

**A GREENHOUSE GAS ANALYSIS OF  
SOLID WASTE MANAGEMENT IN THE  
GREATER VANCOUVER REGIONAL DISTRICT**

by

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## ***ABSTRACT***

### **A GREENHOUSE GAS ANALYSIS OF SOLID WASTE MANAGEMENT IN THE GREATER VANCOUVER REGIONAL DISTRICT**

by Philip K. Barton

A greenhouse gas analysis of the Greater Vancouver Regional District's (GVRD's) solid waste management system is presented in this thesis. This investigation quantifies the greenhouse gas (GHG) emissions resulting from the GVRD's current system of landfilling, incinerating, composting and recycling of the municipal solid waste generated within its boundaries and provides recommendations for future management. The definition of municipal solid waste (MSW) in this thesis is the sum total of all waste generated from residential, industrial, commercial and institutional sources, and excludes the typically categorized demolition and land-clearing (DLC) waste. The waste components newsprint, office paper, ferrous metal, glass, high-density polyethylene, low-density polyethylene, food scraps and yard trimmings are investigated individually while the remaining waste is analyzed as a whole. This research finds that the GVRD solid waste system in 1998, instead of causing greenhouse gas emissions, actually prevented the release of 180,000 tonnes of carbon dioxide equivalent ( $\text{tCO}_2\text{e}$ ). The existing waste management system created GHG benefits largely from landfill carbon sequestration and by allowing recyclables to offset virgin manufacturing by industry. Energy generation during incineration and at landfills also provided some GHG benefits. These benefits are accounted for as negative emissions and more than compensate for the important GHG emissions identified by this research such as landfill  $\text{CH}_4$ ,  $\text{CO}_2$  released during the combustion of diesel fuel and plastics and  $\text{N}_2\text{O}$  emissions. Modelling of this waste system into a spreadsheet program allowed the demonstration of the GHG response to future management changes. Several scenarios were programmed into the Model which illustrate the critical importance future management changes can have on the overall GVRD emissions; of particular relevance when analyzed from the perspective of emissions trading. Major conclusions derived from the scenarios are: the difference between pursuing improvements in landfill gas (LFG) collection and doing nothing could be almost 300,000  $\text{tCO}_2\text{e}/\text{yr}$ , the initiation of electricity generation could reduce emissions by 55,000  $\text{tCO}_2\text{e}/\text{yr}$ , considering incineration as a replacement for landfill disposal could bring in credits of 140,000  $\text{tCO}_2\text{e}/\text{yr}$  when electricity generation is provided, the future methane liability of landfilling requires extensive consideration since modelling ultimate decomposition calculates an emissions increase of over 300,000  $\text{tCO}_2\text{e}/\text{yr}$ . Each of these projects have emissions trading opportunities and at an assumed \$5/ $\text{tCO}_2\text{e}$ , significant revenue could be generated in this manner. A number of recommendations complete this thesis. The most important are: to strongly encourage the GVRD to begin actively participating in emissions trading or to bank credits for future regulatory requirements, to investigate improving the LFG collection system at the Cache Creek Landfill, to investigate electricity generation at the Burnaby Incinerator and to encourage greater recycling of metal, glass and plastic.

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## ***LIST OF ACRONYMS***

AAC	allowable annual cut
BI	Burnaby Incinerator
BNF	biological nitrogen fixation
CAAD	carbon available for anaerobic decomposition
CCLF	Cache Creek Landfill
CPL	Crown Packaging Limited - Paper Mill Division
CSF	carbon storage factor
DLC	demolition and land-clearing (waste)
GERT	Greenhouse Gas Emission Reduction Trading Pilot Program
GHG	greenhouse gas
GVRD	Greater Vancouver Regional District
GWP	Global Warming Potential
HDPE	high-density polyethylene
ICI	insitutional, commercial, industrial (waste)
IPCC	Intergovernmental Panel on Climate Change
LDPE	low-density polyethylene
LFG	landfill gas
MSW	municipal solid waste
MTCE	metric tonnes of carbon equivalent
MWP	mixed waste paper
OCC	old corrugated cardboard
RDO	residential dropoff
TMP	thermo-mechanical pulp
TS	transfer station
USEPA	United States Environmental Protection Agency
VCR	Voluntary Challenge & Registry (Federal Government)
VLf	Vancouver Landfill
WS	worksheet (in spreadsheet Model)

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## ***INTRODUCTION***

A greenhouse gas analysis of the Greater Vancouver Regional District's (GVRD's) solid waste management system is presented in this thesis. This investigation quantifies the greenhouse gas (GHG) emissions resulting from the GVRD's current system of landfilling, incinerating, composting and recycling of the municipal solid waste generated within its boundaries and provides recommendations for future management. The definition of municipal solid waste (MSW) in this thesis is the sum total of all waste generated from residential, industrial, commercial and institutional sources, and excludes the typically categorized demolition and land-clearing (DLC) waste. The waste components newsprint, office paper, ferrous metal, glass, high-density polyethylene, low-density polyethylene, food scraps and yard trimmings are investigated individually while the remaining waste is analyzed as a whole. Waste management is important from a greenhouse gas (GHG) perspective since it contributes to the observed increases in the atmospheric concentrations of all three of the most significant greenhouse gases, carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O). Large quantities of carbon and nitrogen are contained in the municipal solid waste stream and thus there is the potential for significant atmospheric releases of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O. It is these three greenhouse gases which this research investigates.

As a result of the 1997 *Kyoto Protocol to the United Nations Framework Convention on Climate Change*, Canada is committed to reduce GHG emissions. Though it is still unclear in which manner our Federal government will elect to successfully reach its emissions target (an approximate per capita reduction of 30% over the next 10 years), it is quite likely that in the next decade either GHG emissions trading, GHG emissions taxing or direct legislation (or a combination of all three) will be implemented to force reductions in all sectors, waste management included. This research assists the GVRD's assessment of any opportunities which may exist in a future GHG emissions trading environment and/or its assessment of any liabilities which may exist in a future GHG emissions taxing environment. The intent of this research is to provide an important planning tool to assist in determining the future direction of waste management in the GVRD.

This thesis estimates the greenhouse gas emissions resulting from the existing system of landfilling, incinerating, composting (backyard and centralized) and recycling of newsprint, office paper, ferrous metal, glass, plastic (high-density and low-density polyethylene), food scraps and yard trimmings. The remaining waste is grouped together, defined as the Remainder, and is also analyzed. These eight main components of the municipal waste stream were investigated individually so that the current participation in source-separation can be more effectively directed at "greenhouse gas reducing" activities. In addition, the member municipalities were investigated separately to more accurately model the existing system. In order for this analysis to serve as a



planning tool, the GVRD requires an assessment of the existing system – a baseline against which any proposed changes can be compared. For this reason, in addition to this report, an adaptable spreadsheet program has been developed to model the response of GHG emissions to changes in waste tonnages and other improvements made by the program user.

This Introduction chapter consists of 6 parts. The first section, *Background* (1.1), provides a framework of the scope and intent of the research. *Greenhouse Gases & Climate Change* (1.2), the second section, explains the international scientific consensus which is concerned with the increasing atmospheric concentrations of greenhouse gases. The third section, *Solid Waste Management* (1.3), introduces the GVRD's existing system of *Landfilling* (1.3.1), *Incineration* (1.3.2), *Backyard & Centralized Composting* (1.3.3) and *Recycling* (1.3.4). These respective sections briefly discuss the important greenhouse gas implications of these activities. In the fifth section, *Recent Policy Developments* (1.4), new policies with potential to affect waste management in the future are discussed. *Research Objectives* (1.5), the fifth section, present the goals of this investigation. The last section, *Thesis Overview* (1.6), presents an overview of the thesis to assist readers in understanding the analysis performed.

## 1.1 BACKGROUND

The planning of municipal solid waste management is largely influenced by economic and environmental considerations. Current waste management systems, which include various activities such as landfill disposal, incineration, composting and recycling, have occurred as a result of these two main considerations. For example, the relatively recent interest in recycling (starting in the late 1980's) was initiated largely because of increasing awareness in environmental issues and possibly because of economic factors. Landfilling continues to be one of the most popular methods for disposal because the economics are attractive and it satisfies the present environmental (i.e. regulatory) considerations. These systems, which evolved out of the driving factors thus far, could potentially be faced with many changes in the future as a new consideration gains importance.

A new consideration could be the strong international effort to reduce the emissions of greenhouse gases to the atmosphere. There is now an international scientific consensus that human-induced increases in the atmospheric concentrations of greenhouse gases have great potential to raise the surface temperature of the planet. The climatic change which is believed to result could raise global sea levels, increase the intensity of severe weather conditions and increase the frequency of heat waves and droughts. Reducing the emissions of these greenhouse gases will likely be one of the most challenging endeavors of the entire international community in the 21<sup>st</sup> Century.

Briefly, the main greenhouse gas implications of waste management are:

- Emissions of CO<sub>2</sub> from the combustion of diesel fuel during curbside collection, processing at transfer stations and subsequent transportation to landfills, incinerators, recycling or composting facilities.
- Emissions of CH<sub>4</sub> from the anaerobic decomposition in landfills or from anaerobic zones of inadequately aerated compost piles.
- Emissions of N<sub>2</sub>O from the nitrification and denitrification of nitrogen present in organic wastes. This can occur at landfills (predominantly from landfill leachate) or during composting and there can also be thermal formation during incineration.
- Emissions of CO<sub>2</sub> from fossil fuel energy required in the processing of recyclable materials such as paper, metal, glass and plastics into new products.
- The prevention of CO<sub>2</sub> emissions from fossil fuels when energy is produced in the form of steam at incinerators or in the form of recovered and utilized methane at landfills. This energy can prevent the consumption of fossil fuels which would otherwise be necessary.
- The prevention of CO<sub>2</sub> emissions when carbon storage or carbon sequestration occurs. This is the capture and secure storage of carbon that would otherwise be emitted to the atmosphere. This occurs with wastes that resist decomposition in the anaerobic conditions of landfills.
- The prevention of CO<sub>2</sub> emissions by substituting recycled materials for virgin materials. This prevention would be the result of reduced fossil fuel energy consumption when using recycled rather than virgin materials for the manufacture of similar items.

The following matrix illustrates many of these emissions in a waste management context:

Figure 1-1: Important GHGs from Waste Management Operations

	Fossil Fuel-CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	Energy Generation*	Carbon Storage*	Recycled vs Primary - CO <sub>2</sub> *
Collection	++					
Transportation	++					
Landfill Disposal		++	++	+	++	
Incineration	+		++	++		
Centralized Composting	+	+	++		+	
Backyard Composting		+	++		+	
Recycling	++					++

++ major importance

+ minor importance

\* GHG prevention activity (negative emission)

For greenhouse gas emissions to be a new consideration in solid waste planning, it is necessary to have an extensive understanding of the implications presented above. Furthermore, there is tremendous variation among the greenhouse gas emission response of the five main components of the GVRD waste management system: landfill disposal,

incineration, recycling, backyard composting and centralized composting. The need to possess this understanding has fostered the interest in this research.

Three reports and five research papers (of which this author is aware) have also compared the greenhouse gas emissions from waste management processes. However, the rapidly evolving science of greenhouse gas emissions and the importance of localized conditions makes this thesis necessary. As an example of the evolving science, the United States Environmental Protection Agency (USEPA 1998) report did not consider that nitrous oxide is emitted during the composting or landfilling of waste and did not consider that  $N_2O$  emissions from incinerators are a function of the waste nitrogen content. These issues are discussed in Section 2.5 and are quantitatively important for nitrogen-containing wastes such as food scraps and yard trimmings. In fact, none of the reviewed research adequately assesses nitrous oxide emissions. While these limitations do exist in the work by the USEPA, it is important to mention that that report is the most extensive and valuable research available so far; indeed, the provocative questions raised in that work conceived this very thesis. The second report, Environment Canada (1995), was completed before the Intergovernmental Panel on Climate Change (IPCC) developed methodology in which the carbon emissions from the decomposition of sustainable biomass can be considered as "GHG neutral" and need not be counted as an emission. As a result, the Environment Canada report considers composting and waste incineration as sources of  $CO_2$  emissions. In addition, that report does not consider landfill carbon sequestration or the potential for nitrous oxide emissions from waste management. All of these shortcomings also occur in new life-cycle analysis work by the industry groups, Corporations Supporting Recycling and the Environment and Plastics Industry Council (CSR 1999). These industry groups, together with Environment Canada, have developed a spreadsheet program which neglects nitrous oxide emissions, neglects landfill carbon sequestration and ignores the GHG neutrality of biomass carbon emissions.

Five journal papers were located and are reviewed. The paper by Hunt (1995) only analyzed the difference between the landfilling or incinerating of paper and plastic – and is thus incomplete for use here. The papers by Eschenroeder (1999), Aumonier (1996) and Pipatti & Savolainen (1996), while valuable, all compared the impact of landfilling or incinerating municipal solid waste as a whole – they did not investigate any waste components individually. Thus these three studies suffer from inaccuracies resulting from the very local question – *What is municipal solid waste?* A comprehensive methodology for modeling the GHG benefits of landfilling the biodegradable fraction of municipal solid waste versus composting this fraction has been developed at the University of Calgary (Hettiaratchi et al. 1998). This useful model compares landfilling in Edmonton against the new Edmonton Co-Composting facility and determines significant GHG benefits by the management alternative. However, this study assumes zero landfill gas collection for flaring or energy utilization over the next 30 years. As a result, this research gives composting GHG benefits which may be largely undeserved, at least in jurisdictions other than Edmonton.

For readers unfamiliar with the science of greenhouse gases and their inter-relationship with climate change the next section provides an introduction to this important issue.

## 1.2 GREENHOUSE GASES & CLIMATE CHANGE

Greenhouse gases, the most important of which are water vapor, carbon dioxide ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ), and nitrous oxide ( $\text{N}_2\text{O}$ ), allow the atmosphere to act like a greenhouse window – letting in much of the sun's energy while simultaneously only allowing a portion of it to escape immediately back to space. This occurs by permitting the entry of solar energy, which the Earth absorbs and then re-emits in the form of infrared radiation. While some of this infrared radiation escapes immediately back into space, most is temporarily trapped by greenhouse gases. This warms the lower atmosphere and the Earth's surface to a much greater extent than would otherwise have occurred. If it were not for this natural greenhouse effect, the Earth would be  $33^\circ\text{C}$  colder than the average temperature of  $15^\circ\text{C}$  (Environment Canada 1997b). This would result in a chilly mean temperature of  $-18^\circ\text{C}$  on Earth and life would be profoundly different.

Unfortunately, as a result of human activity, in particular the burning of fossil fuels and deforestation, the atmospheric concentrations of the greenhouse gases  $\text{CO}_2$ ,  $\text{CH}_4$  and  $\text{N}_2\text{O}$  and others have been rising. For several thousand years before the Industrial Revolution began in the mid-1700's, a steady balance was maintained in which the atmospheric concentration of  $\text{CO}_2$ , as measured from ice cores, remained within 10 parts per million (ppm) of an average level of 280 ppm (Houghton 1997). However, since the Industrial Revolution this concentration has increased almost 30%, from 280 ppm to over 360 ppm, and continues to increase at an average rate of 1.5 ppm every year (ibid). In addition, the atmospheric concentration of  $\text{CH}_4$  (a greenhouse gas estimated to be 21 times more effective in the trapping of infrared radiation than  $\text{CO}_2$ ) has increased by 145% since pre-industrial times, from a level of 700 parts per billion (ppb) to that of 1721 ppb in 1994 (IPCC 1995a). The third most important greenhouse gas,  $\text{N}_2\text{O}$  – estimated to be 310 times more effective at absorbing infrared radiation than  $\text{CO}_2$  – has increased from a pre-industrial level of 275 ppb to a level of 311 ppb in 1992, an increase of 13% (ibid).

It was in 1827, when a French scientist, Jean Baptiste Fourier, first recognized the warming effect of greenhouse gases in the atmosphere. He also noted the similarity between greenhouse gases in the atmosphere trapping infrared radiation and in the glass of a greenhouse, which led to the phrase “greenhouse effect” (Houghton 1997). In 1896, the Swedish chemist, Svante Arrhenius, calculated what would be the effect of increasing the concentrations of greenhouse gases. He estimated that doubling the concentration of  $\text{CO}_2$  would increase the global average temperature by 5 to  $6^\circ\text{C}$  – an estimate not far from the present understanding (ibid). Nearly 50 years transpired before an amateur British scientist, Guy Stewart Callendar, calculated the warming due to the increasing atmospheric concentration of carbon dioxide from the burning of fossil fuels, and discovered supporting evidence correlating the effect of carbon dioxide on global temperatures (ibid). It was in 1957 that Roger Revelle and Hans Suess of the Scripps Institution of Oceanography in California first raised concern about the implications of fossil fuel-related  $\text{CO}_2$  emissions on global climate change. These scientists published a paper pointing out that with the build-up of carbon dioxide in the atmosphere, human beings were carrying out a large-scale geophysical experiment. “Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in

sedimentary rocks over hundreds of millions of years.” (Revelle and Suess 1957; Houghton 1997) Since then, a great deal of scientific investigation has occurred looking into the mechanisms and interactions of greenhouse gases with climate and climate change.

The understanding of atmospheric science has advanced to such a level today that several position statements of international scientific consensus have recently been distributed. The Intergovernmental Panel on Climate Change (IPCC), a scientific body of leading atmospheric scientists established in 1988 by the United Nations Environment Programme and the World Meteorological Organization, stated in 1995 that:

“Global mean surface temperatures has increased by between 0.3 and 0.6 °C since the late 19<sup>th</sup> century, a change that is unlikely to be entirely natural in origin. The balance of evidence, from changes in global mean surface air temperature and from changes in geographical, seasonal and vertical patterns of atmospheric temperature, suggests a discernible human influence on global climate....Global sea level has risen by between 10 and 25 centimeters over the past 100 years and much of the rise may be related to the increase in global mean temperatures.” (IPCC 1995b)

This has been followed by the American Geophysical Union, a prominent scientific body of 35,000 earth and planetary scientists, stating in a January 1999 position statement that:

“There is no known geologic precedent for the transfer of carbon from the Earth’s crust to atmospheric carbon dioxide, in quantities comparable to the burning of fossil fuels, without simultaneous changes in other parts of the carbon cycle and climate system. This close coupling between atmospheric carbon dioxide and climate suggests that a change in one would in all likelihood be accompanied by a change in the other.”  
(American Geophysical Union 1999; Dunn 1999)

From this international scientific consensus, 160 nations agreed to the *Kyoto Protocol to the United Nations Framework Convention on Climate Change* in 1997. In this Protocol, the 38 developed countries of the world committed themselves to stabilize and ultimately reduce, their atmospheric emissions of greenhouse gases. Developing countries agreed to monitor their emissions and are encouraged to voluntarily reduce emissions but are not subject to binding commitments. Canada signed this convention and is committed to reducing greenhouse gas emissions. Between the commitment period of 2008 to 2012, Canada is required to reduce to a level 6% below what the national emissions were in 1990. Unfortunately, our national emissions were 601 million tonnes of CO<sub>2</sub> equivalent in 1990 (this includes CO<sub>2</sub>, but also CH<sub>4</sub> and N<sub>2</sub>O converted into units of CO<sub>2</sub>), but have increased to 682 millions tonnes in 1997, and are predicted to reach annual emissions of 750 million tonnes by 2010 (Environment Canada 1999). Not only is energy consumption expected to increase in the coming decade, but the population is expected to increase as well. The per capita reductions necessary to reach Canada’s Kyoto commitment, national emissions of only 565 million tonnes per year, will be an enormous undertaking. It will likely represent a decrease of the per capita emissions by 20 to 30%.

The national emissions in 1997, the 682 million tonnes of carbon dioxide equivalents, break down into 76% as carbon dioxide, 13% as methane, 9% as nitrous oxide with various trace gases completing the total (ibid).

Reversing the increase and continuing downwards to satisfy Canada's international commitment will require a strong and determined effort by government and industry. It is also important to recognize that Kyoto is only the beginning. The Kyoto Protocol is inadequate and it is commonly recognized that this agreement will not by itself, significantly reduce the rate of climate change. While it represents a necessary first step towards emission reductions it is only the beginning in a long series of conventions to reduce global emissions (Rolfe 1998). Dutch researchers have estimated that in order to avoid extreme changes in climate (defined as sea level increases of no more than 20 centimetres and global temperature increases of no more than 1°C over the next century), greenhouse gas emissions will need to be reduced to 37% below 1990 levels by 2050 and to 64% below by 2100 (Alcamo and Kreileman 1996). As the reductions to prevent extreme climate change are much greater than the average 5.2% reductions committed by the vast majority of developed countries, the Kyoto Protocol is not expected (by itself) to successfully stop Global Climate Change. Therefore much greater and deeper emission reductions will undoubtedly be required in the future.

Though there is a tremendous amount of uncertainty regarding how our country will actually decrease the national emissions in the coming years, it is likely that reductions will be required by all sectors. Waste management will probably be called upon to decrease its contribution to climate change along with all other sectors, be it industry, government or the general population. Not only will emission reductions to satisfy the Kyoto Protocol be expected from waste management in the next decade but even deeper cuts will be likely in the long-term future.

The next section presents an overview of the GVRD's existing system of solid waste management and discusses the important greenhouse gas implications of these activities. The concepts in the next section represent the opportunities for the participation of waste management in reducing emissions in a carbon-constrained environment.

### **1.3 SOLID WASTE MANAGEMENT**

The solid waste management system of the Greater Vancouver Regional District serves the population of the 1.98 million residents in the 20 municipalities and two electoral areas that make up the metropolitan area of Greater Vancouver. One Fraser Valley municipality, Abbotsford, outside the GVRD boundaries, also participates in this waste management system. For simplicity, Anmore and Belcarra have been included with the City of Port Moody and the Village of Lions Bay has been included with Electoral Area C in this report. As a result, this report will refer to the GVRD as consisting of 23 member municipalities but only 20 municipal entities are investigated.

There are five main components to this waste management system: landfill disposal, incineration, recycling, backyard composting and centralized composting. In 1998, this system managed 1,120,000 tonnes of general waste and 681,910 tonnes of recyclables and composted organics from all the various residential, industrial, commercial and institutional sources represented in these municipalities (GVRD 1999). Two landfills are currently in use by the GVRD, the Cache Creek Landfill and the Vancouver Landfill (at Burns Bog), while one incinerator, the Burnaby Incinerator, is also owned by the GVRD. In 1998, the Cache Creek Landfill provided disposal for 474,873 tonnes of waste, the Vancouver Landfill disposed of 379,554 tonnes and the Burnaby Incinerator combusted 247,078 tonnes (ibid). Recyclables in the GVRD collected curbside and by other means are delivered to a number of depots in the Lower Mainland for processing and subsequent marketing to various industries for reuse. The recycling depots operated by ETL Recycling Services, International Paper Industries and Browning Ferris Industries are just three examples of these.

In addition to recycling, many of the member municipalities have been actively encouraging backyard composting for residents to manage their own food scraps and yard trimmings. In some jurisdictions, backyard composters have been distributed to more than 30% of the population of ground-level (single-family) residences (Pers. comm. Al Lynch 1999). It is estimated that each composter annually diverts 250 kg of food scraps and yard trimmings from collection (Pers. comm. Bev Weber). In order to keep yard trimmings out of the waste stream, a separate curbside collection of yard trimmings has been initiated in many municipalities. Other jurisdictions have elected to provide residential drop-off (RDO) locations. Many of the municipalities have contracted with Fraser Richmond Bio-Cycle (FRBC) to manage the collected yard trimmings. FRBC provides centralized composting of yard wastes by turned windrows and then subsequently markets the finished compost. The City of Vancouver operates its own composting facility at the Vancouver Landfill, and while the RDO of yard trimmings has been in existence for quite some time, they recently initiated curbside collection of yard trimmings.

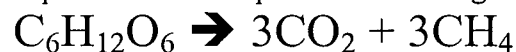
To serve the flows of this large quantity of waste from the member municipalities, several transfer stations (TSs) exist in the GVRD. In total, six transfer stations, the Coquitlam TS, the Vancouver TS, the North Shore TS, the Matsqui TS, the Langley TS and the Maple Ridge TS, facilitate the flow of waste from collection vehicles to disposal sites. In terms of 1998 masses, the Coquitlam TS with 316,360 tonnes, the Vancouver TS with 273,377 tonnes and the North Shore TS with 194,683 tonnes were by far the three most important transfer stations (GVRD 1999).

It is important to recognize that all these operations require fossil energy, predominantly in the form of diesel fuel, a fossil fuel. The curbside collection of wastes, the processing of wastes at transfer stations and the transportation of wastes to disposal facilities all require the combustion of diesel fuel. This combustion directly results in a greenhouse gas emission of approximately 2.8 kg of CO<sub>2</sub> equivalent (includes CO<sub>2</sub>, but also CH<sub>4</sub> and N<sub>2</sub>O converted into units of CO<sub>2</sub>) per L of diesel fuel (Environment Canada 1997a).

The remainder of this section will discuss the greenhouse gas issues associated with the five waste management methods employed in the GVRD: landfill disposal, incineration, recycling and backyard and centralized composting. While discussed in a general manner, the following discussion is particularly suited to the local situation in the GVRD.

### 1.3.1 Landfill Disposal

Landfills are well known to be emitters of methane to the atmosphere. In 1997, landfills in Canada were estimated to have emitted 1 million tonnes of CH<sub>4</sub> or 21.0 million tonnes of CO<sub>2</sub> equivalent. This represents 3.1% of Canada's estimated national GHG emissions of 682 million tonnes in 1997 (Environment Canada 1999). If organic wastes are landfilled the resulting anaerobic decomposition will emit nearly equal parts of CH<sub>4</sub> and CO<sub>2</sub>. The anaerobic decomposition of a simple six carbon sugar is:



The methane represents a strong greenhouse gas emission because it is 21 times more effective as a greenhouse gas than carbon dioxide. However, the CO<sub>2</sub> emission, while being a greenhouse gas, does not have to be considered a greenhouse gas emission. These organic materials were originally formed when photosynthesis fixed the inorganic carbon of CO<sub>2</sub> to organic carbon. The decomposition of these organic materials liberates the same carbon that was originally removed and is therefore completing the cycle. As a result, the CO<sub>2</sub> emission during anaerobic decomposition at landfills is "GHG neutral" and can be ignored as an emission.

The logical extension of this is that if the landfill methane produced can be collected and combusted to CO<sub>2</sub>, then no GHG emission would result. This is indeed what occurs at many active and inactive landfills – methane is collected and flared. However, not all of the methane is collected; while at some sites a large portion is managed in this manner, at other sites much of the methane escapes collection systems - or there is no collection system - and it is emitted to the atmosphere. There is also the potential for microorganisms in the cover material of the landfill to cause the oxidation of CH<sub>4</sub> to CO<sub>2</sub>. Research conducted in the U.S. suggests that about 10% of the methane which had escaped collection was oxidized (Czepiel et al. 1996). Of even greater benefit than collecting all the methane and flaring it, is to collect all the methane and utilize it for energy purposes – to essentially use the landfill methane to replace natural gas, a fossil fuel. By using a GHG neutral bioenergy source like landfill methane to avoid the consumption of a fossil fuel, greenhouse gas benefits are realized. These benefits are the prevented CO<sub>2</sub> emissions from the combustion of natural gas. It is important to recognize that when the carbon in fossil fuels is released to the atmosphere as CO<sub>2</sub>, it is considered to be a greenhouse gas emission. But this carbon was also originally photosynthesized from carbon in the atmosphere. However, the time scale of millions of years necessary to create geological formations of fossil fuels is appropriate for climate change concerns while the months, years or decades time scale for the closed carbon cycle of food or paper is not the carbon of concern. Assessing the CO<sub>2</sub> emissions from composting food waste, carbon which was only fixed 6 months previous, as a greenhouse gas emission would be putting a "red-herring" in front of efforts attempting to reduce emissions from fossil fuels – the main contributor to Global Climate Change.



There are two important remaining issues with landfill disposal: landfill carbon sequestration and nitrous oxide emissions. Landfill carbon sequestration is the capture and secure storage of carbon that would otherwise be emitted to the atmosphere. This can occur when organic waste is disposed in landfills but resists decomposition in the anaerobic conditions. Because this photosynthesized carbon from atmospheric-carbon becomes stored in landfills it reduces the atmospheric concentration of  $\text{CO}_2$ . This concept is thoroughly discussed in Chapter 2 – *Methodology*. For the introduction here it will suffice to state that different waste materials greatly vary in providing landfill carbon sequestration. While newsprint and branches, with their high lignin content, largely resist anaerobic decomposition, office paper and food scraps readily decompose in landfills and provide more methane than carbon sequestration. It needs to be recognized that the disposal of plastics in landfills cannot be considered a sequestration activity. The removal of petroleum products from geological reservoirs, their manufacture into plastics and their disposal in landfills at the end of their useful life is just substituting one sequestration for another (remember that the time scale is again relevant). There is no net difference to the atmosphere and as such must be ignored from the perspective of sequestration.

Much of the nitrogen contained in the food and yard waste components of MSW can be traced back to chemical fertilizers applied onto agricultural lands or onto backyard residences. When these organic wastes are disposed in landfills, the resulting anaerobic decomposition will release the nitrogen as ammonia ( $\text{NH}_3$ ) or ammonium ( $\text{NH}_4^+$ ). Due to the low pH from the presence of volatile fatty acids in the fill, the vast amount of nitrogen will be in the ammonium form. The nitrification of the ammonium to nitrate ( $\text{NO}_3^-$ ) is greatly restricted because of the lack of suitable electron acceptors in the anaerobic conditions. Furthermore, with nitrification restricted, denitrification is also restricted. Thus there is little potential for  $\text{N}_2\text{O}$  to be emitted with the vented landfill gas. However, water percolating through the fill can entrain the ammonium and remove it as landfill leachate. Leachate is typically transferred to wastewater facilities for treatment. From this point forward, the nitrogen is free to nitrify and denitrify (in fact, depending on the treatment plant, the nitrogen may be *encouraged* to nitrify and denitrify) and  $\text{N}_2\text{O}$  emissions are a strong possibility. As much of this nitrogen was originally created by human activity, any subsequent emission as  $\text{N}_2\text{O}$  is an important GHG emission. This is discussed in greater detail in Section 2.5.

### **1.3.2 Incineration**

The GVRD utilizes one incinerator for waste disposal purposes, the Burnaby Incinerator. During 1998, this Incinerator combusted 247,075 tonnes of MSW which resulted in 820,000 tonnes of steam being generated. Over half of this steam was transferred to the adjacent Crown Packaging Limited (CPL) facility for the pulping of cardboard. Were it not for the steam from the Incinerator, CPL would be using natural gas-fired boilers, fossil energy, to produce the necessary steam. Consequently, a definite greenhouse gas benefit from the avoided natural gas consumption is realized by the transfer of steam to CPL.

The combustion of municipal solid waste at the Burnaby Incinerator is supported by the chemical energy inherent in the wastes. With the exception of metals, glass and ceramics, all the other components are organic and will burn. As the oxidation of organic wastes must release CO<sub>2</sub>, it is necessary to once again discuss the origins of the emitted carbon. When biomass wastes such as paper products, food scraps and yard trimmings are combusted, they will be releasing the same carbon previously photosynthesized; they can be considered GHG neutral and thus ignored. In contrast, plastics contain fossil-carbon (as these materials are manufactured from petroleum products). This is carbon that was also photosynthesized but it occurred millions of years ago. Combusting plastics in an incinerator is identical to burning fossil fuels for energy; both contain the carbon of concern in human-induced climate change. While paper, food and yard waste can be considered bioenergy upon combustion, plastics must be considered a source of greenhouse gas emissions. Fortunately, the combustion of plastics generates steam which is used by another industry and thus eliminates the need for the combustion of natural gas (another source of fossil-carbon).

Also of importance with respect to waste incineration is the potential for nitrous oxide emissions. The formation of nitrous oxide can result from five separate pathways:

- thermal conversion of N<sub>2</sub> gas in air to N<sub>2</sub>O during combustion (immediate emis.),
- thermal conversion of N in fuel (wastes) to N<sub>2</sub>O (immediate emission),
- thermal conversion of ammonia (NH<sub>3</sub>) injected in the flue gases (immediate emis.),
- microbial N<sub>2</sub>O conversion of NO<sub>x</sub> emitted and later denitrified (future emission) and
- microbial N<sub>2</sub>O conversion of NH<sub>3</sub> injected but unreacted (future emission).

All of these pathways will be thoroughly discussed in Section 2.5.5.3. For this introduction it should be noted that the thermal conversion of the nitrogen in food waste is likely the greatest source of nitrous oxide emissions during incineration.

### **1.3.3 Backyard and Centralized Composting**

The greenhouse gas implications of the backyard or centralized composting of food scraps and yard trimmings are virtually identical. The greatest exception would be the diesel fuel necessary for the curbside collection vehicles and windrow equipment to perform centralized composting. Both waste materials are biological in origin and thus any CO<sub>2</sub> from decomposition is GHG neutral and can be ignored. By diverting these organic wastes from landfill disposal and composting them, the prevention of any future methane emissions at the landfill is achieved. However, by composting there is also no opportunity for energy generation in the form of steam at the incinerator or collected methane at the landfill.

Also of concern in the composting process, is the potential for nitrous oxide and methane emissions. As with the N<sub>2</sub>O emitted from landfill leachate, N<sub>2</sub>O can result during the microbial leakage associated with the nitrification and denitrification of the nitrogen in the organic wastes. Several research papers have been obtained which report the existence of these emissions. A greater discussion of this issue is provided in Section 2.5.5.2. There is also an opportunity for methane gas to be emitted from composts which

are inadequately aerated. This has been observed to occur with passively aerated static piles (composts which are turned infrequently) and is assessed in Appendices I and J.

