

Strategies for the municipal solid waste sector to assist Canada in meeting its Kyoto Protocol commitments

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Abstract: The Government of Canada has ratified the Kyoto Protocol, committing to a 6% reduction in greenhouse gas (GHG) emissions from 1990 levels during the commitment period of 2008–2012. To attain this target, emission reductions throughout many sectors must be achieved. The waste sector can assist Canada in reducing GHG emissions to meet its commitments under the Kyoto Protocol. In 2001, the waste sector generated 24.8 megatonnes (Mt) of carbon dioxide equivalent (CO₂e) from landfill gas (LFG) generation, wastewater treatment, and incineration. Emissions from the transportation of solid waste were not considered, and are seen to be small. Several strategies for reducing GHG emissions from solid waste are analyzed. Source reduction decreases the amount of material being generated, thus reducing from the source any emissions that might be related to the life cycle of the material. Recycling can reduce GHG emissions by reducing the amount of virgin material being processed, avoiding life cycle emissions. Landfill gas collection for energy recovery can reduce methane (CH₄) emissions from organic wastes in landfills, and the Government of Canada's Climate Change Plan has considered this strategy. Anaerobic digestion converts some of the organic matter in the municipal solid waste (MSW) to both CH₄ and carbon dioxide (CO₂), where the CH₄ can be used to generate power, while composting converts some of the organic fraction to CO₂. Both of these processes produce a soil conditioner as their residue. Waste incineration reduces MSW volume and can generate power, displacing generation from fossil fuels. An integrated approach, considering these techniques where appropriate, can succeed in reducing emissions from the solid waste sector. Policy choices such as extended producer responsibility, minimum recycled content laws, and LFG capture criteria would increase the impact of solid waste management on GHG emissions.

Key words: climate change, Kyoto Protocol, municipal solid waste, source reduction, recycling, landfill gas capture, anaerobic digestion.

Résumé : Le gouvernement du Canada a ratifié le Protocole de Kyoto, et en faisant cet engagement, les émissions de gaz à effet de serre (GES) canadiens devraient être réduites par 6 % des niveaux de 1990, pendant la période de 2008–2012. Pour réaliser ce but, il faut engager une stratégie qui touchera plusieurs secteurs d'activité. Le secteur de déchets solides

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municipal (DSM) peut assister à réaliser ce but. En cours de l'an 2001, le secteur de DSM canadien a généré 24,8 mégatonnes (MT) de dioxyde de carbone équivalent (CO₂e), grâce à l'enfouissement des déchets solides, au traitement d'eau usée, et à l'incinération des DSM. Les émissions de GES produites par le transport des DSM n'étaient pas pris en compte, car ils soient considérés petits. Quelques stratégies de réduction des émissions dans le secteur de DSM ont été analysées. La réduction à la source baisse la quantité de matériaux qui sont générées, et donc réduit les émissions de GES. Le recyclage peut aussi diminuer les émissions de GES, par la réduction des quantités des matériaux vierges qui sont produit, évitant les émissions de cycle d'usage. La récupération des gaz de site d'enfouissement peut réduire les émissions de méthane (CH₄) produites par les déchets biologiques, et puis le plan du Canada sur les changements climatiques propose cette stratégie pour réduire les émissions de GES. La digestion anaérobie des DSM peut transformer les déchets biologiques en CH₄ et CO₂, ainsi que le compostage, qui peut modifier les déchets biologiques en CO₂. De ces deux processus résulte un résidu utilisé comme amendement de sol. L'incinération peut diminuer le volume du DSM et produire de l'énergie, en remplaçant celle générée par les combustibles conventionnels. Les stratégies qui considèrent toutes ces méthodes de disposition des DSM peuvent apporter pour Canada le succès dans la lutte contre les émissions de GES du secteur de DSM. Les choix politiques, comme des règles sur la responsabilité élargie des producteurs et ceux qui établissent un minimum de produits recyclés dans la manufacture des produits, et des critères pour collectionner le gaz de site d'enfouissement, augmenteraient l'effet de gestion de DSM sur les émissions de GES.

Mots clés: changement climatique, Protocole de Kyoto, déchets solides municipal, réduction à la source, recyclage, capture des gaz de site d'enfouissement, digestion anaérobie.

1. Introduction

On 17 December 2002, the Government of Canada ratified the Kyoto Protocol (UNFCCC 2004). Should the Protocol enter into force with Canada as a signatory, Canada will be required to reduce its greenhouse gas (GHG) emissions by 6% from 1990 emissions levels (UNFCCC 1997a). However, meeting this target will require a 30% reduction from the Government of Canada's business-as-usual (BAU) emissions projection for the 2008–2012 commitment period (Government of Canada 2002). To achieve this goal, emission reductions from all sectors that generate GHGs must be considered. The waste sector generates a significant amount of GHGs (Olsen et al. 2003; Environment Canada 2001). This report will analyze the emissions that are generated by the solid waste sector, with a focus on municipal solid waste (MSW), and the ramifications of the Kyoto Protocol on the solid waste sector. The mechanisms through which the Canadian solid waste sector can reduce GHG emissions will be investigated. Specifically, this report will focus on the following mechanisms: source reduction, landfill gas (LFG) collection, recycling, biological transformation of waste through anaerobic digestion and through composting, and incineration.

2. The Kyoto Protocol and climate change

2.1. Greenhouse gases and climate change

There has been much discussion about the possible extent of global climate change due to anthropogenic greenhouse gas (GHG) emissions. This report will briefly address this discussion.

The Earth is habitable largely because of the greenhouse effect that results from the presence of GHGs; without the impact of GHGs, the global surface mean temperature would be -19 °C (Baede et al. 2001). Incoming solar radiation, most particularly in the visible light spectrum, strikes the surface of the planet, and is reflected from the surface as infrared radiation (IR). Clouds and the atmosphere also radiate IR. The GHGs absorb some of this radiation, which increases their kinetic energy. When considered on a global scale, the increased kinetic energy of GHGs causes warming (the greenhouse

Table 1. Relative global warming potentials of eight major GHGs and categories, residence times and atmospheric concentrations in 1750 and 1998 (adapted from Ramaswamy et al. 2001).

Greenhouse gas	Global warming potential over 100-year time horizon (CO ₂ = 1)	Atmospheric residence time (years)	Atmospheric concentration in 1750 (ppb)	Atmospheric concentration in 1998 (ppb)	Radiative forcing due to change in abundance (W/m ²)
CO ₂	1	5–200 ^a	278 000	365 000	1.46
CH ₄	23	12	700	1 745	0.48
N ₂ O	296	114	270	314	0.15
CFC-12	10 600	100	0	0.533	0.17
CFC-11	4 600	45	0	0.268	0.07
PFC	6 500–9 200	2 600–50 000	0	0.083	0.004
HFC	140–11 700	0.3–260	0	0.022	0.003
SF ₆	23 900	3 200	0	0.042	0.002

Note: CFC, chlorofluorocarbon; PFC, perfluorocarbon; HFC, hydrofluorocarbon; SF₆, sulfur hexafluoride.

^aNo single lifetime can be defined for CO₂ because of the different rates of uptake by different removal processes.

effect). On an atmosphere-wide scale, the energy absorbed by GHGs increases the temperature of the planet to the current global mean average temperature of 14 °C (Baede et al. 2001).

Since the onset of the Industrial Revolution, the concentration of GHGs in the atmosphere has increased. There has been an increase in the atmospheric concentration of carbon dioxide (CO₂), largely due to the combustion of fossil fuels for the production of energy, from about 280 ppm in 1750 to the 1999 level of 367 ppm (Baede et al. 2001). Human activity has also generated increases in the atmospheric concentration of other GHGs such as methane (CH₄), nitrous oxide (N₂O), and tropospheric ozone (O₃). Anthropogenic chemicals, including sulfur hexafluoride (SF₆), hydrofluorocarbons (HFCs) (substitutes for chlorofluorocarbons (CFCs), used primarily as a refrigerant and a propellant), and perfluorocarbons (PFCs), have also contributed to the greenhouse effect (Table 1) (Baede et al. 2001). The increased release of the aforementioned GHGs appears to be changing the climate on a global scale, as the accumulation of GHGs has reduced the amount of energy escaping the atmosphere. This could lead to an increase in the global mean surface temperature. The effects would be felt disproportionately in certain parts of the world. For example, global warming would lead to an increase in sea level, threatening low-lying island states (IPCC 2001a). Northern climates, such as Canada, will likely experience greater temperature shifts than tropical climates (Government of Canada 2002).

