, commercial and institutional sources		Construction and demolition sources		Total generation	
Province/Territory	2000[r]	2002	2000[r]	2002	2000[r]	2002	2000[r]	2002
	tonnes							
Newfoundland and Labrador	x	231 291	x	x	x	x	441 828	414 979
Prince Edward Island	x	x	x	x	x	x	x	x
Nova Scotia	246 792	252 012	x	x	x	x	532 616	558 918
New Brunswick	243 300	256 190	x	216 432	x	63 941	529 954	536 563
Quebec[1]	3 175 000	3 471 000	3 581 000	3 196 000	589 200	619 800	7 345 200	7 286 800
Ontario	4 191 337	4 388 239	5 962 868	6 514 191	1 139 271	1 158 701	11 293 476	12 061 131
Manitoba	501 921	494 535	x	566 750	x	86 151	1 130 182	1 147 436
Saskatchewan	305 901	321 069	x	x	x	x	971 989	941 731
Alberta	994 555	1 159 697	x	1 642 843	x	677 395	3 172 598	3 479 935
British Columbia	1 292 999	1 354 177	x	1 933 387	x	562 457	3 709 451	3 850 021
Yukon Territory, Northwest Territories and Nunavut	x	x	x	x	x	x	x	x
Canada	**11 242 405**	**12 008 338**	**14 776 041**	**15 075 307**	**3 288 961**	**3 371 880**	**29 307 405**	**30 455 524**

(Source: Statistics Canada, 2002)

2.3.1 Reasons for waste generation

Being a wealthy society, Canada enjoys a relatively high standard of living and consumes huge quantities of materials. Canadians have not been aware of the true costs of the waste they generate (Mohareb et al., 2004). There are a number of reasons why Canada generates such significant amounts of waste (Statistics Canada 2005):

- Lack of producer responsibility (King et al., 2006).
- Increase in population. Between 2000 and 2002, the population of Canada increased by 2% from 30.6 to 31.3 million, which pushed the waste generation index up by 4%, from 29.3Mt to 30.4 Mt (Statistics Canada, 2005). This increasing trend in waste generation and population growth can also be observed between 1998 and 2000.
- Increase in GDP. The growth in the Canadian economy has influenced the country's solid waste generation, as shown in Figure 1.



(Source: Statistics Canada, 2005)

Figure 1: Solid waste generation and GDP[1] in Canada, 1996-2002

[1] Real GDP is an economic indicator that represents the value of all the goods and services produced within a country at a specific year's prices.

- Decline in the average household size. People living in one and two person households (HHLD) represent one-third of Canada's population, yet generate more than 50% of the residential solid waste produced in Canada (Table 2). The average size of a Canadian household has decreased from 4 to 2.5 persons per household in the 25 years between 1981 and 2006 (Statistics Canada, 2006), which has lead to different shopping habits (Cirko, 2006). Since smaller households tend to produce more waste per capita than larger households, this has resulted in an overall increase in waste generation per capita across Canada. For example, smaller households tend to purchase milk in one litre cartons, rather than in four litre jugs, increasing packaging waste.

Table 2: The size of Canadian households

	2001 HHLDs %	No. of HHLDS	Total Population
1-2 person	58%	6,749,305	10,521,735
>3 person	42%	4,813,675	19,005,565
Total	100%	11,562,980	29,527,300

(Source: Cirko, 2006)

2.4 Waste Disposal

If not diverted, the MSW generated in Canada is either landfilled or undergoes thermal treatment. Landfilling is the most common way to dispose of waste in Canada (Maclaren, 1995). Of the 23 Mt of MSW disposed of in 2000, 95% ended up in landfills, while the remaining 5% was incinerated (Statistics Canada, 2005). This heavy dependence on landfills is of great concern, as 30% of Canada's landfills will run out of space in the next ten years at the current rates of disposal (Statistics Canada, 2005). Even though Canada does not lack space for new landfills, steps to minimize the amount of waste disposed of in landfills still need to be considered. One of the major concerns regarding waste disposal is not only the diminishing capacity of current landfills, but also controversies around current landfill proposals (Fredricksen et al., 2002). For example, the Adams mine, which was proposed as a landfill site for Toronto's waste, faced massive public opposition and disagreement over the environmental impacts of the facility (Fredricksen et al., 2002). Ontario, with a population of over 12 million people, generates about 12 Mt of waste each year, requiring space to dispose of 9.6 Mt of MSW every year (Table 3).

In 2002, Canada generated more than 12Mt of residential and 18 Mt of non-residential (IC&I and C&D) waste (Statistics Canada, 2005); of this 30 Mt, 9.5 Mt of residential, 11.6 Mt of IC&I, and 2.8 Mt of C&D waste were disposed of in landfills, producing 24 Mt of emissions, or 3% of Canada's GHG emissions for 2002 (Table 3) (Environment Canada, 2005). Because such a huge amount of waste is disposed of in landfills, MSW is becoming both an environmental and economic hazard for municipalities and communities (McDougall et al., 1995). Even though most provincial governments have set waste reduction goals, like a 50% reduction in MSW (Maclaren, 1995), waste disposal continues to rise (Table 3).

Table 3: Disposal of Waste, by Source and by Province and Territory, 2000 and 2002

Province/Territory	Residential sources		Industrial, commercial and institutional sources		Construction and demolition sources		Total waste disposed	
	2000[r]	2002	2000[r]	2002	2000[r]	2002	2000[r]	2002
	tonnes							
Newfoundland and Labrador	x	216 218	146 843	140 377	x	19 999	398 818	376 593
Prince Edward Island	x	x	x	x	x	x	x	x
Nova Scotia	171 627	169 649	x	176 625	x	42 921	391 827	389 194
New Brunswick	198 603	203 506	x	154 812	x	55 288	415 058	413 606
Quebec[2]	2 679 000	2 876 000	2 655 000	2 261 000	472 200	406 800	5 806 200	5 543 800
Ontario	3 318 478	3 438 408	4 606 409	5 193 240	1 006 714	1 013 985	8 931 600	9 645 633
Manitoba	451 505	412 612	x	405 954	x	77 990	914 511	896 556
Saskatchewan	272 104	278 692	x	441 109	x	75 323	821 946	795 124
Alberta	824 990	866 398	x	1 380 306	x	643 590	2 750 004	2 890 294
British Columbia	890 789	936 774	1 264 056	1 346 669	426 490	461 458	2 581 336	2 744 901
Yukon Territory, Northwest Territories and Nunavut	x	x	x	x	x	x	x	x
Canada	**9 069 170**	**9 455 204**	**11 203 613**	**11 563 999**	**2 896 087**	**2 816 528**	**23 168 870**	**23 835 730**

(Source: Statistics Canada, 2002)

Total MSW disposal in landfills in 2002 was almost 24 Mt, or approximately 760 kg/person/year, which is an increase of 7 kg/person/year from 2000 (Table 4). Alberta had the highest waste generation at 1117 kg/person/year, while Nova Scotia had the lowest at 598 kg/person/year (Thompson et al., 2006). Similarly, Alberta has the highest waste disposal rate per capita at 928 kg/person/year and Nova Scotia has the lowest at 417 kg/person/year (Table 4). Between 2000 and 2004, an increasing trend is exhibited in the total amount of waste generated, which can be blamed on Alberta, Ontario and British Columbia for their high levels of per-capita generation (Table 4). Nova Scotia, with the lowest per capita disposal rate of 417 kg/person in 2002, has shown the most improvement, with an increase in the rate of diversion per capita by 4% (Table 4). The province of British Columbia, along with every other province, agreed to reduce its MSW disposal per capita to 50% of the 1990 level by the year 2000. However, Nova Scotia was the only province in Canada to reach the 50% waste reduction target, whereas B.C. could only reduce its per capita waste disposal rate by 27.6% by the year 2000, even after many waste reduction efforts (Wagner and Arnold, 2006).

Table 4: Waste Disposal, Diversion and Generation per capita, by Province, 2000 and 2002

Province/Territory	Disposal[1]		Diversion		Generation		Rate of diversion per capita	
	2000[r]	2002	2000[r]	2002	2000[r]	2002	2000[r]	2002
	kilograms per capita						percent	
Newfoundland and Labrador	742	725	80	74	822	799	10	9
Prince Edward Island	x	x	x	x	x	x	20	28
Nova Scotia	416	417	150	182	566	598	26	30
New Brunswick	550	551	152	164	702	715	22	23
Quebec[2]	787	745	209	234	996	979	21	24
Ontario	764	797	202	200	966	997	21	20
Manitoba	798	776	188	217	986	993	19	22
Saskatchewan	804	799	147	147	951	946	15	16
Alberta	914	928	140	189	1 054	1 117	13	17
British Columbia	636	667	278	269	914	936	30	29
Yukon Territory, Northwest Territories and Nunavut	x	x	x	x	x	x	3	10
Canada	**753**	**760**	**199**	**211**	**952**	**971**	**21**	**22**

(Source: Statistics Canada, 2002)

The composition of MSW, which varies by landfill, province, etc., averaged across Canada is as follows: 28% paper and cardboard, 34% food and garden, 11% plastics, 7% glass, 8% metals and 13% textiles and others (Fredricksen et al., 2002). A study done by the EPA showed that around 30% of MSW in Canada is discarded packaging (Fredricksen et al., 2002). So, in order to reduce the amount of packaging disposed of by 50% by 2000, the Canadian Council of Ministers of the Environment (CCME) started the national packaging protocol, which helped them achieve this goal four years ahead of schedule (CCME, 1998).

2.5 Waste diversion and reduction

Waste diversion provides a solution to the multi-billion dollar waste disposal problem by reducing the waste and greenhouse gas emissions being generated by the waste sector. Based on the concept of the “3Rs,” a waste hierarchy was first introduced into a European waste management policy in 1975, which showed that waste should be handled differently based on its characteristics (AMO, 2005). This hierarchy of waste management options is an established framework that deals with two fundamental requirements: that is, first, produce less waste and then implement an effective system for managing the waste that is still produced (McDougall et al., 1999). Jurisdictions that integrate this waste hierarchy in their solid waste management plans have had more success in diverting waste from landfills (e.g., Nova Scotia) (AMO, 2005). A waste hierarchy is widely used as a simple communication tool that consists of the following waste management approaches, in order of importance (AMO, 2005):

- Source Reduction: Decreases the amount of materials being consumed and in the process reduces GHG emissions.
- Recycling and reuse: Diverts materials from landfills and reduces virgin material consumption.
- Composting: Removes a large amount of degradable waste from landfills and prevents, for the most part, the generation of methane emissions.
- Incineration: Generates energy from waste and in the process prevents organic waste from decomposing anaerobically to produce methane.
- Landfilling: Disposes of residue.

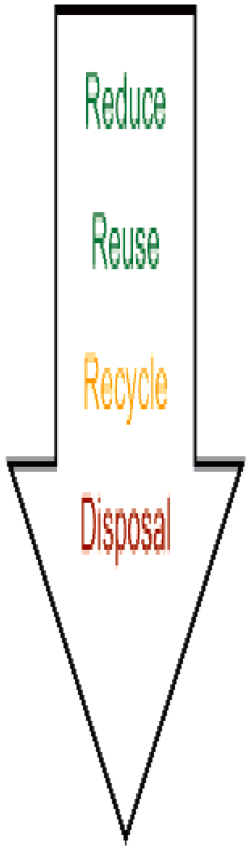


Table 5: Diversion of waste, by source and by province, 2000 and 2002

Province/Territory	Residential sources 2000[r]	Residential sources 2002	Industrial, commercial and institutional sources 2000[r]	Industrial, commercial and institutional sources 2002	Construction and demolition sources 2000[r]	Construction and demolition sources 2002	All sources 2000[r]	All sources 2002
	tonnes							
Newfoundland and Labrador	x	15 073	x	x	x	x	43 010	38 386
Prince Edward Island	x	x	x	x	x	x	x	x
Nova Scotia	75 165	82 363	x	x	x	x	140 789	169 724
New Brunswick	44 697	52 685	x	61 620	x	8 653	114 896	122 957
Quebec[2]	496 000	595 000	926 000	935 000	117 000	213 000	1 539 000	1 743 000
Ontario	872 859	949 830	1 356 460	1 320 952	132 557	144 716	2 361 876	2 415 498
Manitoba	50 416	81 923	x	160 796	x	8 161	215 671	250 880
Saskatchewan	33 797	42 376	x	x	x	x	150 043	146 607
Alberta	169 565	293 300	x	262 537	x	33 805	422 594	589 642
British Columbia	402 209	417 403	x	586 719	x	100 999	1 128 115	1 105 121
Yukon Territory, Northwest Territories and Nunavut	x	x	x	x	x	x	x	x
Canada	**2 173 236**	**2 553 134**	**3 572 428**	**3 511 308**	**392 874**	**536 345**	**6 138 536**	**6 619 794**

(Source: Statistics Canada, 2002)

In Canada, a major concern is that even though the total MSW diverted from final disposal in landfills increased by 8%, from 6.1 Mt in 2000 to 6.6 Mt in 2002, the diversion rate remained the same, at approximately 22%, due to the quantity of landfilled waste growing in tandem with the quantity of diverted waste (Table 5) (Environment Canada, 2005). In 2002, British Columbia had the highest rate of diversion, with 30% of the total waste generated being recycled (Table 5). The highest diversion rate of waste from residential sources, at 41% (0.4 Mt of 1.1 Mt), also occurred in British Columbia (Table 5). In order to minimize waste disposal and achieve emission reductions in the waste sector, the hierarchy of waste management options, like reduce, reuse, recycle, and restore (4R's), has to be followed. Another way to reduce the quantity of MSW produced would be to impose user fees for waste collection. The government of Canada's "Climate Change Plan" did not incorporate the waste management hierarchy to achieve emission reductions, but instead focused solely on GHG emission reductions from landfills (Mohareb et al., 2004).

Waste diversion not only reduces GHG emissions from the waste sector, but also reduces GHG emissions from the transportation of solid waste. Several Canadian cities transport their waste large distances for landfilling. For example, Toronto exports its 4.1 Mt of waste to the U.S. every year (Michigan and New York): this means that every day, six days a week, more than 370 tractor trailer loads of waste is transported for disposal from Toronto to the U.S. (Oates, 2006). At the present waste generation and disposal rates, the continued reduction in landfill space will force those waste transportation vehicles to travel further to reach open landfills. However, the efficient diversion of waste can offset the increase in GHG emissions from the transportation of waste.

Most of the MSW in Canada, or about 66%, is organic; therefore, diverting organic waste from landfills would achieve significant reductions in both the quantity of waste landfilled and GHG emissions (NCCP, 1998). The diversion of recyclable materials, like metals, paper etc., from landfills would achieve greenhouse gas emission reductions and would also reduce the amount of virgin materials being converted into products (Table 6). Recycling offers excellent emission reductions: recycling aluminum to produce aluminum cans reduce GHG emissions by 94% compared to using virgin aluminum to produce cans (Table 6).

Table 6: GHG emission reductions and energy savings achieved using recycled material versus virgin materials

Material (units)	Source	Process energy input (GJ/t of product)	Transport Energy Input (GJ/t of product)	Total energy input (GJ/t of product)	Process energy emissions (t CO_2e/t of product)	Process non-energy emissions (t CO_2e/t of product)	Transport emissions (t CO_2e/t of product)	Total emissions (t CO_2e/t of product)	Energy savings (%)	Emissions reductions (%)
Aluminum cans	Virgin inputs	239	8.7	248	13.6	4.7	0.65	18.9	93	94
	Recycled inputs	17.3	0.47	17.8	1.0	0.08	0.04	1.1		
Steel cans	Virgin inputs	36.8	5.4	42.2	2.8	1.0	0.36	4.1	56	50
	Recycled inputs	13.7	4.7	18.4	0.77	1.0	0.32	2.1		
Glass containers	Virgin inputs	7.5	0.67	8.2	0.4	0.16	0.04	0.61	34	53
	Recycled inputs	5.0	0.4	5.4	0.24	0	0.04	0.28		
Newspaper	Virgin inputs	46.4	0.58	47	2.3	0	0.04	2.4	46	42
	Recycled inputs	25.6	0.03	25.6	1.4	0	0	1.4		

(Source: Mohareb et al., 2004)

2.5.1 Source Reduction

"Source Reduction refers to any change in the design, manufacture, purchase, or use of materials or products (including packaging) to reduce their amount or toxicity before they become municipal solid waste" (EPA, 2006). Material reuse is also a form of source reduction (e.g. using used plastics bags for grocery shopping).