#### 1.3.4 Recycling

Recycling is a critical component of integrated solid waste management. In fact, the mass of waste currently recycled in the GVRD nearly equals the mass which is landfilled and is almost three times that which is incinerated. For this reason, any waste analysis neglecting recycling would be largely inaccurate. As to be discussed, recycling has important greenhouse gas repercussions. However, complicating the *emissions-from-recycling* issue is that many of these repercussions are outside the jurisdictional authority of the GVRD. Nevertheless, they require discussion here.

Recycling requires the expenditure of energy. As most of this energy is derived from fossil fuels, it therefore contributes greenhouse gas emissions to the atmosphere. Recyclables require curbside collection, processing at recycling depots and subsequent transportation to the factories or mills where they will be manufactured into new products. In addition, the manufacturing of new products from recycled materials also requires fossil energy consumption. However, this consumption of energy and the associated greenhouse gas emissions are not the only considerations. There is great potential for large savings in the energy requirements of making Widget A from recycled materials (wholly or in part) as opposed to making Widget A entirely from virgin materials. When recycled materials are substituted for virgin materials and the energy consumption is decreased there is a consequent reduction of greenhouse gas emissions. Extensive research by various organizations have observed decreased energy requirements and decreased GHG emissions by substituting recycled materials for primary materials. However, the converse can also be true; several researchers have questioned the recycling of paper – while it is more energy efficient to make recycled paper than virgin paper, it may actually increase the consumption of fossil energy. In contrast, virgin paper production typically utilizes wood waste as its energy source (wood waste being a form of GHG neutral bioenergy). This research is reviewed in Section 2.6 – *Recycling Analysis*.

The utilization of energy by industry (and the associated GHG emissions) for the manufacture of products used by society is outside the interest of planners in waste management. However, the greenhouse gas implications of landfill disposed or incinerated waste products which could have been recycled require assessment. By disposing or combusting paper products which would otherwise have been recycled, a municipality is preventing the substitution of recycled fibre for virgin fibre at a pulp and paper mill. If there is a GHG benefit to substituting recycled feedstocks for virgin feedstocks, this issue has to be addressed when, disposing or incinerating of recyclables. For example, increasing waste incineration of paper products to generate bioenergy may result in greater GHG emissions at the pulp mill. As a result, the GHG emissions of recycling newsprint, office paper, ferrous metal, glass and plastic (high-density and low-density polyethylene) is investigated in this thesis. It is important to note, however, that the recycling investigation was restricted to comparing the emissions from taking recycled and virgin materials to an identical intermediate product. This is not the same as

manufacturing the final product for it is only following the respective materials until they converge, defined by one consultant as the "Energy Convergence Point" (Tellus 1994). For example, the recycling of ferrous metal is only analyzed until steel ingots have been produced but not a final product. From this analysis it is possible to assess the GHG implications of substituting recycled materials for virgin materials.

Lastly, this thesis presents research into the potential for carbon storage in forests in Canada to be affected by increased paper recycling reducing the demand for the harvesting of primary timber.

It is important to recognize that many of the energy (and thus greenhouse gas) ramifications of virgin vs. recycled manufacturing are outside the authority of waste planners at the GVRD and could cause complications in future emissions trading; not the least of which being "Who owns the emissions credit?". If the GVRD endeavors to reduce the GHG emissions under its responsibility but resulted in increasing the emissions of a manufacturing organization there would be no net benefit to the atmosphere. Full life-cycle impacts need to be taken into account when attempting to reduce emissions. This discussion has further relevance when explained in conjunction with emissions trading where the action has to result in a "net reduction" – the credit cannot be invalidated by indirect emissions leaking from other sources.

Developments in the national and international policy to reduce emissions will be important to the greenhouse gas implications of waste management discussed in this section. The emissions of CO<sub>2</sub>, CH<sub>4</sub> or N<sub>2</sub>O from GVRD's waste management could be reduced in the future and traded for revenue or taxed in the future to force reductions to be implemented. This is the focus of the next section.

## **1.4 RECENT POLICY DEVELOPMENTS**

How can the international effort to reduce emissions of greenhouse gases affect waste management? As previously discussed, in the *1997 Kyoto Protocol* Canada committed to reduce emissions to 6% below the 1990 level between the years 2008 and 2012. Considering that with the population growth during this time, the cuts will represent per capita reductions between 20 and 30%, a monumental undertaking. For the successful attainment of this target, it is very likely that the emissions trading of GHG credits, the taxation of GHG emissions or direct legislation to reduce emissions (or a combination of these three) will be implemented in the next decade. These mechanisms could greatly impact the current economics of waste management. For example, if one activity is demonstrated to result in lower emissions than another, such as using composting to divert organic waste away from landfill disposal (thereby preventing future methane emissions), there is a real GHG benefit translated into an economic motivator in the following ways. In an emissions trading program, composting projects could claim credits for the resulting GHG benefit. These credits could be sold to another party, such as an energy company, which is being forced by regulations to reduce its emissions. The revenue generated by trading credits could then be used to finance the composting

project. Under a taxation system, the methane emissions from a landfill could be taxed as a GHG emission, potentially making composting a more economically attractive activity to pursue instead of landfilling. Both of these systems could profoundly change the current economics of waste management.

Trading is fueled by the government legislating an emissions cap which can only be exceeded by possessing an equivalent amount of emissions credits. A typical GHG emission reduction trade occurs when a buyer with high cost options for emission reductions purchases a lower cost option from a seller and enters into a contract to transfer ownership of the emission reduction credit (ERC) (GERT 1998). To qualify as a greenhouse gas reduction, the activity must result in the atmosphere experiencing a net reduction in greenhouse gas emissions. These reductions are measured against a baseline which is determined by the emissions path that would have occurred in the absence of the specific activity. Greenhouse gas emission reductions become credits when "i) the action has been implemented, ii) the action generates a reduction, and iii) the reduction has been verified." (IISD 1998) These emission reduction credits may be traded within a future legally binding emission trading system or may be accumulated and used against possible future compliance requirements.

Emissions trading is already occurring. A landfill gas utilization project initiated by Norseman Engineering for the Port Mann Landfill will prevent an estimated emission of 210,000 tonnes of carbon dioxide equivalent (tCO<sub>2</sub>e) over the next 14 years (through the upgrade of the LFG collection system). The GHG credits were purchased by a consortium of Canadian energy companies, the Greenhouse Emissions Management Consortium (GEMCo), for \$1 per tCO<sub>2</sub>e and thus the project will be implemented. The resulting \$210,000 payable over the next 14 years as the GHG emission reductions are realized will finance the project. Another example is a proposed composting project in Southern Ontario which is estimated to prevent 31,422 tCO<sub>2</sub>e of future methane emissions over the next 12 years. This will be achieved by diverting 111,000 tonnes of yard waste away from landfill disposal. While up for sale, the GHG credits from this project have not been purchased at this time. Both of these credit trading projects are part of the Greenhouse Gas Emission Reduction Trading Pilot Program (GERT) which is a combined effort between the Federal Government, several provincial environment ministries and a number of industry and non-profit groups (GERT 1998). This pilot program was initiated in June 1998 and will continue as a learning exercise until Dec 2001. The lessons learned in this pilot program will likely prove invaluable to the full-scale implementation of emission trading.

Internationally, carbon taxation is also occurring. Finland is the first country in the world to introduce a CO<sub>2</sub> tax. In September, 1998, this carbon tax on heat and transportation fuels was raised to US\$19.2 per tCO<sub>2</sub>. Also in Scandinavia, the Norwegian government is proposing a carbon tax of US\$13.3 per tCO<sub>2</sub>, and in the United Kingdom, the potential is also strong for instituting a carbon tax (Hanisch 1998).

Though it is not clear in which manner our Federal government will elect to successfully reach its target in the Kyoto Protocol, it appears that every organization at all levels of the

government and each industrial sector will have to reduce emissions. Personal lifestyle changes by Canadians will also be necessary to reduce emissions. These governmental agencies and private companies will likely have to undertake meaningful reductions or purchase the credits, from another party's meaningful reductions. This is part and parcel with the emissions trading option. In contrast, under carbon taxation, meaningful reductions will also occur, but out of brute necessity – it will become too costly to continue emitting. Discussing trading or taxing is all speculative since the required reductions or the price of carbon, either traded or taxed, is yet to be determined. A carbon-constrained environment has yet to be developed and at the GERT pilot program, the carbon credits in the nine projects available for trading as of May 17, 1999, ranged in value from \$1.00 to \$14.00 per tonne of CO<sub>2</sub> equivalent (tCO<sub>2</sub>e) (GERT 1999). BC Hydro has committed over \$2 million for the purchase of GHG offsets over the 2000-2001 time frame (BC Hydro 2000).

The impact that these new policies could have on future waste management are sufficient to warrant this analysis. The next section explains in detail the objectives of this research.

## **1.5 RESEARCH OBJECTIVES**

There are two main objectives to this study: (1) to perform a greenhouse gas emissions analysis of the GVRD's existing solid waste management system and (2), to develop a planning tool which can evaluate the positive and negative GHG impacts of changes to this waste management system. Before attempting to include greenhouse gases in future waste management it is necessary to have a critical understanding of the existing system. This research analyzes the current system and then enables, with a spreadsheet program, changes in waste management to be assessed from the perspective of greenhouse gas emissions. In this spreadsheet program the mass flows of waste into various management processes are variables that can be changed. In addition, parameters important in calculating greenhouse gas emissions, such as the effectiveness of landfill gas collection systems or the energy efficiency of waste incineration, are also variables subject to change by the user. This thesis, together with the spreadsheet program, enables planners to evaluate opportunities which may exist in a future GHG emissions trading program or liabilities which may present themselves in a future GHG emissions taxing system.

This thesis estimates the greenhouse gas emissions resulting from the existing system of landfilling, incinerating, composting (backyard and centralized) and recycling of newsprint, office paper, ferrous metal, glass, plastic (high-density and low-density polyethylene), food scraps and yard trimmings. The remaining waste is grouped together, defined as the Remainder, and is also analyzed. These eight main components of the municipal waste stream were investigated individually so that the current participation in source-separation can be more effectively directed at "greenhouse gas reducing" activities. In addition, the 23 member municipalities were investigated separately to more accurately model the GVRD.

By using the results of this research with the currently debated price of carbon (either traded or taxed), it is possible to assess changes in waste management from the perspective of financial incentives. Any future changes which are performed voluntarily in order to reduce GHG emissions can be claimed for credits. When traded, these credits assist in financing the proposed project. However, if the changes to future operation are required by legislation, their implementation is no longer voluntary and would be ineligible for crediting. The importance of emissions trading in future waste management cannot be understated. However, in order to assess changes it is necessary to have a baseline upon which to improve. This baseline is the existing waste management system.

## 1.6 THESIS OVERVIEW

The end of the first chapter is an opportune moment to present an overview of this thesis. This chapter has introduced the concern with greenhouse gases emissions and the recent developments in policy-making to mitigate global climate change. Together with an explanation of solid waste management in the GVRD, the inter-relationships between emissions and policy are discussed. It is the importance of these inter-relationships which necessitates this research and provides the impetus for Section 1.5 – *Research Objectives*.

The next chapter, Chapter 2 – *Methodology*, explains the calculations which are used to estimate the GHG emissions. This chapter consists of 12 major sections :

- Methodology Introduction
- Global Warming Potential
- Biomass Decomposition/Combustion
- Landfill Carbon Sequestration
- Nitrous Oxide Emissions
- Recycling Analysis
- Uncertainty with the Estimates
- Spreadsheet Program
- Waste Mass Estimates
- Remaining Wastes
- GHG Emissions not Investigated
- Standards

These methods represent the current state of the knowledge on these issues and were developed from an extensive review of available literature. These sections lay out the methods utilized in the 12 appendices. However, the fine details which are necessary to actually calculate greenhouse gas emissions are included in the appropriate appendices for that issue. It is the intent of this thesis that readers learn a specific concept in the next chapter and then refer to the appropriate appendix to learn how it is actually implemented “for number crunching.” As a result, readers should feel comfortable in jumping back and forth to learn the principles used to assess GHG emissions.

The results and discussion of this thesis are presented in Chapter 3 . This is followed by Chapter 4 – *Conclusions & Recommendations*.

The 12 appendices after the *Bibliography* constitute a major portion of this thesis. These appendices present all of the calculations which are used in the spreadsheet program to model emissions. These calculations serve as *sample calculations* to provide readers with an understanding of the numbers and equations contained in the accompanying spreadsheet. Many of these appendices are presented as independent modules which are developed separately. Because of this lack of interdependency, a degree of repetition results for readers. However, in instances of excessive repetition, such as transportation issues after the North Shore Transfer Station for the three North Shore municipalities, only one complete version is provided. The first appendix, Appendix A – *General Calculations*, contains general parameters and calculations which are not specific to either a single municipality or a waste component. This is followed by Appendix B – *Municipality Calculations*, which presents all the diesel fuel consumption data necessary for curbside collection, processing at transfer stations and subsequent transportation to disposal, recycling or composting facilities. This also includes the estimates of the masses of different waste components which are disposed or recycled. It was necessary to estimate waste masses specific to individual municipalities because of the highly variable contribution of wastes from ICI sources which is independent of the residential population of that jurisdiction. This appendix (and the entire report) assumes that waste from Anmore and Belcarra are essentially from the City of Port Moody and that waste from the Village of Lions Bay can be included with Electoral Area C. The next 9 appendices are specific to the 9 waste components analyzed in this thesis. They provide the calculations used to estimate the GHG emissions to be expected from landfilling, incinerating, composting or recycling of newsprint, office paper, metal, glass, plastic, food and yard waste, and remainder. The important results derived in Appendix A through K are the emission factors required to calculate emissions from various management methods. When these emission factors are multiplied by the tonnage of waste managed in this manner, the estimated GHG emission will result. Appendix L – *Spreadsheet Program*, is the last appendix and contains the greenhouse gas Model of the GVRD's existing waste management system.



## ***METHODOLOGY***

The calculations in the appendices are based on the methodology developed in this chapter. An extensive review of previous research and the available guidelines for estimating greenhouse gas emissions is performed for this thesis. In addition, a number of individuals involved in waste management in the Lower Mainland were contacted to acquire data for this investigation. These personal communications with representatives of organizations such as the GVRD, City of Vancouver, Wastech Services, North Shore Recycling Program and Montenay proved invaluable to this work. Much of this collected data is directly used in the calculations in the appendices.

### **2.1 INTRODUCTION**

This chapter explains the important concepts used to develop the methodology for this investigation. Twelve sections are required in this methodology to describe these principles. However, the fine details which are necessary to actually calculate greenhouse gas emissions are included in the associated appendices. For example, the GHG neutrality of combusting newsprint for energy is discussed in Section 2.3 – *Biomass Decomposition/Combustion* but the actual calculations for this energy are developed in Appendix C – *Newsprint Waste Management*. In fact, all the calculations conducted for this study are included in the appendices. It is these calculations that are used to program the spreadsheet.

With the great utility of this spreadsheet program accredited in no small part to the fact that mass inputs and parameters can be changed to calculate new emissions, the calculations provided in the appendices become essentially *sample calculations*. The methodology section, together with the sample calculations in the appendices, serve to provide the reader with valuable information so that changes can be made to the spreadsheet in the future.

Of critical importance to the methodology used throughout this report are the guidelines developed by the Intergovernmental Panel on Climate Change (IPCC) to calculate GHG emissions. Canada and the other 160 signatory parties to the United Nations Framework Convention on Climate Change have agreed to develop inventories of GHGs for the purposes of developing mitigation strategies and monitoring the progress of those strategies (USEPA 1998). These national inventories are estimated using guidelines developed by the IPCC. These guidelines are the three volumes of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 1997). While throughout this investigation an attempt has been made to remain consistent with the IPCC guidelines, in several instances it has been necessary to make changes. This resulted from a careful evaluation of the subject. Most notable is the concept of landfill carbon sequestration (already included in a recent USEPA (1998) report) and the

potential for nitrous oxide emissions. All changes are documented throughout this report. It is my opinion that these changes were necessary to refine the GHG estimates and it is hoped that future IPCC methodology will reflect these changes.

This chapter consists of 12 major sections. The first, Section 2.1 – *Introduction*, provides an overview of this chapter and introduces the methodology used in this report. *Global Warming Potential* (2.2) is the second section and explains the internationally accepted convention by which different greenhouse gases are converted into a common unit based on each gases relative ability to trap infrared radiation. The next section, *Biomass Decomposition/Combustion* (2.3), describes guidelines by the Intergovernmental Panel on Climate Change which draws clear distinctions between CO<sub>2</sub> released from fossil fuel combustion and CO<sub>2</sub> released during the decomposition of biomass. This has important ramifications in this thesis as waste management contributes substantial emissions of both. Section 2.4 – *Landfill Carbon Sequestration*, reviews the available literature on this emerging issue. To properly assess landfill disposal from a greenhouse gas perspective, it is necessary to quantify not only the CH<sub>4</sub> emissions but also the ability of landfills to store the carbon from biomass which resists anaerobic decomposition. The next section, *Nitrous Oxide Emissions* (2.5), presents an extensive review of the current understanding of this important issue. N<sub>2</sub>O can leak from the cells of microorganisms during nitrification and denitrification. Because of the high nitrogen content of food and yard components of MSW, the potential emissions during the management of these wastes is of particular importance. Section 2.6 – *Recycling Analysis*, discusses the methods employed in this study to estimate the emissions associated with recyclables. *Uncertainty with the Estimates* (2.7), presents the uncertainty that is always associated with estimating data. While much of the data in this thesis contains minimal uncertainty, many parameters are highly uncertain and require separate discussion in this section. The next section, *Spreadsheet Program* (2.8), illustrates the workings of the spreadsheet to educate users in its operation. *Waste Mass Estimates* (2.9) provides the methodology utilized to estimate the masses of the 8 waste components analyzed in the 23 member municipalities in the GVRD. Each municipality is analyzed individually because of the large differences between the fractions of waste from residential or ICI sources. After the 8 investigated waste components are removed from MSW there will be still be a remainder. This remainder is discussed in Section 2.10 – *Remaining Wastes* from the perspective of GHG implications. *GHG Emissions not Investigated* (2.11) draws a boundary around the focus of this research, thereby excluding the thousands of direct & indirect sources of emissions which could be included in this study as a result of our energy intensive society. The last section, *Standards* (2.12), provides readers with the units and other conventions used throughout this thesis.

## 2.2 GLOBAL WARMING POTENTIAL

The three greenhouse gases evaluated in this report, CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O, greatly vary in their relative contribution to global warming. Each of these gases has different radiative forcings (the capacity to absorb infrared radiation) and different atmospheric lifetimes. To complicate matters further, there are direct radiative forcing effects or indirect

radiative forcing effects. Direct radiative forcing is when the gas itself is a greenhouse gas. Indirect radiative forcing effects occur when the chemical transformation of the original gas produces a gas or gases that are greenhouse gases, or when a gas influences the atmospheric lifetimes of other greenhouse gases (Environment Canada 1997a). The radiative forcing of CO<sub>2</sub> is estimated to be 0.018 W/m<sup>2</sup>•ppm while that of CH<sub>4</sub> is 0.37 W/m<sup>2</sup>•ppm or 20.6 times greater and N<sub>2</sub>O is 3.7 W/m<sup>2</sup>•ppm or 206 times greater. The atmospheric lifetime of CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub>, is estimated to be 12.2 years, 120 years, and variable based upon the carbon cycle (IPCC 1995).

With all this variation, the concept of Global Warming Potential (GWP) was developed to allow for the comparison of the relative ability of each greenhouse gas to trap heat in the atmosphere. The GWP is defined as:

“the time-integrated change in radiative forcing due to the instantaneous release of 1 kg of a trace gas expressed relative to the radiative forcing from the release of 1 kg of CO<sub>2</sub>... The GWP of a greenhouse gas takes into account both the instantaneous radiative forcing due to an incremental concentration increase and the lifetime of the gas.” (Environment Canada 1997a)

A 100 year reference period is recommended by the IPCC when dealing with global warming potentials (IPCC 1995). The latest information from the IPCC has estimated the 100 year time-frame GWP of CH<sub>4</sub> to be 21 and the GWP of N<sub>2</sub>O to be 310 (relative to CO<sub>2</sub> on a mass basis) (ibid). The GWP for CH<sub>4</sub> also takes into account the indirect contributions due to tropospheric ozone and stratospheric water vapour production. These are the Global Warming Potential values that are used in this report.

## **2.3 BIOMASS DECOMPOSITION/COMBUSTION**

This section presents the internationally accepted guidelines which draw a clear distinction between the CO<sub>2</sub> emitted during the combustion of fossil fuels and the CO<sub>2</sub> emitted during the decomposition or combustion of biomass. The CO<sub>2</sub> from the consumption of fossil fuel results from human activities and is believed to be causing Global Climate Change while the quantitatively greater carbon cycling for biomass is a natural closed process. Separating these two is necessary, for otherwise, this research would have to consider the decomposition of biomass during the composting process as a GHG emission; of little merit when remembering that the alternative is natural rotting on the ground.

The IPCC methodology for addressing CO<sub>2</sub> emissions from biomass has already been mentioned in the introduction but requires further discussion as it is extremely important for this study. Specifically, these are the CO<sub>2</sub> emissions resulting from the decomposition or combustion of paper products, food scraps or yard trimmings, defined as *biomass* for the remainder of this section. The carbon in biomass material was originally removed from the atmosphere by photosynthesis, and under natural conditions, will eventually cycle back to the atmosphere as CO<sub>2</sub>. This carbon is part of a natural

process which cycles through the atmosphere, water, soils and biota, and is far greater in magnitude than carbon resulting from human intervention, the carbon from fossil fuels or deforestation. But the focus of the United Nations Framework Convention on Climate Change is not on these natural processes but on the anthropogenic emissions, emissions resulting from human activities and subject to human control, as it is these emissions that have the potential to disrupt the carbon's biogeochemical cycle and alter the atmosphere's heat trapping ability (USEPA 1998).

The difference in CO<sub>2</sub> emissions from the decomposition of biogenic materials and the combustion of fossil fuels was explained succinctly in a U.S. Environmental Protection Agency report (ibid):

“Thus, for processes with CO<sub>2</sub> emissions, if (a) the emissions are from biogenic materials and (b) the materials are grown on a sustainable basis, then those emissions are considered to simply close the loop in the natural carbon cycle – that is, they return to the atmosphere CO<sub>2</sub> which was originally removed by photosynthesis. In this case, the CO<sub>2</sub> emissions *are not* counted. ... On the other hand, CO<sub>2</sub> emissions from burning fossil fuels *are* counted because these emissions would not enter the cycle were it not for human activity. Likewise, CH<sub>4</sub> emissions from landfills *are* counted – even though the source of carbon is primarily biogenic, CH<sub>4</sub> emissions would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH<sub>4</sub> formation.”

As a result, the CO<sub>2</sub> emissions resulting from composting, incineration or landfilling of biomass are considered to be “neutral” and thus *are not* considered to be greenhouse gas emissions. Therefore, the release of CO<sub>2</sub> during anaerobic decomposition at landfills, the biomass-CO<sub>2</sub> emission from combustion at incinerators and the CO<sub>2</sub> resulting from aerobic decomposition during composting *are not* considered as greenhouse gas emissions. In fact, incineration can just be thought of as an accelerated version of composting with an energy generating component included. It is important to recognize the important assumption that biomass is sustainably grown and harvested. The combustion of paper that was manufactured from unsustainable harvested trees would not be GHG neutral; there is no future tree growth to fix this carbon once again. This assumption is necessary to neglect any CO<sub>2</sub> emissions from biomass decomposition/oxidation. This report assumes that paper products, food scraps and yard trimmings are sustainably harvested.

Separating the CO<sub>2</sub> resulting from fossil fuels and the CO<sub>2</sub> resulting from biomass decomposition or combustion is necessary to prevent effort being wasted on natural processes which are not a concern for Global Climate Change. For example, this distinction causes the calculations in the appendices to account for the diesel fuel consumption (for conversion into units of CO<sub>2</sub> emitted) associated with the curbside collection, transfer station processing and subsequent transportation of yard trimmings to a centralized composting facility. It also includes the diesel fuel consumption necessary to operate the equipment required to perform composting of this material. However, it does not consider any of the emissions which result when this organic material is

oxidized by microorganisms to inorganic CO<sub>2</sub>. This is simply the conclusion of the cycle which started when inorganic CO<sub>2</sub> in the atmosphere was fixed by photosynthesis to organic carbon. Readers may have already noticed that a reference time-frame is inherent in treating biomass decomposition as GHG neutral. Fossil fuels contain carbon which was also originally CO<sub>2</sub> in the atmosphere and was fixed by photosynthesis into the organic carbon of biomass. This occurred millions of years ago and the fossil fuel carbon has been stored deep underground in geological reservoirs in the interim. Liberating this carbon into the atmosphere is fundamentally different than liberating the carbon in an apple core which was photosynthesized 6 months or 6 years ago. Even liberating the carbon in paper products which were photosynthesized by tree growth 50 years ago is fundamentally different than liberating carbon from fossil fuels created millions of years ago. Especially when remembering that a new tree will be growing in the location where the previous one was harvested – the sustainable harvesting assumption. It is these boundaries which are used in the calculations in the appendices.

Landfill methane emissions also require discussion in the context of biomass carbon cycling. If the CO<sub>2</sub> emission from a landfill is neutral but CH<sub>4</sub> emissions are GHG contributions, would it not be more accurate to subtract CH<sub>4</sub> by the CO<sub>2</sub> which would have occurred otherwise. This improvement is based on the fact that the methane results from a biomass waste and if the material can decompose anaerobically (without oxygen), it would likely decompose aerobically (breakdown with oxygen is inherently easier). Though methane is 21 times more effective than CO<sub>2</sub>, it would be more accurate to subtract the CO<sub>2</sub> that would otherwise have occurred if the methane emission did not. This reduces landfill methane emissions by approximately 5% and is defined by this author as *CO<sub>2</sub> Subtraction*. However, this improvement has not been included in this report so that it would be consistent with the IPCC methodology, but it is logical that it may be included in future work.

What if photosynthesis removes CO<sub>2</sub> from the atmosphere to create biomass but the carbon is never returned to the atmosphere? If the biomass resists the decomposition necessary to return the carbon to the atmosphere, this process can be interpreted as a GHG benefit and is analogous to permanently converting grassland to forests to sequester carbon. Both examples are reducing the atmospheric concentration of CO<sub>2</sub> to assist in mitigating Global Climate Change. This removal of carbon from the atmosphere and permanent storage can occur when biomass is disposed in landfills and resists decomposition in the anaerobic conditions. The next section reviews this emerging issue.

## **2.4 LANDFILL CARBON SEQUESTRATION**

The anaerobic decomposition of municipal solid waste has been well documented in the past and will not be reviewed in this thesis. However, this report will address the emerging issue of partial decomposition of organic materials in landfills in this section. The three organic components of municipal solid waste which are critical to the degradation reported in the literature are cellulose (40-50% dry mass), lignin (10-15%) and hemicellulose (9-12%) (Barlaz 1989a). Both the decomposed and undecomposed

organics are of concern in GHG emission considerations. The decomposed portion of the organics leads to methane emissions, whereas the portion resistant to decomposition presents the carbon sequestration potential of landfills. It is important to note that carbon sequestration is not included in the latest IPCC guidelines but was considered in a 1998 analysis by the U.S. Environmental Protection Agency (USEPA 1998).

Even under optimal conditions for biodegradation, complete anaerobic decomposition of organic materials cannot be expected. The presence of recalcitrant lignin and large particle sizes can limit the access of hydrolytic bacteria to some of the biodegradable material (Baldwin et al. 1998; Stinson and Ham 1995; Cummings and Stewart 1994; Wang et al. 1994; Tong et al. 1990). Complicating the matter further still is the fact that lignin concentrations of specific MSW components are highly variable. These issues are important for assessing the GHG emissions associated with landfill disposal and will be the focus of the discussion in this section. After the introduction of cellulose, hemicellulose and lignin biodegradability (2.4.1), a literature review of landfill carbon sequestration is presented (2.4.2). This is followed by a discussion of how this issue is applied to the two GVRD landfills analyzed in this thesis (2.4.3).

#### **2.4.1 Introduction**

It has been reported that over 90% of the methane potential of MSW results from the cellulose plus hemicellulose fraction (Barlaz et al. 1989a) and the remaining biodegradable constituents are soluble sugars and proteins. Cellulose is the principal structural molecule in plants; in fact, half of all the organic carbon in the biosphere has been estimated to be contained in cellulose (Curtis and Barnes 1989). In its frequently occurring fibrous form, its tensile strength is very great and it is insoluble in water. Cellulose is a carbohydrate; a polymer made up largely of glucose, and corresponds to the empirical formula of  $(C_6H_{10}O_5)_n$ . However, the degree of polymerization (DP) is very large, often ranging between 1000 and 5000, giving molecular weights between 163,000 and 810,000. Hemicelluloses are nonfibrous wood components. While cellulose is comprised mainly of glucose units, the hemicelluloses contain primarily sugar units other than glucose – such as xylose or mannose. The DP of hemicelluloses is much lower than cellulose; it is typically  $150 \pm 30$  (McGraw-Hill 1962).

Lignin accounts for between 20 to 30% of wood material and functions as a filler or cementing substance to impart rigidity to the tissues. It is thought that lignin probably exists in wood as branched-chain polymer molecules comprising a vast network. This network may be further intermeshed and/or chemically combined with hemicellulose or other nonlignin components of wood (ibid).

Lignin is highly recalcitrant. Not only does it strongly resist anaerobic decomposition, but it also prevents the decomposition of the embedded cellulose and hemicellulose components of the lignin matrix (Micales and Skog 1997). By themselves, the majority of cellulose and hemicellulose can be readily degraded. Under idealized laboratory decomposition conditions, Barlaz (1989b) observed the decomposition of 72% of the cellulose and hemicellulose of MSW but negligible decomposition of lignin.

There is a great deal of variability in the lignin content of many individual MSW components. This variability is demonstrated in office paper, which is largely delignified (one study measured the lignin content to be 2.3% (Barlaz 1998)), or in branches and newspapers, which are highly lignified (the same study measured lignin contents of 33% and 24%, respectively). The lignin content is "important because it is both a physical and chemical barrier to microbial attack." (Wang et al. 1994) In one study, about 40% of the cellulose in newsprint was degraded, while 90 and 97%, respectively, in delignified office and filter paper decomposed anaerobically (Khan 1997). In another study, the partial delignification of newsprint by acid chlorite treatment significantly increased the amount of cellulose available for decomposition and resulted in about 75% of the cellulose being degraded. By comparison, the cellulose decomposition in untreated newsprint was limited to 50% (Stinson and Ham 1995). Lastly researchers at the USDA Forest Service have performed calculations which "suggest that maximally only 30% of the carbon from paper and 0-3% of the carbon from wood are ever emitted as landfill gas." (Micales and Skog 1997)

#### **2.4.2 Literature Review**

Resulting from the ability of organic components of MSW to resist decomposition, the potential therefore exists for the long-term sequestration of carbon in sanitary landfills. It is worth noting that these are anaerobic conditions largely because there is no identified anaerobic microbial lignin attack (as opposed to white rot fungus which attacks aerobically). In fact, from the perspective of greenhouse gas emissions, the organic carbon deposited in landfills has to be partitioned into one of only three pathways: "(1) eventual atmospheric emission as methane, (2) eventual atmospheric emission as carbon dioxide following microbial oxidation or combustion, and (3) long-term sedimentary storage in landfill reservoirs." (Bogner and Spokas 1995) Two research investigations have attempted to estimate the amount of carbon being sequestered in landfills worldwide. The first one by Bogner and Spokas (1995), also partially described in Bogner (1992), developed a highly conservative estimate based on idealized laboratory decomposition studies with well-mixed waste and elevated moisture contents by Barlaz (1989b). It is likely that actual landfills, with high rates of compaction and restricted moisture infiltration, will have an even greater proportion of recalcitrant organic carbon and thus a greater amount of sedimentary storage would be expected. Bogner and Spokas (1995) estimated that about 30 million metric tonnes of carbon annually enters sedimentary storage by deposition in landfills – a considerable amount when compared to the estimated 20-30 million tonnes of carbon annually entering sedimentary storage worldwide from other sources (mainly marine).

The second investigation into the long-term storage of carbon in landfills was performed by Barlaz (1998) and is also discussed in Eleazer et al. (1997) and USEPA (1998). This also simulated enhanced anaerobic decomposition in laboratory-scale reactors. This research placed various types of organic waste in separate reactor vessels "in which was maintained anaerobic conditions similar to those in a landfill, but controlled to favor maximum methane generation." The experiments included shredding, seeding, leachate recycling and the maintenance of sufficient concentrations of nitrogen and phosphorus to ensure nutrient availability. These reactors were allowed to run for periods varying from

three months to two years. The experiment for each reactor was finished when either no measurable methane was being emitted (below instrument detection limit), or when it was determined that the reactor had produced at least 95% of the methane that it would produce if run indefinitely. The amount of methane and the amount of undecomposed carbon remaining in each reactor at the end of the experiment was measured.

The goal of this second study was to determine the "ultimate biodegradability" that is to be expected. The most significant contribution of this research is the study of the major individual components of MSW separately, and the subsequent determination of component-specific "Carbon Storage Factors". Once again, this storage determination is conservative; actual decomposition in a traditional landfill would be expected to be lower. The measured Carbon Storage Factor (CSF) represents the mass of carbon that was stored (not anaerobically degraded) per initial dry mass of component. Not surprising, the highest storage capability was observed with the high lignin MSW components, and the lowest storage was demonstrated by the lower lignin content materials. The measured CSF for grass, leaves, branches and newsprint was 0.32, 0.54, 0.38 and 0.42 kg C/dry kg, corresponding to lignin concentrations of 23, 43, 33 and 24%, respectively. Food waste and office paper exhibited low storage, with CSFs of 0.08 and 0.05 kg C/dry kg at low lignin concentrations of 11 and 2.3%, respectively. The carbon measured by the CSF includes not only the portion of cellulose and hemicellulose (and in the case of food waste - protein) which resisted anaerobic decomposition, but also most of the lignin content - very little lignin was actually degraded.