It should be recognized that each GHG has a different effect on the atmosphere; one tonne of CO₂ does not have the same effect as one tonne of CH₄. For example, an additional tonne of CH₄ in the atmosphere has 23 times the global warming potential (GWP) of an additional tonne of CO₂ over a 100-year period, as its lower atmospheric concentration increases the amount of radiation available in the window in which it is capable of absorbing IR (Ramaswamy et al. 2001). Methane has a shorter residence time than CO₂ in the atmosphere, therefore the relative GWP of CH₄ compared to CO₂ decreases from 56 over a 20-year period to 6.5 over a 500-year period (Pickin et al. 2002). The unit CO₂ equivalent (CO₂e) is used to measure the impact of different GHGs relative to CO₂ (Table 1). It is standard to discuss CO₂e over 100-year time frames, and this time frame is recommended by the Intergovernmental Panel on Climate Change (IPCC) for use in national GHG inventories (Olsen et al. 2003).

Global mean temperatures have risen by 0.6 ± 0.2 °C over the past century, with most of the warming occurring between 1910 and 1945 and between 1976 and 2000 (IPCC 2001b). It has been noted that, prior to the turn of the millennium, it is very likely that the 1990s was the warmest decade on record, with 1998 being the warmest year on record (Albritton and Meira Filho 2001). The IPCC has stated, “there is new and stronger evidence that most of the warming observed over the last 50 years

is attributable to human activities” (IPCC 2001*b*). With this evidence in place, there have been wide-ranging, international accords struck to mitigate the increase of GHG concentrations in the atmosphere.

2.2. The history of the United Nations Framework Convention on Climate Change and the Kyoto Protocol

From 3–14 June 1992, the United Nations held the Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil. One of the results of this conference was the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC acknowledged (UNFCCC 1992):

...that change in the Earth’s climate and its adverse effects are a common concern of humankind, and

...that human activities have been substantially increasing the atmospheric concentrations of greenhouse gases, that these increases enhance the natural greenhouse effect, and that this will result on average in an additional warming of the Earth’s surface and atmosphere and may adversely affect natural ecosystems and humankind.

The goal of the convention was to achieve stabilization of atmospheric GHG concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. It was agreed at this time that there would be serious efforts implemented to reduce the emissions of GHGs. Canada signed the UNFCCC on 12 June 1992, and ratified the treaty on 4 December 1992. As a developed nation, Canada is listed under Annex I of the UNFCCC (UNFCCC 1992).

The UNFCCC did not set specific GHG emission targets for each nation at the UNCED. The GHG emissions targets were set at the Third Conference of the Parties to the UNFCCC in Kyoto, Japan, from 1 to 10 December 1997, which resulted in the Kyoto Protocol. The Kyoto Protocol commits Annex I nations from the UNFCCC to reduce their overall GHG emissions. This reduction must equal at least 5% from the national emission levels of 1990, and must be accomplished during the commitment period of 2008–2012 (UNFCCC 1997*a*). There are six Annex I nations with commitments that are less than 5% reductions under the Kyoto Protocol, including Russia and Australia. Upon the entry into force of the Kyoto Protocol, Canada will be committed to reducing its GHG emissions to 94% of 1990 emissions over the 2008–2012 commitment period (UNFCCC 1997*a*). Canada signed the Kyoto Protocol on 29 April 1998 and ratified the protocol on 17 December 2002 (UNFCCC 2004).

For the Kyoto Protocol to enter into force, there are two requirements. Firstly, a minimum of 55 nations must ratify it. Secondly, among those nations that ratify it, a minimum of 55% of the 1990 CO₂ emissions from Annex I nations (developed nations and economies in transition) must be accounted for. As of 17 March 2004, there were 121 parties that had ratified or acceded to the protocol, fulfilling the first requirement. Annex I countries that had ratified the Kyoto Protocol account for 44.2% of total Annex I emissions (UNFCCC 2004). Should Russia, responsible for 17.4% of 1990 CO₂ emissions (UNFCCC 1997*b*), ratify the protocol, the Kyoto Protocol would enter into force.

Greenhouse gases, the Kyoto Protocol and Canada

The effects of global warming may be even greater in a nation like Canada that contains temperate, sub-arctic, and arctic zones, than in most other nations. In the taiga areas of the Arctic including the MacKenzie Basin, there has already been an increase in temperature of 1.5 °C over the past century (Environment Canada 1997). Arctic sea ice has shrunk in thickness from an average of 3.1 m to 1.8 m in the past 30 years (Rothrock et al. 1999). The impact of climate change is of great concern to Canada, and as one of the highest emitters on a per capita basis among developed nations (after Australia and the United States) (OECD 2002, 2004), mitigation of emissions are particularly pertinent to Canada.

Canada’s Greenhouse Gas Inventory 1990–2001 (Olsen et al. 2003) is the most recent inventory of Canadian GHG emissions prepared by the Canadian Government, and quantifies emissions by GHG and

by sector. In 1990, Canada emitted 608 megatonnes (Mt) of CO₂e (Table 2). Based on the 6% reduction Canada has committed to under the Kyoto Protocol, Canada must reduce its GHG emissions by 37 Mt from this figure, to 571 Mt of CO₂e. The Canadian government projects that business-as-usual (BAU, i.e., should no action be taken to mitigate emissions) emissions will reach 809 Mt of CO₂e by 2010 (the middle point of the Kyoto Protocol commitment period). Therefore, according to the Government of Canada's climate change plan, GHG emissions must be reduced by 240 Mt CO₂e from the BAU scenario prediction for Canada to meet its commitment under the Kyoto Protocol (Government of Canada 2002). Canadian emissions increases throughout the 1990's; the Canadian climate change inventory (Olsen et al. 2003) calculates that in 2001, Canadians emitted 720 Mt CO₂e, an increase of 18% over 1990 emissions (Table 3). From 2001, Canada must reduce GHG emissions by 150 Mt CO₂e through the 2008–2012 Kyoto Protocol commitment period to meet the Canadian Kyoto commitment. Most of the increase in GHG emissions throughout the previous decade resulted from the energy sector; emissions have remained essentially constant in all sectors except energy and waste (Olsen et al. 2003).

It is worth noting that the GWPs listed in the Canadian climate change inventory are different from those listed in Table 1. The values given in Table 1 are from the IPCC's Third Assessment Report (Ramaswamy et al. 2001), while the climate change inventory uses the GWPs recommended by the IPCC at the third Conference of the Parties to the UNFCCC (Olsen et al. 2003), and accepted in Article 5, Paragraph 3 of the Kyoto Protocol (UNFCCC 1997a). The GWPs accepted at the signing of the Kyoto Protocol are to be used in GHG inventories through the end of the first commitment period in 2012.

The Government of Canada has released the Climate Change Plan for Canada, describing its plans for meeting the terms of the Kyoto Protocol (Government of Canada 2002). There are three stages in this plan. The first stage includes actions that are already underway, which target GHG emission reductions of 80 Mt CO₂e. These actions include 30 Mt of carbon sequestration in agricultural soils and forests, and 50 Mt of emission reductions. The second stage includes new actions that have been outlined in the Climate Change Plan. This stage targets 100 Mt of emission reductions, and focuses more than half of its emission reductions on large final emitters (LFEs). The final stage aims to reduce the final 60 Mt of BAU GHG emissions. The Canadian Government expects that existing and future research and development investments under programs such as the Technology Early Action Measures, Sustainable Development Technology Canada, and Technology Partnerships Canada programs, credit for clean energy export (e.g., natural gas exported to the United States to displace coal), the One-Tonne Challenge for Canadians, and other programs at the provincial and municipal levels may be able to accomplish the remaining emission reductions.

This section presented background on climate change, Canada's GHG emissions, and international agreements, such as the Kyoto Protocol and the UNFCCC, which are aimed at reducing GHG emissions. The report will now focus on GHG emissions from the Canadian solid waste sector.