> *What you must do to prosper in the emerging Natural Economy is to know waste like no one's ever known it before, so you'll know where there's inefficiency, and how to eliminate it. – David Stephenson (Jessen, 2003; p.6)*

Waste is created throughout the life cycle of a product, from the extraction of raw materials to the final product. So, reusing items or reducing material consumption avoids all life-cycle emissions and decreases waste production dramatically. Source reduction has a great impact on the whole waste management hierarchy because fewer materials will be needed to be recycled or sent to landfills or incinerated. In other words, a shift from the designing and selling of products to designing and selling products and performance that the product delivers is necessary for sustainability (Manzini and Vezzoli, 2003). Programs and policies that focus on source reduction include:

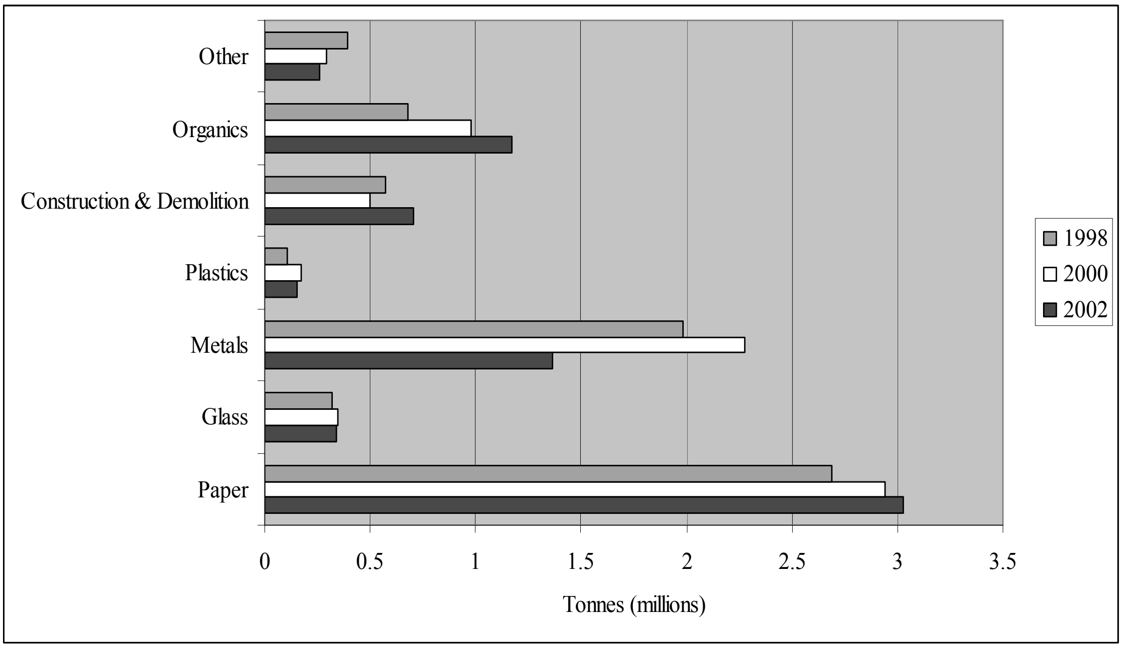
- Extended Product responsibility (EPR): EPR programs at source encourage producers to take the full economic responsibility of the product from cradle to cradle.
- Take Back Programs: Xerox's worldwide cartridge return program allows customers to return used products back via a prepaid return label.
- Pay-as-you-throw: These programs force citizens to pay for their waste disposal and are very effective at reducing waste disposal in landfills. In order to pay lower waste bills, households reduce waste sent to landfills at the source.
- Waste Diversion Acts: Waste Diversion Acts aim at obligating the manufacturers to fund a recycling program.

2.5.2 Recycling

Recycling reduces the need to extract and process raw material, meaning that less energy is often consumed during the manufacturing stage of products that use recycled materials compared to virgin materials (Table 6). Metal recycling was at its peak in 2000, but decreased by almost 30% in 2002 because some recycled metals are of poor quality and cannot be reused until mixed with high quality material (Figure 2). For example, the steel acquired from melting automobile parts can only be used for reinforced concrete but not for making new cars. Sorting waste at its source helps in recovering cleaner and higher quality recyclables (Zickiene et al., 2005).

In 2000, 981 Kt of organic materials were diverted from landfills, which comprised 16% of the 6.1 Mt of total waste diverted from landfills in Canada (Figure 2). Paper recovery rates have gradually increased from 26% in 1990 to over 40% in 2002

(Statistics Canada, 2002). The diversion of materials from landfills has many environmental benefits, including GHG emission reductions due to the reduced use of virgin materials. Recycling reduces GHG emissions from aluminum by 3.9 metric tons of carbon equivalent per tonne of material (MTCE/ tonne) and fine paper by 7.37 MTCE/tonne compared to landfilling (Mohareb et al., 2004). However, recycling is not impact free, as process residues still need to be disposed of at landfills.



(Source: Thompson et al., 2006; Statistics Canada, 2000 and 2002)

Figure 2: Materials recycled by type in 1998, 2000 and 2002

2.5.3 Composting

The biological transformation of waste is the breakdown of organic waste through a combination of biological and chemical processes. Organic waste can be biologically decomposed in two ways: by anaerobic digestion which generates methane and by composting which does not (Mohareb et al., 2004). Anaerobic digestion is the decomposition of organic materials in the absence of oxygen. This type of biological decomposition of MSW is usually undertaken for power generation from the methane it produces (Table 7). This process has the potential to reduce the 23 Mt of Canada's carbon dioxide equivalent GHG emissions, as well as the waste being disposed of in landfills (Mohareb et al., 2004).

Composting is an aerobic process whereby GHG emissions can be avoided through sufficient aeration and the final organic residue can be used as fertilizer. Composting can avoid 1.2 t CO_2e/t of food waste and 0.7 t CO_2e/t of yard waste compared to landfilling (Mohareb et al., 2004). Canada diverts 3% of its total waste through composting programs and this is likely to increase, as locating new landfills can be challenging. A study done by Brunt in 1985 showed that approximately 300kg-500kg of compost can be generated from one tonne of MSW (Mohareb et al., 2004). Another advantage of composting is that it requires very little capital investment. In addition, composting is likely more acceptable than incinerators to the Canadian public, as the number of centralized composting facilities have increased from 255 in 2000 to 351 in 2002 (Statistics Canada, 2002). In 2002, 1.2 Mt of organic materials were composted at these 351 facilities and more will be needed to be constructed in the future if Canadians do not work to reduce their waste generation (Statistics Canada, 2005).

2.5.4 Incineration

Incineration, or thermal treatment, is the burning/combustion of MSW at high temperatures to reduce the volume of waste and to generate energy. Incineration can typically reduce the final volume of MSW by 80% and generate power, simultaneously (Mohareb et al., 2004). Incinerators can offset GHG emissions and the residue from the incineration process can be either landfilled or used in cement. Along with these advantages, however, are many disadvantages, like pollutant emissions (e.g. nitrous oxide, dioxins, difurans, etc.) and huge capital costs. Incineration can play a major role in reducing landfilled materials, but presently isn't prevalent in Canada due to its negative public perception of resulting in adverse health effects from its emissions. Public perception of incineration may remain negative, since the pollutant emissions were the basic reason for banning incineration in Ontario in 1992 (Mohareb et al., 2004).

Incinerators emit nitrous oxide, which has a global warming potential over 296 times that of carbon dioxide and accounted for 17% of Canada's GHG emissions in 2000 (Mohareb et al., 2004). Other air discharges, including dioxins, can be controlled to meet environmental legislative regulations by using expensive filters (McKay, 2002). However, incinerators can also displace energy production, which has the effect of offsetting emissions that would otherwise be generated by traditional power stations (i.e., powered by fossil fuels) (Petts, 1994). In addition, incinerators do not significantly contribute to climate change (e.g. the 21 MSW incineration facilities in Canada have generated about 350 Kt of greenhouse gases from just over 1Mt of waste in 2002 (Statistics Canada, 2006).

2.5.5 Landfills

> *"The largest thing in the world made by humans is an old landfill. The Fresh Kills Landfill on Staten Island is bigger than the Great Wall of China. It covers 2,100 acres, and is so large it can be seen with the naked eye from space." (Jessen, 2003; p.9)*

Unlike the Great Wall of China, this massive landfill is not something of which to be proud. This landfill is simply a result of our general ignorance of the effect of being a wasteful society Canada, unfortunately, is a very wasteful society, as landfilling is the most common way to dispose of MSW in Canada. These sanitary landfills can be viewed as biochemical reactors where the organic waste undergoes anaerobic decomposition to generate LFG and leachate: "Canadian landfills generate about 24 MT of greenhouse gas emissions annually, primarily from methane" (Government of Canada, 2004). Canada currently has 44 landfill sites with landfill gas recovery systems. Of the 44 landfill sites, 16 utilize the gas for electricity generation or direct heating. Currently, over 82 MW of electricity is generated from landfill gas in Canada (Environment Canada, 2003).

It is important to note that regardless of how successful diversion programs are, there will likely be some materials that cannot undergo any further treatment. Therefore, landfills are necessary, but should not be the primary option for waste management. It is evident from the sheer quantity of waste entering our landfills that the root cause of our waste management problems stems from a lack of understanding of the nature of our waste stream. It is this ignorance that has resulted in Canada's poor waste management track record.

2.6 A Canadian success story

In 1995, Nova Scotia introduced a solid waste-resource management strategy to achieve 50% waste diversion by 2000 from 1988 levels (RRFB, 2005). In order to achieve this target, a Resource Recovery Fund Board (RRFB) was established by the province to divert waste from landfills by funding municipal programs, developing industry stewardship programs, administering recycling programs, etc. The province developed a final independent report in 2004 to study waste reduction using the Genuine Progress Indicator (GPI) instead of the economic growth indicator GDP (GPI Atlantic, 2004; Colman, 2001). This is because GPI recognizes resource extraction and use as a cost and waste reduction initiatives as gains rather then costs to the economy. The following outcomes were from the detailed evaluation of Nova Scotia's waste strategy using full-cost accounting principles of the GPI, which consider recycling programs as costs but consider extended landfill life and energy savings from recycling as benefits (RRFB, 2005):

- 99% of residents with curbside recycling
- 76% of residents with curbside organic pickup
- Significant diversion of waste material

2.7 Waste Management Options Comparison

Table.7 provides interesting information on the net GHG emissions from selected materials that can be used to compare various waste management options. As an example, consider recycling 100 tonnes of aluminum cans: this would reduce GHG emissions by 428 metric tonnes of carbon equivalent. The emissions generated during the landfilling of these cans are due to the equipment operating on the landfill site (EPIC, 2002). As shown in Table.7, every tonne of newspaper waste that is avoided would reduce GHG emissions by one metric tonne carbon equivalent (MTCE), while landfilling that same amount of newspapers would result in a reduction of 0.25 MTCE. Similarly, for aluminum cans, recycling offers excellent GHG emission reductions (4.28 MTCE) compared to landfilling (0.01 MTCE). The following table shows decisively the ability of "source reduction" to reduce GHG emissions.

Table 7: Net GHG emissions from Waste Management Options (MTCE/tonne)

Material	Source Reduction	Recycling	Composting		Incineration			Landfilling
			Aerobic	Anaerobic	17.8% eff	37% eff	50 % eff	
Newspaper	-1.00	-0.95	NA	-0.03	-0.24	-0.52	-0.70	-0.25
Office Paper	-1.14	-0.00	NA	-0.08	-0.21	-0.44	-0.60	0.58
Box board	-0.86	-0.77	NA	-0.05	-0.21	-0.44	-0.62	0.04
Broad Definition	NA	-0.74	NA		-0.21	-0.44	-0.60	0.07
Residential Definition	NA	-0.67	NA		-0.21	-0.44	-0.60	0.03
Office Paper definition	NA	-0.93	NA		-0.20	-0.43	-0.60	0.11
Aluminum Cans	-3.28	-4.28	NA	NA	0.03	0.03	0.03	0.01
Steel Cans	-0.93	-0.63	NA	NA	-0.53	-0.53	-0.53	0.01
Glass	-0.15	-0.09	NA	NA	0.02	0.02	0.02	0.01
HDPE	-0.67	-0.41	NA	NA	0.23	-0.42	-0.87	0.01
LDPE	-0.98	-0.54	NA	NA	0.23	-0.42	-0.87	0.01
PET	-1.08	-0.68	NA	NA	0.26	-0.08	-0.31	0.01
Food Scraps	NA	NA	0.00	-0.05	-0.06	-0.17	-0.19	0.17
Yard trimmings	NA	NA	0.00	-0.03	-0.08	-0.14	-0.23	-0.12
Mixed MSW	NA	NA	NA		-0.04	-0.21	-0.32	-0.02

(Source: Adapted from EPA, 1998)

* Note: A positive number denotes a GHG emission while a negative number denotes a reduction in emissions. The higher the negative number, the higher GHG emissions reduction.

- NA: Not applicable, or in the case of composting paper, not analyzed.
- MTCE/ton: Metric tons of carbon equivalent per short ton of material. Material tonnages are on an as-managed (wet weight) basis.
- Source reduction assumes initial production using the current mix of virgin and recycled inputs.
- There is considerable uncertainty in our estimate of net GHG emissions from composting; the values of zero are plausible values based on assumptions and a bounding analysis.
- Values are for mass burn facilities with national average rate of ferrous recovery.
- Values reflect projected national average methane recovery in year 2000.

2.8 Solid Waste Regulations

Regulations have been developed by provincial governments to govern waste management operations in Canada (Government of Canada, 2004). Municipalities have the liberty to choose a waste management program, limit waste disposal, raise disposal prices, or do whatever it is that best fits their needs and/or abilities. The most common regulatory measure used to limit waste disposal is bag limits. Many municipalities recently started contracting waste management practices to private firms because some citizens consider them more cost effective than equivalent municipality operated firms (Statistics Canada, 2005). Millions of tonnes of organic waste have been composted through 18 composting plants in Canada due to the ban on organics at several Canadian landfills. Landfill bans in Nova Scotia have helped the province achieve its 50% waste diversion target by 2000 (Solid Waste as Resource, 2004). A few of the regulations from different provinces follow.

2.8.1 British Columbia

- A recycling regulation *Organic Matter Recycling Regulation* (B.C. Reg. 18/2002) restricts certain types of organic matter, like wood waste, bio-solids, and food waste from entering the disposal site (B.C. MOE website, 2002).
- A regulatory measure used by the district of Kootney in B.C. has banned all recyclable materials, including organics, from landfills since 2001 (Statistics Canada, 2005).
- The city of Vancouver has a garbage can limit of 10 per apartment building with weight not to exceed 20kg per can (Solid Waste By-Law, 2006).
- Effective from 2009, all landfills that receive 10,000 tonnes or more annually in BC are required to manage landfill gas (S.B.C. 2008, c.20, s.37).

2.8.2 Ontario

- According to Ontario's *3R regulations*, all municipalities with more than 5,000 residents are required to provide recycling and backyard composting services to their communities. (Green Ontario, 2006).