In an extrapolation of this data, Barlaz used these results to generate a global landfill carbon storage value. He estimated the global carbon sequestration due to MSW burial to be 118.7 million metric tonnes of carbon annually. This global carbon sequestration value is much greater than the previous value estimated by Bogner and Spokas.

Inspection of these Carbon Storage Factors for development in this thesis has discovered inconsistencies in the data reported by Barlaz (1998). For example, the CSF for leaves was reported as 0.54 kg C per dry kg while the initial carbon content of the leaves was only reported as 0.49 kg C per dry kg. This impossible result raises important questions about the results. The method used to calculate the CSF is a back-calculation based upon the carbon remaining in the reactor at the end of the experiment, but corrections were necessary to attribute the necessary fraction to the seed introduced to insure successful decomposition. It appears the initial carbon content was not used at any time for the calculation of CSF's and that the uncertainty with the correction for the seed has caused problems with some of the CSF's reported. Upon personal communication with Morton Barlaz and Jim Atwater, a new method for estimating Carbon Storage Factors is developed and employed in this thesis. Using the methane emission reported in USEPA (1998) to calculate the moles of CH<sub>4</sub> emitted and by assuming equal moles of CO<sub>2</sub>, it is possible to estimate the *Carbon Available for Anaerobic Decomposition* (CAAD). When this CAAD is subtracted from the initial carbon content reported in Barlaz (1998), a revised CSF results. The actual calculations for the revised CSF's are presented in the respective appendix for each biodegradable material investigated. Only one material changes appreciably with this revision: the CSF for leaves is decreased (from the



previous 0.54 kg C/dry kg to a new 0.43 kg C/dry kg). All the remaining biodegradable waste components (newsprint, office paper, grass and branches) change only slightly. The above revision has not been used on the CSF for food waste due to the fact that the laboratory-scale reactors for food contained a greater proportion of seed than the other reactors. If the above revisions are used on food waste, the CSF increases by 150%, an unreasonable amount. It is this author's belief that the current CSF is likely the more appropriate and it is thus left unrevised.

### 2.4.3 Application to GVRD Landfills

The application of this issue to the analysis in this thesis must be addressed. What proportion of office paper, newsprint, food and yard waste will remain undecomposed in the Cache Creek or Vancouver Landfill? It requires noting that only the sequestration of these four biomass materials is of consequence, because they do not contain the carbon of concern from a climate change perspective. Any carbon which is stored in this manner is a GHG benefit to the atmosphere. However, the disposal of plastics is *not* to be considered a net GHG benefit – plastics contain carbon from petroleum products that, as fossil fuels, was already in storage. As a result, the plastics have simply been moved from one 'storage' state to another, and are not considered in this analysis.

To estimate landfill carbon sequestration and the inverse of this issue, landfill methane emissions, a Time-Dependant model is developed in this thesis. In this model, all of the carbon disposed in a landfill has to eventually follow one of four distinct pathways: atmospheric emission as CH<sub>4</sub>, atmospheric emission as CO<sub>2</sub>, long-term storage or awaiting decomposition (though not yet degraded, this carbon is not to be considered sequestered). In this manner, emissions for the next 20 years are estimated.

In this model, the organic-carbon in the newsprint, office paper and food and yard waste components of MSW disposed in landfills will be partitioned according to the pathways described above. The landfill carbon sequestration estimates as reported by Barlaz (1998), and revised for this thesis as described in the previous section, are likely the most appropriate. However, since the Cache Creek Landfill (CCLF) is a dry landfill (there is little appreciable leachate (Pers. comm. Louie DeVent), the actual sequestration may be greater. The Vancouver Landfill (VLF) is a wet landfill (a substantial quantity of leachate is annually transferred to the nearest wastewater treatment plant (Pers. comm.. Paul Henderson) and is likely better represented by the experiments by Barlaz. If data for dry landfill sequestration becomes available in the future, the estimates can be revised. The flip side of the sequestered fraction is the *Carbon Available for Anaerobic Decomposition* (as described in the previous section) which is the total CH<sub>4</sub> and CO<sub>2</sub> which was emitted from the anaerobic reactors during the enhanced decomposition simulated by Barlaz. This CAAD is used in this thesis to estimate the methane generation potential at the landfills.

At the end of 20 years, organic carbon in this model can decompose (to CO<sub>2</sub> or CH<sub>4</sub>), it can be sequestered or it can simply be awaiting decomposition. However, this is not to say that carbon has to decompose *anaerobically* – organic carbon can be removed in the leachate and be aerobically degraded at wastewater treatment plants. While identifying

this possibility is valuable, the following estimates demonstrate the relative lack of importance of this issue.

At the Vancouver Landfill, 2,115,772 m<sup>3</sup> of leachate was collected and transferred to the Annacis Island Wastewater Treatment Plant in 1999 (Pers. comm.. Paul Henderson). Using a typical BOD<sub>5</sub> concentration of 100 mg/L (Metcalf & Eddy 1991), it is possible to calculate the mass of organic carbon contained in this leachate. This can be compared with the annual loss of carbon as landfill gas as a result of anaerobic decomposition. The most recent estimate is that the landfill gas production rate was 5082 cubic feet per minute in 1999 (Pers. comm. Paul Henderson). These calculations are below.

$$\text{Mass of Carbon in Leachate} = (2,115,772 \text{ m}^3) \left( 100 \frac{\text{mg O}}{\text{L}} \right) \left( \frac{12 \frac{\text{g}}{\text{mol C}}}{32 \frac{\text{g}}{\text{mol O}_2}} \right) \left( 10^{-9} \frac{\text{tonnes}}{\text{mg}} \right) \left( 1000 \frac{\text{L}}{\text{m}^3} \right) = 79 \text{ tonnes of C}$$

$$\text{Volume of LFG} = (5,082 \text{ ft}^3/\text{min}) \left( \frac{1 \text{ m}}{3.28 \text{ ft}} \right)^3 \left( 60 \frac{\text{min}}{\text{h}} * 24 \frac{\text{h}}{\text{d}} * 365 \frac{\text{d}}{\text{yr}} \right) \left( 1000 \frac{\text{L}}{\text{m}^3} \right) = 75.7 * 10^9 \text{ L}$$

$$\text{Mass of Carbon in Landfill Gas} = (75.7 * 10^9 \text{ L}) \left( \frac{1 \text{ mol}}{22.4 \text{ L}} \right) \left( 12 \frac{\text{g}}{\text{mol}} \right) \left( 10^{-6} \frac{\text{tonnes}}{\text{g}} \right) = 40,600 \text{ tonnes of Carbon}$$

The estimated 79 tonnes of carbon leaving the landfill as leachate is virtually irrelevant when compared to the 40,600 tonnes of carbon leaving the landfill as carbon dioxide or methane gas. Furthermore, since the Cache Creek Landfill is a dry landfill with little appreciable leachate (any leachate which is collected is spread on the active face to return the leachate back to the fill (Pers. comm. Louie DeVent)), this issue has even less importance. As a result of the demonstrated lack of importance, the potential for landfill leachate to provide aerobic decomposition of the organic carbon deposited in landfills is ignored.

It is also helpful to compare the mass of carbon in landfill gas with the mass of carbon in place at the landfill site. Since beginning operation in 1966, an estimated 11.3 million tonnes of waste has been deposited in the Vancouver Landfill by 1999 (CRA 1999), or an average 330,000 tonnes per year. By assuming a moisture content for MSW of 25% and a carbon content for MSW of 50%, it can be estimated that each year 124,000 tonnes of carbon is deposited in the landfill. However, only about 40,000 tonnes of carbon, or one part in three, actually escapes in the landfill gas each year. These simple estimates suggest that sequestration is indeed occurring at the local Vancouver Landfill.

Now part of the landfill gas (LFG) resulting from anaerobic decomposition may be collected. The methane gas component can be flared or utilized for energy. The remaining portion will escape collection and will be emitted to the atmosphere. However, some of the CH<sub>4</sub> which escapes collection can still be oxidized to CO<sub>2</sub> by microorganisms in the landfill cover materials prior to emission. New research by Czepiel et al. (1996) estimated the landfill oxidation rate of 10% for landfill methane. This study investigated a landfill that had a 1-2 m cover consisting of sandy-clay loam with intermittent low shrubs and grasses in older sections. This estimate will be used as an oxidation rate representative of the CCLF and the VLF for methane by-passing collection.

The last "fraction" or "partition" for organic carbon in this model is that which has yet to decompose. In this model, part of the organic carbon that will eventually decompose will not do so within the first 20 years; this carbon is part of the CAAD which hasn't yet decomposed after 20 years. Due to its future degradability potential, it cannot be considered as having entered long-term storage.

Critical to this time-dependant modelling is the first-order decay rate constant used. Various decay rates are published in available literature. Several of these were experimented with for this research but it is difficult to know which is of the greatest accuracy. The first order decay rate constant used by the GVRD in modelling methane emissions at the CCLF,  $0.02 \text{ yr}^{-1}$ , can be used to simulate the future degradation in the CCLF (GVRD 1999b). This is the decay rate developed by the U.S. Environmental Protection Agency for dry landfills (USEPA 1997). Unfortunately, this is an estimate of the degradation rate of general MSW and is not specific to any particular waste component. Conestoga-Rovers & Associates used a decay rate constant of  $0.028 \text{ yr}^{-1}$  when modelling the landfill gas at the VLF in a recent assessment for the City of Vancouver (Conestoga-Rovers 1999). This decay constant was developed by Levelton & Associates (for Environment Canada) in a province by province evaluation of landfill emissions (B.H. Levelton 1991). This higher decay rate represents the greater degradation to be expected at a wet landfill over the dry Cache Creek Landfill. When using the  $0.02 \text{ yr}^{-1}$  decay rate it can be estimated that only 33% of the CAAD will degrade within the 20 year time period and when using the higher  $0.028 \text{ yr}^{-1}$ , 43% of the CAAD is expected within the time period. This author believes it more useful to assume that over half of the CAAD of newsprint, office paper and Remainder and that over three-quarters of the CAAD of food scraps and yard trimmings is realized in the first 20 years after disposal (food waste is known to be readily decomposable and since yard waste is comprised of about 50% grass, this component is also easily degraded). By using a decay rate of  $0.04 \text{ yr}^{-1}$  for paper and Remainder disposed in the Cache Creek Landfill, 56% of the CAAD will materialize in the 20 years. For the Vancouver Landfill, the decay rate of  $0.05 \text{ yr}^{-1}$  will result in 64% of the CAAD being depleted. Using  $0.07 \text{ yr}^{-1}$  for the food and yard waste disposed at Cache Creek, 77% of CAAD will be decomposed. At Vancouver,  $0.08 \text{ yr}^{-1}$  calculates that 82% of the CAAD degrades. Lastly, if users wish to model the ultimate methane generation, 100% decomposition of the CAAD, then inputting the decay rate as  $0.14 \text{ yr}^{-1}$  will cause this.

These decay rates are displayed in the table below. Due to the nature of the spreadsheet Model, users can change the decay rates in the future to suit their needs.

Table 2-1: First-Order Decay Rate Constants

Landfill	Waste Component	Decay Rate (year <sup>-1</sup> )	% of CAAD in first 20 years	Source
Cache Creek	MSW	0.02	33	GVRD 1999b
Vancouver	MSW	0.028	43	Conestoga-Rovers 1999
Cache Creek	Paper & Remainder	0.04	56	assumption
Vancouver	Paper & Remainder	0.05	64	assumption
Cache Creek	Food & Yard	0.07	77	assumption
Vancouver	Food & Yard	0.08	82	assumption
either	any	0.14	100	change to ultimate decomposition

Also important in modelling GHG emissions is the expected collection efficiency of the generated landfill gas. This Model slowly increases, year after year, not only the collection effectiveness but also the proportion utilized for energy (to replace fossil energy).

## 2.5 NITROUS OXIDE EMISSIONS

The potential is great for significant releases of nitrous oxide during waste management, especially food and yard waste management, and consequently requires consideration. Given that N<sub>2</sub>O is a strong greenhouse gas, it is estimated to be 310 times more effective in trapping infrared radiation than CO<sub>2</sub>, it has to be considered in this research. In order to facilitate this, the *Global Nitrogen Cycle* (2.5.1) and the *Global Nitrous Oxide Cycle* (2.5.2) must be introduced. This is followed by the *Anthropogenic Interference with the Global Nitrogen Cycle* (2.5.3) and the consequent *Anthropogenic Interference with the Global Nitrous Oxide Cycle* (2.5.4). Finally this human-induced interference will be assessed for its *Implications for Waste Management* (2.5.5). This section will discuss the ramifications for *Landfill Disposal* (2.5.5.1), *Composting* (2.5.5.2) and *Incineration* (2.5.5.3) in turn. A detailed discussion of this can be found in Barton & Atwater (2000). This entire section is a summary of that paper. While it may appear that much of the following information is unrelated to the primary focus of the thesis, this review is provided to impress upon readers the uncertainty of the reported data and the crude understanding of this issue. As a result, the actual emissions measured in the future can and may be much greater than are currently estimated.

### 2.5.1 Global Nitrogen Cycle

Nitrogen is a critical element for life. It is an essential component of amino acids, which are the building blocks of proteins, which in turn are the building blocks of all life. It is estimated that 16% of protein, or 0.16 kg of N per kg of protein, is nitrogen (IPCC 1997). The cycling of global nitrogen throughout terrestrial and aquatic ecosystems and the atmosphere is critical for this building block.

The Earth's atmosphere is 78% by volume molecular nitrogen,  $N_2$  gas, and thus it is an immense reservoir. It is estimated that 5 billion million metric tonnes of nitrogen are contained in the atmosphere, ocean, terrestrial and marine biota, soil organic matter and sedimentary rocks. Although N is abundant, the vast majority of it is in a form which can be used by only a few living organisms (Mackenzie 1998). It is estimated that  $<0.02\%$  (or  $\sim 1$  million million tonnes) of global N is actually accessible to living organisms, most is either diatomic nitrogen ( $N_2$  gas) in the atmosphere ( $\sim 78\%$ ) or tied up in sedimentary rocks ( $\sim 20\%$ ) (ibid). To be available for utilization by living organisms, it must be in the form of reactive or fixed nitrogen (defined as "N bonded to C, O or H (e.g.  $NO_y$ ,  $NH_x$ , organic N)" (Galloway 1998)). Only a few species of aquatic and terrestrial bacteria and blue-green algae can fix the nearly inert  $N_2$  molecule into ammonium ( $NH_4^+$ ) for utilization. This conversion is called biological N-fixation (BNF) and it has been estimated that in preindustrial times,  $90-130 \times 10^6$  metric tonnes of N was annually fixed by this natural process (Galloway 1995). Lightning contributes an estimated additional  $3-5 \times 10^6$  metric tonnes of N fixation annually.

This reactive or fixed nitrogen moves through the terrestrial N cycle by the death of plants and microorganisms, *mineralization* – the breakdown of amino acids, *assimilation* – uptake by plants and by *immobilization* – uptake by microorganisms (Kinzig and Socolow 1994). Assuming an annual fixation rate of 130 million tonnes, this is miniscule in relation to the pool of total nitrogen (1 part in 38 million) or to the pool of reactive nitrogen (1 part in 7800). However it is upon this fixation rate which organisms depend. Since plant and animal life can only utilize reactive nitrogen as nutrients, and not diatomic nitrogen, "all life ultimately depends on nitrogen fixation" (Ayres et al 1994).

For nitrogen to remain in steady state conditions there must also be the return of reactive N to the  $N_2$  reservoir (though this reactive N may transfer through several forms due to oxidations and reductions before returning to  $N_2$ ). The majority of this is accomplished by the microbial processes, *nitrification* and *denitrification*. There is also *pyrodenitrification* which occurs during forest fires. In nitrification, ammonium ( $NH_4^+$ ) is oxidized to nitrate ( $NO_3^-$ ) by mainly autotrophic bacteria under aerobic conditions in order to derive energy. In denitrification, nitrate is reduced to  $N_2$  by mainly facultative heterotrophic bacteria under anoxic (oxygen restricted) conditions. These bacteria use the nitrate as a terminal electron acceptor so that they can concurrently derive energy from the breakdown of organic carbon (Beauchamp 1997). During pyrodenitrification, "two nitrogen atoms that were in separate molecules in plants or soil bind to one another to make  $N_2$ , as the result of a sequence of high-temperature reactions." (Ayres et al. 1994) By these three processes, equal amounts of N (the approximately  $93$  to  $135 \times 10^6$  tonnes N fixed annually) are returned to the atmosphere as  $N_2$  gas.

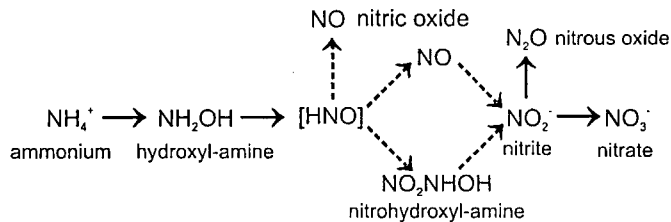
### 2.5.2 Global Nitrous Oxide Cycle

Nitrous oxide ( $N_2O$ ) is a stable gas which leaks from microbial cells during nitrification and denitrification (Firestone and Davidson 1989). Though the predominant product of nitrification is nitrate ( $NO_3^-$ ), and of denitrification is  $N_2$ , a portion of the N can be emitted as nitrous oxide.

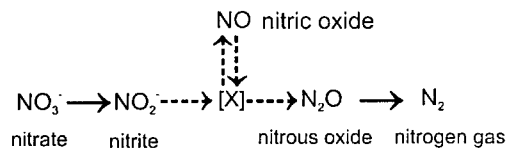
Though some parts of the nitrification and denitrification pathways are not well understood, particularly the pathways encompassing nitric oxide (NO), the generally accepted metabolic pathways are shown below. The dashed lines signify unconfirmed pathways.

Figure 2-1: Nitrification & Denitrification Pathways

NITRIFICATION (Hooper 1984; Firestone and Davidson 1989):



DENITRIFICATION (Firestone and Davidson 1989):



The “hole-in-the-pipe” or “process-pipe” conceptualization by Firestone & Davidson has been used to visualize the  $\text{N}_2\text{O}$  production in soils. These researchers consider that  $\text{N}_2\text{O}$  production is a factor of, (1), the amount of nitrogen cycling between the soil-plant-microbial system, and (2), the ratios of the  $\text{N}_2\text{O}/\text{NO}_3^-$  and  $\text{N}_2\text{O}/\text{N}_2$  products of nitrification and denitrification. These two factors, the overall movement of nitrogen through the *pipe*, and the amount of *leakage* (the size of the holes in the pipe), control the emission of  $\text{N}_2\text{O}$ .

Agricultural research has found that anywhere from 0.001% to 6.8% of the nitrogen applied to fields is emitted as  $\text{N}_2\text{O}$  (Mosier et al. 1996), and the ratio of  $\text{N}_2\text{O}/\text{NO}_3^-$  produced as a result of nitrification has been reported as high as 20% (Martikainen 1985), but is generally below 1% (Firestone and Davidson 1989). Though both processes have been demonstrated to result in  $\text{N}_2\text{O}$  leakage, denitrification is considered to be the major source of  $\text{N}_2\text{O}$  from soils (Sahrawat and Keeney 1986).

The production of  $\text{N}_2\text{O}$  during nitrification in soils has been demonstrated to result from:

“a reductive process in which the organisms use  $\text{NO}_2^-$  as an electron acceptor, especially when  $\text{O}_2$  is limiting. This mechanism not only allows the organisms to conserve limited  $\text{O}_2$  for the oxidation of  $\text{NH}_4^+$  (from which they gain energy for growth and regeneration), but also avoids the potential for accumulation of toxic levels of  $\text{NO}_2^-$ .” (Hutchinson and Davidson 1993; Poth and Focht 1985)

The nitrous oxide leakage during denitrification is considered to result when:

“the availability of oxidant (N-oxide) greatly exceeds the availability of reductant (most commonly organic carbon), then the oxidant may be

incompletely utilized, i.e.  $\text{N}_2\text{O}$  will be produced.” (Firestone and Davidson 1989) “Conversely, when the overall rate of denitrification is limited by the supply of oxidant, most of the N-oxide is converted to  $\text{N}_2$ .” (Hutchinson and Davidson 1993)

The latest estimate of the IPCC (1995) is that  $9 \times 10^6$  tonnes of  $\text{N}_2\text{O}$ -N is naturally emitted to the atmosphere by soil processes, forest and brush fires and the oceans. As there is no chemical loss in the troposphere (the lower  $\sim 12$  km of the atmosphere (Mackenzie 1998)), this  $9 \times 10^6$  tonnes of  $\text{N}_2\text{O}$ -N slowly rises to the stratosphere where it is destroyed. The destruction of  $\text{N}_2\text{O}$  occurs at an altitude above 30 km (in the stratosphere) and returns this nitrogen to the  $\text{N}_2$  reservoir. It takes, on average, 120 years for  $\text{N}_2\text{O}$  to reach this altitude and to be destroyed (IPCC 1995). The  $\text{N}_2\text{O}$  is destroyed predominantly by photodissociation into  $\text{N}_2$  molecules and O atoms. However, approximately 10% of the  $\text{N}_2\text{O}$  reacts with electronically excited oxygen atoms (formed by the photolysis of ozone) to form NO. The production of NO is important in stratospheric ozone chemistry, since NO catalytically destroys ozone (Abbatt and Molina 1993).

### 2.5.3 Anthropogenic Interference of the Global Nitrogen Cycle

The crux of the problem is that humans have approximately doubled the global rate of N fixation, from an estimated pre-industrial rate of  $93\text{-}135 \times 10^6$  tonnes N/yr to an estimated  $243\text{-}295 \times 10^6$  tonnes N/yr fixed currently (Galloway 1998). The increased fixation of elemental  $\text{N}_2$  gas has been a direct result of nitrogenous fertilizer production, human-induced increases in the cultivation of leguminous crops (which host a symbiotic relationship with biological N-fixing bacteria) and by the combustion of fossil fuels. Estimates adapted from Galloway (1998) of this anthropogenic interference are provided in Table 2-2.

Table 2-2: Global Reactive Nitrogen Sources

	Global Nitrogen Fixation (million tonnes N/year)
Natural Biological N Fixation	90-130
Lightning	3-5
Natural Source Subtotal	93-135
Synthetic Fertilizers	80-90
Human-Induced Biological N Fixation	40
Fossil Fuel Combustion	30
<b>Anthropogenic Source Subtotal</b>	<b>150-160</b>
<b>TOTAL SOURCES</b>	<b>243-295</b>
<b>(Percent Anthropogenic)</b>	<b>(51-66%)</b>

Fertilizer production by the Haber-Bosch process fixes  $\text{N}_2$  to ammonia ( $\text{NH}_3$ ) thereby reproducing at high temperature and pressure what bacteria can accomplish with enzymes at ambient temperature and pressure (Kinzig and Socolow 1994). Human-induced biological N-fixation occurs by the increased cultivation of leguminous crops such as soybean and alfalfa which symbiotically host nitrogen fixing bacteria in their root nodules. The last source of reactive N is the by-product of the combustion of fossil fuels.

Whereas nitrogen fixation from fertilizer production and the cultivation of leguminous crops is intentional, the reactive N produced as a result of combustion is not intentional. The combustion of fossil fuels causes nitrogen that was originally in air as N<sub>2</sub> gas or nitrogen that was originally sequestered in the fuel as organic-N to be oxidized to nitric oxide (NO) or nitrogen dioxide (NO<sub>2</sub>).

#### 2.5.4 Anthropogenic Interference of the Global Nitrous Oxide Cycle

As a direct result of enhancing of the global nitrogen cycle, there has been a consequent enhancing of the global nitrous oxide cycle. The atmospheric N<sub>2</sub>O concentration has increased from a pre-industrial level of 275 ppb to a level of 311 ppb in 1992, an increase of 13% (IPCC 1995). This is estimated to contribute 6% of the human-induced increase in the infrared radiation absorbing ability of the atmosphere (Erisman et al 1998). In addition, this concentration continues to increase by about 0.8 ppb annually (IPCC 1995).

The most recent budget, as of 1998, of global nitrous oxide is provided in Table 2-3 (adapted from Mosier et al. (1998))

Table 2-3: Global N<sub>2</sub>O Budget

Global Sources and Sinks of N <sub>2</sub> O (million tonnes N <sub>2</sub> O-N/year)	
Identified Natural Sources	9.0
Identified Anthropogenic Sources	7.2
Total Identified Sources	16.2
Unaccounted Sources	0
Total Sinks (Photolysis)	12.3
Atmospheric Increase	3.9

Agricultural activities dominate the emissions of anthropogenic nitrous oxide with industrial sources (primarily fossil fuel combustion) providing the remainder of emissions.

It is only since 1998 that the budget of N<sub>2</sub>O sources and sinks has been successfully balanced. Previous budgets were not balanced because sinks exceeded sources with the missing emissions labeled as "unaccounted sources." In the newest IPCC methodology, there are new sources of N<sub>2</sub>O which were previously not included (IPCC 1997). In this new methodology, "three sources of N<sub>2</sub>O are distinguished: (i) direct emissions from agricultural soils, (ii) emissions from animal production systems, and (iii) N<sub>2</sub>O emissions indirectly induced by agricultural activities." (IPCC 1997; Mosier et al. 1998) It is the N<sub>2</sub>O emissions indirectly resulting from agriculture with which this research is concerned, because it is the source of the emissions that result from the MSW stream.

Reactive N exported from farms as food products can cause indirect emissions of N<sub>2</sub>O. This reactive N is eventually nitrified and denitrified and N<sub>2</sub>O leakage can result. These



sources of  $\text{N}_2\text{O}$  are considered indirect because they do not actually occur on farms but are nevertheless, agricultural in origin. For instance, the nitrification and denitrification of reactive N used in food production (and the associated  $\text{N}_2\text{O}$  leakage) may occur at wastewater treatment plants. As a result,  $\text{N}_2\text{O}$  emissions from wastewater treatment can be considered indirectly agricultural in origin, in fact, any  $\text{N}_2\text{O}$  emissions from reactive N downstream of food production are indirectly agricultural  $\text{N}_2\text{O}$  emissions. This will be further discussed in the following section, *Implications for Waste Management* (2.5.5).

### 2.5.5 Implications for Waste Management

The existence of anthropogenic nitrogen in MSW has important implications for waste management. Municipalities are typically given the responsibility to perform waste management. Given that fertilizer nitrogen, either in food or yard waste, has the potential to emit  $\text{N}_2\text{O}$  during this management, municipalities are responsible for the emissions. To assess this potential source of GHG emissions, a survey of available research has been performed. This survey only found nine papers on the  $\text{N}_2\text{O}$  emissions from composting, ten papers on the  $\text{N}_2\text{O}$  emissions from waste incineration and only two papers on the  $\text{N}_2\text{O}$  emissions from waste disposed in landfills. However, 26 papers and one patent were found on the  $\text{N}_2\text{O}$  emissions resulting during wastewater treatment – a frequent destination of landfill leachate. Each of the management alternatives, landfill disposal, composting and incineration will be reviewed from the perspective of  $\text{N}_2\text{O}$  emissions in this section.

These papers actually generate many more questions than they answer. For all of the papers, only the immediate emissions of  $\text{N}_2\text{O}$  were measured during the investigated process. There was no attempt to quantify any *future emissions* resulting from ammonia, nitric oxide or nitrate losses during the process, or from the future decomposition of the organic matter. For example, gaseous emissions of  $\text{NH}_3$  are common during wastewater treatment or composting, but atmospheric discharges of this reactive nitrogen are not considered with respect to subsequent  $\text{N}_2\text{O}$  emissions.

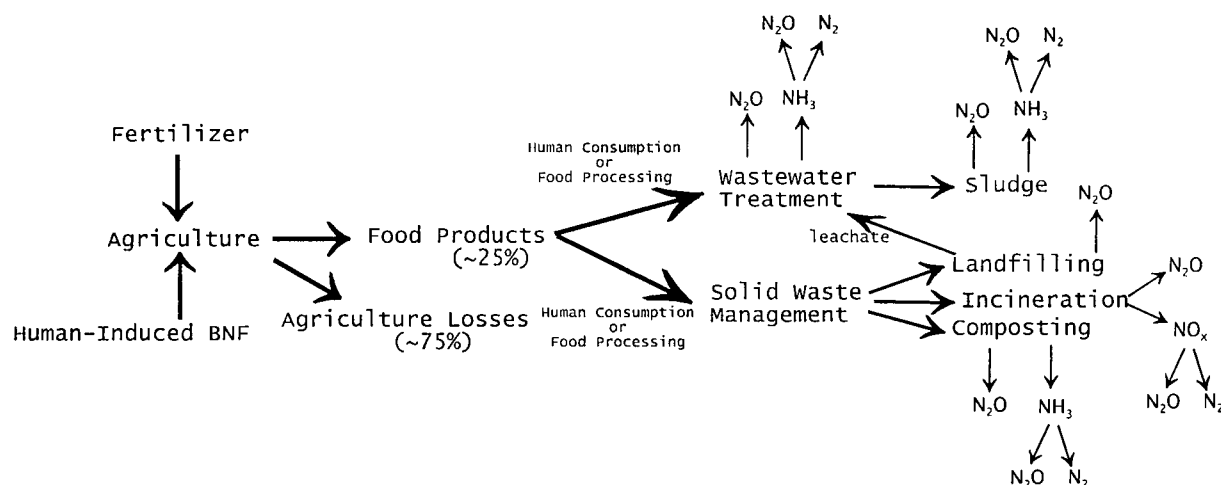
Ammonia has an atmospheric lifetime of only a few hours to a few days and is mainly removed by wet and dry deposition. However, a portion, perhaps 10%, is oxidized to NO, and a third fraction is removed by reacting with nitrates or sulphates to form ammonium-containing aerosols,  $(\text{NH}_4)_2\text{SO}_4$  and  $\text{NH}_4\text{NO}_3$ . These aerosols are later removed by rainfall or dry fallout (Matthews 1994). Nitrogen oxides ( $\text{NO}_x = \text{NO} + \text{NO}_2$ ) are short-lived gases and they have an atmospheric lifetime between 1-10 days. Nitrogen oxides are removed from the atmosphere by conversion to nitric acid ( $\text{HNO}_3$ ), which is followed by wet or dry deposition (Olivier et al 1998; Logan 1983). In addition, nitrogen oxides are suspected to indirectly contribute to global warming – they deplete the atmospheric concentration of the OH radical; a radical which limits the atmospheric lifetime of  $\text{CH}_4$ . With OH depleted, the potential exists for methane to have a longer atmospheric lifetime than it would otherwise be able to (Mackenzie 1995).

Once these nitrogen compounds ( $\text{NH}_3$ ,  $\text{NH}_4^+$ , NO,  $(\text{NH}_4)_2\text{SO}_4$ ,  $\text{NH}_4\text{NO}_3$ ,  $\text{HNO}_3$ , etc) are returned to land or water surfaces by wet or dry deposition, this reactive nitrogen is again available for nitrification/denitrification, and the associated  $\text{N}_2\text{O}$  emissions can result. As

a result, discharges of reduced or oxidized nitrogen compounds only temporally and spatially alter the nitrous oxide emissions but do nothing to prevent these emissions.

Another example of a *future N<sub>2</sub>O emission* originates from the organic nitrogen contained in wastewater sludge or finished compost. As this organic-nitrogen will eventually undergo decomposition, the released ammonium (NH<sub>4</sub><sup>+</sup>) is now available to undergo nitrification and denitrification. A simplified conceptualization of N<sub>2</sub>O emissions during waste management operations and of potential future emissions is demonstrated in Figure 2-2.

Figure 2-2: Potential N<sub>2</sub>O Emissions from Waste Management



To reiterate, N<sub>2</sub>O emissions in waste management from the reactive nitrogen in food waste are considered *indirectly* agricultural in origin by the IPCC. This is because the nitrogen was originally fixed for food production. In addition, the nitrogen component of yard trimmings may also be synthetic fertilizer in origin. During waste management, there can be *immediate* or *future* emissions of N<sub>2</sub>O. Immediate emissions occur during the operation in question, be it wastewater treatment, composting, landfilling or incineration. Future emissions occur as a result of the future nitrification and denitrification of reactive N which exits the operation, usually in the form of ammonia or nitrogen oxides (NO<sub>x</sub> = NO + NO<sub>2</sub>) emissions or organic-nitrogen in compost or sludge. While waste managers are responsible for the release of reactive nitrogen, once the nitrogen is released they have no way of controlling its conversion to N<sub>2</sub>O.

The following sub-sections review the potential for N<sub>2</sub>O emissions to result from wastes that are landfilled, composted or incinerated. It is the intent of these reviews to complement the N<sub>2</sub>O calculations in Appendix C through Appendix K.