3. Greenhouse gases and the solid waste sector in Canada

In 2001, the 30 million residents of Canada generated 720 Mt CO₂e in GHG emissions, equal to 24 t of CO₂e per capita across all sectors (Table 3; Olsen et al. 2003). The disposal of solid waste alone was responsible for 24.8 Mt of GHG emissions in 2001 (Table 4), or 0.83 t CO₂e per capita. This is an increase from 24.3 Mt in 2000. The Canadian climate change inventory measures the waste sector's contribution to GHGs at 3.4% of Canada's GHG emissions (Fig. 1), not including emissions from the transportation of waste or the consumption of energy during the useful life of products (Olsen et al. 2003). This section will discuss the greenhouse impacts of nonhazardous waste, specifically municipal solid waste (MSW), and the sources of GHG emissions related to the waste sector, both directly and indirectly.

Table 2. Canadian greenhouse gas emissions from 1990, the base year for Kyoto Protocol commitments (adapted from Olsen et al. 2003; Ramaswamy et al. 2001).

Greenhouse gas source category	CO ₂	CH ₄	CH ₄	N ₂ O	N ₂ O	HFCs	PFCs	SF ₆	Total
Relative global warming potential (CO ₂ = 1)	1		21		310	140–11 700	6 500–9 200	23 900	
	kt	kt	kt CO ₂ e	kt	kt CO ₂ e	kt CO ₂ e	kt CO ₂ e	kt CO ₂ e	kt CO ₂ e
Energy	432 000	1 600	33 000	27	8 400	—	—	—	473 000
Industrial processes	32 600	—	—	37	11 000	—	6 000	3 000	52 900
Solvent and other product use	—	—	—	1	420	—	—	—	420
Agriculture	7 550	980	21 000	100	31 000	—	—	—	59 200
Land-use change and forestry (non-CO ₂ only)	—	62	1 300	3	960	—	—	—	2 260
Waste	254	900	19 000	3	920	—	—	—	20 200
Total	472 000	3 542	74 300	171	52 700	0	6 000	3 000	608 000

Note: HFC, hydrofluorocarbon; PFC, perfluorocarbon; SF₆, sulfur hexafluoride.

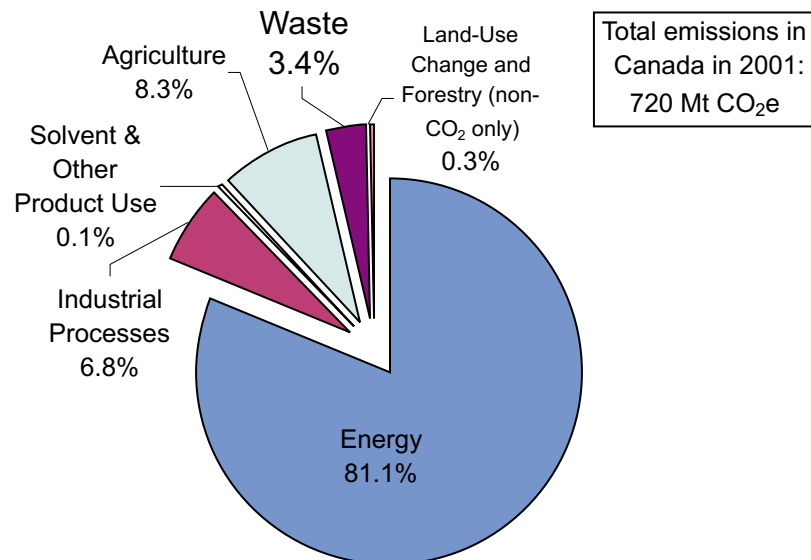
Table 3. Canadian greenhouse gas emissions from 2001 (adapted from Olsen et al. 2003; Ramaswamy et al. 2001).

Greenhouse gas source category	CO ₂	CH ₄	N ₂ O	HFCs	PFCs	SF ₆	Total
Relative global warming potential (CO ₂ = 1)	1	21	310	140–11 700	6 500–9 200	23 900	
	kt	kt CO ₂ e	kt CO ₂ e	kt CO ₂ e	kt CO ₂ e	kt CO ₂ e	kt CO ₂ e
Energy	528 000	45 000	11 000	—	—	—	584 000
Industrial processes	38 300	—	1 600	900	6 000	2 000	49 000
Solvent and other product use	—	—	470	—	—	—	470
Agriculture	–299	24 000	36 000	—	—	—	60 000
Land-use change and forestry (non-CO ₂ only)	—	1 100	1 000	—	—	—	2 100
Waste	284	23 400	1 030	—	—	—	24 800
Total	566 000	93 100	51 070	900	6 000	2 000	720 000

Note: HFC, hydrofluorocarbon; PFC, perfluorocarbon; SF₆, sulfur hexafluoride.

Table 4. Greenhouse gas emissions from the waste sector in Canada, 2000 and 2001 (adapted from Olsen et al. 2003).

Greenhouse gas	CO ₂	CH ₄	CH ₄	N ₂ O	N ₂ O	Total
Relative global warming potential (CO ₂ = 1)	1	CH ₄	21	N ₂ O	310	
	kt	kt	kt CO ₂ e	kt	kt CO ₂ e	kt CO ₂ e
2000						
Solid waste disposal on land	—	1 100	22 600	—	—	22 600
Wastewater handling	—	19	400	3	960	1 360
Waste incineration	282	—	7	—	59	348
2000 Waste total	282	1 120	23 000	3	1 020	24 300
2001						
Solid waste disposal on land	—	1 100	23 100	—	—	23 100
Wastewater handling	—	19	400	3	970	1 370
Waste incineration	284	—	7	—	60	350
2001 Waste total	284	1 100	23 500	3	1 030	24 800

Fig. 1. Greenhouse gas emissions in Canada in 2001, by sector (adapted from Olsen et al. 2003).

3.1. The solid waste sector in Canada

In 2000, 31.38 Mt of nonhazardous solid waste for generated in Canada, equalling 1019 kg of waste per capita (Statistics Canada 2003). Of this total, 7.50 Mt (24%) was diverted for recycling or composting, 22.99 Mt was sent for ultimate disposal at landfills or solid waste incinerators, and the remaining 890 kilotonnes (kt) of the waste was exported for disposal. Mainly through anaerobic decomposition of waste in landfills, the solid waste sector generated 24 300 kt CO₂e in 2000, the year of the most recent waste management industry survey (Table 4) (Olsen et al. 2003). However, only CH₄ from landfills, CH₄ and N₂O emissions from wastewater handling, and emissions from waste incineration are accounted for from the waste sector in the GHG inventory, to the exclusion of waste transport emissions.

Table 5. Methane generated at landfills in Canada, 1990–2001 (adapted from Environment Canada 2002a).

Year	CH ₄ generated at landfills		CH ₄ captured at landfills		CH ₄ emitted from landfills	
	(kt/year)	(kt CO ₂ e/year)	(kt/year)	(kt CO ₂ e/year)	(kt/year)	(kt CO ₂ e/year)
1990	1 093	23 000	211	4 400	883	18 500
1991	1 126	23 600	214	4 500	912	19 200
1992	1 156	24 300	224	4 700	932	19 600
1993	1 184	24 900	229	4 800	955	20 100
1994	1 210	25 400	244	5 100	966	20 300
1995	1 236	26 000	266	5 600	970	20 300
1996	1 262	26 500	289	6 100	973	20 400
1997	1 288	27 000	292	6 100	996	20 900
1998	1 294	27 200	276	5 800	1 018	21 400
1999	1 320	27 700	280	5 900	1 040	21 800
2000 ^a	1 355	28 500	280	5 900	1 075	22 600
2001 ^a	1 440	30 200	340	7 100	1 100	23 100

^aEstimated from LFG capture data (NOPP 2002) and LFG emissions from national GHG inventory (Olsen et al. 2003).

Landfills generate 95% of the GHG emissions from the waste sector accounted for in the GHG inventory, through the production of landfill gas (LFG). The CH₄ fraction of LFG also accounts for 25% of Canada's CH₄ emissions. Landfill gas is comprised of approximately between 45–60% CH₄ and between 40–60% CO₂ (Tchobanoglous et al. 1993). Carbon dioxide emissions from the decomposition or combustion of organic wastes are not included in the inventory, as they are considered as carbon neutral (i.e., they do not increase the atmospheric CO₂ concentration) (Olsen et al. 2003). This is because, as these organic materials were growing, they sequestered CO₂ from the atmosphere; it is assumed that an equal amount of new organic material will grow to replace the displaced organic material (Karthia and Larson 2000). These CO₂ emissions are instead reported among the statistics for agriculture and land-use change and forestry (El-Fadel and Sbayti 2000).