- Effective from 2008, all landfills larger then 1.5 million cubic meters in Ontario are required to capture landfill gas (Ontario Regulation 232/98).
- In Peterborough, Ont., a bag limit, which was implemented in 1995, has lowered the limit from 6 to 2 cans, after which residents pay per bag. This regulation has increased recycling by 49% between 1993 and 2001 (Statistics Canada, 2005).

2.8.3 Quebec

- An update to the 1978 regulation is underway, which would require landfills that receive over 50,000 tonnes of waste per year to regulate waste and capture landfill gas (Government of Canada, 2004).
- Since 2006, Quebec has a surcharge set at $10 per tonne that is applied to residual waste sent to landfills.

2.9 Best Management practices

2.9.1 Producer Responsibility and Voluntary commitments

Extended Producer Responsibility (EPR), which is emerging as a promising alternative to managing product waste, obliges producers to take responsibility for their products post-consumer until the end of the product's life (Spiegelman and Sheehan, 2005). In Canada, this producer responsibility has been established either as a policy or as a legislated EPR program since the nineties: e.g. Nova Scotia's Resource Recovery Fund Board (RRFB). Also, producer responsibility prevents the generation of waste and facilitates recycling by promoting the sustainable development of products. In EPR systems, products do not enter the waste stream, but are recovered through a collection scheme arranged by the producers for their customers (Spiegelman and Sheehan, 2005). "The consumers role is to support and participate in the system, such as endorsing municipal and provincial EPR policies, looking for environmentally benign products and taking waste to the appropriate collection point" (Solid Waste as a Resource, 2004; 110p). So, if every consumer participates and every producer commits to take back their products at the end of their life, then higher rates of recycling can be achieved. Therefore, producer responsibility can significantly reduce the volume of waste being disposed of at landfills. EPR programs have good diversion potential because additional resources are available to fund programs (Solid Waste as a Resource, 2004). However, there are also concerns with EPR. For example: who is responsible for an orphaned product at the end of its life, when the original company no longer exists? (Solid Waste as a Resource, 2004).

Voluntary commitments like office paper collection, etc., are made by waste authorities and a specific industry for minimizing or prevention of waste. In EPR systems, producers and municipalities work closely together to ensure that producers accept the responsibility that the regulations impose, which is not the case with voluntary agreements (Swedish EPA, 2005). A good example for voluntary commitments would be the Swiss Association for Information, Communication and Organization (SWICO), which is an industry led initiative, with more than 400 members that removes electronics from the waste stream for no extra fee (Solid Waste as a Resource, 2004). Ontario and Quebec are testing a form of EPR in which municipalities recover products for recycling, with partial repayment by the industry. Another approach being followed by a few other Canadian provinces (e.g. BC) is allowing producers to recover their own products, while the government sets standards (Spiegelman and Sheehan, 2005).

2.9.2 Ban on Landfilling Organic Waste

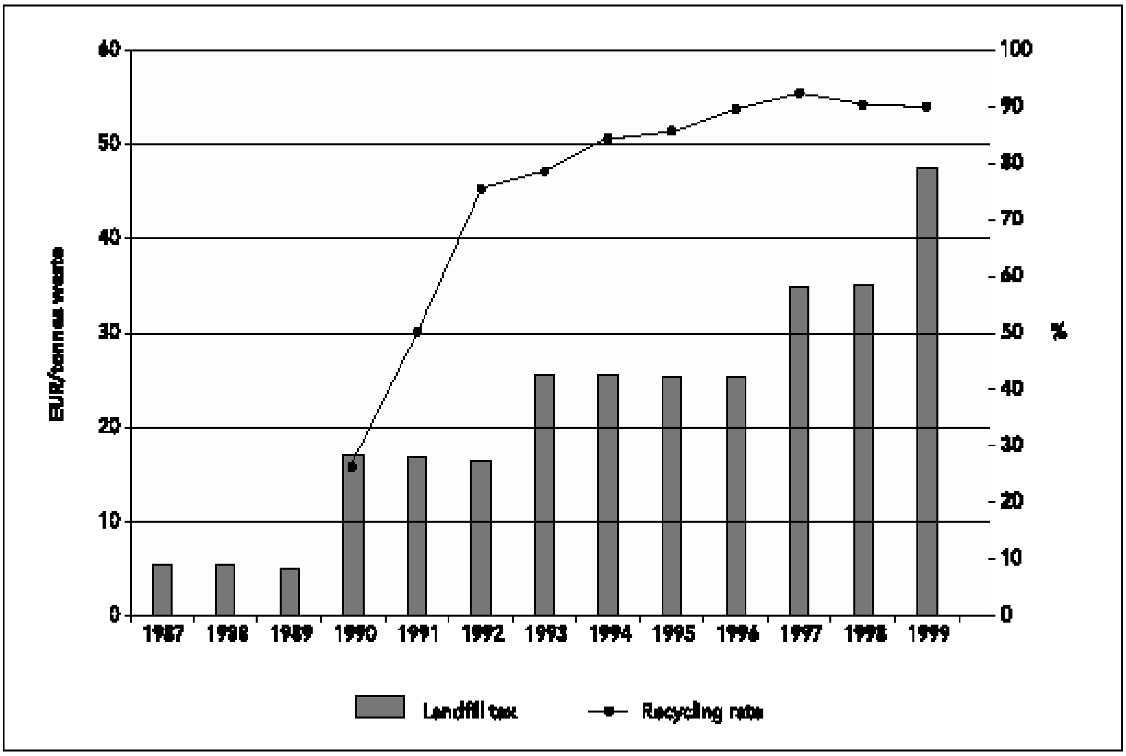
A ban on organics should be encouraged at all landfills because Canadians produce around 7 Mt of organic waste each year, most of which ends up in landfills (Thompson et al., 2006). The aim of a ban of this sort is to reduce environmental impacts and divert all organics and yard waste for composting. If a ban on organics is introduced at all landfills, the quantities of solid waste going to landfill will fall sharply, because organics constitute most of the MSW stream. A ban on organics has forced provinces to move towards composting, with Ontario (29%), Quebec (28%), British Columbia (18%), Alberta (13%) and Nova Scotia (6%) performing the bulk of the composting in Canada (Statistics Canada, 2000).

In Austria, a bio-waste ordinance came into force in 1997 to collect bio-waste separately and to limit the content of organic carbon to 5%. As a result of this ordinance, the recycled bio-waste rose to 13% in 1996 and the recovery of bio-waste has more then doubled (EEA, 2002).

2.9.3 Landfill taxes

A landfill tax "aims to encourage waste producers to produce less waste, recover more value from waste, for example through recycling and composting and to use more environmentally friendly methods of waste disposal" (EEA, 2002). A landfill tax is one of the economic instruments that is used in European countries. This instrument has been very effective for waste minimization. The objective of the tax is to increase the financial incentive to reduce waste quantities and to improve the relative competitiveness of recycling, composting, etc (Swedish EPA, 2005). The purpose of this tax is also to improve source separation, which allows the obtainment of cleaner and higher quality recyclables and at the same time helps to reduce the amount of waste that will be landfilled (Zickiene et al., 2005). This economic instrument is very easy to establish without many changes to the existing waste management system or regulations. But, before a landfill tax is implemented, people should have access to and knowledge of alternatives to landfilling. For a landfill tax to be effective, a weighing machine should be mandatory for all the landfills, which is a large investment that many small landfills cannot afford (EEA, 2002).

In Austria, a *Clean up of Contaminated Sites Act* was passed in 1996, encouraging old landfills to adapt to new technology. This act determines the amount of tax the landfill needs to pay. Because of the act, the tax is now determined not just by the type of waste entering landfills, but also by the quality of the waste and the equipment used in the landfills (EEA, 2002).



(Source: EEA, 2002).

Figure 3: Recycling rate for construction and demolition waste in Denmark compared to the landfill tax

In Denmark, a tax on landfilling waste has created a remarkable recycling market (Figure 3) for construction and demolition waste, which has prompted the Danish Government to set a 90% recycling target for the period 1998-2004 (EEA, 2002). Figure 3 clearly shows that recycling went up before the rise in taxes in 1992; this could be because the market actors wanted to show a change in their behaviour sufficient to warrant the government to reconsider the implementation of its economic measure (EEA, 2002).

2.9.4 Government Grants

A study showed that the amount of waste disposed in landfills was reduced by 370,000 tonnes in Sweden as a result of government grants of approximately 30% of the investment to improve waste management (e.g. composting facilities or E-waste collection facilities) (Swedish EPA, 2005). These grants have not only improved waste management, but have even reduced total GHG emissions by 2%. These government grants have proved to be very effective in many cases. In order to qualify for the grant, commercial properties in Sweden had to collect electronic waste. Even Canadian provinces offer grants like these to encourage waste reduction. The Community Environmental Projects Grants Program is helping small-scale communities in Ottawa to meet their objectives in solid waste diversion.

CHAPTER 3: RESEARCH METHODS

3.1 Study Area

The study area for this research project included only landfill sites that are Canadian, and are active and still accept MSW, even though information was gathered for both active and closed sites. This is because active sites can make a number of operational changes that closed sites cannot, in addition to applying waste diversion programs.

3.2 Definitions

Waste Generation refers to the amount of unwanted materials and products that enter the waste stream before diversion, landfilling, or incineration takes place (EPA, 1998).

Waste Disposal refers to the MSW remaining after diversion (recycling, composting). This waste is usually disposed of in landfills (EPA, 1998).

3.3 Approach

Municipal solid waste data and landfill information was collected by surveying the landfill managers. The following steps were taken to gather the data:

1. A ten page quantitative survey questionnaire, which included all the solid waste disposal data queries for landfills, was developed in conjunction with Environment Canada and Dr. Shirley Thompson (Appendix 1). The survey was initially tested with a few landfill managers to determine the time taken to complete the survey and to clarify the questions.

2. A database with all the major landfill sites information was developed by contacting each province's Ministry of Environment. In 1998, there were approximately

800 active landfills in Canada receiving just under 21 Mt of solid waste (Environment Canada, 2001). Of these 800 landfills, 300 landfills were contacted based on the availability of their contact information. This process was continued until a response rate of 130 was achieved.

3. Surveying landfills across the nation provided useful provincial waste data for quantifying the GHG emissions generated, which helped in designing better waste management strategies. Obtaining waste data was very challenging, as some landfills prefer to maintain confidentiality about their processes. Contacting solid waste managers from Public Works departments and solid waste associations have yielded positive responses regarding landfill contact information. I administered the survey through telephone and via email from September 2006 to April 2007. The survey was followed up at regular intervals after the initial call/email to those who could not respond initially. Special steps were taken during the design of the survey instrument to increase the response rate from landfill operators. The techniques included an Environment Canada letterhead, a user friendly format, and a cover letter with researcher and advisor signatures on the University letterhead.

The survey gathered site-specific data, like types of waste, composition of waste, and diversion activities, along with waste management practices that are being followed. The site-specific solid waste data gathered from the landfill survey was also more useful in improving current waste management practices compared to working with old government data. Some data on waste quantities and composition are available from various sources like Statistics Canada, government reports, and journals, but this landfill survey determined how effective the current solid waste management practices and diversion programs are in controlling waste from entering landfills.

4. The MSW data gathered from all the returned landfill surveys across Canada were entered and statistical analysis was performed to gain insight into the effectiveness of the MSW management practices to achieve waste reduction. I entered all the data into S-Plus 7.0 to analyze relationships between variables such as landfill fee, landfill depth, waste density, waste capacity, and diversion rates. As part of the landfill survey, waste disposal information since 1990 was also gathered to estimate landfill gas emissions.

Linear regression analysis was conducted to evaluate the simultaneous effects of five landfill operational factors on the rate of methane production from 29 active MSW landfills that have LFG recovery systems in place. Typically not all landfill gas is recovered and only 50% to 75% is recovered (Spokas et al., 2006). Therefore, a US EPA (2004) default of 75% was considered and 25% was added to the methane recovery rates to get "methane generation rates".

The following independent variables: depth, density, disposal fees, organic waste, waste diverted and current waste were selected based on results of univariate analyses, where methane generation rates have demonstrated association with the independent variable. I looked for strong linear relationship between the independent and dependent variables, and low correlations among the independent variables.

Once the independent variables were selected, the model was developed by examining the residual plots, which suggested that a multiple regression model was appropriate to isolate the relationship between the independent variable and the outcome variable from the effects of one or more other variables called covariates. Log transformation (base 10) of a few variables (current waste, waste diverted and organic waste) to satisfy the normality and homoscedasticity assumptions was necessary. Logged variables were interpreted in terms of percentage change. For variables that were not transformed, its exponentiated coefficient is considered. The parameter estimated value of each of the independent variables to "methane generation rates" was determined on the basis of t statistics and their P-values of the least-squares parameter estimates.

GHG emission reductions were calculated to better understand the impact of alternative waste management scenarios on GHG emissions. To track GHG emission reductions from different waste management practices, GHG emissions factors (EPA - Net GHG emissions from Waste Management Options) for each of the waste management options expressed in metric tonnes of carbon equivalent were used.

CHAPTER 4: RUNNING OUT OF ROOM AT THE LANDFILL: BEST PRACTICES FOR EXPANDING THE LIFE OF LANDFILLS FROM A 2005 CANADIAN LANDFILL SURVEY

4.1 Introduction

Greenhouse gas emissions, the poor environmental legacy of landfills, and economics of finding sites for new landfills, provide good reasons for Canadian policy-makers to revise waste management practices to reduce the ecological footprint of waste (El-Fadel, 1995; RCO, 1997). Canadians are one of the highest per capita producers of solid waste, with the average Canadian citizen generating 2.94 kg each day (Statistics Canada, 2008). Furthermore, waste generation is increasing, up by 19.4% from 2000 to 2006 (Statistics Canada, 2008), despite the introduction of new recycling and composting programs. Unfortunately, the positive impacts of waste diversion programs have been cancelled out by an overall increase in the amount of waste going into landfills (Statistics Canada, 2008). Statistics Canada (2008) estimates that 35 million tonnes/year of waste is generated, and that more than three quarters (78%) of this ends up in landfills. An estimated 50- 60% of the 35 million tonnes of waste is organics, which could be diverted away from landfills with the help of existing, low-cost technologies.

Diverting organic waste from landfill sites helps to conserve landfill space and to reduce the production of leachate and methane gas. Waste diversion at the household level is imperative, as households produce approximately 37% of Canada's MSW (Statistics Canada, 2008), but diversion of organics by business and industry is almost as important, as they produce the remaining 63% of the waste. Despite Canada adopting a waste management hierarchy for developing solid waste management strategies, landfills still remain the most dominant waste management method in the country, unlike in many countries in the European Union (EU) (Sawell et al, 1996).

This paper focuses on the ecological footprint of landfills and how landfills are impacted by both waste management programs (e.g., diversion programs, waste generation minimization) and landfill management programs (e.g., diversion fees, compaction and depth of landfill changes). Higher disposal fees may be a key factor in these programs, since increases in the price of managing landfill waste increases the cost-effectiveness of alternatives, such as composting, source separation of organics, and recycling. As well, limited landfill space should be utilized more effectively by employing compaction and creating deeper landfills. Deyle and Schade (1991) found that net recycling costs are less than landfill disposal costs when landfill disposal fees are more than $38 per tonne in large cities, and $65 per tonne in small cities. For recycling and source separation of organics programs to gain momentum, recycling and composting costs must be competitive with tipping fees (the cost to landfill waste), which will result in higher participation and recovery amounts of recyclables and organics.

4.1.1 Running out of room at the landfill

The disposal of waste in landfills removes scarce land from valuable agricultural production and development (Tammemagi, 1999). Rather than use acreage for the disposal of waste, it is preferable to use it for agriculture or development and/or maintenance of ecological integrity. In Canada, landfill space is currently in short supply as many of the nation's active landfills are expected to reach capacity within the next few years (McDavid and Verna, 1998). However, the scarcity of landfill space has not traditionally been a consideration in waste management decision-making (Curmally, 2004). Ideally, the current value of landfill space should be calculated based in part on the cost of acquiring a new site and developing and constructing a new sanitary landfill once the older landfill is full (Curmally, 2004). As well, the environmental impact and transportation costs associated with the construction of a new landfill should be considered. These costs represent what it is worth to society to prevent MSW from being landfilled.