#### 2.5.5.1 - Landfill Disposal

Does the reactive nitrogen in landfilled MSW (predominantly in the food and yard waste components) contribute N<sub>2</sub>O emissions to the atmosphere? A literature review has only located two research papers addressing this question. Unfortunately, only the Japanese study actually investigated the N<sub>2</sub>O emissions resulting from waste disposed in landfills –

the other research paper, a Swedish study, examined the emissions from different materials as cover soils. In the Japanese study, two landfills, one active and the other closed, both with over 10 million tonnes of refuse in place, were examined (Tsujimoto 1994). Average  $\text{N}_2\text{O}$  emissions of 40.2 g/day and 7.8 g/day for the active and closed landfills, respectively, were observed in the landfill gas vented. This emission, while important (40 g/d of  $\text{N}_2\text{O}$  will equal the annual greenhouse gas emission of 4.5 tonnes of  $\text{CO}_2$  equivalent [using the  $\text{N}_2\text{O}$  global warming potential of 310] or the combustion of approximately 1600 L of diesel fuel<sup>1</sup>), represents only 9.3 kg of  $\text{N}_2\text{O}$ -N annually or 0.02% of an assumed 50,000 kg of nitrogen in the waste (using a nitrogen content of 0.5% for typical waste (White et al 1995)). Either this small emission indicates limited nitrification/denitrification taking place or limited  $\text{N}_2\text{O}$  leakage of the nitrification/denitrification taking place. (For further discussion of  $\text{N}_2\text{O}$  leakage refer to Section 2.5.2 – *Global Nitrous Oxide Cycle*) Given the anaerobic nature of landfills, it is likely the former. The Swedish study, determined that about 1.6% of sludge nitrogen used as a landfill cover soil will be emitted as  $\text{N}_2\text{O}$ -N during the first two years (Borjesson and Svensson 1997). This is similar to the 1.25%  $\text{N}_2\text{O}$ -N estimate for fertilizer and manure nitrogen found in agriculture research (IPCC 1997) and is not surprising considering that the land application of sludge is analagous to fertilization.

Can appreciable amounts of nitrous oxide eventually become emitted from nitrogenous waste disposed in landfills? The Japanese study has demonstrated the existence of an emission, albeit a small one. Appreciable  $\text{N}_2\text{O}$  emissions likely occur indirectly via landfill leachate or landfill gas. Reactive nitrogen contained in landfilled organic waste is released when anaerobic decomposition occurs. At this point, ammonia-nitrogen is free to undergo nitrification and denitrification, to be leached by water percolating through the fill or to be volatilized in the vented landfill gas. Ammonia nitrogen can dissolve in the percolating water and exit the landfill in the leachate. Landfill leachate is known to be high in nitrogen, with a typical total nitrogen concentration (Organic-N +  $\text{NH}_3$ -N +  $\text{NO}_3$ -N) between 25 and 1600 mg/L for active landfills and between 105 and 170 mg/L for mature landfills (Tchobanoglous et al. 1993). In recent years, leachate ammonia concentrations in excess of 2000 mg/L are even being reported (Henderson and Atwater 1995; Robinson et al. 1998; Rettenberger 1998). On a dry volume basis, the typical ammonia content of landfill gas has been reported between 0.1 and 1.0% (Tchobanoglous et al. 1993). Assuming that a minimum of nitrification (and thus little denitrification) occurs inside the landfill because of the anaerobic environment, the likely pathway of  $\text{N}_2\text{O}$  emissions is from the treatment of landfill leachate or the release of ammonia gas to the atmosphere. As a result, a review of the literature on the  $\text{N}_2\text{O}$  emissions reported during wastewater treatment is necessary along with a discussion of the wet and dry deposition of ammonia emitted to the atmosphere.

A survey of available research conducted on the  $\text{N}_2\text{O}$  emissions from wastewater treatment found 26 papers. Interestingly, the studies of actual wastewater treatment plants observed very low  $\text{N}_2\text{O}$  emissions, but laboratory experiments generally reported much higher  $\text{N}_2\text{O}$  emissions.

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<sup>1</sup> Using the emission estimate of 2.8 kg of  $\text{CO}_2$ /L of diesel from Environment Canada (1997a)

Studies using laboratory-scale reactors have demonstrated high  $\text{N}_2\text{O}$  losses but have also observed a profound ability to affect these emissions; therefore the possibility exists for mitigation of a large portion of these emissions. The conversion of ammonium-nitrogen ( $\text{NH}_4\text{-N}$ ) to  $\text{N}_2\text{O}$  during nitrification has been demonstrated by Zheng et al. (1994) to be between 2.3 and 7.0% at dissolved oxygen (DO) concentrations between 0.1 and 6.8 mg/L. They also found  $\text{N}_2\text{O}$  conversions as high as 16% and as low as 2.3% at solids retention times (SRT) of 3 days and 10 days, respectively. It was concluded that high  $\text{N}_2\text{O}$  production resulted when incomplete nitrification occurred. Thus preventing incomplete nitrification by maintaining DO levels greater than 0.5 mg/L and having SRTs of greater than 5 days would greatly reduce  $\text{N}_2\text{O}$  emissions. By also using reactors, Hanaki et al. (1992) observed that as much as 8% of influent nitrate-nitrogen ( $\text{NO}_3\text{-N}$ ) was transformed to  $\text{N}_2\text{O}$  during denitrification, though several experiments demonstrated very little  $\text{N}_2\text{O}$ . The high conversion to  $\text{N}_2\text{O}$  was observed at a COD/ $\text{NO}_3\text{-N}$  ratio of 3.5, an SRT of 0.5 days and a pH of 6.5. These researchers concluded that " $\text{N}_2\text{O}$  production can be avoided by achieving complete denitrification [by maintaining] high COD/ $\text{NO}_3\text{-N}$  in wastewater, long SRTs and neutral to alkaline pH conditions." Work by Hong et al. (1993) also agrees with this; they concluded that "the lower the ratio of COD/ $\text{NO}_3\text{-N}$ , the higher the percentage of  $\text{N}_2\text{O}$  in the produced gas was" and that short hydraulic retention times resulted in higher  $\text{N}_2\text{O}$  production.

Several papers have reported extremely high  $\text{N}_2\text{O}$  conversion rates in the laboratory. Osada et al. (1995) reported a 35%  $\text{N}_2\text{O-N}$  conversion in a fill and draw activated sludge process while treating swine wastewater under continuous aeration but only a 0.7%  $\text{N}_2\text{O-N}$  conversion during intermittent aeration. Experiments on a sequencing-batch reactor (SBR) found that as much as 40% of the removed nitrogen was emitted as  $\text{N}_2\text{O}$ ; most of which occurred during the low DO period in aeration (Okayasu et al 1997). During the aerobic treatment of swine slurry, nitrous oxide emissions could represent up to 30% of the total nitrogen content of the slurry (Beline et al 1999). Research by Spector (1998), observed that  $\text{N}_2\text{O}$  accumulated to a maximum and was subsequently reduced to  $\text{N}_2$  gas, when reducing nitrate with methanol in a closed reactor. At maximum accumulation, 50 to 80% of the reduced nitrate was in the form of  $\text{N}_2\text{O}$ . This scientist noted that if the same experiment had been performed in an open reactor, "most or all the  $\text{N}_2\text{O}$  retained at  $t_{\text{max}}$  would have been discharged to the atmosphere."

In contrast to this laboratory research are the findings from several investigations at full-scale facilities. Three studies at WWTP's performing biological nitrogen removal (BNR) reported very low  $\text{N}_2\text{O}$  emissions. Kimochi et al (1998) reported  $\text{N}_2\text{O-N}$  conversions between 0.01 and 0.08% of influent nitrogen. This WWTP was modified to attempt to reduce these emissions and they found that by maintaining a dissolved oxygen concentration of over 0.5 mg/L during the aerobic/nitrification stage and allowing 60 minutes for the anoxic/denitrification stage, that complete nitrification and denitrification with a minimum of nitrous oxide production could be achieved. In fact, their findings state: "an optimum combination of aerobic and anoxic conditions and their suitable control are very important for improving nitrogen removal efficiency and controlling  $\text{N}_2\text{O}$  emissions." At a pilot plant, Thörn and Sörensson (1996), observed an average nitrous oxide production rate of  $0.0091 \text{ mg N L}^{-1} \text{ h}^{-1}$  in the denitrification basin.

However there is insufficient information to convert this value into a percentage of influent nitrogen. Research at a Swiss WWTP with a predenitrification anoxic tank followed by three aerobic tanks also observed a very low nitrous oxide emission ( $<0.1\%$  of influent nitrogen) (von Schulthess and Gujer 1996). However, two studies at secondary treatment facilities (aeration tanks only treating biochemical oxygen demand) have also determined negligible emissions. At the municipal WWTP in Durham, New Hampshire, Czepiel et al. (1995) found  $\text{N}_2\text{O}$  emissions of only  $1.6 \times 10^{-6}$  g of  $\text{N}_2\text{O}/\text{L}$  of wastewater or 3.2 g  $\text{N}_2\text{O}/\text{person} \cdot \text{year}$ . Though it is not provided, if one assumes a typical nitrogen content of raw wastewater of 40 mg of N/L (Metcalf & Eddy 1991), this is a  $\text{N}_2\text{O}$ -N conversion of influent nitrogen of only 0.0025%. Sumer et al. (1995) reported an  $\text{N}_2\text{O}$ -N conversion of 0.001% of influent-N at an activated sludge plant in Germany; however, this plant included a pre-trickling filter to increase nitrification in the aeration tank.

If the conversions of reactive nitrogen to  $\text{N}_2\text{O}$  have been demonstrated by these five scientific studies to be extremely low and therefore of almost no importance, then why discuss it? Unfortunately, the complete picture is much more complicated and uncertain to allow for this simple dismissal. At the three BNR plants low emissions were observed; it appears that the processes to successfully promote nitrogen removal are consistent with the same processes which ensure complete nitrification & denitrification and thus minimize  $\text{N}_2\text{O}$  emissions. However, is this representative of all BNR facilities? Kimochi reported that the aerobic/anoxic conditions and their control are very important for controlling emissions. As demonstrated by laboratory research, the possibility exists for poorly operated BNR plants to be important sources of  $\text{N}_2\text{O}$  emissions. Furthermore, for the two investigations at secondary treatment facilities, there is a distinct possibility that the emissions are not low because the nitrification and denitrification which occurs in the WWTP produces little  $\text{N}_2\text{O}$ . Rather, the emissions are low because it appears that little nitrification or denitrification actually occurred at the secondary treatment plant studied by Czepiel et al. (1995). While nitrification was encouraged at the activated sludge plant studied by Sumer et al. (1995), there was little or no opportunity for denitrification. Remember, agricultural research has identified denitrification as the more important  $\text{N}_2\text{O}$  source of the two processes.

An example of past inadequate identification of nitrous oxide emission sources has been demonstrated by a very recent investigation of the South Platte River in Colorado (McMahon and Dennehy 1999). It was found that the  $\text{N}_2\text{O}$  emissions from this single river, which receives Denver's wastewater effluent, approached the emission estimated by Czepiel et al. (1995) for all the primary plants in the U.S. In a much older study, researchers investigating the surface water bodies receiving wastewater effluent from Washington, D.C., U.S.A., found data to imply that "the loss of nitrogen as  $\text{N}_2\text{O}$  could account for between 2 and 4% of the total nitrogen released by the wastewater treatment plants." (McElroy et al. 1978)

As a result of the uncertainty around estimating  $\text{N}_2\text{O}$  emissions from wastewater, the latest guidelines of the IPCC (1997) (and Mosier et al (1998)) advise using an emission coefficient of 0.01 kg  $\text{N}_2\text{O}$ -N/kg sewage-N produced (it ranges between 0.002 and 0.02

kg N<sub>2</sub>O-N/kg sewage-N produced). This estimate assumes that 1% of wastewater nitrogen will be emitted as N<sub>2</sub>O-N either immediately or in the future. This estimate will likely be improved upon with new research. The United States has used this emission coefficient as an estimate in the Environmental Protection Agency's latest national greenhouse gas inventory (USEPA 1999). This results in an estimated emission of 27,000 tonnes of N<sub>2</sub>O from 1997 alone and can be converted to 8.4 million tonnes of carbon dioxide equivalent, MtCO<sub>2</sub>e. While it is only a small part of the 6651 MtCO<sub>2</sub>e estimated to be emitted by the U.S. in 1997, it is a more important part of the 931 MtCO<sub>2</sub>e non-energy related greenhouse gas emissions (energy accounts for 86% of total U.S. greenhouse gas emissions). Furthermore, this may be an underestimate. The estimated nitrous oxide contribution from U.S. agriculture which produced the food in the first place is 283 MtCO<sub>2</sub>e for 1997. Several researchers have estimated the nitrogen efficiency of their respective countries agricultural industry (efficiency of N in food products vs. total N input required) to be 10% for Norway (Bleken and Bakken 1997) and 25% for Germany (Isermann and Isermann 1998). Overall, Isermann and Isermann (1998) estimated the N efficiency of European Union agriculture as only being between 20–30%. Assuming the same to be true for the United States, a similar conversion of about 25% taken from the farm as food products could result in an actual waste derived N<sub>2</sub>O emission as high as 94 MtCO<sub>2</sub>e (from both liquid and solid forms of waste).

To bring this discussion closer to home, the typical ammonia concentration and annual quantity of leachate at the Vancouver Landfill has been obtained from the Landfill Operations Branch of the City of Vancouver (Pers. comm. Paul Henderson). In the 1999 calendar year, 2,115,772 m<sup>3</sup> of leachate was transferred to the Annacis Island Wastewater Treatment Plant with an average ammonia concentration of 157 mg/L as nitrogen. Using the IPCC estimate of 1.0% eventual N<sub>2</sub>O emission from the influent nitrogen to a wastewater facility in the calculations below and a nitrous oxide global warming potential of 310, it is possible to estimate that Vancouver Landfill's contribution of N<sub>2</sub>O from leachate nitrogen is:

$$\text{Mass of Nitrogen} = (2,115,772 \text{ m}^3) \left( 157 \frac{\text{mg N}}{\text{L}} \right) \left( 10^{-9} \frac{\text{tonnes}}{\text{mg}} \right) \left( 1000 \frac{\text{L}}{\text{m}^3} \right) = 332 \text{ tonnes of N}$$

$$\text{N}_2\text{O Emission} = (332 \text{ tonnes N}) \left( 0.01 \frac{\text{N}_2\text{O-N}}{\text{N}} \right) \left( \frac{44 \text{ g N}_2\text{O/mol}}{28 \text{ g N}_2\text{O-N/mol}} \right) (310)_{\text{GWP}} = 1617 \text{ tCO}_2\text{e}$$

As a result of these calculations, it is possible to assess a currently neglected source of greenhouse gas emissions, an estimated 1600 tonnes of CO<sub>2</sub> equivalent annually. To put this in perspective, it would be helpful to compare this with the currently estimated methane emission at this same landfill. The most recent estimate for this landfill is that in 1999, the landfill gas production rate was 5082 cubic feet per minute of which 50% was methane. Staff estimate that approximately 22% of the generated landfill gas is

being collected and flared (Pers. comm. Chris Underwood)<sup>2</sup>. From this data is possible to calculate the current methane greenhouse gas emission:

$$\text{Volume of LFG} = \left(5,082 \frac{\text{ft}^3}{\text{min}} \left( \frac{1 \text{ m}}{3.28 \text{ ft}} \right)^3 \right) \left( 60 \frac{\text{min}}{\text{h}} * 24 \frac{\text{h}}{\text{d}} * 365 \frac{\text{d}}{\text{yr}} \right) \left( 1000 \frac{\text{L}}{\text{m}^3} \right) = 75.7 * 10^9 \text{ L}$$

$$\text{Mass of CH}_4 = (75.7 * 10^9 \text{ L}) \left( \frac{1 \text{ mol}}{22.4 \text{ L}} \right) (0.5)_{\text{METHANE}} * \left( 16 \frac{\text{g}}{\text{mol}} \right) \left( 10^{-6} \frac{\text{tonnes}}{\text{g}} \right) (21)_{\text{GWP}} * (1 - 0.22) = 443,000 \text{ tCO}_2\text{e}$$

The calculations above have estimated the atmospheric emission of methane to be 443,000 tCO<sub>2</sub>e in 1999. When compared to this value, the nitrous oxide emission is less than half a percent. This estimate is likely because the majority of the landfill methane emissions result from the cellulose of disposed paper products. These same paper products also have low or negligible nitrogen contents, and therefore contribute little N<sub>2</sub>O emissions. However, when analyzing the GHG implications of landfilling food or yard wastes (with their high nitrogen contents), N<sub>2</sub>O emissions are of greater importance.. Also remember that the actual N<sub>2</sub>O emissions can be much greater than the currently stipulated guideline of a 1.0% conversion rate. This will be illustrated in the next chapter, *Results of the Analysis* (Chapter 3).

A further complicating factor is that of nitrogen sequestration. Whereas the potential for carbon sequestration was previously discussed, reactive nitrogen can also be stored in landfills and will prevent nitrous oxide emissions. While the calculations above estimate that 332 tonnes of nitrogen exited the VLF as leachate in 1999, 336,633 tonnes of waste was disposed in this landfill in the same year (Pers. comm. Mike Stringer). From an old Environment Canada (1978) report, a MSW moisture content of 24% and a dry MSW nitrogen content of 0.8% results in an estimated 2050 tonnes of nitrogen in the disposed waste. While the annual mass of waste disposed in the VLF has increased in its 30 odd years of existence, the possibility exists that much more nitrogen is being deposited than will have the opportunity to exit.

Not to be overlooked is the possibility that reactive nitrogen, as ammonia, will exit the landfill in vented gas. Future wet or dry deposition will return this ammonia gas to soils or surface water bodies where nitrification and denitrification can occur. Thus the potential for future N<sub>2</sub>O emission also exists from this pathway. If the landfill gas containing ammonia is collected and combusted, the ammonia will be oxidized to nitrogen oxides (NO or NO<sub>2</sub>). This also provides reactive nitrogen to the atmosphere, and with subsequent wet or dry deposition, can nitrify and denitrify. The IPCC provides guidelines for these emissions and estimates that 1% of NH<sub>3</sub>-N or NO<sub>x</sub>-N emitted to the atmosphere will eventually be converted to N<sub>2</sub>O. However, they also provide low and high estimates of 0.2 and 2% respectively. Thus, emission factors for gaseous emissions of ammonia or nitrogen oxides are similar to the emission factor for wastewater-nitrogen. It is not important *how* reactive nitrogen gets out of the landfill, only *how much* reactive nitrogen gets out.

<sup>2</sup> It is important to note that in 1999 Vancouver City Council approved the expenditure of \$5.4 million to upgrade this landfill gas collection system and thereby improve this collection efficiency (Henderson and Underwood 2000).

### 2.5.5.2 Composting

The composting of food and yard wastes will result in  $N_2O$  either during the process itself or by the future nitrification and denitrification of reactive nitrogen leaving the composting process in the form of ammonia emissions, nitrate or organic matter. The available research has demonstrated the existence of  $N_2O$  emissions during the composting process. This is likely  $N_2O$  leakage during the nitrification and denitrification of reactive N in the organic wastes. Researchers have observed a conversion of N to  $N_2O$  ranging from 0.00005 to 2.2% and the findings are summarized in Table 2-4.

Table 2-4: Review of Nitrous Oxide Emissions from Composting

Compost & Method	$N_2O$ -N Loss (% of Initial TKN) <sup>†</sup>	Researcher
Dairy Cow Litter – Static Piles	0.00005 – 0.0005	Sommer and Dahl (1999)
Yard Waste – Turned Windrow	0.5	Hellebrand (1998)
Food & Yard Waste – Tunnel and Static Pile	0.2 – 0.4	Schenk et al. (1997)
Wastewater Sludge & Wood Ash – Aerated Static Piles	0.7*	Czepiel et al. (1996)
Yard Waste – Turned Windrow	1.2	Ballestero et al. (1996)
Bedding & Horse Manure – Turned Windrow	2.2 (after 60 days)	Ballestero et al. (1996)
Swine Feces & Cardboard – Aerated & Turned In-Vessel	0.1	Kuroda et al. (1996)
Not given	0.5 – 0.8	Hellmann (1995) from Hellebrand (1998)

\* data provided in the research paper was adapted to determine this value

<sup>†</sup> TKN = Total Kjeldahl Nitrogen (ammonia-N + organic-N)

The above research documented immediate  $N_2O$  losses during composting, but this is not the complete picture. Additional  $N_2O$  generation is possible from the reactive nitrogen frequently lost during composting, and from the reactive nitrogen contained in finished compost. Nitrogen losses in the form of ammonia occur during composting when C:N ratios are below 20:1 and “the available carbon is fully utilized without stabilizing all of the nitrogen.” (NRAES 1992) In addition, finished compost is typically land applied as a soil conditioner, where the reactive nitrogen is free to nitrify and denitrify. As a result, actual  $N_2O$  losses may be greater than demonstrated by these studies.

For the  $N_2O$  emissions from yard waste composting to be considered a net GHG emission, it would have to be human-induced emissions. In other words, it would have to be  $N_2O$  emissions which would not have occurred naturally without human interference. There are two possibilities when this could occur: (1) yard trimmings which contain anthropogenic N fertilizer (i.e., yard waste resulting from fertilizer applications), and (2), when the human-induced accelerated composting process increases the emission of  $N_2O$  over and above the rotting/decomposition of organic waste which would otherwise occur in nature. While it is a simple concept that any  $N_2O$  emission from anthropogenic



reactive N should be considered a GHG emission, it is difficult in reality, to differentiate between natural and anthropogenic yard waste nitrogen. It is even more complicated to assess the second possibility. In fact, this author has been unsuccessful in finding any scientific research on either of these issues. As a result of these complexities, two assumptions are used in this report: that only 50% of yard waste nitrogen is anthropogenic and that composting does not impact N<sub>2</sub>O emissions which would otherwise occur in nature. By making these assumptions, this research states that only half of the N<sub>2</sub>O emissions resulting from the composting of yard waste can be considered as anthropogenic GHG emissions.

The IPCC methodology does not yet consider composting as a N<sub>2</sub>O source; agriculture is the main human-induced source and wastewater treatment is indirectly considered because of the anthropogenic fertilizer component of wastewater. However, it is likely that composting will be included in the future.

### 2.5.5.3 Incineration

Limited research has demonstrated that emissions of nitrous oxide occur during the incineration of municipal solid waste and wastewater sludge. This research was compiled by de Soete (1993) for an IPCC Workshop and is adapted for use in Table 2-5:

Table 2-5: Review of Nitrous Oxide Emissions from Incineration

Waste - Facility	Temperature (°C)	N <sub>2</sub> O Emission (g N <sub>2</sub> O/tonne waste)	Researcher*
Municipal refuse – Stepgrate	780-880	11-43	Yasuda et al. (1992)
Municipal refuse – Stepgrate	780-980	40-220	Yasuda et al. (1992)
Municipal refuse – Fluidized Bed	830-850	14-123	Yasuda et al. (1992)
MSW – 5 stokers (20-400 tpd)	not given	26-270	Watanabe et al. (1992)
MSW – 3 fluidized bed	not given	97-293	Watanabe et al. (1992)
MSW – rot. kiln (120 tpd)	not given	35-165	Watanabe et al. (1992)
Wastewater sludge – rotary grate	750	227	Yasuda et al. (1992)
Wastewater sludge – fluidized bed	770-812	580-1528	Yasuda et al. (1992)
Wastewater sludge – rotary grate	838-854	684-1508	Yasuda et al. (1992)
Wastewater sludge – rotary grate	834-844	275-886	Yasuda et al. (1992)
Wastewater sludge – rotary grate	853-887	101-307	Yasuda et al. (1992)

\* As quoted in de Soete (1993) – unable to acquire primary reference

The data presented in Table 2-4 demonstrate the limited and highly variable research on the N<sub>2</sub>O emissions resulting from waste incineration. Examples of emission estimates for municipal solid waste incineration which are being used are as follows (Environment Canada 1997a; USEPA 1999; USEPA 1998):

- Environment Canada National Inventory 160 g N<sub>2</sub>O/tonne waste incinerated
- U.S. EPA National Inventory 30 g N<sub>2</sub>O/tonne waste incinerated
- U.S. EPA MSW Analysis 130 g N<sub>2</sub>O/tonne waste incinerated

Though the research is uncertain, the data in Table 2-4 suggest three key points:

1. both the combustion of solid waste and sludge result in the formation of  $\text{N}_2\text{O}$ ,
2. wastewater sludge combustion, which generally has a higher N content than MSW, may result in greater  $\text{N}_2\text{O}$  emissions, and
3. increasing the combustion temperature during sludge incineration may decrease  $\text{N}_2\text{O}$  formation.

Both solid waste and wastewater sludge incineration have been demonstrated to result in the thermal formation of nitrous oxide. While the emissions from MSW incineration range between 11 and 293 g of  $\text{N}_2\text{O}$ /tonne of waste, the emissions from wastewater sludge incineration range from 101 to 1528 g of  $\text{N}_2\text{O}$ /tonne of waste. This may be an indication that sludge, which generally has a higher N content than MSW, may result in greater  $\text{N}_2\text{O}$  formation and therefore emissions. Is thermal  $\text{N}_2\text{O}$  formation a function of nitrogen content? Research has also demonstrated  $\text{N}_2\text{O}$  formation during the fluidized-bed combustion of coal, and two excellent review papers on this subject are Johnsson (1994) and Wojtowicz et al. (1994). This is important, because  $\text{N}_2\text{O}$  formation during coal combustion has been found to "originate mainly from the nitrogen present in the carbonaceous fuel (fuel-N) (Wojtowicz et al. 1994)." Also, recent research on MSW incineration has found a correlation between  $\text{N}_2\text{O}$  formation and the N content of wastes incinerated (Tanikawa et al. 1995). In addition, experiments with the incineration of sewage sludges and various coals found that the sludges yielded higher  $\text{N}_2\text{O}$  emissions, and it was concluded that this was due to the higher nitrogen contents offering a greater potential for  $\text{N}_2\text{O}$  formation. Therefore, the formation of  $\text{N}_2\text{O}$  may likely be the conversion of part of the reactive nitrogen in the combusted material to  $\text{N}_2\text{O}$  gas.

Does increasing the combustion temperature during sludge incineration cause a reduction in thermal  $\text{N}_2\text{O}$  formation? While the results of Yasuda et al. (1992) are variable, the  $\text{N}_2\text{O}$  emission was lowest, 101-307 g/tonne, when the temperature was 853-887 °C. An exception to this was the result of 227 g/tonne at a temperature of 750 °C. Clearly, the only conclusion that can be derived from these results is that future research is greatly required. However, the decrease in  $\text{N}_2\text{O}$  formation with an increased combustion temperature has been conclusively demonstrated in coal research (Wojtowicz et al. 1994; Pels et al. 1994). Unfortunately, as  $\text{N}_2\text{O}$  formation decreases, the formation of NO increases, in fact the sum of fuel nitrogen conversions "was found to be remarkably constant" over a range of temperatures. (Pels et al. 1994) Nitric oxide is also of environmental concern due to its contribution to acid rain and photochemical smog. In contrast, the study by Tanikawa et al (1995) was unable to find a correlation between  $\text{N}_2\text{O}$  emission and temperature during MSW incineration, while sludge incineration experiments by Werther et al (1994) found that increasing the freeboard temperature lead to a decrease in  $\text{N}_2\text{O}$  without a consequent increasing of  $\text{NO}_x$  emissions. It is important to remember that  $\text{NO}_x$  is a future source of  $\text{N}_2\text{O}$  emissions; this reactive nitrogen is short-lived in the lower atmosphere and is returned to terrestrial ecosystems in the form of  $\text{HNO}_3$  and  $\text{NO}_3$  where it is then available for denitrification. Could solid waste and sludge incineration provide an effective means of performing clean denitrification? If the potential exists, the consequent increases in  $\text{NO}_x$  emissions must be contended with.

### 2.5.6 Summary

When nitrogen leaves farms as food products leave the farm it switches responsibility; no longer is it the responsibility of agriculture, the waste management community and municipalities take over. In addition, the nitrogen in yard wastes is assumed in this study to be partially anthropogenic in origin, and are therefore in excess of natural processes. Therefore, any immediate or future nitrous oxide emissions during landfilling, composting or incineration of these wastes must be considered as anthropogenic interference of the global  $N_2O$  cycle.

## 2.6 RECYCLING ANALYSIS

The collection, processing and subsequent marketing of recyclable materials in the GVRD is an inherently complicated system. Several brokers exist and compete for market share throughout the various municipalities. Some municipalities provide their own curbside collection of blue-boxes while others have contracted this collection out to private industry. Blue-box recycling, either at single- or multi-family residences, may be managed by municipal crews, one company or a number of companies. The collection of recyclables at commercial buildings are typically managed by a number of different firms. Increasing the complication, once the recyclables are at the brokers, these materials are processed and marketed to a myriad of potential factories or mills for reuse into new products.

The recycling of paper products illustrates this complexity. Once collected by one of the several methods, paper products can be shipped to mills across North America, and increasingly, recycled paper is shipped overseas to Asia. Similar systems are in place for other recyclable materials. In fact, the destinations of the collected recyclables rapidly change in response to the fluctuating markets for these materials. Brokers, as private enterprises, endeavour to maximize their revenues while concurrently minimizing the expenses incurred as a result of the necessary transportation. Recyclables collected in the GVRD could be delivered to the factories or mills in the region (or within British Columbia) which are designed to handle these materials but recycled paper could also be sent to the Eastern United States. Conversely, recycled paper is imported into Canada from cities in the U.S. to supply the local Newstech Recycling facility (Pers. comm. Pat Martin). This material is transported a great distance; likely requiring a substantial energy outlay and generating greenhouse gas emissions from transportation and handling requirements.

Collaboration with GVRD representatives identified early on in this project that it would be necessary to simplify the complicated and rapidly changing recycling system. Rather than assess the plethora of potential fates for recyclables, it was deemed appropriate to simplify the system by assuming a single recycling facility depot and a single final destination for each type of recyclable. However, this research is performed to assess this pathway in the greater industry context. Concurrent to this, an investigation is also conducted on the ramifications of manufacturing an equivalent product using virgin materials. This research is necessary to ascertain the greenhouse gas benefits or liabilities

of recycled vs. virgin manufacturing. The analysis of manufacturing using virgin or recycled materials is ceased when the convergence point (as discussed in Section 1.3.4) is reached. This investigation is not concerned with the GHG emissions by industry, only the differences between material choices as a result of the available recyclables supply. It is unnecessary in many cases to follow the steps all the way to finished product. This research is presented in the following sub-sections.

The following sections provide a review and analysis of the six recyclable materials investigated in this thesis: newsprint, office paper, ferrous metal, glass and high- and low-density polyethylene. These sub-sections, 2.6.1 to 2.6.6, are provided in a manner different than the rest of *Chapter 2 – Methodology* and requires explanation. The entire recycling analysis is provided here and is not expanded any further in the appendices. This is in contrast to all of the other issues investigated in this thesis where a general overview is presented in Chapter 2 - *Methodology* while the fine details are developed in the appropriate appendix. The investigation of manufacturing and recycling warrants this difference as the literature review and assessment of the local situation are closely tied together. The author believes that when the information is laid out in this manner it is most logical and effective .

### **2.6.1 Newsprint**

Newsprint largely consists of mechanical pulp with a small percentage of full chemical pulp to increase strength (Biermann 1996). This analysis will concentrate on the mechanical pulp component. Mechanical pulp is produced by using only mechanical attrition to pulp the lignocellulosic materials (only water and steam are used – as opposed to chemical pulping which typically uses sodium hydroxide and sodium sulfide) (ibid). Since lignin is retained in the pulp, high yields between 90 and 98% (of the original fibre from the wood chips) are typically achieved (ibid). Mechanical pulp represented 46% of total pulp production in Canada in 1997 (PAPRICAN 1999). While there are two main methods to produce mechanical pulp, stone groundwood (SGW) and thermomechanical pulp (TMP), TMP is responsible for about 85% of the mechanical pulp made in North America (ibid) and it is this process which is reviewed in this section. In the TMP process, “preheated wood chips are fed into the narrow gap formed between a stationary and a rotating patterned disc, or between two counter-rotating patterned discs... By this means, the fibres are gradually separated from each other as the wood material progresses to the discs’ peripheries and the pulp so produced is blown to a cyclone...” (ibid).

As with any manufacturing process, energy is required and greenhouse gas emissions can result when newsprint is produced from wood chips. This can occur whether woodchips (virgin materials) or old newspapers (recycled materials) are used in manufacturing. However, does the substitution of recycled materials for virgin materials reduce this energy consumption and affect GHG emissions? To answer this question, the full GHG emissions resulting from both processes must be known. The acquisition of virgin raw materials and their manufacture into products must be directly compared to the acquisition of recycled materials and their manufacture into equivalent products. Any difference in these total emissions will be the GHG implications of virgin *versus* recycled manufacturing. Valuable to these emission calculations are the questions of what

proportion of energy is derived from fossil energy and what proportion comes from neutral bioenergy. As an industrial sector, pulp and paper is the largest consumer of energy in Canada – using 26% of the total industrial energy demand. However, pulp and paper only derives 44% of its energy needs from fossil fuel energy sources; the remainder is derived from wood waste. This breakdown is critically important to the discussion in this section.

In assessing these issues, a review of available research (2.6.1.1) and an investigation of our local situation (2.6.1.2) is presented. For those unfamiliar with the pulp and paper industry, this review attempts to report all masses in air dry metric tonnes (adt) with an assumed moisture content of 8%.

#### 2.6.1.1 Literature Review

A survey of available literature has located several studies by various organizations:

- United States Environmental Protection Agency (USEPA 1998),
- Franklin Associates Ltd. (FAL 1994),
- Tellus Institute (Tellus 1994),
- University of London (Leach et al. 1997),
- International Institute for Applied Systems Analysis (Virtanen and Nilsson 1992),
- Institute for Papermaking, Germany (Hamm and Gottsching 1993),
- University of Edinburgh (Collins 1998; 1996),
- British Newsprint Manufacturer's Association (BNMA 1995), and
- Aylesford Newsprint, United Kingdom (Aylesford 1998).

In addition to this literature, this author also searched extensively on the Voluntary Challenge and Registry (VCR) website of the Federal Government. This organization was initially established in 1995 by Natural Resources Canada as part of Canada's National Action Program on Climate Change. The VCR's purpose is to encourage private and public sector organizations to voluntarily limit their net greenhouse gas emissions. As of July 28, 2000, there are submissions by 28 pulp and paper organizations. The progress reports by four of these organizations were found to be of particular relevance to this work and will also be discussed in this section.