Despite a 33% increase in landfill gas (LFG) capture and combustion during the 1990s, CH₄ emissions from landfills still increased 22% between 1990 and 2000, due to an increase in the quantity of material decomposing in landfills (Olsen et al. 2002). Neither the increased amount of LFG that was captured between 1990 and 2000, nor the increase in the mass of organic material composted (981 kt of organic material was diverted in 2000 vs. 678 kt in 1998) (Statistics Canada 2003), were sufficient to offset the increase of CH₄ being emitted from landfills (Table 5).

3.2. Emissions from transportation in the Canadian solid waste sector

It is generally believed that the emissions from transportation of solid waste in Canada are small (ICF Consulting 2001). For this reason, there has been no study detailing the emissions from waste transportation across Canada, and these emissions are separate from the waste sector emissions in the GHG inventory. This section will attempt to estimate these emissions.

In several Canadian jurisdictions, MSW is being transported large distances for landfilling. For example, the City of Gatineau transports waste to Lachute, Québec, a 140 km distance.² The transfer vehicles return to Gatineau empty, halving the efficiency of transportation. Since the beginning of 2003, Toronto's waste has been transported by truck to Sumpter Township in Michigan for disposal (an 800 km round-trip) (Kurth 2003). Before this approach was adopted, the city considered landfilling its waste

²F. Tremblay. 2003. City of Gatineau, Québec. Personal communication.

at the Adams Mine near Kirkland Lake, Ontario, 600 km north, transporting the waste by train from a transfer station in Vaughan (Gutteridge 2000).

The emissions from waste transportation are included in the transportation section of the GHG inventory, under the heavy-duty vehicle section. Transportation emissions account for 187 Mt CO₂e of Canada's 720 Mt CO₂e emitted in 2001. Heavy-duty gasoline and diesel vehicles and off-road vehicles emitted 62.2 Mt CO₂e in Canada in 2001 (Olsen et al. 2003). These categories generated 33% of Canada's transport greenhouse gas emissions, equal to 8.6% of Canada's total GHG emissions. Total heavy-duty vehicle GHG emissions are more than double the GHG emissions of the waste sector. However, the exact contribution of the solid waste sector to Canadian GHG emissions of heavy-duty vehicles has not been quantified as yet. The emissions from transportation of MSW are small in comparison to total MSW GHG emission. Torrie (2003a) estimates that GHG emissions from waste transportation are 10 kg CO₂e/t waste for short distance trips, and 20 kg CO₂e/t for longer distance trips for Canadian sources. In the United States, the EPA (2002a) estimated emissions generated from the transportation of the material, either for ultimate disposal or for recycling, at 40 kg CO₂e/t waste. However, this is in conflict with other figures offered by the EPA. The EPA (2002b) estimated MSW waste transport emissions at 3.37 Mt CO₂e for 1999, a year in which 210 Mt of MSW were handled (EPA 2002b) resulting in 16 kg CO₂e/t waste. Based on the above sources, an estimate of 20 kg CO₂e generated for each tonne of MSW handled is reasonable. Further to transportation emissions of 20 kg CO₂e/t MSW managed, Torrie (2003a) estimates that bulldozers, loaders, and compactors at landfills consume 1.5 L of diesel per tonne of waste; at a rate of 2.7 kg CO₂e emitted/kg diesel fuel consumed, these vehicles generate 4 kg CO₂e/t waste. Therefore, heavy-duty vehicles in the solid waste sector generate about 24 kg CO₂e/t waste managed. Considering that Canada generated 31.38 Mt of solid waste in 2000, this would equate to approximately 750 kt CO₂e.

The expectation is that emissions from waste transportation will increase in the near future. There has been a trend towards fewer and larger landfills in North America. In the US, the number of landfills decreased from about 8000 in 1988 to fewer than 2000 by 1999 (EPA 2002c). A reduction in the number of landfills will lead to an increase in the number of kilometres travelled by waste collection and transfer vehicles, in order to reach the more distant landfills. The trend in increasing emissions will also continue if there are increases in the number of collection streams. For example, full implementation of organic waste collection in jurisdictions without current organic waste collection will increase the number of trucks required to haul waste, thus increasing the kilometres travelled by waste collection trucks.

With the current shift towards larger and fewer landfills, it appears that collection and transportation of waste will continue to increase, which will encourage an increase in GHG emissions. Decreasing GHG emissions from transportation in the solid waste sector in the current waste management environment appears very unlikely. Possible efficiency gains by waste collection and transportation vehicles will be offset by the forecasted increase in kilometres travelled. The possibilities for mitigating these emissions are addressed in the next section.

3.3. Mitigating transportation greenhouse gas emissions in the solid waste sector in Canada

There exist several options for mitigating emissions from the transportation of solid waste. The option that has the most potential in the short term is natural gas-fuelled collection vehicles. The first natural gas (NG) refuse collection trucks in North America were incorporated into the New York City Department of Sanitation in 1989 (Gordon et al. 2003). There are now nearly 700 NG trucks in solid waste fleets in the US. Tests have demonstrated an average of 8% reduction in CO₂ emissions from NG trucks, as well as reductions in the emission of criteria air pollutants such as nitrogen oxides (NO_x), particulate matter (PM), and non-methane hydrocarbons. As a further benefit, NG vehicles reduce the health impacts on operators due to their reduced emissions and noise (Gordon et al. 2003). However, the cost of these trucks, at 15–25% greater than the cost of diesel trucks, remains a significant barrier to full deployment, though there are incentives that make NG vehicles more competitive with diesel vehicles.

Natural gas refuelling facilities are rare, and companies and municipalities that integrate NG trucks into the refuse collection fleet often have to build refuelling facilities, at a starting cost of US\$500 000. Maintenance of NG vehicles cost 10–20% more than maintenance of diesel trucks, mostly due to the cost of replacing spark plugs, the need for synthetic oil, and additional control equipment compared to diesel models (Gordon et al. 2003).

There are other fuels and vehicle designs that may become available in the short to medium term with the potential of reducing the pollutant emissions of the transport of MSW. These include vehicles that are fuelled by biodiesel, synthetic diesel (zero-sulfur diesel produced from short-chain hydrocarbons), or liquefied petroleum gas, and hybrid-electric vehicles (Gordon et al. 2003). Of these, hybrid-electric and biodiesel technologies have the greatest potential for reducing GHG emissions, and both of these technologies are available currently. Biodiesel is a diesel substitute produced from renewable sources (vegetable oils or animal fats reacted with either methanol or ethanol) and is capable of being used in new diesel engines with little or no modification, generating no net emissions upon combustion save pollutant emissions (AFDC 2003). Hybrid-electric engines have an electric motor that operates in place of the internal combustion engine (ICE) at times of low power demand. The battery in a hybrid-electric vehicle is charged when the ICE is operating at high demand, or through regenerative braking (OTT 2003).

Another option for reducing transportation emissions is to site landfills or other waste treatment facilities (e.g., waste digestion or incineration facilities) in close proximity to large metropolitan centres, where the greatest volume of waste is produced. This would decrease the distance that MSW would have to travel for ultimate disposal. However, siting landfills closer to large municipalities has proven politically difficult, as is evident from the challenges that Toronto has had in siting a new landfill. Residents of the Greater Toronto Area have been unwilling to allow a landfill to be sited near them (commonly known as the “not in my back yard” (NIMBY) principle). As such, Toronto has not managed to site a landfill in close proximity.

Emissions from waste transport, while not insignificant, remain a small but growing fraction of the total emissions from the waste sector (an estimated 750 kt CO₂e for waste transport in Canada, compared to 23 Mt CO₂e from landfills alone). Waste transport GHG emissions are expected to increase as recycling and organic diversion programs expand and landfills become fewer, more distant from major metropolitan areas and larger. However, the GHG emission reduction benefits of diversion programs greatly outweigh the increase in emissions from the transportation of waste. The following section will discuss the emission reductions possible in through waste management strategies.

4. Meeting the Kyoto Protocol in the Canadian waste sector

Waste management decisions affect the amount of GHG emissions being generated by the waste sector. Source reduction decreases the amount of materials being consumed, eliminating all of the related GHG emissions. Recycling enables the reduction of GHG emissions at many stages of the material life cycle, as it diverts materials from landfills and reduces emissions from the processing of virgin materials (the diversion of rapidly degradable materials such as paper offers significant emission reduction benefits) (Pickin et al. 2002; NOPP 2002). Diversion of organic materials, for either composting or anaerobic digestion, removes a significant portion of readily degradable waste from landfills, preventing these wastes from degrading anaerobically and generating CH₄. Incineration also prevents organic wastes from decomposing anaerobically by combusting these wastes to generate power or steam. This section will explain the life cycle of materials, and at which points in the life cycle of a product a change can be made to reduce GHG emissions.