There is a need to look at suitable alternatives to traditional landfill operations, by allowing more waste to fit into a landfill with the same surface area. Waste density can be increased by compacting waste mechanically, but compacting waste also changes the flow of moisture and nutrients through the landfill, which affects the landfill gas generation rate (Environment Canada, 1996). Increasing the density of MSW decreases the surface area for biological activity, which decreases the landfill gas production rate (McCabe, 1976). Deeper landfills are more economical for leachate infrastructure, land-base (i.e. property cost), and methane recovery. Furthermore, in cold climates, deep landfills provide ground insulation against the ambient temperature, which inhibits the decay of MSW and the growth and survival of the microorganisms that create landfill gas (Yesiller et al., 2005; Tchobanoglous et al., 1993).

4.1.2. Other problems with landfilling

There are many problems associated with landfilling. The organic waste in landfills also causes the formation of leachate and greenhouse gas emissions. Landfills often contain hazardous materials (El-Fadel et al., 1995). Additionally, siting a new landfill is politically divisive, since the "not in my backyard" syndrome occurs because nobody wants the increased risk of exposure to toxic material and/or lowered property value that result from a waste site moving nearby (Baxter et al., 1999). Expansion of existing waste disposal facilities or the siting and development of new disposal sites is politically and technically difficult because of stringent environmental regulations and public concern over potential contamination of ecosystems (Okeke and Armour, 2000).

4.1.3 Methane production

Due to high rates of waste generation per capita, limited organic diversion, and few landfills that recover methane, Canada has the second highest methane emissions per capita from solid waste disposal on land among the numerous countries in the United Nations Framework Convention on Climate Change Parties (UNFCC, 2003). Landfill gas (LFG) is made up of roughly half methane and half carbon dioxide (CO_2), which are two potent greenhouse gases, as well as small amounts of hydrogen, oxygen, nitrogen, hydrogen sulphide and trace amounts of non-organic compounds and volatile organic compounds (Gardner et al., 1993; Schumacher, 1983). In Canada, methane emissions account for approximately 12.6% of Canada's CO_2 equivalent (eCO_2) GHG emissions, with almost one-quarter (24%) of those emissions arising from landfills (Canadian Electricity Association, 2002). The amount of methane generated by landfills depends on the metric parameters of the landfill site (i.e., size, depth, density, and management practices), solid waste disposal rates, and composition (EPA, 1995).

The methane component of LFG contains energy that can be used to generate electricity, heat buildings, fuel industrial processes, or run vehicles (Qin et al., 2001). Utilization of energy from LFG not only aids in the control of local environmental impacts, but also avoids the consumption of fossil fuels that would otherwise be required to generate an equal amount of energy (Gonyo, 1996). To reduce GHG emissions, methane can be recovered in a catchment system for power or heat, or burned to reduce it to carbon dioxide (a far less potent GHG than methane). The gas can be collected and sent via pipeline to heat nearby industrial or agricultural operations; if enough gas is present it can be used to generate electricity, which can be sold into the power grid. For example, the 25 MW electricity generating plant at the Centre de Tri et d'Élimination des Déchets, one of the 52 landfills in Canada recovering methane, powered 8,200 single detached houses at an initial cost of CAD $37 million with a payback period of only five years (Natural Resource Canada, 2008).

Although landfill gas comprises only about 3% of Canada's GHG emissions (Environment Canada, 2006), some Canadian provinces are targeting methane capture. The Ontario government made it mandatory for new and existing landfills to install a system to capture methane if the operating landfill is larger than 1.5 million cubic meters; this action will have the effect of reducing GHG emissions by over 4 million tonnes per year (SWANA, 2008). However, many other provinces have not begun to consider regulations that either ban organics from landfills or require landfill gas recovery.

The prevention of methane reaching the atmosphere, rather than using the methane to produce energy, produces the largest GHG reduction: 95% of the benefit of preventing methane from reaching the atmosphere is related to climate change and only 5% to the energy gain (CEC, 1996). Despite its benefits, methane recovery is essentially an "end of the pipe" solution, which does not actively tackle the root cause of waste generation. Source separation of organics for composting reduces methane generation, as does recycling paper and cardboard (Thompson and Tanapat, 2004).

4.1.4 Waste Diversion Programs and Policies that can make a difference

Waste diversion, particularly combined with other policies like disposal limits and bans, results in landfill emission reductions and extends the life of landfills. Policies are needed to support waste diversion programs. Recycling programs started at the municipal level in urban centres in the mid to late 1980s (Thompson et al., 2008; Statistics Canada, 2002), but are not available in many rural and northern communities. Table 1 shows the programs currently operating in Canada, but these are generally regional or provincial and not wide-spread across the country. However, deposit-refund systems for bottles, which provide a cash incentive to recycle that improves recycling rates, exist in most provinces, with the exception of Ontario and Manitoba. The "recycling credit" concept has been in practice in the EU for quite sometime (Turner et al., 1995), but not in Canada. A recycling or tax credit represents the value of the savings made by the municipality by diverting (i.e. recycling) households' waste (Scharf, 1999). These savings can be paid back to the recyclers that are involved in collecting household waste for recycling (Turner et al., 1995).

User pay systems for garbage collection encourage recycling and composting by providing users with an economic disincentive to dispose of materials that can be recycled or composted and exist in a number of Ontario and British Columbia communities, including Stratford, Ontario. Source reduction focuses on reducing waste at the source by rejecting over-packaging and disposable products and encouraging extended producer responsibility that changes product design and/or manufacturing processes to create more sustainable practices (Ferrara and Missios, 2004; Sterner and Bartelings, 1999). The "pay-as-you-throw" and "bag-limit" systems designed and followed by the EU, USA, and a few Canadian municipalities also help to reduce MSW.

Converting waste into nutrients by diverting and treating organic waste is practised to various degrees in approximately 30% of households across Canada (Statistics Canada, 2004). In most municipalities, curb-side composting programs are limited to the collection of yard waste, but others (i.e., Halifax Regional Municipality, Toronto Region, Edmonton, etc) also collect food waste. Bans on organics in landfills are in place in Nova Scotia (NS) (since 1998) and Prince Edward Island (PEI), with curb-side organic waste pickup available to 70% of NS residents (Friesen, 2000) and year-round curb-side pickup to all PEI residents for $175 a year. In response to NS' landfill ban on organics, Halifax Regional Municipality achieved a 68% organics diversion; this landfill ban on organics also resulted in NS reducing its waste disposal rate to about half that of other provinces, with an overall 56% diversion rate from landfills (Thompson et al., 2008; Wagner and Arnold, 2006). Halifax's rate of organic diversion almost reaches those of 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 nation-wide policies that require source separation of organics. Austria's waste diversion rate of 87% was accomplished in part by a large number of people composting at home and the high diversion rate reduced municipal landfill and waste collection costs (ECN, 2007). Source separated organic municipal programs are a more recent development, only starting to become popular across Canada in early 2000 (van der Werf and Cant, 2006). Diversion of 50% of Canada's organic waste, or 2.9 million tonnes/year, through composting is considered feasible according to van der Werf and Cant (2006). Higher disposal fees encourage this diversion, particularly when alternatives like recycling or organic source separation are less expensive by comparison. Extended producer responsibility for some products, such as engine oil, has consumers returning the product at the cost of the producer, who then can recycle the product.

Table 1: Programs and Policies to Improve Waste Management in Canadian and other Jurisdictions

Policy Option	Jurisdictions enacting	Program, policy or regulation
Landfill disposal ban on organics Composting	NS, PEI	Ban organics from municipal landfills which requires municipalities to start composting promotion programs and/or separate source organics pick-up.
Mandatory Recycling	Pennsylvania, U.S.	Source separation of materials and/or their subsequent recycling
Tipping fee surcharges	GVRD – BC	Extra fee in addition to tipping fees ensuring economic viability of alternatives
Deposit-refund systems	Most provinces except Ontario and Manitoba	Require consumer pay deposits on items, which are refunded upon return for diversion
High disposal fees	Most municipalities in Ontario and British Columbia	Landfill rates per tonne are priced higher than recycling or composting, thereby making diversion the economic choice
User Pay Systems	Few cities in Ontario (e.g., Stratford) and in BC	Residents pay by unit volume or weight for waste services
Extended Producer Responsibility	Number of products in all provinces	Consumer pays an up-front fee to cover the recycling of this product (e.g., oils, tires)
Mandatory landfill gas recovery	Ontario for large landfills	Landfills required to recover methane
Bag limits	Some locations in Ontario	Limits on the number of garbage bags collected

(Source: Adapted from information in FCM, 2004 with new information obtained from our National Survey)

I surveyed municipal landfills across Canada from September 2006 to April 2007. Statistics Canada does a survey of waste management every two years but this does not consider landfill audits or landfill management characteristics (Statistics Canada, 2004), unlike our survey.

4.2 Methods

1. Surveyed 300 landfills regarding waste and landfill gas collecting a 12 page survey on waste management, landfill management, and methane emissions and

collected waste audit data; whenever possible, this was done in co-operation with Environment Canada (Appendix 1).

2. The survey findings were compared with Statistics Canada (2004) data to determine representativeness of our sample. And, per-capita waste generated was calculated using equation 1 as the total waste from our sample (13.5 million tonnes) was 41% of that of Statistics Canada, which represents the whole of Canada's waste. We divided the total waste by population of Canada x 41% to estimate per capita waste from our sample:

$$C = T / (41\% * P) \tag{1}$$

C = per capita waste
T = total waste in national survey sample = 13.5 million tonnes
P = population of Canada in 2005= 32 million (Statistics Canada, 2008)

In this study, the landfills were widely distributed geographically and their catchments encompassed a diverse collection of sites. Therefore, this comparison is for the quality of the data collected, which depends on how representative the sample is.

3. Waste composition data which was a subsample of the total survey (*n*=17) was analysed to study the municipal solid waste stream break down. Seventeen active landfills had waste composition audit data available. For this study, a waste stream analysis was used to determine the composition of MSW which was classified into six material categories. The waste composition percentages of each material were provided by the landfill managers.

4. The survey data was descriptively summarized (averages and standard deviation) by province to determine how waste management differs by province for landfill capacity, waste generation, waste diversion, disposal fees, landfill depth, and waste compaction using S-Plus 7.0.

Simple linear regressions were conducted to evaluate the linear relationships between landfill operational practices. The assumptions for each linear regression, namely, independence, homoscedasticity and normality, were tested using residual plots and normal-probability plots.

5. The impact on landfill space (years remaining) was determined assuming few different scenarios i.e. if waste diversion rate is increased to either 50% or 75% from the current rate. Additionally, 40 meters depth and 1000 kgs/m^3 density of waste along with an attainable 50% diversion rate were taken into account to determine the duration of the remaining waste capacity in one of the scenarios. The landfill waste capacity scenarios for the 97 active landfills were calculated using equation 2:

$$R = C - (W * 1.08^t) * D \qquad (2)$$

R = Remaining landfill capacity (million tonnes)
C = waste capacity (million tonnes)
W = waste landfilled (million tonnes)
t = time (annual increases in waste of 8% is estimated)
D = waste diversion rate (assumed 50% scenario and 75% scenario)

A consistent annual increase of 8% per year for total waste landfilled was assumed based on this being the average increase in landfilled amounts in the years 2003, 2004, and 2005.

The remaining capacity was calculated by subtracting the extrapolated annual waste disposal amounts from the total available airspace (capacity). This method relied entirely on assumptions about waste diversion and disposal rates.

4.3 Results and Discussion

1. Landfill participation in the Canada-wide survey

The response rate for the Canada-wide survey was 43%, with 130 landfills responding, of which 97 were active. The response rate for landfills capturing landfill gas was 100%, or 52 out of 52.

2. Survey findings compared to Statistics Canada

The sample represented 13.5 million tonnes of waste/year, which is 41% of the total amount of waste calculated by Statistics Canada (2004). Statistics Canada's waste generation estimates represent the total waste produced in Canada through imputing missing data not obtained in their "Waste Management Industry Survey for Business and Government Sectors" every two years. In our sample, 1.7 million tonnes (12.6%) was diverted and 11.8 million tonnes (87.4%) was disposed of in landfills, as reported by landfill managers. Landfill managers reported that approximately 60% of the waste disposed of in landfills was organic waste. A finding of 2.82 kg of waste per capita was slightly higher than the estimate of 2.62 kg per capita for 2002 (Statistics Canada, 2004) but lower than the estimate for 2006 of 2.94 kg/capita (Statistics Canada, 2008). Although the total amount of waste diverted from landfills was about 12.6% in 2005, the overall quantity of waste disposed of increased by 8% between 2004 and 2005. This increasing waste generation rate essentially cancelled out any reductions in landfilling made by diversion programs.

3. Landfill waste composition data

Seventeen active landfills in four different provinces (Ontario, Quebec, Alberta, and British Columbia) had waste composition audit data (Table 2). The organic composition in landfills ranged from 41% to 100%, with an average of 63% (SD = ± 6).

This data shows that organic waste diversion has the potential to decrease waste amounts by more than half. Figure 1 separates the organics fraction into its basic categories for the 17 active landfills. Organic waste had a normal distribution with a low dispersion. The sample for recyclables and other waste was not normally distributed.

Table 2: Summary of Mean Averages and Standard Deviation of Audited Waste Composition for Each province (by weight)

Province	*% Organic Waste*	*% Recyclables*	*% Other Waste*
Alberta (*n*=5)	59 ± 15	8 ± 4	33 ± 16
British Columbia (*n*=4)	65 ± 11	10 ± 9	25 ± 18
Ontario (*n*=5)	58 ± 10	12 ± 10	30 ± 8
Quebec (*n*=3)	69 ± 19	6 ± 4	25 ± 15
Canadian Average	**63 ± 6**	**9 ± 3**	**28 ± 4**

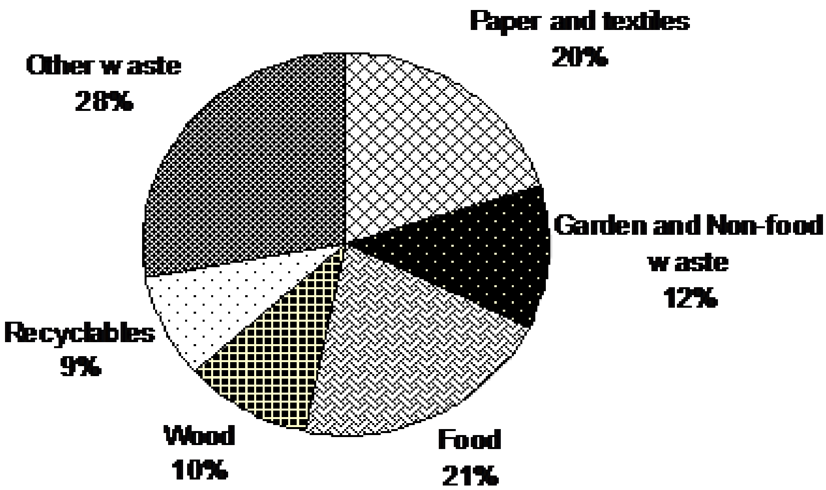


Figure 1: Waste Composition (by weight) from audits of 17 landfills across Canada

4. Findings regarding waste management and diversion

In 2005, according to the 97 active landfills surveyed, approximately 87.4% of the solid waste was landfilled and 12.6% was recycled or composted. The Industrial, Commercial, and Institutional (IC&I) waste comprised 35% of the total, as shown by Table 3, which shows the amount of MSW generated by each sector provincially.