It appears that, of this research, the work by the two consulting firms, Franklin Associates Ltd. (FAL 1994) and the Tellus Institute (Tellus 1994), are the most extensive investigations. As a result of their demonstrated expertise, these two companies were contracted by the United States Environmental Protection Agency to perform a further analysis (USEPA 1998). Thus, the recent USEPA report is a collaborative effort of these two organizations and results in valuable improvements over the previous work published individually by these two. This review will only present the most recent work, that which is provided in the USEPA report.

Both firms analyzed wood chip acquisition and manufacture into virgin newsprint in the U.S. to determine an average expected emission for each tonne of virgin newsprint manufactured. FAL calculated this emission to be 2.18 tCO<sub>2</sub>e per tonne newsprint and Tellus calculated 2.22 tCO<sub>2</sub>e per tonne newsprint. These two estimates are subsequently averaged for further development in the USEPA report. These estimates include the

emissions from on-site energy consumption, off-site emissions from power generation for the electricity used at the mill and emissions at a chemical factory for any additives (herein defined as process energy). These estimates also include the transportation-related emission of the raw materials (herein defined as transportation energy). It was found that the process energy was of much greater importance than the transportation energy necessary for raw material acquisition. FAL and Tellus estimated that 96 and 98% of the emissions resulted from process energy consumption, respectively, with the remainder being transportation-related. The FAL process energy emissions resulted from the consumption of 39.5 GJ per tonne newsprint; 58% came from electricity (predominantly coal generation in the U.S.), 33% resulted from natural gas and 6.5% from biomass. The Tellus process energy emissions originated from 39.5 GJ/tonne but a similar breakdown is not provided (steam is listed as a fuel source but it is not stipulated what fueled the necessary boiler).

Both these firms also assessed the GHG ramifications of recycling old newsprint into equivalent new products. They estimated the energy expended during the acquisition of recycled newsprint and the process energy expended during the manufacturing. It was assumed that 100% recycled inputs were used. FAL determined that 1.58 tCO<sub>2</sub>e/tonne newsprint and Tellus calculated 1.54 tCO<sub>2</sub>e/tonne newsprint. These estimates were also averaged for further development in the USEPA report. As with woodchips, the process emissions dominated over the transportation emissions; process energy was 95 and 89% of the total emissions for FAL and Tellus, respectively. FAL estimated that 26.7 GJ of process energy is expended per tonne of newsprint manufacture (60% from electricity and 39% from natural gas). Tellus estimated that 21.5 GJ of process energy was necessary to manufacture a tonne of newsprint, and once again a similar breakdown was not provided. Both of the total energy estimates for recycled production are significantly lower than those for virgin production.

It appears that the most important issues concerning these estimates are: (1) the total process energy required, and (2) what type of energy is used. Electricity, which is generated primarily from coal in the U.S. (56% of national electricity generation; USEPA (1998)), and natural gas, were the most important energy sources observed in both virgin and recycled manufacturing. FAL identified only a small fraction of energy, 6.5%, from biomass (invariably wood waste) during virgin newsprint production. While biomass energy is GHG neutral (zero emission), this relatively small fraction does not allow for much impact on the total GHG emissions.

A recent report by the Pulp & Paper Research Institute of Canada (PAPRICAN 1999) provides energy data that can compare virgin production against recycled production but does not calculate any GHG emissions. The typical energy requirement for the TMP process is between the range of 1600 and 3000 kWh/bone dry tonne (bdt) of mechanical pulp. Assuming the moisture content of an air dry tonne (adt) to be 8%, these values can be converted to a range between 5.3 and 9.9 GJ/adt. These can be compared with the reported gross energy consumption of a newsprint deinking facility of 820 kWh per adt of pulp (600 kWh/adt of electrical power and 220 kWh/adt of process steam) or 3.0 GJ/adt. This results in an energy difference of between 2.3 and 6.9 GJ/adt for the direct

comparison of TMP and deinked pulp. From the perspective of newsprint papermaking, there is no difference between deinked pulp and virgin mechanical pulp from the TMP process. By including the typical energy for newsprint papermaking, a range between 4.6 to 7.7 GJ/adt (3.4 to 5.5 GJ/adt of process steam and 1.2 to 2.3 GJ/adt of electrical power; same report), it is possible to calculate the overall energy requirement for making virgin or recycled newsprint. Assuming averages of the ranges above, virgin newsprint manufacture requires 13.8 GJ/adt and recycled manufacture requires 9.2 GJ/adt – a difference of 4.6 GJ/adt. These energy values are substantially lower than that reported by the USEPA. However, part of the difference may result from mill energy consumption not taking into account the energy losses realized by producing the electricity or steam to generate mill energy. Yet even assuming an energy conversion efficiency of 60%, the PAPRICAN data are still substantially lower than the 39.5 GJ/tonne reported for virgin newsprint and 21.5 to 26.7 GJ/tonne reported for recycled newsprint by the USEPA.

The remaining research available on the GHG implications of newsprint recycling is primarily concerned with comparing incineration with recycling. It appears that there is a scientific debate occurring in Europe which is questioning the validity of ever increasing recycling initiatives. Research at the University of London and at the University of Edinburgh, questioning recycling, appears to have sparked “counter-research” by a large member of the recycling industry, Aylesford Newsprint Ltd (ANL). Not surprisingly, the research by ANL, which was conducted by the consulting firm, Ecobalance UK, came to opposite conclusions. Unfortunately, these studies do not directly compare manufacturing with virgin woodchips against manufacturing with recycled newsprint. Rather they assess recycling against incineration plus virgin newsprint production. It is not possible to separate out the recycling versus virgin production component in these studies. In addition, most of these studies are not specific to newsprint but instead, analyze wastepaper as an entity. Nevertheless, the findings of this research are reviewed here.

Matthew Leach at the University of London performed a systems analysis of virgin and recycled wastepaper as resources flowing in and out of cities (Leach et al. 1997). They found that even when including the virgin paper production, the environmental impact of incineration for energy was lower than that of recycling. Or in other words, the energy generation of paper incineration more than offsets the energy benefit which would have been realized by using recycled paper instead of woodchips to produce new paper. The research recognizes that modern pulp & paper mills obtain most of their energy requirements from wood waste; discarded parts of the tree such as bark. In contrast, the re-pulping of wastepaper into new paper products uses energy which must usually come from fossil fuel sources. As stated in a review of this research by Pearce (1997), Leach reckoned that “in terms of fossil energy used to supply a tonne of paper in the United Kingdom, virgin paper accounts for roughly half as much energy as recycled paper.”

Researchers at the International Institute for Applied Systems Analysis in Austria (IIASA 1992) analyzed this issue using three scenarios: (1) maximum recycling of wastepaper (90% collection), (2) selective use of recycled fiber with consequent virgin production

and (3) zero recycling – 100% incineration with energy recovery – and also the consequent virgin production. Only the maximum and zero-recycling scenarios are discussed here in the interest of simplicity. The overall energy demand is 25% greater for zero recycling than maximum recycling. However, about 80% of the total energy is derived from GHG-neutral wood waste in the zero recycling case, compared with only 45% in the maximum recycling scenario. In fact, the fossil fuel demand is about 100% larger in the maximum recycling scenario. This paper is also comprehensively reviewed in Cockram (1994).

The study by the Institute for Papermaking (Hamm and Gottsching 1993) in Germany, used a slightly different tack and modelled the impact of using wastepaper not as a fibre source for new paper production but as an energy source for new paper production. Their estimated possibility of substituting part of the fossil energy used in papermaking could potentially reduce fossil fuel use by 65% (as compared with present practices). However, the authors state that 70% of this wastepaper would have to be imported to satisfy demand; this point raises strong questions of the results.

Lyndhurst Collins, at the University of Edinburgh, has published two discussion papers questioning the interest in recycling when the alternative, for much of the United Kingdom, is waste incineration with energy recovery (Collins 1998; 1996). These papers, while very informative, do not provide the results of any studies. Rather, they review other work and discuss the current scientific & political understanding. Of note, is the review of an independent study conducted by the British Newsprint Manufacturer's Association (BNMA 1995), which this author has not been able to acquire. The BNMA study concluded, as quoted by Collins (1996), "there seems to be no clear winner in the comparison between recycling and incineration. With better technology and higher ratios, the case for recycling improves".

In contrast to the findings by all these European organizations, are the results of the study published by Aylesford Newsprint Limited (ANL) which was prepared by the independent consulting firm, Ecobalance UK (Aylesford 1998). This investigation compared the recycling of old newsprint at the ANL facility against incineration with energy recovery. The incineration scenario also includes the alternative newsprint production which is necessary. This 'alternative' source is assumed to be a mix of mills from the UK and abroad who could satisfy the customers of ANL in ANL's absence. Many possible environmental impacts are assessed in addition to GHG emissions, and the overall conclusion is that "Recycling of used newspapers and magazines at ANL is environmentally preferable to the incineration for energy recovery." The ANL system results in 11% less fossil fuel CO<sub>2</sub> emissions than incineration with alternative newsprint production. The incinerator scenario causes about 1.4 tCO<sub>2</sub>/tonne newsprint while ANL results in about 1.25 tCO<sub>2</sub>/per tonne. In addition, when including methane and nitrous oxide, ANL is estimated to have 15% less impact on the Greenhouse Effect than incineration.

Due to the scarcity of data on the issue of virgin *versus* recycled manufacture it is necessary to assess our local situation. Furthermore, the relatively close proximity of the



GVRD to a number of pulp & paper mills and an available forest resource, likely results in important differences with the U.S. research. In addition, British Columbia's predominant use of hydroelectric facilities for power generation has significant GHG implications when compared with the largely coal-fired electricity generation in the U.S. The next sub-section presents data that were obtained from several pulp and paper operations in the region to estimate emissions.

#### 2.6.1.2 Local Situation

Several organizations were contacted for this research. However, only three facilities provided data for this research. These include (along with their activity in brackets):

- Howe Sound Pulp & Paper (wood chips → virgin newsprint)
- Newstech Recycling (old newsprint → de-inked newsprint pulp)
- Pacifica Papers (wood pulp + de-inked pulp → newsprint with recycled content)

As a result of discussions with those contacted, an important factor has been recognized; a point missed by much of the research previously reviewed. This is the inherent variability of the pulp & paper industry resulting from the fact that there is no such thing as a typical pulp mill or a typical paper mill. Many TMP mills use sawdust, wood shavings and bark as a source of energy in power boilers. With sawmills in close proximity, there are readily available sources of wood waste for clean bioenergy. As a result, an integrated pulp & paper facility, a combined pulp mill and papermaking facility, will have much lower GHG emissions than a stand-alone paper mill which has to rely on externally supplied electricity and natural gas. (A stand-alone paper mill typically does not have any power boilers even if wood waste is available at nearby sawmills.) Furthermore, the integration of pulp and paper production removes the need to dry pulp for shipment (wet pulp is transported directly to paper-making machines); the drying of pulp can consume up to 40% of the energy used in a pulp mill (NCCP 1998). This author has observed that a number of pulp mills are in the process of upgrading their wood waste utilization with power boilers (to replace natural gas consumption) and/or with turbo-generators (to replace the need for external electricity). The following data collected by these facilities contacted have borne out this variability.

At Howe Sound Pulp & Paper (HSPP, operated by Canadian Forest Products), newsprint is manufactured entirely from wood chips. This is an integrated pulp & paper facility which performs both pulping and papermaking. There is no recycled paper content in this product as it is manufactured for export to Japan with the intent to provide new paper to replace losses. Canadian Forest Products has performed extensive life-cycle analyses on all of their products. Their analysis of newsprint production at HSPP was provided to this author upon personal communication with Mike Bradley, Director of Technology, Canfor Pulp and Paper Marketing. At HSPP, virgin newsprint production (production from wood chips) requires the energy utilization of 35.9 GJ per tonne newsprint. This energy results from biomass (56%), hydroelectricity (18%) and natural gas (27%). As the combustion of biomass (fines and wood waste) is bioenergy (carbon neutral) and there are no emissions from hydroelectricity, it follows that GHG emissions can only result from the combustion of natural gas. This natural gas consumption includes on-site

usage (mill) and off-site usage by BC Hydro in the generation of electricity for the mill (using the provincial average for thermal electricity generation).

The following calculations estimate the GHG emissions from this newsprint production.  
 CO<sub>2</sub> Emission from Natural Gas Combustion = 1.88 kg/m<sup>3</sup> (Environment Canada 1997a)  
 Energy of Natural Gas (typically) = 1020 BTU/ft<sup>3</sup> = 37,843 kJ/m<sup>3</sup> (Perry's 1984)  
 Energy Fraction from Natural Gas = 26.7%  
 Total Energy Consumption = 35.9 GJ

$$\text{CO}_2 \text{ Emissions} = (0.267) \left( 35.9 \frac{\text{GJ}}{\text{tonne}} \right) \frac{\left( 1.88 \frac{\text{kg CO}_2}{\text{m}^3} \right) \left( 10^6 \frac{\text{kJ}}{\text{GJ}} \right)}{\left( 37,843 \frac{\text{kJ}}{\text{m}^3} \right) \left( 10^3 \frac{\text{kg}}{\text{tonne}} \right)} = 0.48 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

While the HSPP energy requirement of 35.9 GJ/tonne is similar to the value reported by the EPA of 39.5 GJ/tonne, the emission of 0.48 tCO<sub>2</sub>e/tonne, is only 21% of the USEPA estimate, 2.2 tCO<sub>2</sub>e/tonne. This low emission may be a direct result of being an integrated pulp & paper mill. In fact, in terms of all production by HSPP, GHG emissions per tonne have decreased from 1.25 tCO<sub>2</sub>e/tonne in 1990 to 0.26 tCO<sub>2</sub>e/tonne in 1997 (CANFOR 1999). This decrease in emissions is the result of "HSPP burning increased quantities of wood residue and natural gas in place of bunker "C" oil and energy efficiencies realized from a \$1.3 billion mill modernization and expansion". Furthermore, the electricity requirements of the mills in the USEPA study were largely provided by fossil fuel combustion, whereas BC Hydro is largely hydroelectric. It needs to be mentioned that this estimate of 0.48 tCO<sub>2</sub>e/tonne does not include the harvesting and transportation of wood chips to the mill for processing while the USEPA study included this transportation. The USEPA study estimated the transportation emissions at 0.06 tCO<sub>2</sub>e/tonne, therefore it is likely appropriate to add this to the HSPP emissions. This results in a total of 0.54 tCO<sub>2</sub>e/tonne. While this estimate does not include any emission associated with the production of chemicals consumed, there is only minimal a chemical requirement for mechanical pulping, so this potential is likely negligible.

Abitibi-Consolidated Inc. submitted an extensive progress report to the Voluntary Challenge & Registry and their two Newfoundland mills, Grand Falls and Stephenville, provide valuable data to this review. Both of the mills are integrated pulp & paper operations turning wood chips into newsprint with very low recycled content (Pers. comm. Michael Innes). In 1997, the energy consumed at Grand Falls was 18.8 GJ/tonne newsprint and was 20.8 GJ/tonne at Stephenville. The GHG emissions are reported as 0.326 tCO<sub>2</sub>e/tonne newsprint for Grand Falls and as 0.548 tCO<sub>2</sub>e/tonne for Stephenville (Abitibi-Consolidated 1999). These emission factors do not include purchased electricity from the Newfoundland utility. However, electricity in Newfoundland is largely hydroelectric (with some thermal generation); it has an emission average of 190 tCO<sub>2</sub>e/GWh – less than half of a low-efficiency natural gas generation (500 tCO<sub>2</sub>e/GWh, Pers. comm. John Duffy). This report estimates the indirect GHG emissions from purchased electricity as 67,823 tCO<sub>2</sub>e. By assuming equal consumption by each facility, dividing by the annual production of 212,000 tonnes at Grand Falls and 181,000 tonnes at Stephenville, an indirect emission factor of 0.173 tCO<sub>2</sub>e/tonne newsprint results. When added to the direct emissions reported above, an overall emission factor of 0.499 tCO<sub>2</sub>e/tonne newsprint for Grand Falls and as 0.721 tCO<sub>2</sub>e/tonne for Stephenville is

estimated. The emission by the Grand Falls mill is on par with that reported by HSPB and the Stephenville mill is 50% higher.

Against virgin production can be compared the production using old newsprint. Newstech Recycling is a de-inking pulp mill which supplies recycled fibre to Pacifica Papers, a stand-alone paper mill, in addition to others. Data has been obtained from both these organizations to assess GHG emissions. Newstech produces de-inked pulp from old newspapers, old magazines and telephone directories which are purchased throughout western Canada and the U.S. mid-west. In 1999, 168,000 tonnes of old newsprint was converted into 141,000 tonnes of de-inked newsprint pulp. This required the consumption of 220 MWh of electricity each day for 350 days of the year, 143,489 GJ of natural gas and 8,321 GJ of landfill gas (Pers. comm. Pat Martin). While the landfill gas is GHG neutral, the emissions from the other sources of energy are assessed below:

Electricity Consumption = 220 MWh each day for 350 days of the year = 277,200 GJ

[220 MW=220 MJ/s \* h/d \* 3600 s/h \* 350 d/yr 1GJ/1000MJ= 277,200 GJ]

BC Hydro provincial emission average = 30 tCO<sub>2</sub>e/GWh = 0.00833 tCO<sub>2</sub>e/GJ

[30 tCO<sub>2</sub>e/GWh \* (1/3600 GWh/GJ)=0.00833 tCO<sub>2</sub>e/GJ] (BC Hydro 1998)

Natural Gas Consumption = 143,489 GJ

CO<sub>2</sub> Emission from Natural Gas Combustion = 1.88 kg/m<sup>3</sup> (Environment Canada 1997a)

Energy of Natural Gas (typically) = 1020 BTU/ft<sup>3</sup> = 37,843 kJ/m<sup>3</sup> (Perry's 1984)

Mass of old newsprint processed = 168,000 tonnes

Mass of newsprint pulp produced = 141,000 tonnes

Conversion Efficiency =  $\frac{\text{Mass of Newsprint Pulp Produced}}{\text{Mass of Old Newsprint}} = \frac{141,000}{168,000} \cdot 100 = 84\%$

Electricity Emissions =  $\frac{(277,200 \text{ GJ}) \left( 0.00833 \frac{\text{tCO}_2\text{e}}{\text{GJ}} \right)}{(168,000 \text{ tonnes})} = 0.014 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$

Natural Gas Emissions =  $\frac{(143,489 \text{ GJ}) \left( 1.88 \frac{\text{kgCO}_2}{\text{m}^3} \right) \left( 10^6 \frac{\text{kJ}}{\text{GJ}} \right)}{(168,000 \text{ tonnes}) \left( 37,843 \frac{\text{kJ}}{\text{m}^3} \right) \left( 10^3 \frac{\text{kg}}{\text{tonne}} \right)} = 0.042 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$

Total Emissions = Electricity + Natural Gas = 0.014 + 0.042 = 0.068 tCO<sub>2</sub>e/tonne

For discussion purposes :

Electricity per pulp produced =  $\frac{(277,200 \text{ GJ})}{(141,000 \text{ tonnes})} \cdot \frac{10^6 \text{ kWh}}{3600 \text{ GJ}} = 546 \text{ kWh/adt}$

NG & Methane per pulp produced =  $\frac{(143,489 + 8321 \text{ GJ})}{(141,000 \text{ tonnes})} \cdot \frac{10^6 \text{ kWh}}{3600 \text{ GJ}} = 297 \text{ kWh/adt}$

Total Energy Consumption = 3.0 GJ/adt = 843 kWh/adt

Total emission by the Newstech facility is estimated at 0.372 tCO<sub>2</sub>e per tonne of old newsprint processed. Newsprint is processed with a conversion efficiency of 84%, for each tonne of old newsprint brought in, it can be expected that 840 kg of de-inked pulp will result. There was also the utilization of six chemicals but only three of these were used in an appreciable amount: sodium hydroxide to swell the fibers (14 kg/tonne), hydrogen peroxide as bleach to brighten the pulp (20 kg/tonne) and sodium silicate to buffer the peroxide (21 kg/tonne). Tellus (1994) has estimated the energy consumed in

producing sodium hydroxide at 32.5 MJ/tonne. Even if all this energy was provided by natural gas, it only results in a miniscule GHG emission of 0.023 kgCO<sub>2</sub>e/tonne newsprint. As a result, this report assumes that emissions from these chemicals are negligible. It is important to observe that the electricity consumption, 546 kWh/adt, and the natural gas and landfill methane consumption, 297 kWh/adt, at Newstech is on par with the values reported in the previously reviewed PAPRICAN (1999) report. This report provides typical de-inking mill data as 820 kWh per adt of pulp (600 kWh/adt of electrical power and 220 kWh of process steam).

Data has been obtained from Pacifica Papers, in Powell River, for the subsequent conversion of the de-inked pulp to newspapers. Pacifica Papers is a stand-alone paper mill and should therefore not be utilizing wood waste as an energy source. However, this facility does combust wood waste and in early 1998 installed a new fluidized bed boiler to replace 4 natural gas-fired boilers. "This installation reduced the use of fossil fuels by 59%" (Pacifica Papers 1998). In 1999, Pacifica Papers used 59,565 tonnes of de-inked pulp (recycled), 73,710 tonnes of stone groundwood pulp (wood chips), 130,322 tonnes of chemithermal mechanical pulp (wood chips), 79,056 tonnes of kraft fiber (wood chips), 1,660 tonnes of cull rolls (rejects from mill) and 50,907 tonnes of clays and fillers to produce 410,981 tonnes of newsprint and 15,761 tonnes of sludge. This sludge makes up part of the wood waste fed to their power-boiler. This process required, in 1999, the consumption of 904,158 MWh of electricity and 2,008,376 GJ of natural gas (Pers. comm. Ray Dyer). This 343,313 tonnes of pulp is converted into newsprint with a recycled content of approximately 17%. With the calculations below, it is assumed that this energy consumption can be evenly distributed over all of the pulps used so as to estimate the emissions which would result from the manufacture of newsprint with a 100% recycled content. The calculations below are based on tonnes of pulp used.

Electricity Consumption = 904,158 MWh

BC Hydro provincial emission average = 30 tCO<sub>2</sub>e/GWh (BC Hydro 1998)

Natural Gas Consumption = 2,008,376 GJ

CO<sub>2</sub> Emission from Natural Gas Combustion = 1.88 kg/m<sup>3</sup> (Environment Canada 1997a)

Energy of Natural Gas (typically) = 1020 BTU/ft<sup>3</sup> = 37,843 kJ/m<sup>3</sup> (Perry's 1984)

Mass of de-inked pulp processed = 59,565 tonnes

Mass of pulps derived from wood chips = 284,748 tonnes

Mass of newsprint produced = 410,981 tonnes

Total Mass of Pulps = Deinked + Wood Pulp = 59,565 + 284,748 = 344,313 tonnes of pulp

$$\text{Conversion Efficiency} = \frac{\text{Mass of Newsprint Produced}}{\text{Mass of Inputs}} = \frac{410,981}{426,742} \cdot 100 = 96\%$$

$$\text{Electricity Emissions} = \frac{(904,158 \text{ MWh}) \left( 30 \frac{\text{tCO}_2\text{e}}{\text{GWh}} \right)}{(344,313 \text{ tonnes}) \left( 1000 \frac{\text{MWh}}{\text{GWh}} \right)} = 0.079 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\text{Natural Gas Emissions} = \frac{(2,008,376 \text{ GJ}) \left( 1.88 \frac{\text{kgCO}_2}{\text{m}^3} \right) \left( 10^6 \frac{\text{kJ}}{\text{GJ}} \right)}{(344,313 \text{ tonnes}) \left( 37,843 \frac{\text{kJ}}{\text{m}^3} \right) \left( 10^3 \frac{\text{kg}}{\text{tonne}} \right)} = 0.290 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\text{Total Emissions} = \text{Electricity} + \text{Natural Gas} = 0.079 + 0.290 = 0.369 \frac{\text{tCO}_2\text{e}}{\text{tonne pulp}}$$

The calculations above estimate that 0.369 tCO<sub>2</sub>e are emitted per tonne of pulp used in newsprint production at Pacifica Papers. There is also a conversion efficiency of 96%; 1 tonne of pulp (together with the appropriate quantities of clay and fillers) will typically produce 960 kg of newsprint. Similar to Newstech, there is also the consumption of several chemicals. The greatest usage, 3,441 tonnes annually, is sodium hydroxide. When this is distributed over the total pulp used for paper-making, the result is 10 kg per tonne. As it was previously estimated that the consumption of 14 kg of sodium hydroxide at Newstech results in a miniscule emission of 0.023 kgCO<sub>2</sub>e during its production, the chemicals at Pacifica are also safely ignored here.

By assuming that all of the sources of pulp at Pacifica require the same energy requirement in paper-making, it is possible to estimate the emissions to be expected from producing a tonne of newsprint. It has been estimated that one tonne of old newsprint delivered to Newstech Recycling will be converted into 840 kg of de-inked pulp with an emission of 0.068 tCO<sub>2</sub>e. When this 840 kg of de-inked pulp is delivered to Pacifica Papers, if assumed to be the same as the other pulp sources, it will result in 840kg\*0.96 or 806 kg of newsprint being produced. This will be at an emission rate of 0.369 tCO<sub>2</sub>e per tonne pulp used or an emission of  $0.369 \times 0.84 \text{ tonne} = 0.310 \text{ tCO}_2\text{e}$ . Added to the emissions of Newstech, an estimate of  $0.068 + 0.310 = 0.378 \text{ tCO}_2\text{e}$  to produce 806 kg of newsprint results. As a unit of one tonne of newsprint, manufacturing a 100% recycled content would result in 0.47 tCO<sub>2</sub>e. As this does not include transportation emissions, the USEPA estimate of 0.12 tCO<sub>2</sub>e/tonne can be used instead. The total for recycled newsprint production becomes 0.59 tCO<sub>2</sub>e/tonne.

While at HSPP it was estimated that a 0.54 tCO<sub>2</sub>e emission results per tonne of virgin newsprint manufactured, it has been calculated that recycled manufacture, using Newstech Recycling and Pacifica Papers, results in a slightly larger GHG emission, 0.59 tCO<sub>2</sub>e per tonne of newsprint with a 100% recycled content.

Another possibility for recycling old newsprint is to have the de-inking facility inside an integrated pulp & paper mill. This is the situation at Pine Falls Paper Company in Pine Falls, Manitoba. This mill produces 170,000 tonnes of newsprint annually with a recycled content of 22%. Pulp for the newsprint is produced from woodchips (groundwood and sulfite), deink (old magazines and newspapers) and purchased kraft (PFPC 1999; Pers. comm. Brian Kotak). The recycled content results from the de-inking processes on-site. Including the indirect GHG emissions from purchased electricity, this organization's progress report submission to the VCR estimates that 0.80 tCO<sub>2</sub>e is emitted per tonne of newsprint produced. Much of this emission results from the combustion of coal as there is no natural gas available. However, new wood waste and biosolids incinerators in mid-2001 will increase on-site energy generation and reduce coal consumption by over 50%. This emission factor is higher than both HSPP and Newstech/Pacifica but will greatly decrease in the future.

There are best-case and worst-case scenarios possible for virgin and recycled production which can be discussed in the context of the above data. An integrated pulp & paper

facility could bring in large quantities of wood waste and become energy self-sufficient to produce virgin newsprint. This facility also has the advantage of not having to dry the market pulp for shipment. Little GHG emissions would result in this "best" scenario. The worst-case scenario for virgin production would be a stand-alone pulp mill providing mechanical pulp to a stand-alone paper mill with the pulp mill only supplying part of its own energy needs and the paper mill relying exclusively on fossil energy. In Canada, this scenario could occur with both mills situated in Alberta where purchased electricity is provided by coal combustion at thermal power plants. This second scenario would result in very high GHG emissions. Howe Sound Pulp & Paper is in between these scenarios but lies closer to the former. On the recycled side, two similar scenarios are also possible. A de-inking facility could be integrated with a pulp and paper facility where large quantities of bioenergy are available. In this scenario, minimal GHG emissions could result. The worst-case scenario would be a stand-alone de-inking facility paired with a stand-alone paper mill with both operations relying exclusively on fossil energy. Once again, this would result in very high GHG emissions per unit of production and could occur if both operation's relocated to Alberta. While the Newstech plant relies on external energy, the electricity is largely zero emission hydroelectric power, and the Pacifica Paper mill supplies part of its operation with bioenergy. The Newstech/Pacifica Papers data analyzed lie in between these two extremes. What if these operations did exist in Alberta? By changing the BC provincial average GHG emission intensity for electricity generation from the current 30 tCO<sub>2</sub>e/GWh (BC Hydro 1998), to the Alberta average, (this author cannot locate the emission average for Alberta – will use the Canada's average for fossil-generated electricity 880 tCO<sub>2</sub>e/GWh (Environment Canada 1999)), the production of recycled newsprint would result in 3.3 tCO<sub>2</sub>e per tonne! This is a dramatic increase from previous estimates and even doubles the estimates developed by FAL and Tellus.

Of greater importance than whether newsprint is made from woodchips or old newspapers is whether bioenergy is utilized during production. And if external electricity is relied upon – where does this electricity come from? The literature review and discussion above has demonstrated the lack of any cut & dry certainty to these issues. While the USEPA (1998) work estimated a substantial GHG benefit for recycling newsprint, it appears they largely neglected the variability existing within the pulp & paper industry. All assumptions are inherently inaccurate with this industry because of this extreme variability. This author believes that the safest assumption at the present time is to assume no difference between virgin and recycled manufacture. In fact the lack of Canadian research into this issue is surprising – given the important role that pulp & paper and wastepaper recycling have today. An industry wide analysis of virgin and recycled paper production in Canada is indeed warranted.

So as to have newsprint recycling remain a zero GHG emissions activity, the curbside collection of this material and any other transportation will not be accounted for. This allows newsprint recycling to exactly break even with the alternative virgin production and to allow a zero impact in the Model.

### 2.6.2 Office Paper

Office paper or fine paper (its name in the pulp & paper field) is typically made from bleached kraft or sulfite softwood pulps (Biermann 1996). Kraft mills accounted for 50% of Canada's pulp production in 1997, sulphite/semi-chemical pulps made up 4.3% and the remainder was mechanical pulp (PAPRICAN 1999). This review will concentrate on kraft pulp production. Kraft pulping is a full chemical pulping method using sodium hydroxide and sodium sulfide at high pH and elevated temperature and pressure in order to dissolve much of the lignin fibers (Biermann 1996). Largely because of the delignification which occurs to make fine paper, the yield of pulp from the initial wood chips is only about 50% (NCCP 1998). However, this loss is also interpreted as an advantage over mechanical pulping because this removed lignin can be used for bioenergy purposes. "Canadian kraft mills are typically 60 to 80% energy self-sufficient and the upper limit of self-sufficiency has not yet been achieved. With the emerging energy-efficient technologies, it is conceivable that a mill could be designed and operated so that is essentially self-sufficient (PAPRICAN 1998)." In another report, the energy self-sufficiency of kraft mills in Canada has been cited as 79% (PAPTAC 1999). Currently in Finland, kraft mills generate excess electricity which is placed in the national grid to generate revenue (ibid). In fact, "an integrated pulp and paper mill in New Brunswick now sells surplus power to NB Power..." (NCCP 1998).

The two consulting firms, Franklin Associates Ltd. (FAL 1994) and the Tellus Institute (Tellus 1994), also performed an extensive investigation of office paper recycling. Subsequent to this work, these consultants were contracted by the United States Environmental Protection Agency to perform a further analysis (USEPA 1998), and it is this recent work which is reviewed here.

Both firms analyzed wood chip acquisition and manufacture into virgin office paper in the U.S. to determine the expected emission for each tonne of virgin office paper produced. FAL calculated this emission to be 2.30 tCO<sub>2</sub>e per tonne office paper and Tellus calculated 2.14 tCO<sub>2</sub>e per tonne office paper. Both these estimates include the process energy (factory or electricity consumption) and the transportation-related emission of the raw materials. These estimates were averaged for further development in the USEPA report. It was determined that the process energy, greatly dominated over the transportation energy necessary for raw material acquisition. FAL and Tellus estimated that 91 and 94% of the emissions resulted from process energy consumption, respectively, with the remainder being transportation-related. The FAL process energy emissions resulted from the consumption of 63.7 GJ per tonne office paper; 50% came from biomass, 25% from electricity (predominantly coal generation in the U.S.), 10% directly from coal and 9% from natural gas. The Tellus process energy emissions originated from 40.8 GJ/tonne but a similar breakdown is not provided (steam is listed as providing 77% of the energy requirement but it is not stipulated what fueled the boiler).

These results can be directly compared with their assessment of utilizing recycled materials in manufacturing in a similar manner as presented in the previous section on newsprint. The consultants estimated the energy expended during the acquisition of recycled newsprint and the process energy expended during the manufacturing. It was

assumed that 100% recycled inputs were used. When this was not feasible, data were extrapolated to estimate as such. FAL determined that 2.02 tCO<sub>2</sub>e is emitted per tonne office paper and Tellus calculated 1.69 tCO<sub>2</sub>e per tonne office paper. These estimates were also averaged for further development in the USEPA report. As with woodchips, the process emissions dominated over the transportation emissions; process energy was 94 and 90% of the total emissions for FAL and Tellus, respectively. FAL estimated that 30.7 GJ of process energy is expended per tonne of office paper manufacture (the most important energy fractions are 49% from electricity and 24% from natural gas). Tellus estimated that 24.1 GJ of process energy was necessary to manufacture a tonne of office paper, but a similar breakdown was not provided. Both of the total energy estimates for recycled production are significantly lower than for virgin production.

In the previously discussed PAPRICAN (1999) report, data for kraft pulping are also provided. The typical energy requirement for a kraft mill is 17.0 GJ/adt of process steam and 3.2 GJ/adt of electrical power. Unfortunately, this 20.2 GJ/adt cannot be compared to the FAL or Tellus values, for this value does not include energy losses in generating the steam or electricity or the energy associated with producing the chemicals consumed.