4.1. The life cycle of materials

The life cycle of any material involves 4 stages — virgin material extraction, manufacturing, materials management, and ultimate disposal (NOPP 2002). All materials in use go through these four stages.

This section will focus on goods that may ultimately be disposed of in landfills. The first stage ranges from the mining of metals (e.g., iron and aluminum) and petroleum (for plastics and other uses) to the harvesting of trees (for paper) and food. The life cycle of aluminum will be used as an example.

Metal processing and manufacturing converts aluminum ore to products that are of benefit to society (e.g., soda cans). These aluminum products are consumed and then sent for disposal at a landfill or a waste-to-energy plant, or recycled and sent to a materials recovery facility (MRF). At a MRF, aluminum wastes are separated and marketed to metals processors, who direct the recovered material on to manufacturers. The recycled aluminum is then returned to market, and once consumed, can be sent to MRFs, where the process of separation, processing, manufacturing, and consumption can occur repeatedly, until the aluminum is landfilled (NOPP 2002). Life-cycle energy consumption and GHG emissions tend to be greater for the production and transport of virgin materials compared to raw materials (Table 6).

Municipalities promote the recycling of aluminum; 62.2% of aluminum was recycled in the US in 1995 (Strong 1997). Promotion of aluminum recycling is due to the high value of aluminum; the market value of recycled aluminum in 1998 ranged between US\$600/t and US\$1120/t (Hickman 1999). Though aluminum comprises only 1–2% of the total recovered mass from a municipal recycling program, it contributes 35–45% of the revenue generated from the sale of recycled materials. Manufacturing products from recycled aluminum reduces energy consumption by 93% from manufacture from virgin aluminum ore (EPA 2002a). Recycling aluminum in Canada reduces net GHG emissions by 3.89 t CO₂e for each tonne of aluminum that is recycled instead of landfilled. Table 7 demonstrates the emission reductions possible for several MSW management options for various MSW components, taking into consideration the impact of carbon sequestration. The difference between any two options listed equals the GHG emissions savings for the lower emissions option.

Torrie (2003b) addresses the greater emission reductions demonstrated through recycling than through source reduction for some of the materials listed in Table 7. The guiding assumption in Table 7 is that source reduction avoids the production of material that would have been produced from the current mix of virgin and recycled inputs, thus the emissions would have been a mix of the emissions from producing materials from recycled inputs and from virgin inputs (Table 6). For the recycling cases, Torrie (2003a, 2003b) assumed that recycling avoided GHG emissions that would have been generated had the materials been produced solely from virgin inputs, rather than from the current mix of recycled and virgin inputs as is the case for source reduction.

4.2. Actions for the solid waste sector to assist Canada in achieving its Kyoto Protocol commitments

A hierarchy of waste management options has been established for waste management options, in order to minimize waste being landfilled. This hierarchy also applies to reducing GHG emissions from the solid waste sector as well, and is as follows (RCO 1998):

- (1) Waste reduction
- (2) Reuse
- (3) Waste recycling
- (4) Biological treatment of waste (digestion and composting)
- (5) Waste disposal with energy recovery
- (6) Waste disposal without energy recovery

Canada's Climate Change Plan (Government of Canada 2002) has not used the waste management hierarchy in its attempt to achieve emission reductions; instead, it focuses emission reductions from the waste sector solely on reducing GHG emissions from landfills. The first stage of the climate change

Table 6. Emission reductions and energy savings achieved through production using recycled materials versus virgin inputs in the United States (adapted from EPA 2002a).

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 ₂ e/t of product)	Process non-energy emissions (t CO ₂ e/t of product)	Transport emissions (t CO ₂ e/t of product)	Total emissions (t CO ₂ e/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		

Table 7. GHG emissions from MSW management options, with consideration for carbon sequestration (tonnes CO₂e/tonne) (adapted from ICF Consulting 2001; NOPP 2002; Torrie 2003a, 2003b).

	News-print	Fine paper	Cardboard	Mixed paper	Aluminum	Steel	Glass	HDPE	PET	Other plastics	Food waste	Yard trimmings
Net source reduction emissions	-3.55	-5.48	-4.94	-5.12	-2.03	-1.59	-0.47	-1.97	-2.85	-2.20	n/a ^a	n/a ^a
Net recycling emissions	-2.75	-3.12	-3.30	-3.04	-3.89	-0.98	-0.07	-1.40	-3.42	-1.85	-0.11 ^b	-0.88 ^b
Net anaerobic digestion emissions	-0.38	-0.28	-0.20	-0.19	0	0	0	0	0	0	-0.27	-1.12
Net combustion emissions	-0.26	-0.22	-0.22	-0.22	0.01	-0.78	0	2.39	2.5	2.27	-0.05	-0.07
Net landfilling emissions (50% LFG recovery)	-0.86	2.05	0.16	0.28	0	0	0	0	0	0	0.53	-0.50
Net landfilling emissions (no LFG recovery)	-0.39	4.25	1.13	1.28	0	0	0	0	0	0	1.14	-0.16

^aBecause of the nature of food wastes and yard trimmings, source reduction is not seen as a viable waste reduction strategy for these waste categories.

^bRecycling emissions reductions are for the composting of food waste and yard trimmings.

plan includes a program to reduce landfill emissions by 2.2 Mt CO₂e through two pilot LFG capture projects under the Green Municipal Investment Fund. This action will reduce solid waste sector GHG emissions by 9% (Government of Canada 2002). The climate change plan outlines another 8 Mt CO₂e of emission reductions that are possible at low cost through LFG capture. This would reduce emissions (from the 24.8 Mt CO₂e emitted in 2001 by the waste sector) by 32%. This section will analyse LFG capture and utilization, among other waste management strategies to reduce GHG emissions, including source reduction, recycling, biological transformation of the organic fraction prior to landfilling (by composting and anaerobic digestion), and incineration.

An integrated solid waste management (ISWM) system can be used to analyze alternatives for handling solid waste, accounting for environmental, financial, social, and political considerations. Integrated solid waste management systems consider ways to reduce waste and to gain the most value from the waste being landfilled, or at least to minimize the costs. The five aforementioned options should be considered in an ISWM plan, though not all will be applicable in all cases. The first waste management technique that will be analyzed for its greenhouse emission reduction potential is source reduction.

4.2.1. Source reduction

Source reduction is the best way to reduce emissions in the waste sector, as well as reducing landfilling requirements. Source reduction refers to changes in design, manufacture, purchase or use of materials or products (including packaging) to reduce their contribution to the MSW stream (EPA 2002d). The reuse of material is also considered a form of source reduction (e.g., bringing cloth or used plastic bags to grocery stores for shopping to avoid the use of new bags). Reusing materials and reducing material consumption avoids all life-cycle emissions for the products that would replace this material.

An example of source reduction can be seen in soft drink bottles in the US. Plastic soft drink bottles of 2 L in volume have been reduced in weight by 28% (from 68 g to 51 g) since 1977, reducing by 250 million lbs (113 000 t) the amount of plastic that would otherwise enter the American waste stream annually (EPA 2002d). Considering that these soft drink bottles are made of polyethylene terephthalate (PET), and that source reduction saves 2.85 t CO₂e/t of PET compared to landfilling, this action reduces annual emissions by 320 kt CO₂e. Paper products also have very favourable emissions reductions from source reduction compared to landfilling, as is evident in Table 7. Source reducing fine paper versus landfilling without gas recovery decreases GHG emissions by 9.7 t CO₂e/t paper (Torrie 2003b).

Extended producer responsibility (EPR) programs create incentives for reducing waste at its source. These EPR programs encourage producers to alter the design of products in order to reduce the environmental impact of those products. They are designed so that producers bear economic responsibility for the products that they create throughout the life cycle of the product (Environment Canada 2002b). The Green Dot program in Germany, one of the most successful EPR programs, has decreased packaging consumption in Germany from 13 Mt to 11.5 Mt between 1991 and 1997, and reduced residential and small business packaging from 7.6 Mt in 1991 to 5.1 Mt in 2001 (Schiffler 2002).