Table 3: Canada's municipal solid waste classified by source in 2005

Province	*% Residential*	*% IC&I*	*% C&D*	*% Other Waste*
British Columbia (*n*=6)	42	45	11	2
Alberta (*n*=30)	51	25	14	10
Ontario (*n*=34)	59	27	10	4
Quebec (*n*=15)	52	35	7	6
New Brunswick (*n*=5)	43	25	31	1
PEI (*n*=1)	28	57	13	2
Nova Scotia (*n*=6)	27	31	41	1
Average	**43**	**35**	**18**	**4**

Thirty percent of the 97 active landfills had organic waste diversion of at least 10,000 tonnes each in 2005. As shown in Table 4 the diversion rates are especially high in the Atlantic Provinces, where PEI and NS prohibit organic materials in landfills. The diversion rate in PEI and NS is 54% and 22%, respectively (Table 4). The higher diversion rate in PEI reflects landfill closures in the year 2000 of all but one landfill, which strictly prohibits organics. NS has 17 landfills, including 10 construction and demolition (C&D) landfills, and 70% of the population source separates their organics, receiving curb-side organic waste pick-up (Wagner and Arnold, 2006). A few other municipalities use user-pay systems e.g., bag tags, weight based, subscription etc. (Wagner and Arnold, 2006; FCM, 2004).

Organic waste generated by households mostly includes kitchen (e.g., food waste) and green (e.g., grass clippings and leaves) waste. In 2005, only a small portion of this waste stream was recovered or composted. Overall, in 2005, of the 12.6% of the total waste Canadians diverted across the 97 landfills, approximately 60% of these diverted materials were organics. In 2005, curb-side organic waste collection programs were implemented in many jurisdictions and the tonnage estimated to be composted at centralized composting facilities was approximately 7% of the landfilled waste. Diversion programs for recyclable materials were in place in most urban locations, but less than 805 kilo tonnes (kt) of recyclables were diverted in 2005. While two Canadian provinces ban organics in landfills, no municipalities in the survey have similar bans. Organic waste diversion is typically voluntary at the household and business level. Only in a few communities in Canada is there an incentive to divert organics, in the form of a user pay systems or charge per bag. However, in municipalities where the cost of disposal is high such as Halifax, NS, there is a strong incentive to implement curb-side compost programs to avoid costs. If households and businesses can reduce organic waste going to landfills, there will be a great weight reduction in the total amount disposed of in landfills because organics contribute up to 60% of the MSW waste stream. Therefore, any instrument that maximizes waste reduction behaviour will ultimately result in reduction of the amount of waste sent for disposal and an increase in diversion rates.

Table 4: National survey findings for 97 (active sites) of 130 landfills organized by province in 2005

Province	Average landfill life remaining (years)	Average Landfill Depth (m)	Total Waste disposed in 2005 (tonnes)	Current Waste (tonnes)	Waste Capacity (tonnes)	Average Density (kg/m3)	Average Disposal Fees ($)	Waste diversion rate (%)
AB (*n*= 30)	40 ± 38	15 ± 8	1,443,681	22,674,427	102,054,139	500 ± 350	25 ± 20	13 ± 9
BC (*n*=6)	22 ± 15	18 ± 3	1,287,247	25,898,000	53,800,000	900 ± 150	65 ± 0	29 ± 18
NB (*n*=5)	92 ± 38	17 ± 3	281,447	3,287,849	22,775,000	750 ± 60	61 ± 8	3 ± 3
NS (*n*=6)	34 ± 22	25 ± 6	275,324	1,520,699	10,045,760	730 ± 180	64 ± 30	22 ± 11
ON (*n*=34)	17 ± 16	21 ± 8	3,911,351	64,234,313	155,156,327	725 ± 250	63 ± 21	12 ± 12
PEI (*n*=1)	11 ± 0	22 ± 0	33,376	148,400	371,000	700 ± 0	100 ± 0	54 ± 0
QC (*n*=15)	25 ± 15	22 ± 13	4,821,571	105,315,590	196,313,230	900 ± 200	50 ± 23	6 ± 6
Unweighted Average* or Total	**Average 34 ± 27**	**Average 20 ± 3**	**Total 12,053,997**	**Total 223,079,278**	**Total 540,515,456**	**Average 750 ± 135**	**Average 62 ± 22**	**Average 20 ± 17**

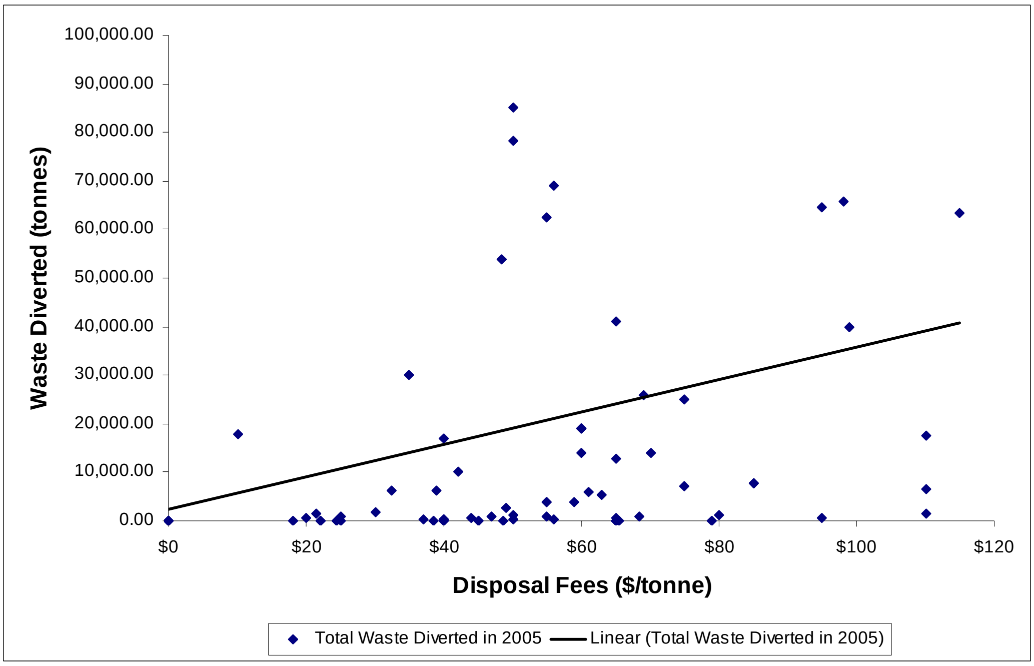


Figure 2: Waste diversion (tonnes) versus Disposal fees at 97 Canadian landfills

Higher disposal fees were positively related to waste management practices, increased composting rates (Figure 2), greater compaction of waste (Figure 3), and increased depth of landfills (Figure 4). A higher disposal fee was statistically significantly related to higher waste diversion with a R^2 of 0.226 (P-value < 0.05), indicating that 23% of the variation of waste diversion was explained by landfill disposal fee (Table 5).

Table 5: Simple Linear model summary for Disposal Fees vs. Waste Diverted

Variable	Parameter Estimate	Standard Error	*t* Stat	*P*-value[2]
Intercept	-3880.348	3317.297	-1.170	0.245
Disposal Fees	285.636	57.311	4.984	0.000

Typically, landfills with higher disposal fees have higher diversion of waste. For example, Otter Lake landfill in Halifax, Nova Scotia has a disposal fee of $115.00/tonne and diverted 30% of its total waste in 2005. Another example is the City of Orillia landfill in Orillia, Ontario; this landfill charges a disposal fee of $110.00/tonne and diverted 35% of its total waste in 2005. The average disposal fee across Canada is $62 ± 22, with much

[2] The smaller the *P*- value, the greater the influence of the independent variable

lower fees in Alberta ($25 ± 20) and much higher rates in PEI ($100). Landfill disposal fees have not only promoted higher rates of waste diversion, but have also prompted landfill managers to use best management practices, like high density waste compaction (Fig 3) and increased landfill depth (Fig 4), to extend landfill life. A simple summary of the regression output for these relationships is given by the following tables (Table 6 & 7)

Table 6: Simple Linear model summary for Disposal Fees vs. Density

R^2	0.316			
Variable	Parameter Estimate	Standard Error	*t* Stat	*P*-value
Intercept	368.788	57.563	6.407	0.000
Disposal Fees	6.231	0.994	6.265	0.000

Table 7: Simple Linear model summary for Disposal Fees vs. Depth

R^2	0.211			
Variable	Parameter Estimate	Standard Error	*t* Stat	*P*-value
Intercept	6.856	2.156	3.181	0.002
Disposal Fees	0.177	0.037	4.766	0.000

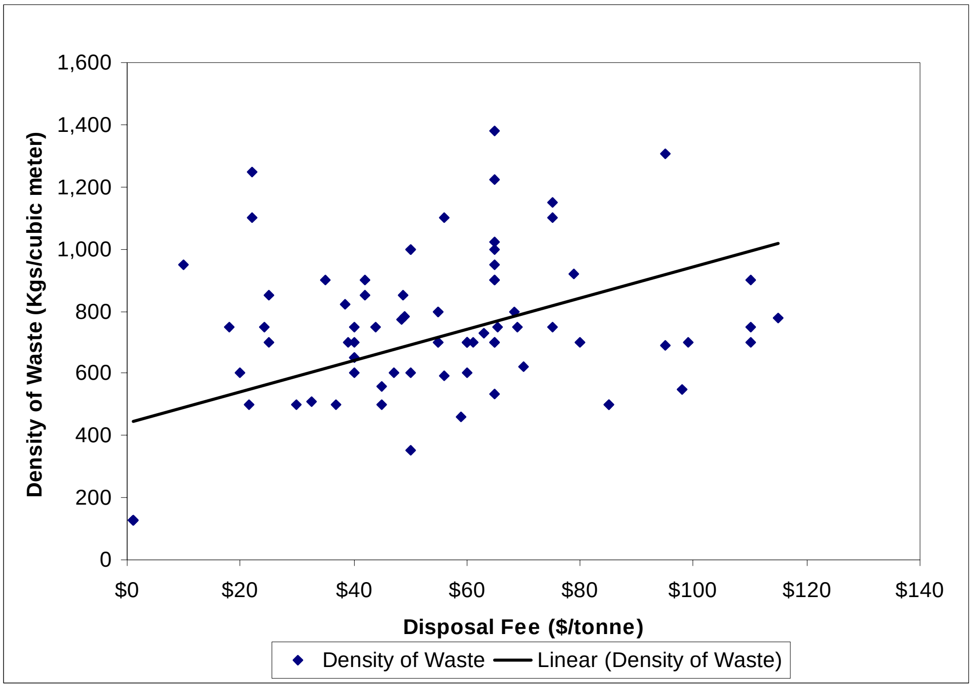


Figure 3: Density of Waste in kg/cubic meter versus Disposal Fee for 97 Canadian landfills

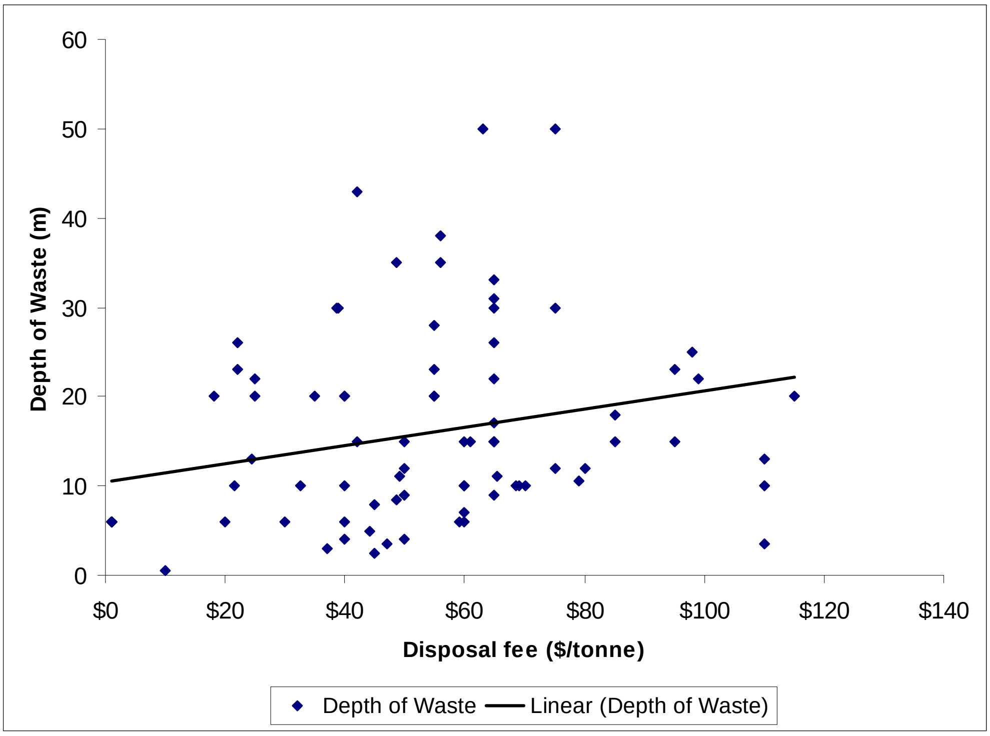


Figure 4: Landfill Depth in meters versus Disposal Fee for 97 Canadian landfills

Major landfills are saving space by having higher rates of waste compaction and increasing their landfill depth. The average density of waste is approximately 750 kg/cubic meter, with the national range varying from 125 to 1300 kg/cubic meter. Compaction is practiced by all major landfills. However, most smaller landfills receiving less than 5000 tonnes per annum of waste do not practice compaction. A higher disposal fee is statistically significantly (P-value < 0.05) related to the density of waste, with an R^2 value of 0.316. The relationship in Figure 3 has a slope of 6.23, indicating that whenever disposal fees raises by one dollar, density increases by approximately 6.23 kg/cubic meter.

A higher disposal fee is statistically significantly (P-value < 0.05) related to the depth of landfills, with a R^2 of 0.211. Figure 4 shows that for every increase in disposal fee of one dollar a 0.18 meters deeper landfill occurs. The average depth of Canadian landfills is 20 meters, with a large variability across provinces with the deepest being 50 meters. Deeper landfills help improve landfill capacity and landfill methane recovery. Figure 5 shows that deeper landfills tend to also compact their waste. This seems to indicate that when landfills operators recognize the benefits of one of these actions (i.e., increasing depth or compaction) they typically recognize the benefits of doing the other (Table 8).