A recent report by the Pulp and Paper Technical Association of Canada (PAPTAC 1999) has cited the total energy consumption of 24 Canadian kraft mills in 1996 as between 30 and 61 GJ/adt with an average of 40.4 GJ/adt. It is unclear as to why this data is twice that of the PAPRICAN report.

To obtain actual data with which to compare against the U.S. research, Weyerhaeuser and Domtar, were contacted but declined to participate in this analysis. There is no de-inking facility for office paper in Western Canada. Tony Kaptein at the Prince Albert, Saskatchewan, facility of Weyerhaeuser spent a considerable amount of time explaining to this author the inherent complications in acquiring accurate data. The Prince Albert operation is an integrated pulp and paper mill which produces a number of different pulps and paper products and it would be a fairly involved process to separate out the energy requirements. Furthermore, the mill will soon drastically change its external energy consumption with the installation of a new turbo generator in August and a new bark boiler in September. While the mill currently produces 30% of its own electricity, the new turbo generator will allow the mill to produce 80 to 100% of its own electricity. This is very important from a GHG perspective as electricity generation in Saskatchewan is largely fossil fuel based. The new bark boiler will offset natural gas consumption. In fact, the GHG emissions for the Weyerhaeuser Canada group of companies, formerly MacMillan Bloedel, is approximately 37% below its 1990 levels. Currently, 59% of Weyerhaeuser Canada's fuel energy demand is supplied by biomass fuels (Weyerhaeuser 1999).

Weldwood of Canada Ltd operates two kraft pulp mills producing bleached kraft pulp for making fine paper, one in Quesnel, B.C., and the other in Hinton, Alberta. Emissions data for these facilities are available on the VCR website (Weldwood 1999). Including the indirect emissions from using electricity in B.C. and from using electricity in Alberta, it is reported that 0.33 tCO<sub>2</sub>e resulted per tonne of kraft pulp produced at Quesnel and



0.58 tCO<sub>2</sub>e resulted per tonne of kraft pulp produced in Hinton. As this does not include chemicals consumed during the process, data from Tellus (1994) estimated an energy requirement of 2.6 GJ/tonne office paper for the manufacturing these chemicals. Assuming the energy is completely provided by natural gas, an emission of 0.13 tCO<sub>2</sub>e per tonne is estimated. Even with this indirect chemical emission added to the higher emission at Hinton, it is still less than a third of the value reported by Tellus in the USEPA (1998) report. It is unlikely that even when emissions for papermaking are included, that emissions could ever approach the estimates reported in USEPA (1998). This serves as another example of the high estimates by FAL and Tellus.

While this investigation is largely without any data with which to compare recycled and virgin production of office paper, only isolated pieces of information exist, it would appear that much of the same uncertainty that exists with newsprint also occurs with office paper. In fact, the low conversion rate of wood chips to kraft pulp, 50% largely because of the loss of lignin, adds a new complication. Whereas TMP mills frequently bring in wood waste to burn in power boilers, kraft mills produce their own wood waste without any external inputs and currently approach energy self-sufficiency of 80%. Furthermore, some kraft mills in the world, and one in New Brunswick, are actually exporting surplus energy. It appears that de-inking facilities may even have greater difficulty in competing against an energy self-sufficient kraft mill, especially if that de-inking facility is stand-alone and relies on natural gas and external electricity for its energy demands. It is important to recognize that there will be little difference between bleached kraft pulp and de-inked pulp for the papermaking operations necessary to manufacture fine (office) paper. Furthermore, an integrated kraft pulp and paper mill will also have the advantage of not having to dry its pulp for shipment – an energy savings of as much as 40% (see previous section).

The previous section finished with the safe assumption that there is no GHG benefit to newsprint production. Virgin office paper (manufactured from a nearly energy self-sufficient integrated pulp and paper facility) could even have smaller GHG emissions than production with recycled fiber. Once again, there is significant variability present within this complicated industry. While the USEPA and their consultants estimated a substantial GHG benefit for recycling office paper, it appears they largely neglected this variability. As with newsprint, the most appropriate assumption will be to assume no GHG benefit with the important caveat that research is greatly needed on this issue.

To enable office paper recycling to remain a zero GHG emissions activity, the curbside collection of this material and any other transportation will not be accounted for. This allows office paper recycling to exactly break even with the alternative virgin production and to allow a zero impact in the Model.

### 2.6.3 Ferrous Metal

Ferrous metal (steel) is a readily recyclable material and the recycling of metallic scrap back into iron and steel furnaces has long been an economically viable means of utilizing ferrous waste materials. Iron ore is the most important raw material in making steel. Coal is typically used as a source of energy with limestone ( $\text{CaCO}_3$ ) and lime ( $\text{CaO}$ ) used as fluxing agents (substances that remove impurities from the molten iron or steel). The production of virgin molten steel involves the following steps:

- extraction and processing of the necessary iron ore, coal, limestone and lime,
- blast furnace ironmaking, and
- basic oxygen furnace steelmaking.

The production of molten steel with a 100% post-consumer content requires only the electric arc furnace steel making of densified steel scrap.

These steps, particularly the extraction and processing, require a number of different organizations. The analysis of these steps by two consulting firms will be reviewed in this section.

Two consulting firms, Franklin Associates Ltd (FAL) and the Tellus Institute (Tellus), performed investigations of the GHG emission implications of virgin steel can production and the recycling of steel cans back into steel ingot while on contract with the United States Environmental Protection Agency (USEPA 1998). These organizations analyzed the raw material acquisition and manufacture of steel cans in the United States so as to compare with their analysis of the acquisition and processing of post-consumer steel cans also into containers. FAL estimated the typical emission of virgin manufacture to be 4.2  $\text{tCO}_2\text{e}$  per tonne steel can. This estimate includes both process energy and transportation energy emissions but also non-energy process emissions resulting from the release of  $\text{CO}_2$  from limestone. These emissions break down into 2.8  $\text{tCO}_2\text{e}$  per tonne steel resulting from process energy consumption, 1.0  $\text{tCO}_2\text{e}$  per tonne steel of non-energy process emissions and 0.4  $\text{tCO}_2\text{e}$  per tonne steel resulting from the transportation emissions during raw material acquisition. The process energy consumption for one tonne of steel cans is estimated at 36.6 GJ. Tellus estimated the typical emission of virgin manufacture to be 4.9  $\text{tCO}_2\text{e}$  per tonne steel can. These emissions break down into 3.8  $\text{tCO}_2\text{e}$  per tonne steel resulting from process energy consumption, 1.0  $\text{tCO}_2\text{e}$  per tonne steel of process non-energy emissions and 0.1  $\text{tCO}_2\text{e}$  per tonne steel resulting from the transportation of the post-consumer steel cans. A much reduced process energy requirement is estimated, 13.7 GJ/tonne compared to 36.6 for virgin steel. The FAL and Tellus estimates were averaged for further development in the USEPA report and are also averaged here for an estimate of 4.55  $\text{tCO}_2\text{e}$  per tonne virgin steel cans.

This estimate of virgin manufacturing can be directly compared with the assessment of utilizing post-consumer steel in manufacturing. Assuming a 100% recycled content, FAL determined the energy expended during the acquisition of recycled steel and the process energy expended during the manufacturing. It was assumed that 100% recycled inputs were used. FAL determined that 2.1  $\text{tCO}_2\text{e}$  is emitted per tonne of recycled steel utilized. These emissions break down into 0.8  $\text{tCO}_2\text{e}$  per tonne steel resulting from process energy

consumption, 1.0 tCO<sub>2</sub>e per tonne steel of process non-energy emissions and 0.3 tCO<sub>2</sub>e per tonne steel resulting from the transportation of the post-consumer steel cans. A much reduced process energy requirement is estimated, 13.7 GJ/tonne compared to 36.6 for virgin steel. Tellus determined that 2.3 tCO<sub>2</sub>e is emitted per tonne of recycled steel utilized. These emission breaks down into 1.2 tCO<sub>2</sub>e per tonne steel resulting from process energy emissions, 1.0 tCO<sub>2</sub>e per tonne steel of process non-energy emissions and 0.1 tCO<sub>2</sub>e per tonne steel resulting from the transportation of the post-consumer steel cans. A much reduced process energy requirement is estimated, 19.7 GJ/tonne compared to 48.8 for virgin steel. The FAL and Tellus estimates were averaged for further development in the USEPA report and are also averaged here for an estimate of 2.2 tCO<sub>2</sub>e per tonne recycled steel cans.

By comparing the consultants estimates of virgin versus recycled steel can production, it is possible to derive a GHG benefit of utilizing post-consumer steel. For a tonne of steel and including the necessary transportation, the difference between 4.55 tCO<sub>2</sub>e for virgin and 2.2 tCO<sub>2</sub>e for recycled is 2.35 tCO<sub>2</sub>e. This 2.35 tCO<sub>2</sub>e is the GHG benefit to be expected from recycling a tonne of steel cans rather than disposing them in a landfill and necessitating further virgin production to replace this material. While these estimates were developed for the steel used in steel cans, this is ubiquitous with steel for any purpose. To determine whether this GHG factor is appropriate for use in this investigation, the local situation has been assessed.

All recycled and scrap steel collected in the GVRD by Allied Salvage & Metal is exported to the United States (Pers. comm. George Weinstein). This is likely representative of other metal recyclers since there is no local smelter or foundry for steel. The purpose of Allied Salvage & Metal, and others, is to accumulate and process scrap steel for recycling. They wait until they have a batch of sufficient size and of appropriate quality before shipping it to a smelter or foundry in the United States.

As previously discussed, a number of different organizations participate in the production of molten steel. Due to this complexity, the opportunity to analyze the life-cycle of steel production does not presently exist. As a result, the estimates developed by the two consultants on behalf of the USEPA will be used here. Since there isn't a local steel smelter or foundry in the GVRD, and since recycled steel scrap is exported to the United States, it is also appropriate to use the recycling estimates developed by the U.S. consultants. As the transportation component of GHG emissions is included in the USEPA report, the emissions associated with the recycling of steel in the GVRD are not specifically analyzed in this thesis.

#### 2.6.4 Glass

Glass, like ferrous metal, is also a readily recyclable material. In fact, in the United States in 1991, it was estimated that cullet (waste glass) made up about 30% of the input to new manufacturing (two-thirds of the cullet is post-consumer waste and the remainder is in-house scrap) (Gaines and Mintz 1994). The energy analysis of glass recycling by Gaines and Mintz (1994) of the Energy Systems Division of the Argonne National Laboratory provides an excellent description of the manufacturing involved and the energy implications. This report is reviewed here.

Glass is manufactured from 4 main raw materials. These include sand (silica), limestone ( $\text{CaCO}_3$ ), soda ash ( $\text{Na}_2\text{CO}_3$ ), and feldspar (aluminium silicates with potassium, sodium, calcium or barium) with sand making up the bulk of the raw material input. Glass-container production includes mixing of the raw materials, melting at  $2800^\circ\text{F}$ , then forming, annealing and finishing. Melting is by far the most energy-intensive step in the process, because of the large quantities of material which must be heated to high temperatures. This energy is typically provided by natural gas and electricity. This is the step in which cullet content can influence energy consumption and greenhouse gas emissions. Cullet can aid the melting of the batch and allows operation at a lower furnace temperature; both of which contribute to reducing energy consumption. Furthermore, the substitution of recycled glass for the virgin feedstocks limestone and soda ash can prevent the release of  $\text{CO}_2$  which occurs when these materials are reacted to form glass. There is no physical barrier to the allowable recyclable content; glass containers can be manufactured with 100% cullet.

Gaines and Mintz (1994) determined the primary energy consumption of bottle manufacturing and the necessary transportation as being 19.7 GJ/tonne with no post-consumer recycling, 18.4 GJ/tonne with the 1991 recycled content (approximately 23%) and 17.2 GJ/tonne with maximum recycled content. While the total primary energy use decreases as the percent of glass recycled rises, the maximum energy saved is only about 13%. Furthermore, as the percent of recycled glass rises, cullet quality is likely to decline, leading to a higher reject rate and therefore increasing energy consumption. However, energy consumption is not necessarily the same as greenhouse gas emissions because the necessary reactions with limestone ( $\text{CaCO}_3$ ) and soda ash ( $\text{Na}_2\text{CO}_3$ ) result in the evolution of  $\text{CO}_2$  gas; carbon that was previously sequestered in geological formations. This is a non-energy related greenhouse gas emissions and this same report calculated that 0.15 tonnes of  $\text{CO}_2$  is released for each tonne of glass containers manufactured without any post-consumer content. As a result of this shortcoming, an actual GHG analysis of glass manufacture and recycling is necessary. This is the next report reviewed.

The consulting firm, Franklin Associates Ltd (FAL), performed the only GHG analysis of glass container manufacturing and recycling of which this author is aware. This was on contract with the United States Environmental Protection Agency (USEPA 1998).

This firm analyzed the raw material acquisition and manufacture of glass containers in the United States so as to compare with their analysis of the acquisition and processing of

post-consumer glass also into containers. They estimated the typical emission of virgin manufacture to be 0.65 tCO<sub>2</sub>e per tonne glass. This estimate includes both process energy and transportation energy emissions but also process non-energy emissions resulting from the release of CO<sub>2</sub> from limestone and soda ash. This estimate assumes a post-consumer content of 0%. These emission breaks down into 0.44 tCO<sub>2</sub>e per tonne glass resulting from process energy consumption (79% of which was derived from natural gas), 0.16 tCO<sub>2</sub>e per tonne glass of non-energy process emissions and 0.04 tCO<sub>2</sub>e per tonne glass resulting from the transportation emissions during raw material acquisition. As with other recyclables, transportation is of minor importance, only 6% of total emissions. Surprisingly, the energy consumption estimated by FAL, 7.7 GJ/tonne glass, is much lower than the previously discussed estimate of 19.7 GJ/tonne glass by Gaines and Mintz (1994). It is unclear why these two organizations had such differing estimates.

This estimate of virgin manufacturing can be directly compared with the assessment of utilizing post-consumer glass in manufacturing. Assuming a 100% post-consumer content, FAL estimated the energy expended during the acquisition of recycled glass and the process energy expended during the manufacturing. FAL determined that 0.28 tCO<sub>2</sub>e is emitted per tonne of recycled glass manufactured. This emission breaks down into 0.24 tCO<sub>2</sub>e per tonne glass resulting from process energy consumption (92% of which was derived from natural gas), 0 tCO<sub>2</sub>e per tonne glass of non-energy process emissions at the factory (no new limestone or soda ash is required) and 0.04 tCO<sub>2</sub>e per tonne glass resulting from the transportation of the post-consumer glass. The transportation is of increased importance in this process, comprising 14% of emissions. As with the virgin analysis, the estimate for the energy requirement, 5.1 GJ/tonne glass, is much lower than the estimate by Gaines and Mintz (1994) of 17.2 GJ/tonne glass.

By comparing the FAL analysis of virgin versus recycled glass production, it is possible to derive a GHG benefit of utilizing post-consumer glass. For a tonne of glass and including the necessary transportation, the difference between 0.65 tCO<sub>2</sub>e for virgin and 0.28 tCO<sub>2</sub>e for recycled is 0.37 tCO<sub>2</sub>e. This 0.37 tCO<sub>2</sub>e is the GHG benefit to be expected from recycling a tonne of glass rather than disposing it in a landfill and necessitating further virgin production to replace this material.

To determine whether this benefit is appropriate to this region, our local situation is also investigated. In the GVRD, post-consumer glass enters the recycled waste stream through curb-side collection, residential drop-off or various commercial recycling initiatives. This glass is processed at recycling facilities and much of it is transported to Consumers Glass in Lavington, B.C., for use as cullet in container manufacture. Valuable information has been obtained by personal communication with Donna O'Dwyer of this organization. Consumers Glass produces glass containers with a recycled content of approximately 11%. Greater post-consumer content would be preferable and readily utilized but the supply is simply not available. Depending on how much cullet is used in production, energy savings between about 3 and 15% can be realized.

Consumers Glass used 67,757 tonnes of silica sand, 18,499 tonnes of limestone, 22,447 tonnes of soda ash, 6,023 tonnes of Syenite (refined feldspar) and 13,715 tonnes of post-consumer glass in 1999 (total inputs = 128,441 tonnes) to produce 110,289 tonnes of glass containers. The difference between inputs and outputs, 18,152 tonnes, is cullet that will be used for future glass production. Cullet from previous glass manufacturing in 1998 also carried cullet forward into the 1999 production year. During 1999, 51,910 MWh of electricity and 777,980 GJ of natural gas was consumed by this organization. The following calculations calculate the GHG emissions.

Electricity Consumption = 51,910 MWh

BC Hydro provincial emission average = 30 tCO<sub>2</sub>e/GWh (BC Hydro 1998)

Natural Gas Consumption = 777,980 GJ

CO<sub>2</sub> Emission from Natural Gas Combustion = 1.88 kg/m<sup>3</sup> (Environment Canada 1997a)

Energy of Natural Gas (typically) = 1020 BTU/ft<sup>3</sup> = 37,843 kJ/m<sup>3</sup> (Perry's 1984)

Mass of container-glass produced = 110,289 tonnes

$$\text{Electricity Emissions} = \frac{(51,910 \text{ MWh}) \left( 30 \frac{\text{tCO}_2\text{e}}{\text{GWh}} \right)}{(110,289 \text{ tonnes}) \left( 1000 \frac{\text{MWh}}{\text{GWh}} \right)} = 0.014 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\text{Natural Gas Emissions} = \frac{777,980 \left( 1.88 \frac{\text{kgCO}_2}{\text{m}^3} \right) \left( 10^6 \frac{\text{kJ}}{\text{GJ}} \right)}{(110,289 \text{ tonnes}) \left( 37,843 \frac{\text{kJ}}{\text{m}^3} \right) \left( 10^3 \frac{\text{kg}}{\text{tonne}} \right)} = 0.350 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\text{Total Emissions} = \text{Electricity} + \text{Natural Gas} = 0.014 + 0.350 = 0.364 \frac{\text{tCO}_2\text{e}}{\text{tonne pulp}}$$

The emission for Consumers Glass is lower than the FAL estimate, but the emission above does not include the non-energy release of CO<sub>2</sub> from the consumption of limestone and soda ash (estimated by FAL to be 0.12 tCO<sub>2</sub>e/tonne) and does not include the energy consumption associated with the acquisition and transportation of the sand, limestone, soda ash and feldspar raw materials (not available in USEPA (1998)).

The FAL estimate is likely appropriate for use in this GVRD analysis and the 0.37 tCO<sub>2</sub>e is assumed to be the GHG benefit expected from recycling a tonne of glass in this investigation.

### 2.6.5 High-Density Polyethylene

The manufacture of high-density polyethylene (HDPE) products requires a number of steps from various different organizations. Production using virgin resins is a complicated process which includes:

- petroleum & natural gas extraction and refining,
- ethylene production via thermal cracking,
- slurry or gas phase polymerization process,
- compounding, extrusion & palletizing, and
- blow molding polyethylene products.

Production using recycled resins requires these steps:

- Collection and baling of post-consumer plastics
- Plastic resin separation and granulation
- Cleaning and drying
- Extruding and pelletizing
- Blow molding polyethylene products

The GHG emissions by these processes have been estimated by Franklin Associates Ltd. (FAL 1994) and the Tellus Institute (Tellus 1994). Subsequently, these consultants were contracted by the United States Environmental Protection Agency to perform a further analysis (USEPA 1998). It is the most recent work which is reviewed here. However, both these consultants did not include the blow molding of polyethylene products. Rather, their analysis ceased with resins (not finished products) as this was sufficient for comparison purposes; manufacturing a plastic product is not affected whether the resin used is virgin or primary in origin.

Both firms analyzed the raw material acquisition and manufacture of virgin HDPE resins in the U.S. to determine the expected emission. They estimated the emissions from energy consumption during raw material acquisition and subsequent processing (process energy) and the transportation-related emissions of the raw materials (transportation energy). FAL also identified process non-energy emission during the life-cycle but it is not stated how these emissions occur. FAL estimated the total of these emissions to be 2.3 tCO<sub>2</sub>e/tonne HDPE with a breakdown of 2.0 tCO<sub>2</sub>e per tonne HDPE from process energy, 0.2 tCO<sub>2</sub>e per tonne HDPE of process non-energy emissions and 0.1 tCO<sub>2</sub>e per tonne HDPE from the transportation energy. As with other recyclables, transportation is of minor importance, only 4% of emissions. Tellus estimated the total of these emissions to be 3.4 tCO<sub>2</sub>e/tonne HDPE with a breakdown of 2.9 tCO<sub>2</sub>e per tonne HDPE of process emissions, 0.2 tCO<sub>2</sub>e per tonne HDPE of process non-energy emissions and 0.3 tCO<sub>2</sub>e per tonne HDPE of transportation emissions. As with the FAL assessment, transportation is of minor importance, only 9% of emissions. The average of the FAL and Tellus estimates is 2.85 tCO<sub>2</sub>e/tonne HDPE.

These consultants also investigated the emissions from the alternative realization of recycled HDPE resins. This is the same end product as the previous estimate and can be directly compared. Their investigation included process energy and non-energy emissions resulting from the washing and processing of post-consumer HDPE materials to generate recycled resins and transportation energy consumed during the acquisition of this post-consumer HDPE. FAL estimated the total of these emissions to be 1.0 tCO<sub>2</sub>e/tonne HDPE with a breakdown of 0.85 tCO<sub>2</sub>e per tonne HDPE from process energy and 0.16 tCO<sub>2</sub>e per tonne HDPE from the transportation energy. Tellus estimated the total of these emissions to be 1.3 tCO<sub>2</sub>e/tonne HDPE with a breakdown of 1.2 tCO<sub>2</sub>e per tonne HDPE of process emissions and 0.1 tCO<sub>2</sub>e per tonne HDPE of transportation emissions. The average of the FAL and Tellus estimates is 1.15 tCO<sub>2</sub>e/tonne HDPE.

By comparing the estimates of virgin versus recycled HDPE resin production, it is possible to derive a GHG benefit of utilizing post-consumer HDPE. For a tonne of HDPE and including the necessary transportation, the difference between 2.85 tCO<sub>2</sub>e for

virgin and 1.15 tCO<sub>2</sub>e for recycled is 1.7 tCO<sub>2</sub>e. This 1.7 tCO<sub>2</sub>e is the GHG benefit to be expected from recycling a tonne of HDPE rather than disposing it in a landfill or combusting it in an incinerator and therefore necessitating further virgin production to replace this material. To determine whether this GHG factor is appropriate for use in this investigation, the local situation has been assessed.

The manufacture of plastic containers using virgin resins is performed in the Lower Mainland by Portola Packaging. This firm only utilizes virgin resins produced by the petroleum industry in the United States. They do not use any virgin resins produced in Canada nor any post-consumer resins. As previously discussed, there are a number of steps to prepare resins for use in the manufacturing of plastics containers. The main steps include petroleum & natural gas extraction and refining, ethylene production, polymerization and pelletizing. Due to this complexity, and the number of potential organizations involved, this research will use the work by FAL and Tellus instead of attempting to develop a separate estimate for this virgin production. Furthermore, as resins used in the Lower Mainland actually originate from the United States, this author believes that the estimates by the U.S. consultants are appropriate for use here.

Post-consumer HDPE plastic materials such as bottles and others are recycled in the GVRD. This occurs at Merlin Plastics of Annacis Island. This organization generates recycled resins for export to California. In fact, all of the recycled resins from this facility are shipped to California where some new plastics must have a minimum recycled content (Pers. comm.. Tony Mouchachen). While plastics in the GVRD are recycled, it is important to recognize that the production of recycled plastic bottles does not occur here. However, recycled HDPE resins can be down-graded into non-food-grade materials such as buckets or plastic lumber. Tony Mouchachen of Merlin Plastics was contacted to obtain energy data but declined to participate in this research. Therefore, the estimates developed in the USEPA report are used in this thesis. As the transportation component of GHG emissions is included in the USEPA report, these emissions are not specifically analyzed in this thesis.

#### **2.6.6 Low-Density Polyethylene**

Low-density polyethylene is a material very similar to high-density polyethylene and for the purposes of this research behaves the same. As a result, much of the discussion in the previous section (2.6.5) is also applicable here. In addition, emission estimates from the USEPA work are reviewed.

Franklin Associates Ltd. (FAL) and the Tellus Institute (Tellus) also investigated LDPE manufacture and recycling for the United States Environmental Protection Agency (USEPA 1998). They estimated the emissions from energy consumption during raw material acquisition and subsequent processing (process energy) and the transportation-related emissions of the raw materials (transportation energy). FAL also identified process non-energy emission during the life-cycle but it not stated how these emissions occur. FAL estimated the total of these emissions to be 2.7 tCO<sub>2</sub>e/tonne LDPE with a breakdown of 2.4 tCO<sub>2</sub>e per tonne LDPE from process energy, 0.2 tCO<sub>2</sub>e per tonne HDPE of process non-energy emissions and 0.1 tCO<sub>2</sub>e per tonne LDPE from



transportation energy. Tellus estimated the total of these emissions to be 4.4 tCO<sub>2</sub>e/tonne HDPE with a breakdown of 3.9 tCO<sub>2</sub>e per tonne LDPE of process emissions, 0.2 tCO<sub>2</sub>e per tonne HDPE of process non-energy emissions and 0.3 tCO<sub>2</sub>e per tonne LDPE of transportation emissions. The average of the FAL and Tellus estimates is 3.55 tCO<sub>2</sub>e/tonne LDPE.

These consultants also investigated the emissions from the alternative realization of recycled LDPE resins. This is the same end product as the previous estimate and can be directly compared. Their investigation included process energy and non-energy emissions resulting from the washing and processing of post-consumer LDPE materials to generate recycled resins and transportation energy consumed during the acquisition of this post-consumer LDPE. FAL estimated the total of these emissions to be 0.93 tCO<sub>2</sub>e/tonne LDPE with a breakdown of 0.77 tCO<sub>2</sub>e per tonne LDPE from process energy and 0.16 tCO<sub>2</sub>e per tonne LDPE from the transportation energy. Tellus estimated the total of these emissions to be 1.7 tCO<sub>2</sub>e/tonne LDPE with a breakdown of 1.6 tCO<sub>2</sub>e per tonne LDPE of process emissions and 0.1 tCO<sub>2</sub>e per tonne LDPE of transportation emissions. The average of the FAL and Tellus estimates is 1.3 tCO<sub>2</sub>e/tonne LDPE.

By comparing the estimates of virgin versus recycled LDPE resin production, it is possible to derive a GHG benefit of utilizing post-consumer LDPE. For a tonne of LDPE and including the necessary transportation, the difference between 3.55 tCO<sub>2</sub>e for virgin and 1.3 tCO<sub>2</sub>e for recycled is 2.25 tCO<sub>2</sub>e. This 2.25 tCO<sub>2</sub>e is the GHG benefit to be expected from recycling a tonne of LDPE rather than disposing it in a landfill or combusting it in an incinerator and therefore necessitating further virgin production to replace this material. As with HDPE, it is the USEPA estimates which are used in this thesis.

### **2.6.7 Forest Carbon Sequestration**

Can the recycling of paper products affect the carbon storage in forests? This impact would be derived from the belief that "paper and wood recycling tend to reduce timber harvesting, and possibly lengthen rotation ages, leaving more carbon sequestered in the forests." (Ince et al. 1995) Does recycling reduce the demand for timber harvesting and therefore allow greater carbon sequestration? The state of forestry in Canada and a literature review of available research on forest sequestration issues is presented in this section. In addition, the helpful discussions with individuals at the Canadian Pulp and Paper Association, the B.C. Ministry of Forests and the Canadian Forest Service are also provided.

The United States Environmental Protection Agency estimates that the rate of carbon uptake has exceeded the rate of carbon release in US forests since about 1977 (USEPA 1998). This carbon sequestration, "primarily due to forest management activities and the reforestation of previously cleared areas" (ibid), has been estimated to offset about 5% of US energy-related CO<sub>2</sub> emissions (USEPA 1999). In the USEPA (1998) analysis, an extensive modeling investigation was performed to estimate the amount of forest carbon sequestration per ton of paper product which is recycled. They, together with the United States Department of Agriculture (USDA) – Forest Service, found that a relationship

does exist between recycling and forest carbon sequestration. It was determined that 0.80 tonnes of additional carbon can be expected to be sequestered if one tonne of paper is recycled. This is equivalent to preventing the emission of 2.9 tCO<sub>2</sub>e to the atmosphere. Their model treats “forest product markets in the US and Canada as a single integrated economic and biological system.” However, Canadian forest inventories are not modeled in the same way or detail as the US forest inventories. This is an important limitation given that much of the economically marginal paper production is from Canadian pulp sources – recycling in the U.S. would impact mainly Canadian forests.

Peter Ince and others at the USDA – Forest Service have also modeled the carbon sequestration issue together with the fossil energy consumption implications of virgin vs. recycled paper production (Ince et al. 1995). These researchers found that by increasing the 1990 recovered paper utilization rate of 27% to 56% by 2010, that the annual emission of 180 million tonnes of CO<sub>2</sub> could be prevented in the U.S. Unfortunately, a breakdown of the GHG reductions into forest carbon sequestration or process energy savings is not provided.

To determine whether this US research is appropriate for application in this thesis, the Canadian situation requires investigation.

Canada’s landmass of 977 million hectares contains 418 million hectares of forest. Of these forests, 245 million hectares or 59% is considered to be commercial forests. However, “due to accessibility limits, environmental constraints, land ownership, land-use constraints and operability issues, only 119 million hectares or about half of the commercial forest is considered to be available for timber production at present”. Canada, along with only Russia, Alaska and parts of Scandinavia, has a predominance of the slow-growing natural (never-harvested) boreal forest. “Canada’s forest is weighted toward relatively young (29%) and mature (59%) stands of trees, while over-mature stands make up most of the remainder...” (all information from NCCP (1998)) Of the 119 million hectares of available commercial forest, only 1.1 million hectares was harvested in 1998 (Natural Resources Canada 2000). In fact, natural disturbances impacted a much greater area; forest fires destroyed 1.7 million hectares in 1998 and insects defoliated 5.1 million hectares (ibid). However, some of the burnt and defoliated forests can still provide salvagable timber. The maximum allowable production levels – the Allowable Annual Cut (AAC) – was even greater than the harvested area in 1998. While the AAC in 1998 was 241 million m<sup>3</sup>, only 175 million m<sup>3</sup> or 73% was actually harvested (ibid).

This AAC consists largely of first-growth forest which has not previously been harvested. This is in contrast to activities in the US which are harvesting mainly second growth trees (Pers. comm. Bill Wilson). By the current practice of harvesting mainly first growth trees, the forest industry is removing trees which are past their biological maturity (trees which are no longer growing and fixing carbon from the atmosphere). By harvesting stands which are no longer growing and photosynthesizing, forestry operations are allowing the replacement with actively growing seedlings to further fix carbon while much of the harvested tree will be converted into various wood products.

Industry-wide statistics are annually published by the Canadian Pulp and Paper Association (CPPA 1999) and the following discussion will compare 1990 data (when the utilization of post-consumer paper began rapidly expanding) with the most recent data, that for 1997. The production of paper, paperboard and market pulp went from 23.7 million tonnes in 1990 to 29.1 million tonnes in 1997. Much of this production was a result of waste from sawmills. Most trees in Canada are not harvested to make paper. Rather, they are harvested to make lumber. As not all of round logs are turned into lumber, the remaining wood, excluding the bark, is typically chipped for use in pulp mills. The harvest of industrial roundwood was 156 million m<sup>3</sup> in 1990 yet only 42 million m<sup>3</sup> was roundwood directly for pulping; the majority was for lumber production. Approximately 55 million m<sup>3</sup> or 57% of the total virgin fibre consumed by the pulp and paper sector was wood waste from sawmills. In 1998, the national harvest had climbed to 182 million m<sup>3</sup>, but only 33 million m<sup>3</sup> was roundwood directly for pulping; an even greater amount, 74 million m<sup>3</sup> or 69% of virgin fibre consumed by the pulp and paper sector, was wood waste from sawmills. While the total harvest of industrial roundwood increased between 1990 and 1997, the roundwood directly consumed at pulp and paper mills actually decreased. The amount of wood waste generated at sawmills which is transferred to pulp and paper operations is remarkably consistent with the rule of thumb provided to this author by Mike Whybrow of the B.C. Ministry of Forests. He explained that approximately 40% of a round log delivered to a sawmill becomes lumber, 40% becomes wood chips and 20% becomes wood waste such as sawdust, shavings or bark which is typically combusted in the power-boilers of pulp mills or are disposed of in beehive burners. It is important to recognize that currently nearly of 70% of the virgin fibre used at Canadian pulp operations rely on wood waste from sawmills.

Along with the wood chips from sawmills or from roundwood harvested especially for pulping is combined the de-inked pulp produced from recycled paper products. While 1990 marked the beginning of strong growth in the utilization of postconsumer paper by the pulp & paper industry, it is not a new occurrence. As far back as 1980, 1.1 million tonnes of recycled paper was used in producing 13.5 million tonnes of paper and paperboard for a utilization rate of 8.4% (CPPA 1999). In 1990, 1.8 million tonnes of recycled paper was used to produce 16.5 million tonnes of paper and paperboard, a utilization rate of 11.2%. The most recent available data is for 1998. In this year, 4.7 million tonnes of recycled paper, along with virgin fibre, produced 18.7 million tonnes of paper and paperboard for a utilization rate of 24.9%.