Canadian EPR programs have typically been voluntary, unlike the Green Dot program. As an example, in 1990, the Canadian Council of Ministers of the Environment established the National Packaging Protocol, a voluntary packaging stewardship program (Environment Canada 2002b). The National Packaging Protocol targeted a 50% reduction in packaging wastes being landfilled in Canada by the year 2000, from the 1988 baseline of 5.41 Mt. This target was surpassed by 1996, by which time packaging waste being landfilled had decreased by 51.2%, from 5.41 Mt in 1988 to 2.64 Mt (CCME 1998). 50% of the reductions were accomplished through new source reduction and reuse initiatives, with recycling and reuse initiatives reducing the amount of landfilled packaging waste a further 50%. New packaging used decreased 21%, from 6.18 Mt in 1988 to 4.89 Mt in 1996 (CCME 1998). However, most of these reductions resulted from savings in manufacturing.

To present, there has been little success in implementing programs in Canada that place the burden

of waste disposal costs on all materials producers, as is the case with the Green Dot program. There are, however, some provincial programs that require certain materials to be disposed of at the expense of the manufacturers, such as a post-consumer residuals stewardship program in British Columbia that handles solvents and flammable liquids. The province of Ontario is, through its Waste Diversion Act, aiming to increase the obligation of manufacturers to 50% of the cost of recycling programs (Environment Canada 2002b). However, the responsibilities of manufacturers in the Waste Diversion Act in Ontario would not match the responsibilities of those involved in the Green Dot program, where all costs of disposal and recycling are borne by manufacturers. A Canadian EPR program requiring manufacturers to take full financial responsibility for their packaging from cradle to grave, in the same manner as the Green Dot program, would lead to increased source reduction in packaging and material wastes, reducing the amount of material being landfilled, as well as life cycle emissions from material processing.

4.2.2. Recycling

Recycled materials can substitute for raw materials in many manufacturing processes, reducing the need to extract and process raw materials. Recycled materials generally require less energy during the manufacturing stage (Table 6). This reduction, depending on the energy mix in the location of production, may lead to significant reductions in GHG emissions. Recycling paper reduces the number of trees being harvested, preserving a carbon sink. Carbon sinks are vital to Canada's plans to meet the Kyoto Protocol; the Canadian Government has made serious efforts at international climate change negotiations for the permission to use carbon sinks to offset GHG emissions (Government of Canada 2002).

In 1998, 24.0% of the waste generated in Canada was being diverted from landfills (Statistics Canada 2003). Canadians generated 28.1 Mt of waste in 1998 (about 0.9 t/person year), and diverted 6.7 Mt of that waste (Statistics Canada 2003). By 2000, that fraction had decreased slightly to 23.9%, as 7.5 Mt of the 31.3 Mt of waste generated in Canada was diverted.

In the Canadian Waste Management Industry Survey performed by Statistics Canada (2003), organic materials (totalling 981 kt in 2000) were included within the recycling statistics. Nine hundred and eighty one kilo tonnes of organic materials were diverted in 2000 (. Diverted organic wastes are usually composted; however, three Ontario municipalities, Guelph, Newmarket, and Toronto, treat at least a portion of the organic waste stream through anaerobic digestion. This will be discussed further in section 4.2.4.

Other materials that are recycled at high volumes are ferrous materials, mixed paper, newsprint, boxboard, construction and demolition materials, and glass (Table 8). This diversion of material from landfills has already achieved significant reductions in GHG emissions by reducing the amount of virgin materials being converted into goods (Table 6; Table 7). Recycling offers excellent emission reduction prospects; recycling aluminum reduces emissions by 3.9 t CO₂e/t compared to landfilling, while recycling fine paper reduces GHG emissions by 7.37 t CO₂e/t when compared to landfilling without energy recovery.

Greenhouse gas emission reductions achievable through recycling are not part of the Government of Canada's climate change plan. Rather, the National Office of Pollution Prevention (NOPP), a department of Environment Canada, oversees recycling programs at a national level with a view towards the GHG benefits of recycling programs (NOPP 2002). Minimum recycled content requirements create markets for recyclable materials, encouraging diversion of waste (Mt. Auburn and Northeast-Midwest 1993) and reducing GHG emissions. Environment Canada's Environmental Choice program is a voluntary program that encourages minimum recycled content in products (e.g., a minimum recycled content of 40% for newsprint, of which 25% of the final product must be from post-consumer sources) (Environmental Choice 2003). Given the GHG benefits of recycling materials, any program that encourages recycling for resource conservation reasons will have a GHG co-benefit.

Table 8. Materials prepared for recycling or reuse by type, and GHG emission reductions achieved through recycling (adapted from Statistics Canada 2003; ICF Consulting 2001; NOPP 2002; Torrie 2003a, 2003b).

Type of materials	Amount of material recycled (2000) (kt)	Greenhouse gas emissions reductions achieved through recycling compared to	
		landfilling with no LFG recovery (kt CO ₂ e) ^a	landfilling with 50% recovery of LFG (kt CO ₂ e) ^b
Newsprint	658	1 550	1 240
Cardboard and boxboard	555	2 460	1 920
Mixed paper	1 725	7 450	5 730
Glass	344	24	24
Ferrous metals	1 905	1 870	1 870
Copper and aluminum	43	170 ^c	170 ^c
Other metals	328	n/a ^d	n/a ^d
Plastics	171	320 ^e	320 ^e
Construction and demolition	502	n/a ^d	n/a ^d
Organics	981	710 ^f	370 ^f
Other materials	291	n/a ^d	n/a ^d
Total	7 500	14 600	11 600

^aThese figures were determined by multiplying the amount of material recycled with the difference between per ton emissions from recycling and per ton emissions from landfilling with no gas recovery.

^bThese figures were determined by multiplying the amount of material recycled with the difference between per ton emissions from recycling and per ton emissions from landfilling with LFG recovery.

^cEmissions reductions given are for aluminum, as per Table 7.

^dEmissions reduction data not available for these materials in Table 7.

^eEmissions are assumed to be for the category "other plastics", as per Table 7.

^fRecycling of organic material is assumed to be the composting of yard materials, as per Table 7.

4.2.3. Landfill gas capture for energy recovery

Landfills can be viewed as biochemical reactors, where the organic materials disposed in the landfill react with water to produce LFG and leachate (Tchobanoglous et al. 1993). Food wastes and yard trimmings undergo anaerobic decomposition readily. Those organic wastes with high lignin content, such as textiles, rubber, leather, and woody yard wastes, degrade slowly and may not degrade at all (Tchobanoglous et al. 1993). Some of this carbon may become sunk at the landfill (NOPP 2002). Some carbon-based wastes, such as plastics, are virtually non-biodegradable, and thus will generate no LFG.

At present, many landfills in Canada do not capture the LFG that is generated. The lack of LFG capture causes LFG to comprise 95% of the emissions from the solid waste sector (Olsen et al. 2003). However, LFG capture is becoming a greater priority. The suitability of landfill sites in Canada for LFG recovery has been assessed (Environment Canada 1999; Conestoga-Rovers and Delphi 1999). Landfill sites that do not meet the criteria listed in Table 9 would not merit the collection of LFG. Eighty-six landfills in Canada do meet these criteria (Conestoga-Rovers and Delphi 1999). Of the 86 that meet the criteria for LFG capture, there were 42 LFG collection systems in Canada in 2000, collecting about 280 kt of CH₄. These landfills avoided GHG emissions of 5.9 Mt CO₂e in 2000, without consideration for displaced fuel or electricity. At eight of these locations, the collected LFG was being converted to electricity (Olsen et al. 2002). These sites generated 85 MW from 194 kt of CH₄ captured that year (NOPP 2002). Eight more LFG collection systems were feeding the collected gas to nearby industries, for a total of 16 sites that were generating energy from LFG (Olsen et al. 2002). By 2001, LFG captured from landfills had increased to 340 kt CH₄ (7.1 Mt CO₂e) collected at 47 sites, with 208 kt CH₄ (from the same 16 sites mentioned above) being used to generate energy or electricity (NOPP 2002).

Table 9. Criteria for landfill gas collection at landfills (adapted from Conestoga-Rovers and Delphi, 1999).