Table 8: Simple Linear model summary for Depth vs. Compaction of Waste

R Square	0.291			
Variable	Parameter Estimate	Standard Error	*t* Stat	*P*-value
Intercept	438.891	50.371	8.713	0.000
Depth	15.463	2.620	5.902	0.000

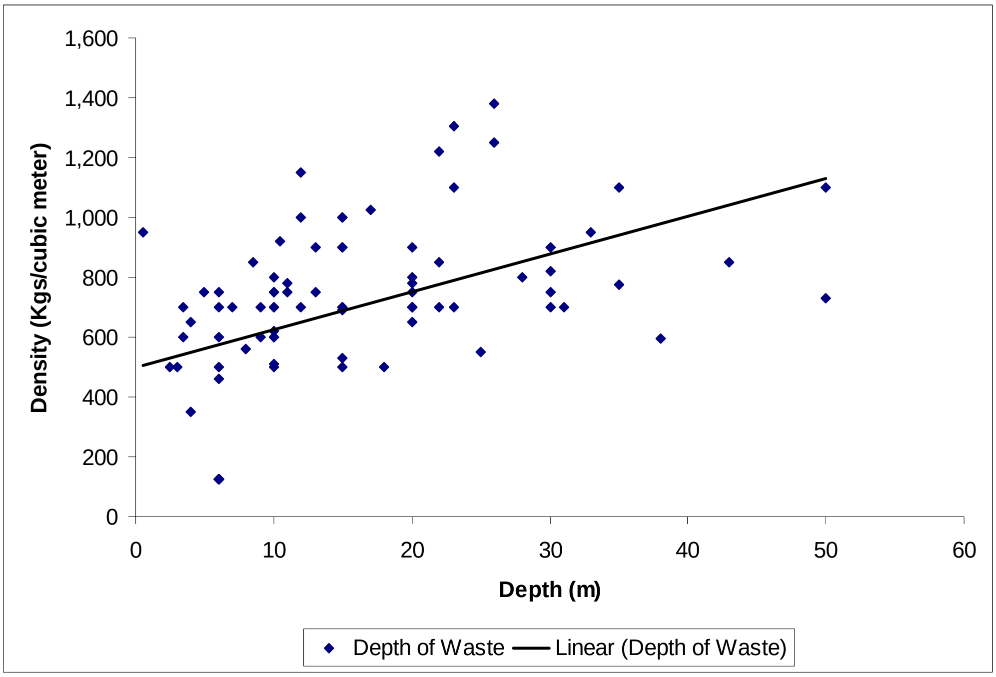


Figure 5: Density of waste versus Depth of landfills across 97 active landfills

5. Findings of landfill lifespan

Almost one third (30%) of the landfills surveyed reported closure dates of before 2010-2012 and almost one-half (45%) of the landfills are predicted to run out of space in the next 15 years (by 2020). The existing 97 active landfills currently have 540 million tonnes of landfill capacity. The average life span reported for active landfills is 50 years, but the average lifespan of closed landfills was only 20 years. The higher lifespan of active landfills suggests that either the more recently constructed landfills are currently being built larger or that managers are overestimating the lifespans of landfills. The service lifespan for which the landfills were designed ranges from five years to 150 years. Conserving landfill space through increased waste diversion allows the service lifespan of the landfills to be almost doubled which can extend a landfill by seven to fifteen years. Increasing compaction and depth increases the space for waste that cannot be reasonably diverted through other waste diversion programs (Fig 6).

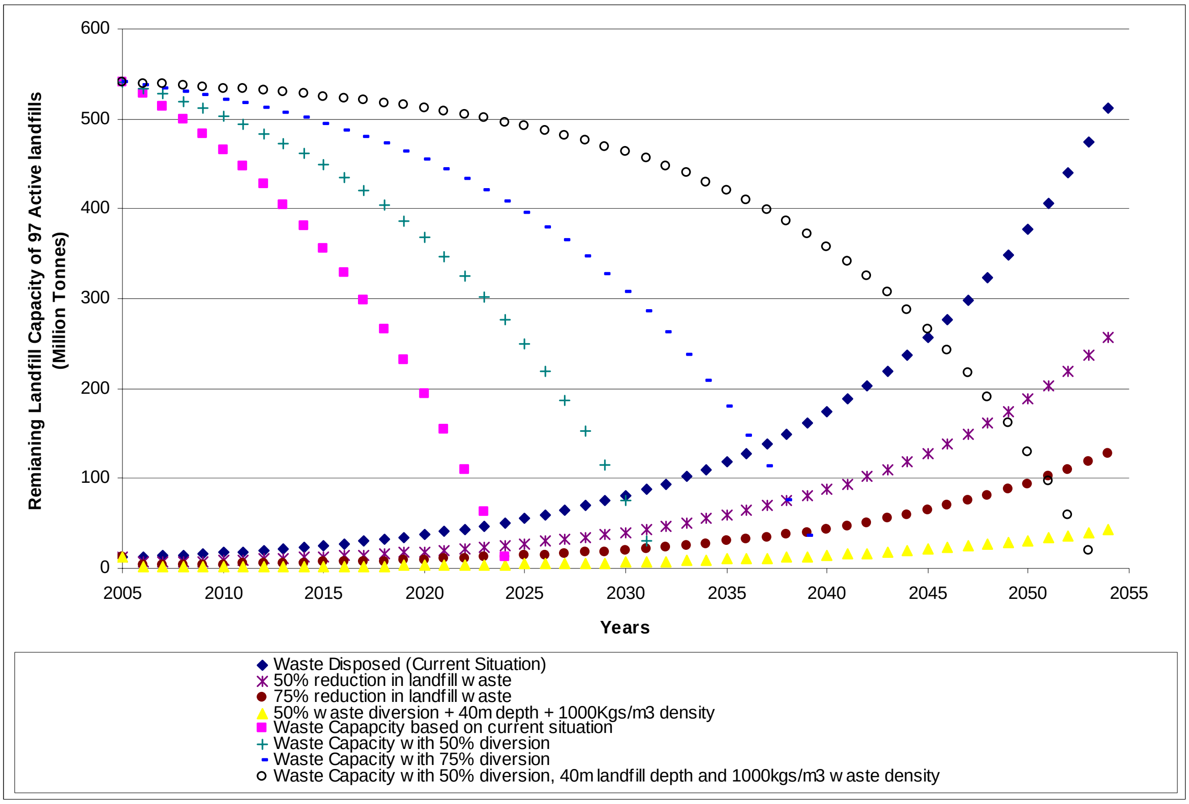


Figure 6: Landfill Waste Capacity Scenarios from 97 active landfill sites in Canada

Landfill space is a scarce resource. Based on the current waste generation and diversion rates, the survey showed that by 2024 all 97 active landfills that participated in the survey will run out of landfill space (Fig 6). However, diverting 50% of the waste generated and increasing landfill depth and landfill waste compaction rates preserves valuable landfill space for future generations (Fig 6). These landfill management techniques create additional space for waste without having to take productive agricultural or industrial land to site new landfills. Better landfill management practices (increased landfill depth and waste compaction) and diverting potentially valuable materials away from landfill sites can save considerable landfill space (Fig 6).

4.4 Conclusion

While waste management programs that reduce waste's ecological footprint are springing up across Canada, much more has to be done. Composting should be part of a comprehensive waste management system that emphasizes source reduction, reuse, and recycling. Extended producer responsibility, recycling credits, and higher disposal fees also provide incentives to recycle. A comprehensive waste-management system also has to include increasing waste diversion and extending landfill capacity without using more surface area by making deeper landfills and compacting waste to a greater degree. To achieve these results, economic incentives and disincentives are key.

Higher disposal fees may lead to greater waste compaction rates (higher density) and greater landfill depth, as well as more waste diversion. These measures can more than double the life of a landfill, which means extending the life of an average landfill by at least 25 years. Greater depth expands the size but not the surface area occupied by a landfill. If the national average for landfill depth is increased to that of the deepest existing landfill, this will nearly double the amount of waste that can be accommodated in these landfills. Landfill disposal fees impact the quantity of waste disposed of at landfill sites. The MSW waste stream has many materials that are not appropriate for landfill disposal (e.g. organics, paper, wood, etc.). Therefore, higher landfill disposal fees can act like a barrier and restrict the disposal of certain materials in landfills. If the cost to put waste materials in landfills is more expensive than recycling or composting, there will be a greater incentive for municipalities to pursue programs that divert more waste away from landfills. For example, while waste diversion is practiced in most areas of the country, it is most prevalent in areas where landfill disposal fees are high. A study done by Deyle and Schade (1991) found that net recycling costs are less than landfill disposal costs when landfill disposal fees are more than $38 per tonne in the large cities and $65 per tonne in the small ones (Goldman and Aya, 2001). For recycling and source separation of organics programs to gain momentum, recycling and composting costs must be competitive with tipping fees, which will result in higher participation and recovery amounts of recyclables and organics.

Landfill capacity could be greatly increased using better landfill management practices and techniques. By increasing compaction (i.e., increasing compaction from 125 to 1300 kg/cubic meter), landfill operators that are not presently compacting their waste could increase the amount of waste they fit into the same space by about ten times. Even for those compacting to the national average of 750 kg/cubic meter, a 50% increase in density to 1125 kg/cubic meter, or more, can be achieved. Compaction expands the waste capacity of landfills without increasing the landfill's volume. The depth should also increase beyond the 20 meter average. Overall, landfill capacity can be increased by 25% by increasing the average depth by 5 meters and can be increased by 50% by increasing the average depth by 10 meters. Therefore, increasing compaction and/or depth would extend the lifespan of future landfills by 50% or 75% or greater. In addition, diverting waste by 50% is possible as well, as is exemplified within the EU and in Halifax. Many EU countries, including Austria, Belgium (Flanders), Germany, Switzerland, Luxembourg, Italy, Spain (Catalonia), Sweden, and the Netherlands divert 80% of their organics (ECN, 2007). Municipalities or provinces across Canada should encourage more organic waste diversion through subsidized backyard composting. Furthermore, municipalities looking to initiate better waste management practices should look to programs that have documented their recycling and composting success stories, with a full accounting of costs and revenues, since these provide the best models for other communities looking for ways to improve their waste diversion and recycling rates.

There are numerous strategies for encouraging the reduction of solid waste. Source reduction is key: reducing waste at the source by rejecting over-packaged goods and disposable products and by implementing extended producer responsibility programs, which help to bring about environmentally friendly product design and production techniques (Ferrara and Missios, 2005; Sterner and Bartelings, 1999). The "pay-as-you-throw" and "bag-limit" systems designed and followed by the EU, some municipalities in USA, and a few Canadian municipalities are also good strategies for reducing MSW. However, waste reduction strategies need to be implemented across the nation. This would reduce MSW production over time and may increase diversion (e.g., recycling and composting) rates.

The lifespan of current landfills can be increased through waste diversion and source reduction, which reduce the quantity of waste entering landfills, and by increasing landfill capacity by employing greater waste compaction and increasing landfill depth. A few landfills in Canada are using compaction methods and deep landfill designs that allow more waste to fit into landfills than previously thought possible. When landfill volume is used more effectively, the additional capital costs needed to locate, permit, construct, and operate a future replacement landfill are lessened. As well, deeper landfills are more economical: they require smaller liners and methane recovery catchment systems, take up less land, and cause a higher rate of methane recovery to occur.

Most waste management technologies are mature and have been successfully implemented for decades in many countries. Therefore, instead of depending on landfills to make responsible choices, the government of Canada should identify the waste management practices that are economically and environmentally viable and promote their implementation in landfills nation-wide, with the help of economic incentives.

Canada should consider using a recycling credit system for a variety of items, including tires, used oil, and old newspapers, for every tonne of material that the household recycles. A recycling or tax credit is the value of the savings made by the municipality by not having to landfill any household waste that is recycled (Scharf, 1999). This way the province or municipality can promote recycling in their region by crediting recyclers. The value of the credit can vary across municipalities due to differences in disposal costs and can be paid for each tonne of household or industrial waste that is recycled. However, any material, like organics, aluminum cans, paper, cardboard, glass, etc., that is removed from the household and IC&I waste stream should be made eligible for a recycling credit. This way there could be a higher composting and recycling success rate.

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CHAPTER 5: A TOOL TO BETTER QUANTIFY LANDFILL GAS EMISSIONS FROM LANDFILLS

5.1 Introduction

Landfill gas, produced by the biological decomposition of refuse placed in a landfill, is approximately 50% methane (CH_4) and 50% carbon dioxide (CO_2) (Ayman et al., 2005; Tchobanoglous et al., 1993). Although both CH_4 and CO_2 are greenhouse gases, methane is more of a concern due to its higher global-warming potential at 25 times that of carbon dioxide over a 100 year period (IPCC, 2007). The total amount of atmospheric methane originating from landfills worldwide is estimated to range from 9 to 70 Tg[3]/year (Spokas et al., 2006). However, these estimates are based on limited data and assume near optimal conditions for anaerobic decay (Mohareb et al., 2008). To better understand methane gas generation, there is a need for landfill operational practices to be included in the current landfill models.

The amount of methane generated by landfills depends on many factors including the parameters of the landfill site (their depth, density, management practices), and solid waste disposal rates and composition (EPA, 1995). For example, waste compaction slows gas production increasing the density of the landfill contents, decreasing the rate at which water and microorganisms can infiltrate the waste (EPA, 1993; McCabe, 1976). Another important factor is the depth of the landfill, which influences the landfill temperature from geothermal heat and the lack of surface air influences (Yesiller et al., 2005). The depth of the landfill site also impacts methane generation through differences in access of air and the density of solid waste due to the waste insulation (Bogner and Spokas, 1993). Deeper landfills are more efficient at collecting landfill gas, because deeper wells draw landfill gas from a larger volume of refuse than shallow ones and require less piping

[3] 10^{12} grams = 1 mega tonne or 1 million tonnes

(ATSDR, 2001). As well, greater suction can be applied without drawing in air from the surface. Nevertheless, considerable uncertainty remains with respect to the quantitative emissions of methane from landfills (Mohareb et al. 2008). Regardless of which landfill gas production model is used, several inputs are consistently required for calculating methane emissions (Spokas et al., 2006). Most first-order decay models consider percent organic waste, waste quantity (tonnes) per year, decay rate and moisture content. Industry sources complain that these first order models used for estimating methane generation from landfills consistently estimates higher gas generation than the amount actually recovered. Therefore, to evaluate the extent to which operational factors impact methane generation, twenty nine of the 97 active landfills that have LFG capture units and are measuring the gas flow were considered for exploratory data analysis.

Historically, for landfill gas recovery projects, methane generation at landfills has been modeled using the Scholl Canyon model (Environment Canada, 2007; Blaha et al, 1999), based on waste inputs, climate variables and other factors. A study done by Thompson et al (2009) showed that the Scholl Canyon model typically overestimated methane recovery rates and the US model consistently underestimated methane recovery rates. European Pollutants Emission Register (EPER) models were wildly inaccurate in estimating methane generation rates in Canada (Thompson et al., 2009). Landfill gas models continue to receive criticism due to poor accuracy and lack of verification (Barlaz et al., 2004; Borjesson et al., 2000). In order to accurately estimate methane generation in landfills on a global basis, a model is needed that is responsive to a wide range of landfilling practices. This model will be different considering density, depth and other factors of landfills collected during a national survey, which are not currently considered in models. Not all of the gas generated is recovered and so a loss factor must be considered. The LFG generated in landfills is partitioned into recovered, emitted, oxidized and internally stored in the landfill (Bogner and Spokas, 1993). Even though landfill gas captures up to 99% have been documented, the default collection efficiencies are typically assumed to be between 50% and 75% by many regulators (Huitric et al, 2007). Conversely, recovery rate is also dependent on landfill cover design, such as final soil cover and geomembrane composite covers (Spokas et al., 2006; Hilger and Humer, 2003). I evaluated the accuracy of the statistical model by comparing the methane generation estimates against methane recovery rates.

5.2 Methods

1. I surveyed 52 major landfill sites to obtain necessary model inputs, and methane recovery rates for landfills in 2005.
2. The relationships between recovered gas and landfill depth, current waste in place, disposal fee, organic content and waste diverted were studied at the 0.05 probability level, using S-Plus statistical software version 7.0. Logarithmic transformation of few variables was used to approximate a normal distribution. The predictive equation is:

   *Log (2005 Recovered Methane Emissions) = - 4.800 + 0.544*log (Current waste) + 0.011*Depth of waste + 0.511*log (Organic waste disposed) – 0.265*log (Waste Diverted in 2005) + 0.005*Disposal fees.* (1)

   Where,

   <u>Independent Variables:</u>

   Waste diverted in 2005 from the landfill (log) [Tonnes]

   Total current waste (log) [Tonnes]

   Organic waste disposed in 2005 (log) [Tonnes]

   Depth of the landfill [Meters]

   Disposal fee/tipping fee of the landfill [Dollars]

Dependent variable:

Recovered landfill gas in 2005 (log) [Kilo Tonnes]

The five independent landfill variables were not correlated with each other ($|r| <$ 0.6). All variables followed a normal distribution.

3. The absolute percentage error of the statistical model was evaluated by comparing modeled methane gas generation estimates with actual recovery rates using equation 2.

$$AE = 1-(Y/X) \tag{2}$$

AE = Absolute error model

X = modeled LFG generation

Y = LFG Recovered[4].