Given that nearly 70% of virgin fibre used in pulp & paper production is from trees not harvested directly, what effect has recycling had on fibre demand? Both David Church (Canadian Pulp & Paper Association) and Mike Whybrow (B.C. Ministry of Forests) believe that the recycling of paper products has served to 'stretch' the fibre resource. While roughly the same amount of wood chips were being utilized prior to recycling as is currently being utilized – the main difference is that recycled fibre now allows more paper to be produced. This belief is indeed borne out by available data. Virgin fibre consumed by the pulp and paper industry was 97 million m<sup>3</sup> in 1990 and had only slightly increased to 107 million m<sup>3</sup> in 1998 (CPPA 1999). This increase came not from direct

harvesting of roundwood but from increased utilization of wood waste. The greater wood waste and recycled fiber enabled pulp & paper production to increase from 23.7 million tonnes in 1990 to 28.5 million tonnes in 1998. As previously discussed, direct harvesting of roundwood actually decreased during this period – from 42.1 million m<sup>3</sup> in 1990 to 33.4 million m<sup>3</sup> in 1998 (ibid). Assuming that wood waste utilization is already at a maximum (this author has not been able to find any data on this), it could logically be concluded that increased harvesting of roundwood for pulping would be necessary to satisfy fibre demand. Especially when considering that the AAC is currently only at 73% - there is 27% of additional harvesting available. However, this harvesting will only occur if the economics are attractive; pulping has to make money and traditionally it is the lumber which brings in the large revenues. Also, geographic considerations are important as much of this available AAC may be a great distance from the pulp mills which require this raw material. To complicate matters further, it is the opinion of Mike Whybrow that additional demand for paper would be supplied not by increased harvesting in Canada but by fast-growing plantations in tropical or sub-tropical countries. Bill Wilson (Canadian Forestry Service) is of a similar opinion and also believes that additional demand would spur on investigations into the potential of non-timber sources of pulp such as flax, hemp or agricultural residues. Assuming increased harvesting did to take place, while it may appear to lead to increased GHG emissions, removing zero net growth primary forest with a young actively photosynthesizing seedling may also have advantages.

Contrary to the USEPA (1998) report, which is designed for municipalities in the United States, this thesis is analyzing the GHG emissions solely from the GVRD waste management system. For this reason, a different tack can be employed to derive a forest carbon estimate. Paper is recycled so that the pulp & paper industry has the required minimum recycle content to remain in the marketplace. If the GVRD disposes of paper, instead of recycling, the free market value of recycled paper products would logically have to increase. With the value increasing, it is conceivable that other jurisdictions would increase their recycling to satisfy any shortage. Increased harvesting of roundwood strictly for pulping is unlikely as this does nothing to reach the minimum recycled content in new paper products. If the GVRD removed its recycled paper supply, to burn for carbon-neutral bioenergy generation for instance, an incentive would result for other cities to pull more paper out of their waste stream for recycling. In this situation, if the GVRD chooses to recycle or chooses not to, there is little GHG implication. Probably the only implication would result from increased transportation to import recycled paper back to B.C. from the U.S. This research assumes that the GVRD's choice in isolation to recycle or not to recycle has zero GHG benefit or liability.

## 2.7 UNCERTAINTY WITH THE ESTIMATES

As with any estimating procedure, there is uncertainty in the results. This study is no exception. While much of the data, especially the diesel fuel consumption data, has very little uncertainty, there are other values for which a lack of confidence exists. In this report, it was decided that high, low and best-guess estimates will be provided with data and factors that have a high level of uncertainty. Factors for which there is minimal uncertainty will only have one value; high and low estimates will not be provided. The range of potential values (the range between the high and low values) will be included in brackets after the best-guess value. When values with uncertainty are summed, the best-guess, high and low estimates will be summed respectively to calculate the resulting best-guess, high and low estimate.

In many cases, the uncertainty results from the prevailing lack of understanding of the process being analyzed. Unfortunately, two of the most uncertain issues, landfill methane and nitrous oxide emissions, are also some of the most quantitatively important from a greenhouse gas perspective. Nevertheless, estimates are required and have therefore been developed. It is hoped that when the level of understanding grows in the future, that it will be possible to incorporate the new understanding into the model.

Only two significant figures are reported in the results of this research. This is likely the most appropriate given the uncertainty in the underlying data.

## 2.8 SPREADSHEET PROGRAM

In addition to this report, the second important deliverable from this research study is a spreadsheet program to facilitate future waste management planning. This spreadsheet is programmed so that the mass flows of waste into various management methods (landfill disposal, incineration, composting and recycling) are variables that can be altered. Also, parameters that are important for calculating GHG emissions, such as the effectiveness of landfill gas collection systems, are also programmed as variables (**in bold**) so that improvements in the future will cause the Model to recalculate emissions. The spreadsheet also allows for the development of a new landfill and a new incinerator. It is the intent of this spreadsheet to Model the GVRD's existing system and provide planners with a tool to calculate the future emissions to be expected from decisions made today.

This section describes the inner workings of the spreadsheet program to give readers an understanding of this Model. This section begins by explaining the 34 worksheets which are the complete spreadsheet (2.8.1). These worksheets simply represent the sample calculations provided in the appendices. The only difference being that when structured in a spreadsheet, changes in waste masses or parameters will immediately demonstrate the response on GHG emissions. The inter-relationships of these individual worksheets are effectively illustrated to readers by the use of two examples (2.8.2). After these two sub-sections, an understanding of this spreadsheet Model should be attained. Together

with the sample calculations provided in the appendices, waste management planners should feel confident enough to make future improvements to the Model.

Several scenarios of specific interest to the waste planners at the GVRD are also inputted into the spreadsheet Model. These are potential management alternatives already being discussed at the GVRD and it was identified that it would be particularly valuable to include their evaluation in this thesis. The last sub-section (2.8.3) is the discussion of the several scenarios of specific interest to the GVRD.

### **2.8.1 Explanation**

This spreadsheet program contains 34 individual worksheets to calculate the emissions from the GVRD's existing system of solid waste management. Though at the outset, this spreadsheet may appear to be extremely complicated, it is actually quite simple. The 34 worksheets can be divided into four categories to facilitate explanation. These four main groups, *Results*, *General*, *Municipal and Waste*, are organized so that the most relevant parts to planners are up front, in the beginning, and that further exploration in the spreadsheet would reveal data and calculations of greater detail and complexity.

These groups and their associated worksheets are:

Table 2-6: List of Worksheets

GROUP	#	NAME OF WORKSHEET
Results Group	1	GHG Emissions
	2	Waste Tonnages
	3	Emissions Factors
	4	Factor List
General Group	5	General Parameters
Municipality Group	6	City of Abbotsford
	7	City of Burnaby
	8	City of Coquitlam
	9	Corporation of Delta
	10	City of Langley
	11	Township of Langley
	12	District of Maple Ridge
	13	City of New Westminster
	14	City of North Vancouver
	15	District of North Vancouver
	16	District of Pitt Meadows
	17	City of Port Coquitlam
	18	City of Port Moody
	19	City of Richmond
	20	City of Surrey
	21	City of Vancouver
	22	District of West Vancouver
	23	City of White Rock
	24	Electoral Area A
	25	Electoral Area C
Waste Group	26	Newsprint Waste Management
	27	Office Paper Waste Management
	28	Ferrous Metal Waste Management
	29	Glass Waste Management
	30	High-Density Polyethylene Waste Management
	31	Low-Density Polyethylene Waste Management
	32	Food Waste Management
	33	Yard Trimmings Waste Management
	34	Remainder Waste Management

The first worksheet (WS#1) presents the results of the entire spreadsheet program – it is the total greenhouse gas emissions from all the municipalities. WS#2 (Waste Tonnages) is the mass, in tonnes, of each component of the waste stream from each municipality under investigation. This waste tonnage is multiplied by the emission factors in WS#3 to calculate the greenhouse gas emission results in WS#1. The last worksheet in the Results Group is WS#4 (Factor List). This is simply a list of all the emission factors from the

next 30 worksheets to serve as a transition for ease of programming WS#3. Factors from WS#5 through WS#34 first are entered into the Factor List (WS#4) and then are automatically organized for Emission Factors (WS#3). The General Parameters worksheet (WS#5) is the location of factors and calculations which are not municipality or waste component specific. Examples of these factors include physical constants, landfill gas collection efficiencies and energy conversion during incineration. Examples of calculations include the transportation emissions associated with transfer stations, subsequent transport to landfills or the incinerator or landfill equipment. The next 20 worksheets, WS#6 to WS#25, comprise the Municipality Group. (While there are 23 member municipalities in the GVRD, Anmore and Belcarra are contained within the City of Port Moody municipality and the village of Lions Bay is included with Electoral Area C for this Model.) These worksheets contain all the factors which are municipality-specific such as waste mass estimates and curbside collection. As each municipality has different distances involved in waste management (and therefore different diesel fuel consumption), it was necessary to analyze each municipality individually. The last 9 worksheets, WS#26 to WS#34, are the waste component-specific group, and contain the detailed information on Newsprint Management (WS#26), Office Paper Management (WS#27), Ferrous Metal Management (WS#28), Glass Management (WS#29), HDPE Management (WS#30), LDPE Management (WS#31), Food Waste Management (WS#32), Yard Trimmings Management (WS#33) and Remainder Waste Management (WS#34). These worksheets contain the factors necessary to calculate the emissions to be expected when these materials are either disposed in the Cache Creek or Vancouver Landfills, combusted at the Burnaby Incinerator or undergo backyard or centralized composting. WS#34 (Remainder Waste Management) is an analysis of the remaining fraction of the waste stream after the 8 main components are removed. This waste fraction will be discussed in greater detail in Section 2.10 – *Remaining Wastes*.

In the nine worksheets which assess the individual waste components, some of the emission factors are negative values. For example the energy benefit of landfill gas utilization at the Cache Creek Landfill and the energy generation at the Burnaby Incinerator are negative emissions. This results from the fact that these factors actually *reduce* greenhouse gas emissions and to be included in this thesis are calculated as negative values – when the amount of emission reduction is the value provided. In addition to energy at a landfill or incinerator, negative emission factors are presented in this thesis as a result of landfill carbon sequestration or sequestration in finished compost. These GHG benefits are converted to negative emission factors after all calculations are completed when presented in the appendices. In the spreadsheet program, each emission reduction is multiplied by -1 to convert to a negative value.

### **2.8.2 Examples**

The workings and interconnections of these worksheets can be illustrated by using examples. The GHG emissions resulting from the incineration of food scraps in the District of North Vancouver (tCO<sub>2</sub>e) can be calculated by multiplying two numbers, the mass of food scraps incinerated (tonnes) and the GHG emission factor for food waste incineration (tCO<sub>2</sub>e/tonne). The mass of food scraps is determined from GVRD data on solid waste generation together with waste characterization data – the result is provided



in WS#2 (Waste Tonnages). When the GHG emission factor for food waste incineration is calculated it can be found in WS#3 (Emission Factors), but calculating this value, and all others, is essentially the bulk of this research. The factor is dependent on data in WS#5 (General Parameters), data specific only to the District of North Vancouver (WS#15), and data specific only to the incineration of food waste (WS#32). There is a series of five steps required to combust food waste from this municipality. Food waste requires curbside collection, processing at the North Shore Transfer Station and then transportation to the Burnaby Incinerator. All three of these steps require diesel fuel consumption and have been estimated in WS#15 (District of North Vancouver). Curbside collection of general waste is 0.014 tCO<sub>2</sub>e/tonne, Factor 1 (WS#15 – F#1), processing at the transfer station is 0.0013 tCO<sub>2</sub>e/tonne, Factor 4 (WS#5 – NSTS: F#1) and the transfer to the Burnaby Incinerator is 0.0026 tCO<sub>2</sub>e/tonne (WS#5 – NSTS: F#8). Once at the Incinerator, WS#32 (Food Waste Management) is necessary for energy generation. The energy benefit of incineration results in -0.097 tCO<sub>2</sub>e/tonne, Factor 10 (WS#32 – F#10), but the GHG emissions during incineration are 0.091 tCO<sub>2</sub>e/tonne, Factor 1 (WS#32 – F#11). By totaling all these steps together, it is possible to calculate the overall emission factor as tonnes of CO<sub>2</sub> equivalent per tonne of food waste. The emission factor provided in WS#3 (Emission Factors) is the total of these factors, 0.010 tCO<sub>2</sub>e/tonne. While a negative emission may seem odd, this will be fully discussed in the next chapter.

Examine the tabulation below of this example:

Table 2-7: Incineration of Food Waste from District of North Vancouver

WS#	Worksheet Name	F#	Factor Name	tCO <sub>2</sub> e/ tonne
15	District of North Vancouver	1	Curbside Collection of General Waste	0.014
15	District of North Vancouver	4	Transfer Station Equipment	0.0013
15	District of North Vancouver	8	Transport to the Burnaby Incinerator	0.0026
32	Food Waste Management	7	Energy Generation from Waste Incineration	-0.097
32	Food Waste Management	8	GHG Emissions from Waste Incineration	0.091
<b>TOTAL =</b>				<b>0.010</b>

For another example, let us calculate the emissions from the centralized composting of yard waste generated in the City of Vancouver. The series of steps required in this process are: curbside collection of yard trimmings (WS#21 – F#3), processing at the Vancouver Transfer Station (WS#21 – VTS: F#1), transport to the composting facility at the Vancouver Landfill (WS#21 – F#5), fuel consumption by composting equipment (WS#5), GHG emissions of centralized composting (WS#33 – F#12) and the long-term sequestration of compost (WS#33 – F#13). Totaling all these factors will result in the emission factor for the centralized composting of yard waste generated in the City of Vancouver. These emissions are tabulated on the next page.

Table 2-8: Centralized Composting of Yard Waste from City of Vancouver

WS#	Worksheet Name	F#	Factor Name	tCO <sub>2</sub> e/ tonne
21	City of Vancouver	3	Curbside Collection of Yard Waste	0.027
21	City of Vancouver	4	Transfer Station Equipment	0.0009
21	City of Vancouver	6	Transport to the Composting Facility	0.0033
5	General Parameters		Composting Equipment	0.019
33	Yard Waste Management	12	Emissions from Centralized Composting	0.105
33	Yard Waste Management	13	Long-Term Sequestration of Compost	-0.10
TOTAL =				0.05

The overall emission factors in WS#3 are simply a total of all the necessary factors associated with the process under investigation. There are three parts to every activity, a municipality-specific part (What is the municipality?), a waste-specific part (What waste material is being analyzed?) and a general part (this is the depository for general data not specific to either municipalities or materials). The spreadsheet has simply been programmed to total the appropriate individual factors for each of the possible activities in WS#3 (Emission Factors). Changes in the variables or parameters at any stage will be reflected in the final results presented in WS#1 (GHG Emissions). However, it is important to distinguish between variables and results cells in the spreadsheet. New data or parameters should only be typed into variable cells (**in bold**) so that a new result can be calculated. Result cells contain the mathematical functions necessary to calculate the result from the available data and parameters. Improvements to the spreadsheet should not be performed by typing new numbers into the results cells for this would erase the calculations.

The utility of the spreadsheet Model comes from the ability to change the existing system and model the response in GHG emissions. Logically, the questions thus result: What are the modifications possible and what are the limitations in the Model? A list of the most important variable changes to users follows.

- Waste mass estimates for generation, recycling and disposal can be altered in the municipality-specific worksheets (WS#6 – WS#25).
- The mass flows of waste to transfer stations and direct or transferred mass flows to disposal facilities in the GVRD can be altered in the General Parameter Worksheet (WS#5) to recalculate the percentage of waste disposed in each facility.
- Curbside collection fuel consumption data can be altered in the municipality-specific worksheets (WS#6 – WS#25).
- Fuel consumption by transfer station equipment, landfill equipment or for transportation to landfills or incinerators can be altered in the General Parameter Worksheet (WS#5).
- Landfill methane collection for flaring or energy utilization can be altered in the General Parameter Worksheet (WS#5).
- Energy conversion during incineration and the fraction of steam to CPL or to a turbo-generator can be altered in the General Parameter Worksheet (WS#5).
- The GHG benefit of preventing steam generation by CPL or of preventing electricity generation by BC Hydro can be altered in the General Parameter Worksheet (WS#5).

- Global Warming Potential of CH<sub>4</sub> and N<sub>2</sub>O can be altered in the General Parameter Worksheet (WS#5).
- The first-order decay rate constants for anaerobic decomposition can be altered in the waste-specific worksheets (WS#26 – WS#34).
- The *Carbon Available for Anaerobic Decomposition* for each material can be altered in the waste-specific worksheets (WS#26 – WS#34).
- The *Carbon Storage Factor* for each material can be altered in the waste-specific worksheets (WS#26 – WS#34).
- The moisture content, nitrogen content and net energy content for each material can be altered in the waste-specific worksheets (WS#26 – WS#34).
- The N<sub>2</sub>O conversion rates for food and yard waste can be altered in WS#32 & WS#33.
- The GHG benefit of the utilization of recyclables by industry can be altered in the waste-specific worksheets (WS#26 – WS#34).
- The removal of entire categories of emissions such as landfill sequestration or the benefit of recycling is possible by deleting their values in Factor List (WS#4).

The above list is not exhaustive – many other minor modifications are possible within the framework of the Model.

While the Model is flexible, there are limitations to the allowable changes. For example, the spreadsheet will not allow major changes to transfer stations in the municipalities. Waste from the three North Shore municipalities must be delivered to the North Shore Transfer Station. Once there, waste is free to be transferred to the Cache Creek, Vancouver or a Future Landfill, or the Burnaby or Future Incinerator. The same is true for Coquitlam and Port Coquitlam; waste must be delivered to the Coquitlam Transfer Station.

### 2.8.3 Modelling Scenarios

Of particular interest to planners at the GVRD is the GHG response of eight scenarios for future waste management alternatives. Using the existing system programmed into the Model as the baseline, any scenario inputted will recalculate new GHG emissions. Each of these scenarios can be directly compared with the baseline to identify whether the emissions increase or decrease. The first five scenarios are potential planning changes to the current management system. The last three scenarios demonstrate the response of the Model to changes in interpretation of the emission estimates (and do not actually represent management changes). These eight scenarios are the following.

- No future increases of the landfill gas collection efficiency at the Cache Creek or Vancouver Landfill and no allowance for energy utilization.
- Decreasing the fraction of steam transferred to Crown Packaging Limited (CPL) from the existing 56% to 37%; CPL will require less steam in the future (Pers. comm. Ken Carrusca).
- Allowing a turbo-generator to convert the unused steam fraction to electricity; increasing from the current 0% to 57% of steam after CPL decreases its need. (assuming 6% is required internal for plant operation)
- Hypothetically allowing incineration to replace all landfill disposal at the proposed steam usage of 37% to CPL.
- Hypothetically allowing incineration to replace all landfill disposal at 37% to CPL and 57% to electricity generation.
- Ultimate (complete) decomposition of the CAAD in the wastes – to remove the 20 year time period.
- Removal of landfill carbon sequestration benefits from the Model.
- Removal of recycling and forest sequestration benefits from the Model.

The scenarios can be programmed by following the instructions below. However, it is necessary to erase changes when finished unless otherwise stated. The first scenario is performed by changing the gas collection percentages in WS#5 – General Parameters. For the year 1999, Cache Creek is assumed to flare 43% and use 0% for energy – copying these numbers down to the year 2018 will model no future increases. The same can be performed for the Vancouver Landfill. The 22% flared and 0% for energy in 1999 can be copied down to 2018 to model no changes. The second scenario, scheduled to occur in the near future as CPL has a reduced requirement for steam from the Incinerator, can be inputted by changing the Fraction of Steam Sold to CPL (Row 177 in WS#5 – *General Parameters*) from 56% to 37%. While this scenario is in effect, the third scenario can be added – to change the Fraction of Steam to Generate Electricity in a Turbo-Generator (Row 178 in WS#5 – *General Parameters*) from 0% to 57%. To program the fourth scenario, all previous changes have to be reversed and the table Percentage Distribution of Waste Disposal (blocks J41 to O63 in WS#5 – *General Parameters*) requires changing. This table contains the calculations to determine the breakdown of waste disposal for each municipality. To get all waste disposed at the Burnaby Incinerator, users need to set the Incinerator at 100% and all other facilities at 0% for each of the municipalities. While the Burnaby Incinerator cannot currently handle all this waste, this change hypothetically models the GHG emissions to be expected if it could. Users could also use Future Incinerator to model this hypothetical scenario but they would have to

provide data for the necessary transportation. Also necessary to complete this scenario is changing the Fraction of Steam Sold to CPL (Row 177 in WS#5 – *General Parameters*) from 56% to 37%. While this scenario is in effect, the fifth scenario can be programmed - change the Fraction of Steam to Generate Electricity in a Turbo-Generator (Row 178 in WS#5 – *General Parameters*) from 0% to 57%. After reversing these changes, the sixth scenario can be implemented by changing all the decay rate constants in WS#26 to WS#34 to  $0.14 \text{ year}^{-1}$  to allow complete decomposition of the CAAD within 20 years after disposal. The seventh scenario, removing carbon sequestration can be programmed in the simplest manner by deleting all reference to sequestration in WS#4 – *Factor List*. This can be performed by deleting cells H22 to Z22 and cells H26 to Z26. The eighth and last scenario is to remove the benefits of recycling from the Model. This can be implemented by deleting all reference to recycling in WS#4 – *Factor List*; these are cells H36 to Z36.

These instructions are provided to demonstrate how modifications can be performed by users. The results of these scenarios are presented and discussed in the next chapter. The next section (2.9) is concerned with finding the appropriate data to place in WS#2 – *Waste Tonnages*. By using previous work performed by consultants on behalf of the GVRD, it is possible to estimate the required data.

## 2.9 WASTE MASS ESTIMATES

Up to now this report has strictly been concerned with the greenhouse gas emissions associated with waste management and the development of emission factors based on tonnes of CO<sub>2</sub> equivalent per tonne of waste. These completed emission factors estimate the emissions to be expected when managing a specific component (newsprint, food scraps, HDPE, etc...) in a specific manner (landfilling, incineration, composting, etc...). But how much newsprint is recycled? How much newsprint is incinerated? How much newsprint is landfilled? Furthermore, it is necessary to be municipality-specific. How many tonnes of food waste from Burnaby was incinerated, landfilled or composted in 1998? How many tonnes of office paper from Vancouver are recycled, landfilled or incinerated in 1998? The mass (tonnes) of each of these fractions is required so as to multiply with the emissions factors (tCO<sub>2</sub>e/tonne) to calculate the overall emissions (tCO<sub>2</sub>e). This section develops the estimates for each of the analyzed components in each of the municipalities and it is these estimates which are used to calculate GHG emissions.

There are three important concepts critical in analyzing waste. These are:

1. a mass of waste generated,  $M_{\text{GEN}}$ ,
2. a mass of waste recycled or composted,  $M_{\text{REC}}$  or  $M_{\text{COM}}$ , and
3. a mass of waste disposed,  $M_{\text{DIS}}$ .

These factors are inter-related by the law of conservation of mass such that: “waste that is generated but not recycled has to be disposed of.” As a formula this is represented by

$$M_{\text{GEN}} - M_{\text{REC}} = M_{\text{DIS}}$$

If not diverted from disposal by recycling programs, generated wastes will either be landfilled or incinerated. Consequently, the mass disposed ( $M_{DIS}$ ) can be further subdivided into the mass landfilled or the mass incinerated. Backyard or centralized composting activities are analogous to recycling programs as they serve a similar purpose – diverting waste from necessary disposal. Thus, for use with food scraps, the equation would become:

$$M_{GEN} - M_{COM} = M_{DIS}$$

Since there is only one equation and three unknowns, mathematics dictates that it is necessary to find data for two of the variables and then the third unknown can be solved for. Using newsprint as an example, the mass collected and delivered to recycling depots is typically recorded and reported to municipalities on an annual basis; this would be  $M_{REC}$ . The mass generated ( $M_{GEN}$ ), i.e. the mass of newspapers distributed and consumed by residents has likely changed little over the years and data for this generation on a per capita basis is available in reports. However, the mass of newsprint disposed ( $M_{DIS}$ ) has changed dramatically in recent years. In the 1980's, before strong recycling initiatives, the vast majority of newsprint and other paper products were disposed in landfills or incinerators, while in the 1990's, recycling completely reversed this. Recycling now manages a majority of the newsprint in many jurisdictions and paper bans specifying maximum allowable quantities have even been instituted at disposal facilities. These programs have greatly decreased the mass of newsprint requiring disposal. Without the results of a recent waste study which has accurately measured the mass of newsprint still in MSW (remember that even with strong recycling programs there will still be disposal), it is very difficult to estimate this mass. As a result, this third variable will be solved for. The other variables,  $M_{GEN}$  and  $M_{REC}$ , were acquired by available data and reports. This also holds true for the other 8 components of MSW analyzed.

In 1993, three consultants (CH2M Hill Engineering, KPMG Peat Marwick Stevenson & Kellogg and Resource Integration Systems) performed an extensive analysis of the GVRD's waste management and recycling programs (GVRD 1993). In their report, three sources of residential waste, urban single family, urban multi-family and rural single family, and nine major ICI (Industrial, Commercial and Institutional) groups were analyzed for 17 major waste components. All the estimates for this consultant report were based on 1991 data but unfortunately, this thesis requires more recent data, 1998 preferably, and much has changed in the preceding years. As a result, large portions of their data are projected into 1998 numbers.

A municipality's residential and ICI waste generation ( $M_{GEN}$ ) estimated in 1991 can be divided by the population at that time to develop per capita estimates. Using the municipalities' population in 1998 (projections from the census in 1996), it is possible to update this waste generation. This is of greater accuracy than calculating per capita generation for the entire GVRD as a whole; different municipalities have varying fractions of their waste from commercial sources. For example, the CH2M Hill report estimated that 63% of Vancouver's waste is generated from ICI sources but only 40% of Coquitlam's waste is derived from this sector. This issue is of significant importance to

the generation of office paper. However, two important assumptions are necessary by doing this. Firstly, that increasing residential population is also an indication of increasing ICI activity and that secondly, that the per capita waste materials generated by society have not changed appreciably in the last nine years. This second assumption was demonstrated by an investigation of solid waste disposal and recycling in the GVRD by Margaret Wojtarowicz (2000). Both assumptions will be necessary because of the lack of a more recent waste audit from which to acquire data. It should be noted that improvements in the future understanding of these wastes should be included in the adaptable spreadsheet program.

Individually by municipality, the generation of waste from six material categories in the CH2M Hill report were directly adaptable for use in this report. The six materials directly adaptable include newsprint, glass, ferrous metal, HDPE, food and yard waste. Assumptions are necessary to convert part of the mixed paper category into office paper and part of the mixed plastics category into low-density polyethylene (LDPE). The consultants report estimated that of the 199,000 tonnes of mixed paper (excluding newsprint or corrugated cardboard) disposed in the GVRD, that 27,000 tonnes was office paper, or 14%. Assuming that the mixed paper recycling rate, 27% of generated mixed paper, is representative of office paper, then it can be assumed that 14% of generated mixed paper is also office paper. Similarly, the consultants report estimated that of the 93,000 tonnes of mixed plastics (excluding HDPE and PET) disposed in the GVRD, that 42,300 tonnes was LDPE, or 45%. Assuming that the mixed plastics recycling rate, 8% of generated mixed plastics, is also representative of LDPE, then it can be assumed that 45% of generated mixed plastics is LDPE. It is hoped that future understanding will improve the accuracy of these estimates.

After estimating waste generation, it is necessary to estimate the mass of waste which is recycled ( $M_{REC}$ ). As previously discussed, municipalities annually publish this data. As recycling programs dramatically expanded in the 1990's, it is preferable to obtain the most recent data. However, to be consistent with the rest of this report, 1998 is the year used for data gathering and not 1999. The GVRD has provided the required data of the mass of residential materials which were recycled ( $M_{REC}$ ) and the mass of residential compostables which were composted ( $M_{COM}$ ) (Pers. comm. Andrew Marr).

Unfortunately, their data analysis differs from that employed in this research. Their *Mixed Paper* does not separate out office paper, their *Metal* does not separate ferrous metal, and their *Plastic* does not differentiate between HDPE, LDPE and other plastics. As a result, this research will assume that 14% of *Mixed Paper* is office paper, that 50% of *Metal* is ferrous metal, that 33% of *Plastic* is HDPE and that 33% of *Plastic* is LDPE. These assumptions result from an inspection of the generation masses estimated in the CH2M report. Finally, the last complication with the recycling data provided by the GVRD, is the category listed as *mixed recyclables*. These are commingled recyclables that are only weighed prior to sorting, and as a result, the masses are differentiated into paper, glass, metal, etc..., categories. These *mixed recyclables*, 12,342 tonnes in 1998, are a relatively low 9% of the 132,880 tonnes of recyclables in that year. By using four municipalities in which there is no mass of *mixed recyclables*, Coquitlam, Langley Township, Maple Ridge and Surrey, it is possible to estimate an average percentage for

recyclables in the GVRD. This average percentage is applied to *mixed recyclables* and added to the appropriate category. This is presented in Table 2-9: Correction for Mixed Recyclables, on the following page.

Backyard composting is estimated by the number of composters active in each municipality. While it is estimated by the GVRD that each composter annually diverts 250 kg of food scraps and yard trimmings from collection (Pers. comm. Bev Weber), it is further necessary to separate these two masses. By what is essentially a best-guess, this author assumes that 167 kg of the diverted waste was yard trimmings and that 83 kg was food scraps (or two parts yard trimming to each part food scraps). This guess results from the authors' understanding that backyard composting vessels are used more frequently for managing yard waste than food waste.

Unfortunately, the GVRD does not possess any municipality-specific data on the collection of specific recyclables from ICI sources because of the numerous private haulers which overlap jurisdictional boundaries. They only have ICI recycling data for the entire GVRD region. Since this research requires the ICI recycling rate of specific recyclables, the total mass of ICI recyclables divided by the total mass of ICI waste (pre-recycling) is assumed to serve as the recycling rate for the individual waste components analyzed in this thesis. Both masses were provided by the GVRD.

With all these assumptions, it is hoped that when data collection improves, new inputs can be provided to the spreadsheet program.

Using the City of Burnaby as an example, the wastes generated, the wastes recycled and the wastes disposed are presented in Table 2-10 on the following page. Similar tables for each of the other municipalities are included in WS #5 to WS#25. It requires noting that Anmore and Belcarra have been included with the City of Port Moody. Also, Matsqui has been included along with the City of Abbotsford (at the time of the CH2M Hill report these were separate municipalities but have now been amalgamated). As previously discussed, by subtracting the waste recycled and composted ( $M_{\text{REC}}$  &  $M_{\text{COM}}$ ) from the waste generated ( $M_{\text{GEN}}$ ), the mass of waste disposed ( $M_{\text{DIS}}$ ) can be calculated.



Table 2-9: Correction for Mixed Recyclables

1998 - RESIDENTIAL RECYCLING PROGRAMS IN THE GVRD - WMA - RECOVERED TONNES BY MATERIAL

	ONP	Mxd Ppr	OCC	Glass	Metal*	Plastic	Mixed Recyclables	TOTAL
Abbotsford	3104	553	2849	318	202	119	0	7145
Burnaby	3496	3620	290	54	715	58	1541	9774
Coquitlam	2605	1960	120	636	199	222	0	5742
Delta	2251	2170	1065	824	583	322	0	7215
Langley City	539	351	438	117	37	41	0	1523
Langley Township	2607	565	630	652	391	130	0	4975
New Westminster	1060	678	117	2	366	10	271	2504
North Vancouver City	1489	440	78	17	26	5	485	2540
North Vancouver District	3456	1092	131	29	44	9	1170	5931
Maple Ridge	1644	466	2969	333	965	25	0	6402
Pitt Meadows	255	270	0	0	0	0	125	650
Port Coquitlam	0	0	0	0	0	0	1944	1944
Port Moody	198	474	117	199	86	61	171	1306
Richmond	4455	3322	159	30	298	10	1631	9905
Surrey	7497	5551	0	1605	516	561	0	15730
Vancouver	8428	7254	575	131	2653	31	3961	23033
West Vancouver	2162	683	81	18	28	5	719	3696
White Rock	375	676	61	0	0	0	219	1331
Electoral Area A	99	962	277	42	214	9	105	1708
Electoral Area C	46	35	62	43	9	2	0	197

\* -the value for Surrey is for 1999 as the correct value for 1998 is unavailable.