Date of site closure	Minimum waste in landfill at site closure (tonnes)
Prior to 1980	Not considered further
1980–1985	>2.5 million
1985–1990	>2.0 million
1990–1999	>1.5 million
Active landfills	>1.0 million

Large, active landfills are capable of generating significant amounts of power. An example is the Waterloo Landfill (near Waterloo, Ontario), which already contains 5 Mt of waste. This landfill has recently begun generating 3.5 MW of power from the LFG produced at the site (OPG 2001). This landfill has a capacity of 15 Mt of waste and will receive waste until 2027. The plant and gas collection system expanded in 2003, and the plant now has a capacity of 8.0 MW (OPG 2001).

As mentioned at the beginning of section 4.2, the only planned action to reduce emissions from the waste sector in the Climate Change Plan for Canada is the capture of LFG (Government of Canada 2002). Actions underway will reduce emissions by 2.2 Mt CO₂e, while the second stage in the plan aims to reduce LFG emissions by 8 Mt CO₂e. It remains to be decided among federal, provincial, and municipal governments whether emission reductions from the capture of LFG should be traded in a domestic emissions trading system, or whether LFG capture should be mandated through regulation, which would remove the surplus nature of the emission reductions, rendering them ineligible for trading (Government of Canada 2002).

4.2.4. Biological transformation of waste

Organic waste, particularly food and yard waste, can be decomposed biologically in two ways: (i) by anaerobic digestion, where the waste is decomposed in a contained area such that it generates CH₄ emissions at a sufficiently high rate to be useful for energy recovery; or (ii) by composting, so that the decomposed waste does not create CH₄ emissions. This section discusses the emissions savings possible and the other benefits for these two options.

4.2.4.1. Anaerobic digestion for energy recovery

Anaerobic digestion is the decomposition of organic materials in the absence of oxygen. Its products are similar to LFG. However, in an anaerobic digester, the process of anaerobic decomposition of organics is accelerated to produce usable volumes of CH₄ in a shorter time.

Anaerobic digestion of MSW is a novel application of anaerobic digester technology in Canada. There are three Canadian locations where anaerobic digestion of the organic fraction of MSW is being undertaken for power generation: the Super Blue Box Recycling (SUBBOR) plant operated by Eastern Power in Guelph, Ontario; the Canada Composting Inc. (CCI) plant in Newmarket, Ontario, which uses the BTA process; and a demonstration plant with the BTA process in Toronto. The SUBBOR process was developed in Canada to anaerobically digest the organic fraction of solid waste, and is said to be capable of generating biogas with 60–65% CH₄ content (Vogt and Holbein 2001). The SUBBOR plant is capable of accepting 25 000 t/year of waste, and can generate 10.4 GWh/year, enough for 900 homes (NOPP 2003a). Canada Composting Inc. uses the BTA process, developed in Germany (CCI 2000). The CCI plant can accept 150 000 t/year of waste, and can generate 13.3 GWh/year, equal to the annual electrical consumption of 1150 homes (NOPP 2003b). Toronto also uses the BTA process in its demonstration anaerobic digestion plant, which can process 25 000 t/year of source separated organic waste (BTA & Co KG 2003).

The CH₄ that is generated by anaerobic digestion, when captured and combusted for power generation, results in biogenic CO₂ emissions, which are not counted in national GHG inventories. The organic residue can be used as a peat-like fertilizer. Should anaerobic digestion of MSW prove to be both technically and financially viable in the Guelph, Newmarket, and Toronto cases, the potential for GHG reductions is evident, as converting the gas from anaerobic digestion to energy can displace the need for fossil fuel-based power generation. This technology has the potential to significantly reduce the 23 Mt CO₂e/year emitted from landfills, and is a waste management strategy that reduces both the amount of waste being disposed in landfills and waste sector GHG emissions.

4.2.4.2. Composting

Composting is an aerobic process in which organic materials are consumed, producing CO₂ and a compost product. Though some CH₄ is generated in regions of compost piles that have depleted the oxygen supply, this is seen as a negligible source of CH₄. Much of the CH₄ that may be generated within a compost pile will be oxidized before reaching the surface of the pile, once it has migrated from the anaerobic zones to the aerobic zones (EPA 2002a). Proper mixing and aeration of compost piles will limit CH₄ production (Tchobanoglous et al. 1993).

In 2000, 981 000 t of organic materials were composted in central off-site facilities (Statistics Canada 2003). Overall, organics comprised 13% of the 7.5 Mt of the material diverted from landfills in Canada. Composting in Canada is concentrated in five provinces, with Ontario (29%), Québec (28%), British Columbia (18%), Alberta (13%), and Nova Scotia (6%) performing the bulk of the composting in Canada (Statistics Canada 2003). This data does not include material that was composted at home by Canadians. In the City of Ottawa in 1999, 23 700 t of organic materials were collected for central composting, and it is estimated that a further 7000 t were composted domestically (30% of the material diverted for central composting) (Solid Waste Division 2000). Projected throughout Canada, this would imply that a further 290 000 t of organic material is being composted domestically.

Composting is useful in avoiding GHG emissions, as it is an aerobic process. Composting, with sufficient aeration, generates biogenic CO₂ instead of CH₄ from the degradation of organic material. Composting reduces emissions from organic waste by a significant amount compared to landfilling without energy recovery (1.2 t CO₂e/t for food wastes and 0.7 t CO₂e/t for yard trimmings) (Table 7). It is estimated that through composting, Canada avoided emissions of about 500 kt CO₂e in 2000, assuming that the compost that was diverted was diverted from landfills with the same LFG capture characteristics as the national standard of 24%.

Composting produces a useful by-product that can be used as a soil conditioner. Approximately 300 kg to 500 kg of compost can be produced from 1 t of municipal solid waste (Brunt et al. 1985). Another benefit of composting is that it requires relatively little capital investment, requiring typically the land upon which the composting occurs, leachate collection systems, and either aeration pipes (for static piles) or mechanical equipment such as front end loaders for turning the material (for turned windrows) (Tchobanoglous et al. 1993). Canada already diverts 3% of its total waste stream through composting programs (Statistics Canada 2003), and this is likely to increase as municipalities become more concerned about the challenges of siting new landfills when those that are currently in operation are scheduled to close. Halifax, N.S. and Edmonton, Alta. are examples of cities that are currently diverting organics from landfills for centralized composting.

4.2.5. Incineration for energy recovery

Incineration is the combustion of MSW at high temperatures to reduce its volume and to generate power or steam. Incineration of waste is a relatively uncommon method for reducing landfilled materials in Canada, due to public perception of the health hazards that result from it. As a result of the negative public opinion of MSW incinerators, a ban on new incinerators was introduced in Ontario in 1992, though this ban was repealed in 1996 (Hunter 1998). In spite of the repeal of this ban, the lack of public

acceptance of incinerators has meant that only one MSW incinerator has since been approved. However, incineration of MSW is very common in Japan, where 77% of MSW is treated by this method (Gielen and Moriguchi 2002). Incineration reduces the volume of material that needs to be landfilled; the final volume of incinerated MSW is typically 20% of the initial volume. Incineration is usually coupled with power generation facilities; in the United States, 30 million tons (27 Mt) of MSW are incinerated annually, generating 2800 MW of power (IWSA 2000). Incineration can offset energy production, and depending on the location, it may offset emissions from power generation using fossil fuels. Since much of MSW is from biological sources (e.g., paper, food, and yard wastes), and these sources are not considered to add CO₂ to the carbon cycle, combustion of the biological components of MSW generates no net GHG emissions (Table 7). The residues from incineration can either be landfilled or can be utilized. For example, the fly ash from incineration can be mixed with cement (Rémond et al. 2002).

Eight MSW incineration facilities operated in Canada during 2001. Of these, five generated power, one (in Burnaby, B.C.) generated steam, and two (each of which processes less than 25 000 t of waste per year) did not recover energy. In 2001, 2.67 PJ were exported from waste-to-energy operations in Canada.

There are negative aspects to MSW incineration, which have curbed the use of the technology in Canada. Incineration produces pollutant emissions such as PM, NO_x, sulfur oxides, hydrogen chloride (HCl), dioxins, furans, and heavy metals including mercury and lead. Nitrous oxide, one of the nitrogen oxide gases produced by the high temperature combustion within incinerators, adds to the radiative forcing of incinerator emissions. In Canada, N₂O emissions from waste incineration accounted for 17% of the radiative forcing of incineration emissions (Olsen et al. 2003). One of the power-generating MSW incineration sites, the Solid Waste and Reduction Unit (SWARU) in Hamilton, has since been closed due to the pollution it generated. This site was responsible for over 95% of dioxin and difuran emissions from MSW incineration installations in Canada in 2001, generating 10.01 grams international toxicity equivalents/year (g I-TEQ/year), out of a total of 10.45 g I-TEQ/year from all waste incinerators in Canada.³

To address pollution from incineration, standards have been set to control dioxins and difurans, lead, cadmium, mercury, PM, sulfur dioxide, HCl, NO_x, and carbon monoxide emissions, in order to minimize the impact of incinerators on public health. The British Columbia Ministry of the Environment (Municipal Solid and Biomedical Waste Branch 1991) has set standards regulating emissions from MSW incinerators with capacities greater than 400 kg/h (Table 10). These standards are more stringent than the most recent Canada-wide standards (CCME 1989).