Typically, not all landfill gas is recovered and only 50% to 75% is recovered (Spokas et al., 2006) Therefore, a US EPA (2004) default of 75% was considered and 25% was added to the methane recovery rates to get "methane generation rates". These "methane generation rates" were used to estimate the probabilistic future methane generation estimates based on past data.

5.3 Results and Discussion

1. Survey findings on landfill gas across Canada

Gas recovery systems reduced 6.69 million tonnes (Mt) of carbon dioxide (eCO_2) equivalent annually. The total amount of methane captured increased slightly from 2003 to 2005, from 312 kilo tonnes (kt) (6.56 Mt of eCO_2) to 314 kt methane (6.69 Mt of eCO_2). This slight increase was a result of nine landfills starting methane recovery, balanced by 22 landfills that no longer operate, many of which are decreasing their

[4] These emissions are based on the actual quantity of LFG that was recovered with the measured methane content of the gas.

emissions. The captured methane is burned to reduce methane to CO_2. Of the 52 landfill sites surveyed, only 30 are active and still receive municipal solid waste (MSW). 29 of the 30 landfills provided landfill and waste data (Table 1).

Table 1: Characteristics of 29[5] of 30 active LFG projects by Province
Note: 22[6] landfill gas recovery collected from closed landfill

Province (number of landfills surveyed)	Total Waste Disposed in 2005	Waste Diverted (%)	Waste Capacity (tonnes)	Average Density (Kg/m3)	Average Depth (m)	Disposal Fees ($)	Total LFG captured (tonnes /yr)
NS (*n*=1)	157,771	29%	3,600,000	780	20	115	5,390
QC (*n*=11)	4,751,289	6%	192,458,548	934 ± 190	24 ± 16	44	141,180
ON (*n*=10)	1,715,671	11%	67,968,776	893 ± 269	20 ± 8	64	39,390
AB* (*n*=1)	250,000	44%	13,500,000	850	43	42	4,170
BC (*n*=6)	1,387,247	28%	65,300,000	850 ± 123	15 ± 4	65	25,680
Total (*n*=29)	8,261,978	24%	342,827,324	861 ± 57	24.4 ± 10	66	215,800

* Edmonton, AB

The total amount of landfill gas recovered from both closed and open landfills (52 landfills) was 314 kt of methane in 2005. Of that 215,800 or 60% of the landfill gas recovered is from landfills that continue to receive waste. Those landfills recovering methane are the larger landfills. These larger landfills typically have better management, including greater density, increased depth, higher diversion rates and more expensive disposal fees. For example, a Quebec landfill that recovers 28 kt of landfill gas annually has a capacity of 40 million tonnes with over 5 million tonnes of available landfill space, 50 m depth, 1100 kgs/cubic meter and a disposal fee of $75/tonne. In contrast, most of Alberta’s landfills average 15 meter depth and have diversion rates that range from 4% to 13%. Edmonton was the only landfill surveyed in Alberta with a 44% waste diversion rate. Evidently, Edmonton does not reflect provincial policies but is impacted by

[5] Only 29 of the 30 were able to provide landfill and waste data
[6] Of the 52 LFG capturing landfills 30 are active and 22 are closed sites

municipal policies. Approximately one-third (32%) of the landfills recovering methane will be closed within five years.

2. Landfill Gas Model

Depth of waste, organic waste, waste diversion and current waste in place were all factors that significantly influenced amount of methane recovered. These factors may be important because currently the MSW industry is undergoing a transformation in the way it manages waste. Importantly, by improving landfill operational practices, the transition from traditional landfill (open dump approach) to engineered sanitary landfills can be successfully managed. Other factors considered had no significant effect on methane recovery. For example, disposal fees had no effect on log (recovered landfill methane recovery rates) when collectively analyzed with other independent variables (P-value = 0.078). Alternately, when disposal fee was plotted against waste diversion, landfill disposal fees tend to influence the selection of the waste management method. All these inputs to the model were available from the 2005 survey for all 29 landfills (Table 2).

Table 2: Parameter estimates of the five independent variables associated with methane production rates from 29 active landfills

Variables	Parameter Estimate	Standard Error	t Stat	P-value
(Intercept)	-4.800	0.701	-6.849	0.000*
Waste in Place (log)	0.544	0.123	4.437	0.000*
Depth of Waste	0.011	0.004	2.607	0.016*
Organic Waste (log)	0.511	0.104	4.906	0.000*
Waste Diversion (log)	-0.265	0.096	-2.777	0.011*
Disposal fees	0.005	0.002	1.842	0.078

*Statistically significant at 0.05

Residual standard error: 0.293 on 23 degrees of freedom

Regression Statistics	
Multiple R^2	0.912
R Square	0.832
Adjusted R^2	0.796
Standard Error	0.254
Observations	29

F-statistic: 22.829 on 5 and 23 degrees of freedom

The *P*-value is 0.000

Variation explained:

An R^2 value of 0.832 ($n = 29$) indicates that 83% of the total variability in 2005 landfill methane production rates can be predicted from the independent variables in our model.

Explaining the Coefficients:

Current Waste:

In instances where both the dependent and independent variables are log transformed, the coefficient can be interpreted as follows: for every 10% increase in the current waste amounts, we can expect a 5.3% (since $1.10^{0.544} = 1.053$) increase in the average amount of methane recovered from landfills, holding all other variables constant.

Depth of Waste:

When the dependent variable is log transformed and the independent variable is in its original metric, the coefficient can be interpreted as follows: for every one meter increase in the depth of waste, a 1.1% increase in the average amount of methane recovered from landfills can be predicted, holding all other variables constant, since $\exp(0.011) = 1.011$.

This means deeper landfill sites enable more efficient recovery of methane. Three out of four landfills that participated in the landfill gas capture survey and have a gas recovery rate greater than 60% are over 20 meters deep. Deeper landfills also allow more protection of waste from Canada's cold winter climate, as the bacteria that generate methane shut down at low temperatures.

Organic waste:

Organic waste influences methane generation in landfills. This model concludes that a 10% increase in the biodegradable fraction of solid waste disposed at landfills would contribute towards a 5% (since $1.10^{0.511} = 1.050$) increase in the average amount of methane recovered from landfills, holding all other variables constant. Alternately, keeping organics out of the landfill is the best way to reduce the amount of methane generated at landfills.

Waste Diversion:

Enhanced waste diversion programs should be considered with the objective of maximizing reductions of landfill. For every 10% increase in waste diverted from landfills, this model would predict a 2.5% (since $1.10^{-0.265} = 0.975$) decrease in the average amount of methane generated at landfills, holding all other variables constant.

3. Recovered vs. Modeled Methane:

In an environment as complex as landfills, everyday landfill operational practices can influence the rate of methane production. In general, there appears to be a strong relationship ($R^2 = 0.832$) between recovered methane and the predictor variables used in this model. This suggests that our model captures the most important factors influencing methane production.

Table 3: Accuracy of model based on 29 active landfills compared to methane recovery rates

Landfills	Recovered Methane (kt)	Linear Predicted Methane (kt)	Model Error (%)
Landfill 1	7.16	3.33	115%
Landfill 2	36.81	38.45	4%
Landfill 3	1.34	1.10	22%
Landfill 4	19.47	14.39	35%
Landfill 5	3.06	4.70	35%
Landfill 6	0.34	2.38	86%
Landfill 7	0.77	0.56	37%
Landfill 8	29.20	19.54	49%
Landfill 9	30.16	30.67	2%
Landfill 10	46.36	32.31	43%
Landfill 11	19.63	8.86	122%
Landfill 12	0.63	0.61	5%
Landfill 13	8.57	27.32	69%
Landfill 14	11.58	6.16	88%
Landfill 15	14.66	12.95	13%
Landfill 16	1.01	1.89	46%
Landfill 17	3.21	2.34	37%
Landfill 18	4.54	7.32	38%
Landfill 19	2.63	2.24	17%
Landfill 20	1.58	2.15	27%
Landfill 21	1.98	2.20	10%
Landfill 22	2.63	3.83	31%
Landfill 23	5.55	9.88	44%
Landfill 24	0.61	2.17	72%
Landfill 25	1.28	2.35	46%
Landfill 26	25.39	14.98	69%
Landfill 27	2.92	4.87	40%
Landfill 28	3.37	4.53	26%
Landfill 29	0.58	1.37	57%
Average:			**44.38%**
SD			**30.69%**

Table 3 compares the methane generation estimates of the statistical model to recovery rates. The fraction of methane recovered ranged from 30% to 200% of the predicted generation. The mean absolute error of the statistical model is estimated to be 44% (Standard Deviation = 31%), based on the difference between modeled and recovered gas extraction rates divided by modeled methane production estimates. This error percentage is not surprising because the model is consistently underestimating methane production.

It is uncertain how well this model will translate to other landfills, as it is an empirical, rather than mechanism-based model. Although the cost of disposal would have no direct impact on changing the methane generation rates the impact of disposal fee may relate to methane generation by increasing organic diversion, creating deeper landfills or denser landfills, as the price of disposal increases.

Other factors that the model did not look at may make a difference and explain some of the additional variability. Moreover, the methane recovery rate is highly dependent on the landfill final cover type e.g. geo-membrane, clay, soil etc. and on the type of LFG collection system. This underestimation of the model may be because a significant portion of the methane (4 % to 50%) is oxidized through the landfill cover (Spokas et al, 2006). In addition, a default collection efficiency rate of 75% that have no bearing on site-specific conditions should be avoided and a methodology should be developed to calculate collection efficiency specifically for each landfill. Sometimes, a 75% efficiency rate does not seem technically feasible because of the landfills' existing gas recovery systems and final covers. A number of LFG capture systems across Canada operate at efficiencies ranging from 6% to 50%, making the default 75% efficiency rate a source of error.

5.4 Conclusion

Governments across Canada are struggling with the rising costs associated with managing the country's increasing quantity of wastes being generated across the country. These increasing quantities of wastes will result in higher levels of methane emissions from landfills in the future. Municipalities are reluctant to invest in methane recovery projects due to the high uncertainty in estimating methane production rates and total gas yield, which are needed to accurately determine payback periods for the capital and operational costs of any project. A simple model that takes landfill operations into consideration is explored to determine if other approaches to the methane generation models dependent on decay rates are possible. This simple model can determine the impact of different management approaches (e.g., depth, diversion and disposal fee). Other models need all the historical data, decay rates and data on organics from waste audits that are rarely undertaken at landfills. This landfill model uses data that is readily available. The landfill model clearly showed that depth, diversion, waste in place and organic matter are the key factors of those considered that influence greenhouse gases. The linear regression analysis showed that recovered landfill emissions are positively correlated with landfill depth, capacity and organic waste and negatively correlated with waste diversion. However, it is uncertain whether this model could be used to accurately estimate emissions for other landfills. The model was validated for only the 29 landfills considered.

Disposal fees when collectively accommodated in the linear analysis is not significant. Even though the effect of landfill fees on recovered methane amounts is non-significant, it still could have a positive effect on reducing waste going to landfills. Further, Schwarz and Steininger's (1997) study concluded that a rise in waste disposal costs directly triggered waste reduction. Canada's high greenhouse gas (GHG) per capita from MSW disposal requires that new strategies to reduce landfill gas generation include landfill operation standards and methane recovery.

This study deals with landfill gas production from actual landfills based on local factors. An important point to notice is that the gas volume increased along the depth of the landfill. This could be because anaerobic conditions could be better developed in the deeper part of the landfill (Zacharof and Butler, 2003). Chiemchaisri et al (2007) studied the depth-density dynamics with regards to methane production from landfills and suggested that biodegradation of solid waste had taken place to a greater extent at the bottom of the landfill. However, methane production greatly depends on moisture content and it is greatly influenced by rainfall precipitation and water infiltration through the final cover soil (Thompson et al., 2009). Further, diverting waste from landfills to a composting or recycling facility produces significant changes in the overall production of greenhouse gases. The US EPA predicts a decrease of methane emissions when diverting organic waste from landfills (Visse, 2004).

Landfill operational inputs to the model require more research to reduce the error percentage. Most landfills have not conducted a waste composition study, which is required to calculate the organic waste fraction. Waste composition fluctuates widely within Canada, making it inaccurate to assign a national organic waste percentage value. The organic waste percentages for each of the 29 landfills assigned are based on provincial organic waste percentage averages. In the future, this input may become better documented when municipalities examine the impact of waste diversion initiatives by conducting waste audits. To reduce the impact of landfills on GHG, waste diversion and/or methane recovery is required. Meanwhile, effective gas recovery systems and final landfill covers are very effective in recovering methane, thus significantly reducing the environmental impact of landfill methane recovery rate.

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CHAPTER 6: WASTE DIVERSION OPTIONS THAT AFFECT GREENHOUSE GAS EMISSIONS

6.1 Introduction

Waste management affects methane generation. Source reduction has emerged as the top priority in the 3R's hierarchy, although there are numerous economic and practical barriers that stand in the way of widespread source reduction in Canada (Allaway, 1992). One of the major reasons is virgin raw materials are often priced so cheaply in Canada that efficient use of materials carries no significant economic advantage (Brown, 1999). Reuse could save resources and reduce waste generation, but it is sensible only if materials can be used again in their original form without requiring intensive processing. As a result, waste diversion (recycling and composting), though not a substitute for source reduction and reuse, offers significant opportunities for waste reduction, with potential reduction in landfill emissions (Sandulescu, 2004).

Organic waste is the fuel that creates landfill gas (Saft and Elsinga, 2006). Organic waste is material that will break down naturally and can be processed in the presence of oxygen by composting or in the absence of oxygen using anaerobic digestion (El-Fadel, 1995). Organic waste for this research is identified as: garden waste, food waste, forestry waste, paper and cardboard products. Despite the variability in solid waste composition, organic waste is a large segment of Canada's waste stream and is more than 60% of the waste we generate. According to the available estimates, this equates to two-third's of a tonne per person per annum. Composting of yard waste has become widespread in Canada, and some communities compost food waste as well (Environment Canada, 2002). About 0.8 million tonnes of organic waste was diverted in 2005 from 97 active landfills across Canada. The organic waste breakdown is: 33% is readily compostable (i.e. 21% is food waste and 12% is yard trimmings), 20% is paper and 10%

is wood. However, composting is an option available only for food scraps, and yard waste and soiled paper (Environment Canada, 2002). Research suggests that during composting operations, any methane generated within the pile is oxidized and converted to CO_2 (Castro-Wunsch and Ng-Grondin, 2001).

The inert recyclables (e.g. steel, aluminum, glass, plastics etc.) from 97 active landfill sites accounted for 9% of the landfilled waste in 2005. Recycling can have a significant impact on reducing greenhouse gases because it requires less energy than manufacturing from virgin materials and thereby avoiding life cycle emissions (Finnveden et al., 2005). The degree of treatment varies from simply re-melting aluminum cans to the thermal de-polymerization of plastics and synthetic fibres (IPCC, 2001). In addition, 20% of the waste landfilled was paper and cardboard. If unsoiled it too could be recycled but as organic material decays can also be composted (Graves and Telford, 1993).

The study determined the effect of an alternative MSW management option on GHG emissions. This study developed an approach for estimating GHG savings potential of by-products by comparing landfilling to alternatives. The scope of the study included waste diversion data from ninety-seven active landfill sites to examine opportunities for greenhouse gas emissions (GHG) reduction from a life-cycle perspective. Emission factors were used to identify if waste diversion can contribute to reducing emissions from the solid waste sector. The primary application of the GHG emission factors is to support decision makers, because implementation of any waste diversion initiative to reduce methane would have an immediate impact on GHG emissions.

6.2 Methods

I determined the amount of GHG emissions avoided by waste diversion options (recycling and composting) from 1.7 million tonnes of waste diverted from 97 active landfill sites using emission factors. Material-specific emissions factors from Environment Canada (2005) were considered for three MSW management practices: recycling, composting, and landfilling. These emissions factors represent the cumulative emissions summed across all GHG emissions, which means the emission factors of a waste management strategy for a given material are established based on the difference between the alternative scenario (recycling/composting) and the baseline scenario (landfilling). Table 1 represents the emission factors from MSW management options compared to landfilling in metric tonnes of carbon-dioxide equivalents ($MTCO_2e$).

Table 1: Net GHG emission factors ($MTCO_2e$/tonne) from MSW management options compared to landfilling

i-values	Material	Composting – E_f	Recycling - E_f	P_j
	Newsprint		(1.53)	
	Office paper		(4.38)	
	Mixed paper		(3.98)	
	Cardboard		(3.54)	
1	**Average (Paper & Cardboard)**		**(3.36)**	20
	Aluminum		(6.51)	
	Steel		(1.20)	
	Glass		(0.12)	
	Plastics		(2.73)	
2	**Average (Other Recyclables)**		**(2.64)**	9
3	Food Discards	(1.04)[7]		21
4	Yard Trimmings	0.09		12

(Source: Adapted from Environnent Canada, 2005 and Thompson et al, 2005)

A life-cycle analysis based software tool developed by ICF consultants that uses the above mentioned emission factors was used to weigh the GHG impact of different waste practices. The total GHG emission savings from materials that are diverted from the 97 active landfills were calculated using the following formula shown below:

[7] The number within brackets represents the net GHG emission reductions from that material

$$G = \sum_{i=1}^{4} x_i$$

G= sum of GHG emissions savings from Material ($MTCO_2e$), and

i = index variable (Table 1)

$$x_i = P_{ji} * A_{mi} * E_{fi}$$

Where,

P_{ji} = Fraction of waste material of component j in the total solid waste stream diverted in 2005 (Table 1) for component i

ji = Component of diverted waste that is either composted or recycled

A_{mi} = Amount of organic or recyclable waste diverted in 2005 (tonnes) for component i

E_{fi} = Net GHG emissions factor ($MTCO_2e$/tonne) (Table 1) for component i

6.3 Results and Discussion

Waste diversion's impact on GHG is significant enough for local governments to target composting and recycling to curb the effect of waste on climate (Fig 1). A higher rate of waste diversion is statistically significant to GHG emission reductions with a R^2 of 0.951 (P-value < 0.05), indicating that 95% of the variation in GHG emissions saved was explained by waste diversion. Recycling and composting avoided approximately three million $MTCO_2e$ of material life-cycle emissions from 1.7 million tonnes of waste that was diverted from 97 landfill sites in 2005. To avoid more GHG emissions, governments should focus on creating sustainable markets for organics and recyclable materials by providing financial incentives that encourage the development of new waste diversion technologies. Furthermore, these results show that CO_2e can be avoided by the production of compost. Readily composting organic waste diverted from landfills in 2005 actually proved beneficial and produced a net decrease of 0.53 million $MTCO_2e$ emissions.

Municipalities should fund and develop waste diversion programs with a great emphasis on organic waste diversion. Even though demand for compost is limited at this time as there is uncertainty around the consistency of the quality of the compost (CCME, 2005), composting is still an excellent way to turn readily biodegradable waste into a soil amendment, simply and economically (Diaz et al, 2002). One issue that devalues this option is organics that are not source separated would compromise the quality of the compost (Kelleher, 2007). Therefore, to get better quality and economic benefits from compost, source separation of organics should be encouraged (e.g. Toronto Green Bag program).

The life cycle emission factor estimates shows that the amount of CO_2e avoided through recycling was 2.5 million tonnes. This high number is because recycling processes save more energy than composting by avoiding the use of virgin material inputs. However, recycling alone cannot improve the GHG situation from the solid waste sector. Focusing on two materials could divert 62% of the total waste stream (33% organics and 29% recyclables) and can produce a net decrease in methane emissions. In 2005, waste diverted from the 97 active landfills actually produced a net decrease of approximately three million tonnes of GHG emissions. Waste diversion programs that are well planned and executed have proven to be quite successful at reducing both waste and greenhouse gas emissions (Batool and Chuadhry, 2009; Bhattarai, 2005; Tanskanen, 2000; Hong and Adams, 1999)

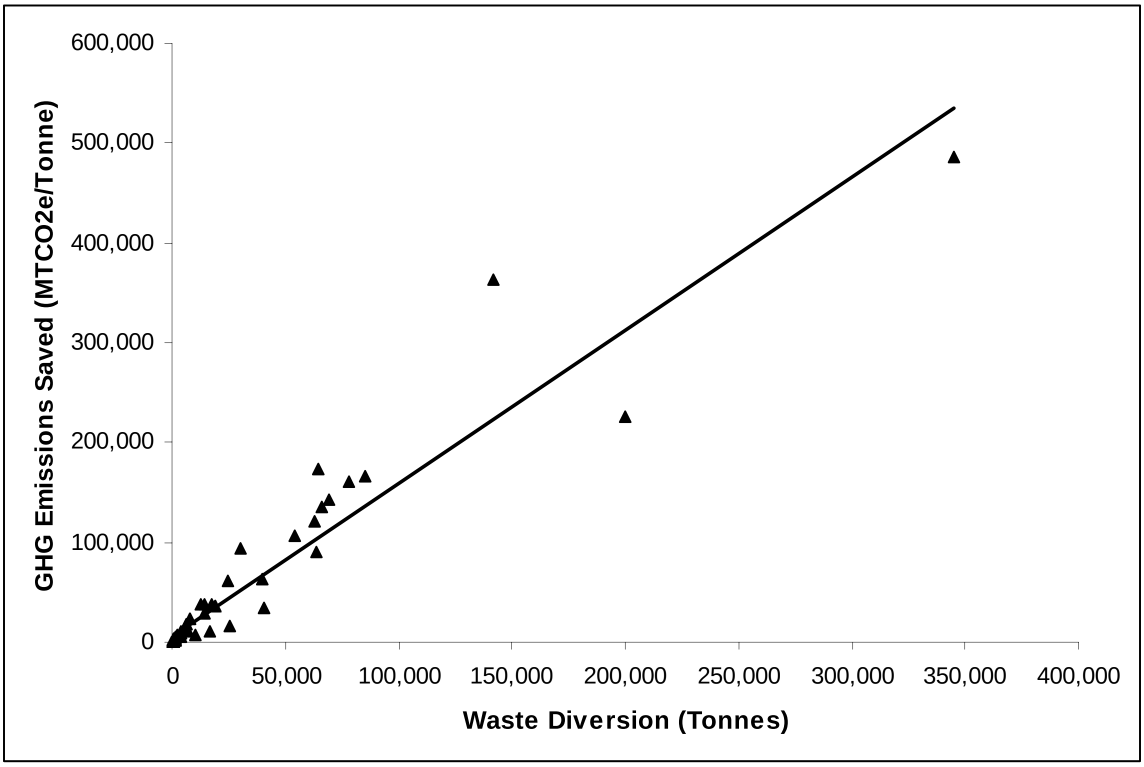

Figure 1: Greenhouse emissions saved by composting and recycling including saving embodied energy in products

6.4 Conclusion

Waste diversion seemed to be a very environmentally appealing option as it avoided three million tonnes of CO_2e from 1.7 million tonnes of waste that was diverted from 97 landfill sites in 2005. Therefore, provincial governments should encourage recyclers by offering "recycling or tax credits' for every tonne of material that the local recycler collects for recycling. The "recycling credit" concept has been in practice in the EU for more than a decade (Turner et al., 1995). A recycling or tax credit is the value of the saving made by the municipality in not having to landfill any household waste that is recycled (Scharf, 1999). The province/municipality can choose to pay this saving in disposal costs back to the recyclers that are involved in collecting household waste for recycling (Turner et al., 1995). This way the province or municipality can promote recycling in their region. The value of the credit can vary across municipalities due to differences in disposal costs, and can be paid for each tonne of household or industrial waste that is recycled. However, any material like organics, aluminum cans, paper, cardboard, glass, etc. that is removed from the household and IC&I waste stream should be made eligible for a recycling credit.

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CHAPTER 7: CONCLUSION

Landfills will always play a key role in the solid waste management portfolio, because it is not possible to reduce, reuse, recycle or compost all components of the MSW stream. Therefore, proper management of landfills is important to keep environmental problems to a minimum. Too often a sustainable landfill is defined in terms of its design rather than the more appropriate goal of managing the waste entering the landfill using sustainable practices (Westlake, 1997). In Canada, problems with poorly managed landfills arise with variable standards of management. For example, fewer than 50% of the participating landfills have GHG monitoring systems and leachate collection systems in place. Additionally, a well managed landfill with daily and final cover protocols causes fewer pollution problems.

Sustainable best practices like increased depth, compaction, waste diversion, odour control, leachate management and landfill gas capture will not only help landfills blend into the surrounding environment but will also provide additional waste capacity and longer life of existing landfill cells. A landfill's design life extends many years if its basic parameters like depth and compaction of the solid waste are increased. Currently, MSW delivered to the landfill has a density of 200 to 300 kilograms per cubic meter. If suitable compaction equipment is employed, this waste can be compacted to a density of 1,000 to 1,300 kilograms per cubic meter as in place waste. Strong relationships were found between landfill space, waste diversion, depth, waste compaction and landfill disposal fee. An important find of this research is that better landfill practices and techniques can more than double the life of a landfill, which means extending the life of an average Canadian landfill by at least 25 years. Best practices to extend landfill life include deep landfills, higher disposal fees and more diversion practices. Deeper landfills are more economical for infrastructure of liner, reduced land base and higher methane recovery in deeper wells.

Along with landfill space, greenhouse gas emissions from landfills are also a major concern. Municipal solid waste that is deposited in a landfill undergoes anaerobic biodegradation to generate landfill gas. A linear model has been developed that explores other approaches to estimating methane generation for landfills using recovered methane from landfill sites. The model uses landfill operational information that is easily available to landfill managers/operators. After quantification, the model predictions were verified with recovered methane amounts reported by 29 active landfill sites. The landfill gas production estimates predicted by the linear model when plotted against the recovered landfill gas had a regression coefficient, R^2, of 0.832. In addition, the linear regression showed that landfill gas generation is sensitive to landfill depth, waste diversion and biodegradable waste fraction (i.e. organic waste), but is less sensitive towards disposal fee. The model's respective mean absolute error with methane production rates was out by 44% and with additional data from other landfills the model can be further refined to make better predictions. However, the model's generalizability to estimate other landfills is uncertain and requires further exploration.

In 2005, there was recovery of recyclables (including organics), but only a small portion of the waste stream was recovered or composted. Diversion programs for recyclable materials were in place but less than 805 kilo tonnes was diverted in 2005. Even though curb-side organic waste collection programs were implemented in many jurisdictions, the tonnage estimated to be composted at centralized composting facilities in 2005 was approximately 7% of the waste estimated to be landfilled. Overall in 2005, Canadians diverted 12% of all the waste generated across 97 landfills; approximately 60% of these diverted materials were organics. Most waste management methods that were successfully implemented in many other countries are mature and can be replicated in Canada. Therefore, instead of depending on landfills, Canada should identify different waste management practices that have the potential to significantly mitigate both direct and indirect GHG emissions from the waste sector

Different management approaches yield different results. Composting organics reduces greenhouse gas emissions by preventing waste from decaying anaerobically in landfills. I found that composting organic waste diverted in 2005 from the landfills produced a net decrease of 0.53 million metric tonnes of eCO_2. Although, the 3Rs could save resources and reduce waste generation, reduce and reuse may work if fewer raw materials and less energy can be used or materials can be used again in their original form. Although recycling is not a substitute for source reduction and reuse, it still offers significant opportunities for waste reduction, with potential reduction in greenhouse gases. In 2005, recycling 0.80 million tonnes of recyclable waste diverted produced a net decrease of 2.50 million metric tonnes of eCO_2 emissions. The overall impact of waste diversion on GHG emissions is significant enough for local governments to divert the organic and recyclable waste before it is disposed of, thereby extending the life of landfills and achieving landfill emissions reduction. Therefore, municipalities should fund and develop waste diversion programs with a great emphasis on organic and recyclable waste diversion.

Recycling and composting may hold the most promise to cope with current waste management problems but regardless of how successful our attempts at waste diversion might be there will always be that final substance whose disposal is inevitable. Therefore, a long term solution to this solid waste problem is to progressively improve the performance of current waste management practices in order to reduce more waste. Higher landfill disposal fees can act like a barrier and restrict the disposal of materials in landfills, on top of other policy options like landfill disposal bans of organics. If the cost to landfill materials is more expensive then recycling or composting, there will be a greater incentive for municipalities to pursue programs that divert more waste away from landfills. In addition, composting should be a part of the local waste management system that emphasizes recycling. Provinces across Canada should encourage more waste diversion through subsidized backyard composting and curbside recycling programs. Diverting recyclable and organic wastes from landfill sites helps to conserve landfill space and to reduce the production of leachate and methane gas.

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Appendix 1

UNIVERSITY OF MANITOBA

Natural Resources Institute
70 Dysart Rd,
Winnipeg, Manitoba
Canada R3T 2N2
General Office (204) 474-7170
Fax: (204) 261-0038
http://www.umanitoba.ca/academic/institutes/natural_resources

July 14, 2006

Dear Sir/Madam,

To improve the Canadian national greenhouse gas generation inventory your assistance is required. Please accept this request for at least 30 minutes of your time to complete a "Methane Generation Landfill Survey" for Environment Canada's Greenhouse Gas Division to help fulfill the reporting requirements for the United Nations Framework Convention on Climate Change (UNFCC) and Canada's previous commitment to the Kyoto Agreement. Please find attached a copy of the survey along with a supporting letter from Environment Canada. This information will also determine options that would assist in reducing methane generation through solid waste management towards a master thesis.

Please complete the survey and return by e-mail or if you prefer to send the solid waste audits and GHG emission reports, feel free to do so. Also, please suggest a convenient time for us to follow up on the survey by telephone or provide the name/e-mail of someone in a better position to answer or verify this survey. This survey will collect the 2005 landfill gas capture data for the Environment Canada report entitled "*Inventory of Landfill Gas Recovery and Utilization in Canada*", and if completed fulfills the requirements of the 2005 survey.

Thank you very much for your time. I welcome your thoughts regarding the survey and landfill gas generation. Feel free to contact me at umbonam@cc.umanitoba.ca, or at (204) 298-2787.

Sincerely,

B. Rathan Kumar

Rathan Bonam
NRI Master's Student
E-mail: umbonam@cc.umanitoba.ca
Fax: 204-261-0038

As project manager and academic advisor, I would like to thank you for your time and consideration. If you have any further questions or concerns please do not hesitate to contact me collect at (204) 474-7170 or s_thompson@umanitoba.ca or the Human Ethics Secretariat at (204) 474-7122.

Very Truly,

Dr. Shirley Thompson, PhD, M.Eng. Assistant Professor,
Natural Resources Institute, University of Manitoba, 70 Dysart Rd, Winnipeg, MB,
phone: (204) 474-7170 fax: 204-261-0038 E-mail: s_thompson@umanitoba.ca

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[8]:

Landfill closure or expected closure date[9]:

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)[10]:
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 ($):

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?

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

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)[11]:

[ ] t CH_4/year

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

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

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): [ ]

---

[11] 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.

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:

Please list the landfill and waste regulations that prevail in your region:

☐ 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

LFG capture rate for all of those years that the landfill has been capturing prior to 2005:

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

Methane captured for all of those years that the landfill has been capturing prior to 2005:

In order to convert the captured methane from volume units to mass units we require the pressure and temperature for which the flow-meter is calibrated (e.g. A landfill gas flow-meter may be calibrated to provide a read-out based on a standard pressure and temperature of 1 atmosphere and 0 ^{o}C):

Pressure: ☐ (Atm)

Temperature: ☐ (^{o}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		Output		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.