The cost of MSW incineration is greater than other traditional waste management options, and they have not been able to compete financially with other waste treatment options. Economies of scale typically permit incineration as a competitive waste treatment technology in large urban areas where waste quantities generated exceed 3000 t/d (O'Leary and Walsh 1995). The emissions control systems that must be installed in order to meet air quality standards are also costly. These two conditions act as barriers to the further development of MSW incinerators in Canada.

It is possible that incineration could play a more significant role in Canada in reducing landfilled material, should public perception of incineration change. However, anaerobic digestion and composting are likely to remain more palatable to the Canadian public as methods to convert the organic fraction of MSW, with anaerobic digestion capable of generating power from MSW in instances where it is cost-effective.

Now that the alternatives for reducing GHG emissions in the solid waste sector in Canada have been analyzed, conclusions can be drawn as to which of these alternatives are best suited to reducing GHG emissions in the Canadian waste sector in order to meet Canada's Kyoto Protocol commitments.

³Alain David. 2003. Personal communication.

Table 10. Stack emission limits for municipal solid waste incinerators (Municipal Solid and Biomedical Waste Branch 1991; CCME 1989).

Contaminant	B.C. Limit	CCME Limit
Arsenic ^a	4 µg/Rm ³	1 µg/Rm ³
Cadmium ^a	100 µg/Rm ³	100 µg/Rm ³
Carbon monoxide	55 mg/Rm ^{3b}	57 mg/Rm ^{3c}
Chlorobenzenes	1 µg/Rm ³	1 µg/Rm ³
Chlorophenols	1 µg/Rm ³	1 µg/Rm ³
Chromium ^a	10 µg/Rm ³	10 µg/Rm ³
Hydrogen chloride	70 mg/Rm ³	75 mg/Rm ³ or 90% removal ^b
Hydrogen fluoride	3 mg/Rm ³	20 mg/Rm ³
Lead ^a	50 µg/Rm ³	50 µg/Rm ³
Mercury ^a	200 µg/Rm ³	200 µg/Rm ³
Nitrogen oxides (NO _x as NO ₂)	350 mg/Rm ³	400 mg/Rm ³
Opacity	5%	5%
Polychlorinated biphenyls	1 µg/Rm ³	1 µg/Rm ³
Polycyclic aromatic hydrocarbons	5 µg/Rm ³	5 µg/Rm ³
Sulphur dioxide	250 mg/Rm ³	260 mg/Rm ³
Total hydrocarbons (as methane (CH ₄))	40 mg/Rm ³	20 mg/Rm ³
Total particulate	20 mg/Rm ³	20 mg/Rm ³
Total PCDDs & PCDFs ^c	0.5 ng/Rm ³	0.5 ng/Rm ³

Note: Rm³, dry cubic metres at 25 °C and 101.3 kPa; concentrations corrected to 11% O₂.

^aThe concentration is total metal emitted as solid and vapour.

^bFor refuse-derived fuel (RDF) systems the limit is 110 mg/Rm³.

^cRDF systems should maintain a limit of 114 mg/Rm³.

^dThe least restrictive of these requirements apply.

^eExpressed as toxicity equivalents.

5. Conclusions and recommendations

This paper has analysed the Kyoto Protocol, Canada's GHG emissions targets under the protocol, and the strategies through which the MSW sector can reduce its GHG emissions.

Source reduction reduces the amount of material being produced, avoiding emissions from the outset, and as such is the most desirable option. Source reduction requires education of the public and of manufacturers, plus a great deal of political will. Extended producer responsibility programs that place full product liability on producers can encourage source reduction; this has already occurred in Germany. There are significant emission reduction gains achievable through source reduction, especially for paper and paper product wastes.

Recycling must remain part of ISWM plans, as a method to not only reduce the amount of material being sent to landfill, but also to reduce GHG emissions from the waste sector (Table 6; Table 7). Of particular benefit is the reduction in the volume of virgin materials that need to be processed, and the energy required to process these materials. The GHG emissions benefits of recycling should lead to further encouragement of this practice. Minimum recycled content legislation for new products would further encourage recycling programs and reduce GHG emissions.

At present, LFG capture and combustion appears the most desirable manner of achieving significant emission reductions from the current baseline in the solid waste sector in the near term. Ninety-five percent of the solid waste sector's emissions, as demonstrated in the GHG inventory result from LFG (Olsen et al. 2003). Landfill gas capture is the only waste management strategy mentioned within the Climate Change Plan for Canada to reduce emissions (Government of Canada 2002). Canada should continue encouraging the capture of LFG for power and heat, and should encourage flaring of LFG at those sites without the capacity to generate enough LFG for utilization to be feasible.

Anaerobic digestion of the organic fraction of MSW can be integrated with recycling and source reduction programs that limit the amount of non-degradable materials being landfilled. Should the technology for anaerobic digestion prove successful and cost-effective in the Canadian context, it would appear to be the best treatment option for the organic fraction of MSW for the long-term abatement of GHGs. This is because the CH₄ generated from anaerobic digestion can be used to generate energy, not only eliminating CH₄ emissions but also displacing fossil fuel-based generation. It is more desirable than capturing LFG, as a greater fraction of CH₄ is captured, and the fixed carbon becomes a useful by-product instead of adding mass to landfills. However, it is possible that the technology will not be as practical or may not be ready for dissemination soon enough to help Canada meet its Kyoto commitments. Regardless, anaerobic digestion should be focused on as a long-term solution to cutting GHG emissions in the MSW sector, due to the energy benefits that arise. A long-term ISWM system should consider anaerobic digestion if the technology is proven successful and cost-effective.

Composting can be useful in an ISWM program for several reasons. Composting reduces GHG emissions through the conversion of rapidly decomposing matter to CO₂ (as opposed to CH₄). As well, composting diverts waste from landfills and produces a useful by-product with minimal initial investment. Centralized composting is a near-term solution for reducing material to be landfilled and reducing GHG emissions. Residential composting should remain part of integrated solid waste management plans in the future. While it is not as effective as centralized composting and is difficult to practice in multi-unit residential buildings, residential composting avoids waste collection costs and collection vehicle emissions.

Incineration of MSW does not appear to be a favourable manner of reducing waste being sent to landfill, reducing GHG emissions, and generating power from MSW. Incineration plant costs are prohibitive for small population centres. The poor public perception of incineration makes it unlikely that incineration will become a common method of reducing GHG emissions in Canada, and the end of operation of SWARU in Hamilton demonstrates the pressure to find alternatives to MSW incineration. However, pollutant emissions from incinerators are being addressed, and it is possible that public perception may change on MSW incineration. If this were to occur, MSW incineration may become more acceptable waste management option. Incineration can achieve significant reductions in GHG emissions for the solid waste sector.

Transportation emissions can be reduced by facilitating the creation of landfills in closer proximity to large urban areas, such as Toronto. However, this is unlikely to happen, due to the NIMBY principle. Waste management emissions are estimated at 3% of the MSW sector's emissions, and thus should not be the main focus of emission reduction efforts in the solid waste sector. Transport emissions are expected to increase as more diversion programs come into effect, and diversion programs will have far greater emission reduction benefits than the emissions increases of increased transportation. Decreases in the emissions of transportation vehicles, through the use of biodiesel, natural gas, or hybrid-electric vehicles, would offset some of the increase in kilometres travelled that are foreseen in the sector.

There has already been an effort to capture LFG and reduce the GHG emissions in the waste sector in Canada. Waste diversion (recycling and composting) programs demonstrate a commitment to reduce waste being landfilled, and concurrently GHG emissions from waste. Extended producer responsibility programs and the anaerobic digestion plants in Guelph, Newmarket, and Toronto also demonstrate a Canadian commitment to this end. These options offer the solid waste sector many means for it to assist Canada in reducing GHG emissions.

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