RELATIVE PERCENTAGES:

Coquitlam	45	34	2	11	3	4	0	100
Langley Township	52	11	13	13	8	3	0	100
Maple Ridge	26	7	46	5	15	0	0	100
Surrey	48	35	0	10	3	4	0	100

AVERAGE PERCENTAGE USED AS REPRESENTATIVE OF GVRD:

Average Mix	43	22	15	10	7	3	0	100
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CORRECTED RECYCLABLE MASSES:

	ONP	Mxd Ppr	OCC	Glass	Metal	Plastic	TOTAL
Abbotsford	3104	553	2849	318	202	119	7145
Burnaby	4155	3959	526	207	829	98	9774
Coquitlam	2605	1960	120	636	199	222	5742
Delta	2251	2170	1065	824	583	322	7215
Langley City	539	351	438	117	37	41	1523
Langley Township	2607	565	630	652	391	130	4975
New Westminster	1176	738	158	29	386	17	2504
North Vancouver City	1696	547	152	65	62	18	2540
North Vancouver District	3956	1350	310	145	131	40	5931
Maple Ridge	1644	466	2969	333	965	25	6402
Pitt Meadows	308	298	19	12	9	3	650
Port Coquitlam	832	428	297	192	144	51	1944
Port Moody	271	512	143	216	99	65	1306

Richmond	5153	3681	408	191	419	53	9905
Surrey	7497	5551	0	1605	516	561	15730
Vancouver	10122	8126	1180	523	2947	134	23033
West Vancouver	2470	841	191	89	81	24	3696
White Rock	469	724	94	22	16	6	1331
Electoral Area A	144	985	293	52	222	12	1708
Electoral Area C	46	35	62	43	9	2	197

Table 2-10: City of Burnaby Waste Generation, Recycling & Disposal

**MASS OF WASTE GENERATION (M<sub>GEN</sub>):**

Waste Material	Residential Generation	ICI Generation	Population of Municipality	Residential Generation	ICI Generation	Population of Municipality	Residential Generation	ICI Generation	Total Generation
	1991	1991	1991	per capita	per capita	1998	1998	1998	1998
	(tonnes)	(tonnes)		(kg/cap*yr)	(kg/cap*yr)		(tonnes)	(tonnes)	(tonnes)
Newsprint	8,279	3,602	158,858	52	23	191,600	9985	4344	14330
Mixed Paper	13,025	19,112	158,858			191,600			0
Office Paper	1,824	2,676	158,858	11	17	191,600	2199	3227	5426
Ferrous Metal	1,061	10,914	158,858	7	69	191,600	1280	13163	14443
Glass	2,069	2,979	158,858	13	19	191,600	2495	3593	6088
HDPE	690	1,213	158,858	4	8	191,600	832	1463	2295
Mixed Plastics	3,695	8,541	158,858			191,600			
LDPE	1,663	3,843	158,858	10	24	191,600	2005	4636	6641
Food Waste	5,451	11,116	158,858	34	70	191,600	6574	13407	19982
Yard Waste	5,433	4,261	158,858	34	27	191,600	6553	5139	11692

Total ICI waste generated in 1998= 164,172tonnes

Total ICI waste recycled in 1998= 67,479tonnes

ICI Recycling Rate= 41%

# of backyard composters = 8,968

**MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):**

Waste Material	Residential Generation	ICI Generation	Residential Recycling	Backyard Composting	Centralized Composting	ICI Recycling	Total Recycling	Backyard Composting	Centralized Composting
	1998	1998	1998	1998	1998	1998	1998	1998	1998
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
Newsprint	9,985	4,344	4,155			1,786	5,941		
Mixed Paper			3,959						
Office Paper	2,199	3,227	554			1,326	1,881		
Metal			829						
Ferrous Metal	1,280	13,163	415			5,411	5,825		
Glass	2,495	3,593	207			1,477	1,684		
Plastics			98						
HDPE	832	1,463	32			601	634		
LDPE	2,005	4,636	32			1,905	1,938		
Food Waste	6,574	13,407		744	0	5,511		744	5,511
Yard Waste	6,553	5,139		1,498	8,004	2,112		1,498	10,116

Total waste disposed in 1998= 129,089tonnes

Total waste recycled in 1998=

87,526 tonnes

**MASS OF WASTE DISPOSED ( $M_{DIS}$ ):**

Waste	Total	Total	Waste
Material	Generation	Recycling	Disposal
	1998	1998	1998
	(tonnes)	(tonnes)	(tonnes)
Newsprint	14330	5,941	8,389
Office Paper	5426	1,881	3,546
Ferrous Metal	14443	5,825	8,618
Glass	6088	1,684	4,405
HDPE	2295	634	1,662
LDPE	6641	1,938	4,703
Food Waste	19982	6,255	13,727
Yard Waste	11692	11,614	78
Remainder		51,755	83,962

When estimating the masses of wastes in this manner several errors occur however. In eight municipalities it is estimated that more yard waste is composted than is even generated. These municipalities are: Abbotsford, City of North Vancouver, District of North Vancouver, City of Port Coquitlam, City of Richmond, District of West Vancouver and Electoral Area A. Either the yard waste generation estimate by CH2M Hill was too low or the amount of yard waste generated in these municipalities has increased faster than the population. Rather than have negative values for the mass of yard waste disposed in these municipalities (the subtraction of waste generated and waste composted), the generation estimate is ignored and the mass of yard waste disposed is set at zero.

Special modifications are also necessary for Electoral Area A (U.B.C./U.E.L.) and Electoral Area C (Bowen Island/Howe Sound). ICI waste generation is not considered for Electoral Area A in the CH2M report. It appears that U.B.C. was combined with the City of Vancouver from the perspective of ICI waste for that report. As a result, this research uses the ICI waste generation per capita values developed for the City of Vancouver. Another necessary modification at this Electoral Area occurs in response to the fact that accurate data on recycling in 1998 is not available. However, 1999 values are available and are used instead. ICI data on Electoral Area C is also not available. However, personal communication with Mike Stringer has informed this author that the assumption of zero ICI activity from this Electoral Area is acceptable.

## 2.10 REMAINING WASTE

This thesis assesses specific waste components with the intent that the current participation in source-separation could be more effectively focused on GHG emission reducing activities. It has also been observed that previous greenhouse gas studies limit their accuracy and effectiveness by regarding municipal solid waste as a single entity. While this study analyzed specific components to make the research of greater value, problems still arise. After the eight investigated components of solid waste are removed, there will still be waste remaining. This is waste which does not fall under the categories of newsprint, office paper, ferrous metal, glass, HDPE, LDPE, food scraps or yard trimmings. For purposes of this research, this remaining waste is defined as *Remainder*. The Remainder may include such items as corrugated cardboard, textiles, rubber, aluminum, other plastics in addition to many other materials. Using this category, Remainder, is necessary due to the large number of materials represented in the municipal solid waste stream. Assessing all of the various pieces far outstrips the available time and funding for this work. In fact, in an extensive undertaking by the USEPA (1998) similar to this, only 11 individual components of the MSW stream were analyzed; this was estimated to only account for 55% of total waste generated in the United States.

Three sources of reference are used to determine the materials represented in the Remainder. The most important of these is the CH2M Hill report completed for the GVRD in 1993 (GVRD 1993). Data from Franklin Associates Ltd (FAL 1998) and Tchobanoglous (1993) is also provided to provide readers with a 'ball-park' of estimates by other organizations. This data is presented in the table below.

Table 2-11: Waste Percentages

COMPONENT	PERCENTAGE OF MSW GENERATION	PERCENTAGE OF RESIDENTIAL MSW DISPOSED
	FAL (1998) <sup>1</sup>	Tchobanoglous et al. (1993) <sup>2</sup>
Newsprint	5.9%	Total Paper=36%
Office Paper	3.2%	Total Paper=36%
Steel Cans <sup>3</sup>	1.3%	5.8
Glass	5.3%	9.1
HDPE	0.6%	Total Plastics=7%
LDPE	0.01%	Total Plastics=7%
Food Scraps	10.4%	8.0
Yard Trimmings	13.4%	17.3
	<b>Total=40.1%</b>	<b>Not applicable</b>

<sup>1</sup> Percentage of 1996 United States generation of MSW.

<sup>2</sup> Typical Composition of 1990 U.S. residential MSW (including recyclables).

<sup>3</sup> It requires noting that the definition of steel cans is narrower than the category of ferrous metal used in this thesis.

Now in 1991, the GVRD disposed of 1,128,000 tonnes of waste from all residential and ICI sources. The 1993 CH2M Hill report estimated what materials constituted this 1,128,000 tonnes. These estimates are provided in the following table (the low and high range estimates have been removed):

Table 2-12: Waste Estimates by CH2M Hill Engineering

Waste Type	Tonnage	Percent of Total
<b>Paper</b>	<b>368700</b>	<b>32.7</b>
Newspaper	68700	6.1
Corrugated Cardboard	108200	9.6
Fine	27000	2.4
Glossy Magazines, Fliers, Books	24300	2.2
Packaging Paper	46300	4.1
Other Paper	94300	8.4
<b>Glass</b>	<b>32900</b>	<b>2.9</b>
Food and Beverage Containers	26500	2.3
Other Glass	6400	0.6
<b>Metal</b>	<b>57800</b>	<b>5.1</b>
Aluminum Food and Beverage	4000	0.4
Ferrous Food and Beverage	14800	1.3
Other Ferrous and Aluminum	25300	2.2
Non-Ferrous	3200	0.3
Other/multi-material	10500	0.9
<b>Plastic</b>	<b>98800</b>	<b>8.8</b>
PET Food and Beverage	1700	0.2
HDPE Food and Beverage	6800	0.6
Film and Bag Plastics (LDPE)	42300	3.7
PVC	9200	0.8
Expanded Polystyrene (PS)	5900	0.5
Other Plastics	14200	1.3
Multi-Resin Materials	18700	1.7
<b>Organics</b>	<b>361000</b>	<b>32.0</b>
Food Waste	95200	8.4
Yard Waste	124100	11.0
Landclearing/landscaping	27700	2.5
Wood Waste	68300	6.1
Miscellaneous Organics	45700	4.0
<b>Rubber</b>	<b>8200</b>	<b>0.7</b>
Used Tires	2200	0.2
Other Rubber	6000	0.5
<b>Natural Textiles and Leather</b>	<b>41300</b>	<b>3.7</b>
Natural Textiles	38100	3.4
Leather	3200	0.3
<b>Other/White Goods</b>	<b>1100</b>	<b>0.1</b>
Bulky Goods	9800	0.9
Construction, Demolition	22600	2.0
Miscellaneous Combustibles	15400	1.4
Non-Combustibles	32900	2.9
Household Hazardous	11300	1.0
Other Materials	66500	5.9
<b>TOTAL =</b>	<b>1,128,000</b>	<b>100.0</b>

Table 2-12 can be altered in two ways. Firstly, the eight investigated components of this research (newsprint, office paper, ferrous metal, glass, HDPE, LDPE, food scraps or yard trimmings) can be removed. For the component, *Other Ferrous and Aluminum*, 80% will be assumed to consist of ferrous metal. Secondly, the remaining materials will be consolidated into their respective categories. The new table is below:

Table 2-13: Components of the Remainder

Waste Type	Tonnage	Percent of Remainder
Paper	273100	39.2
Metal	22800	3.3
Plastic	49700	7.1
Organics	141700	20.3
Rubber	8200	1.2
Natural Textiles and Leather	41300	5.9
Other/White Goods	1100	0.2
Bulky Goods	9800	1.4
Construction, Demolition	22600	3.2
Miscellaneous Combustibles	15400	2.2
Non-Combustibles	32900	4.7
Household Hazardous	11300	1.6
Other Materials	66500	9.5
<b>TOTAL =</b>	<b>696,400</b>	<b>100.0</b>

The remaining waste fraction, estimated at 62% of the total waste stream, requires investigating from a GHG perspective. Specifically: What is the potential for landfill methane emissions? What is the potential for landfill carbon sequestration? What is the energy to be derived from incinerating the Remainder? If the waste is combustible, does it release biomass carbon or fossil carbon? Does the Remainder contain any reactive nitrogen which could contribute N<sub>2</sub>O emissions? These are the necessary questions to determine the GHG consequences of disposing of the Remainder. However, an important fraction of the Remainder is also recycled. The recycling of old corrugated cardboard (OCC) and mixed waste paper (MWP) occurs throughout the GVRD. This is the fate of much of the Remainder. In addition to the GHG implications of disposing of the Remainder in a landfill or incinerator, it is important to assess the GHG benefits or impacts of recycling part of the Remainder. Both disposal and recycling are discussed below.

The first two questions, landfill methane and landfill carbon sequestration, are inter-related due to the partitioning of the *carbon available for anaerobic decomposition* and the *carbon entering sequestration*. As it is difficult to estimate a carbon storage factor (CSF) for the wastes in Table 2-13, this thesis could default to using the CSF for mixed MSW published in USEPA (1998). This CSF is 0.18 tonnes of carbon sequestered per wet tonne of MSW. As the lignified newsprint and yard waste has already been investigated individually, this author believes it is more appropriate to half this CSF - reduce it by 50%. As a result, the CSF used in the Model is assumed to be 0.09 tonnes C per wet tonne of MSW. If this is the *carbon entering sequestration*, what is the *carbon available for anaerobic decomposition*? The carbon to provide methane emissions will be the initial biodegradable carbon which is not sequestered. It will be contributed by *paper products* (39.2%), *organics* (20.3%), *natural textiles and leather* (5.9%) and *miscellaneous others*. In fact, these pieces represent well over half of the Remainder; 70% will be assumed. For lack of more accurate estimates, this research assumes the carbon content measured for mixed MSW, 40%, is appropriate for this 70% organic fraction. Also a moisture content of 30% is assumed. With these assumptions it is possible to calculate the landfill disposal implications of the Remainder. This is developed in Appendix K.

The next two questions, energy generation and the partition of biomass carbon or fossil carbon, are important for waste incineration. The net energy content of mixed MSW has been reported as 11,600 kJ/kg in USEPA (1998). While this included the materials already investigated individually, it is used here as an approximate energy content of the Remainder. To answer the second question, it is important to take from Table 2-13 that combustible organics consists of *paper products* (39.2%), *organics* (20.3%), *plastics* (7.1%), *natural textiles and leather* (5.9%) and *miscellaneous combustibles* (2.2%). By using a carbon content for plastics of 85% (see Appendix G) with the percentage mass of plastics (7.1%), and a negligible moisture content, it can be calculated that each tonne of Remainder contains 60.4 kg of fossil carbon. By using a dry carbon content for biodegradable organics of 50% (in Tchoganoglous et al. (1993) most carbon contents are between 45 and 60%) with the percentage mass of biodegradable organics (approximately 70%), and an assumed moisture content of 30%, it is possible to estimate that each tonne of Remainder contains 245 kg of biomass carbon [ $1000\text{kg} \times 0.70 \times (1 - 0.30) \times 0.50 = 245$ ]. Thus, fossil carbon represents only one carbon in 5 or 19.7% of total carbon. As a result, a fifth of all the CO<sub>2</sub> emissions from incineration of the Remainder are attributable to the fossil carbon in plastics. Expressed differently, 0.060 tonnes of fossil carbon will be emitted as CO<sub>2</sub> during the incineration of one tonne of Remainder.

The final question is: Does the Remainder contribute any N<sub>2</sub>O emissions? For simplicity purposes, this study assumes that all the reactive nitrogen in MSW is represented in the food and yard wastes already assessed. However, there is a possibility that nitrogen exists in wood wastes and textiles. If future work demonstrates that nitrogen is an important component of the Remainder, this assumption will underestimate the emissions.

The largest component of the Remainder is paper at 39%. This is likely old corrugated cardboard (OCC), magazines and other mixed papers. This is also the portion of the Remainder which is most likely to be recycled to the greatest extent and not disposed of. OCC and mixed waste paper (MWP) are typically two categories of recyclables in the waste field which are appropriate for discussion here. Other potential recyclables could also be plastics other than HDPE or LDPE and metal other than ferrous. However, the masses of these materials are just a fraction of the paper component. As a result, only paper will be evaluated here.

Are there any GHG implications for recycling the OCC and MWP components of the Remainder? MWP probably suffers from the same uncertainty Section 2.6 demonstrated for newsprint and office paper. Section 2.6 developed the assumption that no GHG benefit results by recycling these materials – likely appropriate for MWP. FAL and Tellus estimated the GHG benefit of recycling corrugated cardboard boxes which was published in USEPA (1998). Both of these consulting firms estimated that the manufacturing of recycled cardboard boxes caused *greater* GHG emissions than the manufacturing of virgin cardboard boxes. FAL estimates 1.09 tCO<sub>2</sub>e/tonne to produce virgin cardboard and 1.61 tCO<sub>2</sub>e/tonne to produce recycled cardboard. Tellus estimates 1.93 tCO<sub>2</sub>e/tonne to produce virgin cardboard and 2.18 tCO<sub>2</sub>e/tonne to produce recycled cardboard. These emissions include transportation-related emissions. There is a large

spread between these estimates. This author is not very confident with the accuracy of these estimates – they are probably as uncertain as the other paper products. As a result, the safest assumption is to believe that no GHG benefit occurs when recycling OCC and MWP out of the Remainder and since OCC and MWP are being used as proxies for recycling of the Remainder, zero GHG benefit is assumed for Remainder.

## **2.11 GHG EMISSIONS NOT INVESTIGATED**

As there is a tremendous number of sources of greenhouse gases and the use of fossil fuels is so pervasive in Canada, this analysis cannot attempt to quantify all the possible emissions from waste management. There are likely to be thousands of individual sources of GHG emissions resulting from the direct and indirect operations associated with waste management. As a result, the development of this analysis has tried to focus only on the most significant and quantitatively important emissions.

Examples of the GHG emissions not investigated include:

- Coal consumed during the refining of iron ore to produce steel for collection vehicles, transfer trucks and construction of the Burnaby Incinerator.
- Fossil fuels consumed during the construction of the landfills, transfer stations and the Incinerator.
- Greenhouse gases from the upstream production of diesel fuel.
- Greenhouse gases from the upstream production and transmission of natural gas.
- Electricity consumption for waste management facilities (except at the Incinerator, where it was included to demonstrate the minor importance of this issue).
- Displacement of the emissions associated with the manufacture of chemical fertilizers (especially nitrogenous fertilizers) through the use of compost.

It should be mentioned that rough calculations have indicated that construction-related GHG emissions are of virtually no importance when investigating the GHG's per tonne of waste over the lifetime of an incinerator or landfill. Using the Burnaby Incinerator as an example, and by assuming that 1000 tonnes of concrete and 1000 tonnes of steel were used during its construction, it is possible to demonstrate these calculations. Using a published GHG emission factor for cement of 0.5 tCO<sub>2</sub>e per tonne cement (Environment Canada 1997a), and assuming that a third of concrete is actually cement, it can be calculated that 170 tCO<sub>2</sub>e will result from the 1000 tonnes of concrete in the Incinerator. By using a life-cycle GHG emission estimate developed for the fabrication of steel cans, 4.5 tCO<sub>2</sub>e per tonne of steel cans, it is possible to calculate that 4,500 tonnes of CO<sub>2</sub> will be emitted to manufacture the 1000 tonnes of steel used in the Incinerator. However, when these emissions are divided by an assumed 30 year life of the Incinerator which combusts 250,000 tonnes of waste annually, it turns out that only 0.0006 tCO<sub>2</sub>e results per tonne of waste over the Incinerator's lifetime. This is less than one kg of CO<sub>2</sub> per tonne of waste. By the response indicated by this rough calculation, it is deemed safe to ignore any construction-related GHG emissions.



## 2.12 STANDARDS

There are three standards consistently used throughout this report which are noteworthy to minimize the potential for confusion. These are:

- The unit for assessing greenhouse gas emissions.
- The moisture content convention used.
- The consistent use of 'wet' waste or 'as-is' basis for reporting.

Throughout this report, the greenhouse gas emission will be quantified as a unit of tonnes of carbon dioxide equivalent and signified as tCO<sub>2</sub>e. The "equivalent" refers to the use of Global Warming Potentials (See Section 2.2) to calculate all GHG's in terms of CO<sub>2</sub>. It should be noted that this unit needs to be recognized, since in climate change circles a standardized unit has not yet been developed. Some reports might refer to tonnes of CO<sub>2</sub> while others may refer to tonnes of carbon or MTCE (metric tonnes of carbon equivalent). The conversion from a mass of CO<sub>2</sub> to a mass of carbon is simple enough, it only requires multiplying by the difference in molecular mass:

$$\text{tCO}_2\text{e} = \frac{44\text{g/mol of CO}_2}{12\text{g/mol of C}} * \text{MTCE}$$

$$\text{MTCE} = \frac{12\text{g/mol}}{44\text{g/mol}} * \text{tCO}_2\text{e}$$

The convention used for calculating moisture content in this study is the wet-weight method of measurement; the method most commonly used in the field of solid waste management (Tchobanoglous et al. 1993). As defined in the engineering handbook, *Integrated Solid Waste Management*, percentage moisture content is the mass of the water divided by the wet mass of the material (ibid).

The masses of all waste components in this report are consistently wet weight, on an as-is basis for typical waste. The use of dry weight for the wastes does occur in several calculations and is specified as such.

## ***RESULTS & DISCUSSION***

The results of the entire GHG analysis are presented in this chapter. These results include the investigation of the GVRD's existing solid waste management system (Section 3.1 – *Existing System*) and the greenhouse gas response of the eight scenarios assessed (Section 3.2 – *Scenarios*). These results are presented together with a discussion of their importance; the discussion being primarily concerned with evaluating the emissions for their implications to emissions trading and emissions taxing. In addition, future legislation to reduce GHG emissions, the so called command-and-control regulations, will be discussed in the context of its particular importance to the emissions trading opportunities identified. The Conclusions & Recommendations in Chapter 4 will complete this thesis.

Both positive and negative GHG emissions are presented and discussed in this chapter. Positive GHG emissions contribute to Global Climate Change while negative GHG emissions result from activities which actually reduce GHG emissions and help to offset the positive emissions. These negative GHG emissions are in fact of benefit from a GHG perspective. Readers should be aware that negative emissions and GHG benefits are used interchangeably throughout this chapter. Negative GHG emissions are benefits with no negative sign necessary but when benefits are discussed in this chapter the negative sign in front of the emission will remain.

### **3.1 EXISTING SYSTEM**

Results of this research are the greenhouse gas emission estimates (Worksheet #1) calculated by multiplying the waste tonnages (Worksheet #2) by the appropriate emission factors (Worksheet #3). Both the waste tonnages and emission factors are estimates themselves; their development is described in Chapter 2 – *Methodology* and the appendices. Results in this thesis are estimated for wastes generated and managed in 1998. All calculations estimate what are the GHG emissions resulting from wastes in that year. Namely, the waste tonnages are for 1998 and the emission factors have been developed to model the approximate emissions to be expected from the management processes. Incineration, composting and recycling are essentially immediate activities, but it is necessary to model landfill methane emissions into the future while remembering that these greenhouse gases are from the wastes disposed in 1998 (and not from waste disposed in other years).

The emission factors, waste mass estimates and GHG emissions from all of the municipalities are provided in Appendix L – *Spreadsheet Program* and Worksheets #1, #2 and #3. In this section, the largest municipality of the GVRD, the City of Vancouver, will be discussed in detail as an example. The discussion of this municipality is readily applicable to the others. Only two significant figures are provided with the emissions

data presented in this section. As a result, slight differences can occur between the numbers here and the values in the spreadsheet.

The crux of this thesis is to create the GHG emission factors. Their development comprised the majority of the effort in this work. However, emission factors are of little use without waste masses to multiply with. Both waste mass estimates and emission factors for the City of Vancouver are presented and analyzed here.

Vancouver is the largest member municipality of the GVRD with a 1998 population of 552,481 and significant ICI activity. While 206,323 tonnes of waste was recycled in 1998, 346,991 tonnes of waste remained for disposal. Of the wastes collected for disposal, 225,740 tonnes went to the Vancouver Transfer Station, 83,761 tonnes went to the North Shore Transfer Station, 22,374 tonnes went to the Coquitlam Transfer Station, 8,899 tonnes went directly to the Vancouver Landfill and 6,217 tonnes went directly to the Burnaby Incinerator. When considering the waste flows out of the transfer stations in 1998, Worksheet #5 – *General Parameters* calculates that approximately 68% of Vancouver's waste was disposed at the Vancouver Landfill, with the Cache Creek Landfill taking 18% and 14% going to the Burnaby Incinerator. Or as tonnes, 236,061 tonnes was disposed at the Vancouver Landfill, 61,290 was disposed at the Cache Creek Landfill and 49,641 tonnes was combusted at the Burnaby Incinerator. The estimates for each waste component are provided in the table below. The eight materials individually assessed (newsprint, office paper, ferrous metal, glass, HDPE, LDPE, food scraps and yard trimmings) represent 42% of the disposed waste stream and 42% of the recycled stream. The Remainder fraction makes up the remaining 58% of the disposed waste and 58% of the recycled materials.

Table 3-1: Waste Mass Estimates for the City of Vancouver (tonnes)

	Cache Creek Landfill	Vancouver Landfill	Burnaby Incinerator	Recycling	Backyard Composting	Centralized Composting	TOTAL
Newsprint	4,669	17,984	3,782	15,178			41,614
Office Paper	1,813	6,981	1,468	5,284			15,545
Metal	4,531	17,451	3,670	17,187			42,840
Glass	2,741	10,556	2,220	5,516			21,033
HDPE	891	3,431	722	2,112			7,155
LDPE	2,285	8,801	1,851	5,053			17,990
Food Scraps	7,319	28,190	5,928		1,979	16,837	60,253
Yard Trimmings	1,235	4,758	1,001		3,981	28,112	39,087
Remainder	35,806	137,907	29,000	105,084			307,797
<b>TOTAL</b>	<b>61,290</b>	<b>236,061</b>	<b>49,641</b>	<b>155,414</b>	<b>5,960</b>	<b>44,949</b>	<b>553,314</b>

The best-guess emission factors (tCO<sub>2</sub>e/tonne of waste) of each of Vancouver's waste management processes are presented in the table below.

Table 3-2: GHG Emission Factors for the City of Vancouver (tCO<sub>2</sub>e/tonne)

	Cache Creek	Vancouver	Burnaby		Backyard	Centralized
	Landfill	Landfill	Incinerator	Recycling	Composting	Composting
<b>Newsprint</b>	-1.2	-1.2	-0.41	0.0		
<b>Office Paper</b>	0.59	0.83	-0.34	0.0		
<b>Metal</b>	0.035	0.020	-1.2	-2.4		
<b>Glass</b>	0.035	0.020	0.016	-0.37		
<b>HDPE</b>	0.035	0.020	2.1	-1.7		
<b>LDPE</b>	0.035	0.020	2.1	-2.3		
<b>Food Scraps</b>	0.26	0.32	0.010		0.057	0.13
<b>Yard Trimmings</b>	-0.53	-0.50	0.058		-0.032	0.054
<b>Remainder</b>	-0.033	0.095	-0.020	0.0		

Important differences can be recognized in the emission factors above. Newsprint and office paper are discussed first. The most favourable disposal method for newsprint is landfilling, not incineration, with the Cache Creek Landfill the preferred site. In fact, landfilling and incineration are of greater benefit than even recycling. Landfilling of newsprint results in lower emissions (-1.2 tCO<sub>2</sub>e/tonne for Cache Creek and -1.2 tCO<sub>2</sub>e/tonne for Vancouver) than the Burnaby Incinerator (-0.41 tCO<sub>2</sub>e/tonne) largely because of landfill carbon sequestration. In fact, switching newsprint from the Incinerator to Cache Creek will reduce GHG emissions by 0.8 tCO<sub>2</sub>e/tonne. The calculations in Appendix C – *Newsprint Waste Management* find that landfill sequestration causes significant GHG benefits (-1.4 tCO<sub>2</sub>e/tonne) which more than compensates against the future methane emissions (0.17 tCO<sub>2</sub>e/tonne). While the combustion of newsprint at the Burnaby Incinerator generates carbon-neutral energy, some of which is used to offset natural gas consumption at Crown Packaging Limited (CPL), the GHG benefits are a fraction of that caused by landfill sequestration. The emission factors for the two landfills differ because of the slightly higher decay rate used to represent the wet Vancouver Landfill and because of the different transportation-related emissions. Office paper is delignified and provides far less resistance to anaerobic decomposition than newsprint. As a result, office paper exhibits a completely different GHG response. Office paper disposal at Cache Creek results in 0.59 tCO<sub>2</sub>e/tonne, disposal at Vancouver results in 0.83 tCO<sub>2</sub>e/tonne but incineration causes -0.34 tCO<sub>2</sub>e/tonne. With a greatly reduced carbon sequestration factor (-0.10 tCO<sub>2</sub>e/tonne) as compared to newsprint, the future methane emissions (0.80 tCO<sub>2</sub>e/tonne for Cache Creek) dominate. Once again the differences with the two landfills derive from decay rates and transportation. Even with the lower energy content of office paper, due to the presence of inert clays and fillers, important GHG benefits result from the generation of this carbon-neutral energy to offset natural gas. Now in the other direction, switching office paper from disposal in Cache Creek to combustion at the Incinerator results in emission reductions of nearly 1 tCO<sub>2</sub>e per tonne of office paper. Recycling is estimated to result in 0 tCO<sub>2</sub>e/tonne placing it in between incineration and landfilling as the preferred management method.

The four non-biodegradable waste components analyzed, ferrous metal, glass, HDPE and LDPE, greatly simplify matters at the landfills. Since these materials cannot contribute methane emissions, only transportation and equipment-related diesel fuel consumption causes emissions for the landfill disposal of these wastes. However, incineration and recycling processes are quite responsive to these wastes. The recycling of metal back to industry for the manufacture of new products offsets the mineral extraction and smelting which would otherwise be necessary. The utilization of recycled metal by industry results in substantial GHG benefits,  $-2.4 \text{ tCO}_2\text{e/tonne}$ , and is actually the largest GHG benefit observed in this research. Part of this benefit can also occur when metal passes through an incinerator. If ferrous metal is contained in the MSW sent to the Burnaby Incinerator, part of this metal is recovered from the ash by magnetic separation and sent to processors for recycling. A GHG benefit of  $-1.2 \text{ tCO}_2\text{e/tonne}$  has been estimated for metal sent to the Burnaby Incinerator to represent this additional recycling opportunity. Inert glass does not have any GHG response to landfilling or incineration (besides transportation) but results in benefits when recycled. Glass cullet has a reduced energy requirement for production when compared against raw materials, thereby causing recycled glass to have a GHG benefit of  $-0.37 \text{ tCO}_2\text{e/tonne}$ . The high and low-density polyethylene plastics result in significant GHG emissions when incinerated,  $2.1 \text{ tCO}_2\text{e/tonne}$ . This results from the fact that these materials are made from petroleum products and therefore consist of fossil-carbon. Upon combustion, the resulting fossil-based  $\text{CO}_2$  causes a large GHG emission ( $3.1 \text{ tCO}_2\text{e/tonne}$ ) which is only partly compensated by the energy benefit ( $-1.1 \text{ tCO}_2\text{e/tonne}$ ). These issues cause incineration to be the least attractive disposal method from a GHG perspective. However, substantial benefits can be realized by recycling plastic. A benefit of  $-1.7 \text{ tCO}_2\text{e/tonne}$  occurs when recycled HDPE replaces virgin production and a benefit of  $-2.3 \text{ tCO}_2\text{e/tonne}$  occurs when recycled LDPE also replaces virgin production.

Food scraps and yard trimmings are the last two waste components analyzed individually. Both will decompose anaerobically in a landfill but only yard trimmings will provide significant landfill carbon sequestration ( $-0.75 \text{ tCO}_2\text{e/tonne}$  versus  $-0.09 \text{ tCO}_2\text{e/tonne}$  for food scraps). Food scraps disposed at Cache Creek result in  $0.32 \text{ tCO}_2\text{e/tonne}$ . This is a combination of future methane ( $0.40 \text{ tCO}_2\text{e/tonne}$ ), energy generation ( $-0.06 \text{ tCO}_2\text{e/tonne}$ ), landfill sequestration ( $-0.088 \text{ tCO}_2\text{e/tonne}$ ) and nitrous oxide emissions ( $0.038 \text{ tCO}_2\text{e/tonne}$ ). Using a slightly higher decay rate to represent the Vancouver Landfill, the overall emission factor is  $0.41 \text{ tCO}_2\text{e/tonne}$ . The increase is caused by the higher future methane emission. It is valuable to compare this landfill disposal against incineration. Energy generation at the Burnaby Incinerator contributes a benefit of  $-0.10 \text{ tCO}_2\text{e/tonne}$  which is largely cancelled by  $\text{N}_2\text{O}$  emissions. Together with the transportation-related emissions, an overall emission factor of  $0.010 \text{ tCO}_2\text{e/tonne}$  is estimated. Diverting food waste from Cache Creek to incineration can provide an emission reduction of  $0.33 \text{ tCO}_2\text{e/tonne}$ . Both backyard and centralized composting result in higher emissions than incineration but are still preferable over landfilling. Backyard composting causes  $0.057 \text{ tCO}_2\text{e/tonne}$  strictly from  $\text{N}_2\text{O}$  emissions. Centralized composting also causes  $0.057 \text{ tCO}_2\text{e/tonne}$  from  $\text{N}_2\text{O}$  but has been estimated to also release  $\text{CH}_4$  ( $0.020 \text{ tCO}_2\text{e/tonne}$ ) due to inadequate aeration. Since composting does not present any opportunity to generate energy and subsequently offset fossil-based

energy production, it does not allow for the counteracting benefit that incineration has. From a strictly GHG perspective, ignoring any other environmental economic or social issues, it is preferable to incinerate food waste than to compost it.<sup>3</sup>

Two other management alternatives exist for food waste generated in the GVRD but were not analyzed by this thesis. Kitchen waste disposal units (garburators) likely manage appreciable quantities and International Bio-Recovery in North Vancouver is a new company testing and marketing their aerobic digestion technology. The household waste disposal units send the shredded food waste to the nearest wastewater treatment plant where it is oxidized to CO<sub>2</sub>. As this treatment utilizes aerobic decomposition, it is similar to composting but there is energy consumption at the plant required for machinery. International Bio-Recovery uses aerobic digestion so is also similar to composting but may have considerable energy consumption. Steam from natural gas-fired boilers is first used to heat up a food waste slurry (to initiate digestion) and then steam is also used to dry a de-watered slurry to pellets. Electricity consumption is also necessary for the various pumps, aerators, shredders and mixers used at the facility. While it would be valuable to compare this process with traditional composting, its direct competitor, this organization has declined to participate in this research (Pers. comm. Fahimeh Mirminachi).

While readers may have found it thought-provoking that landfilling newsprint is of greater GHG benefit than even recycling, it is equally intriguing that sequestration causes landfill disposal of yard trimmings to be preferable over backyard or centralized composting. The overall emission factor for the disposal of yard trimmings at Cache Creek is -0.53 tCO<sub>2</sub>e/tonne and for the Vancouver is -0.50 tCO<sub>2</sub>e/tonne. These activities are of greater benefit than incineration (0.058 tCO<sub>2</sub>e/tonne), backyard composting (-0.032 tCO<sub>2</sub>e/tonne) and centralized composting (0.054 tCO<sub>2</sub>e/tonne). Given the choice, landfilling at Cache Creek is the preferred management method for yard trimmings. The significant landfill sequestration of yard waste (-0.75 tCO<sub>2</sub>e/tonne) more than compensates against the future methane emissions (0.18 tCO<sub>2</sub>e/tonne), and this is using a higher decay rate than used for paper which calculates that 77% of the Carbon Available for Anaerobic Decomposition actually degrades within the 20 year period. Both types of composting are estimated to release N<sub>2</sub>O and centralized composting also emits CH<sub>4</sub> as with the food waste, but in contrast, an assumption has been used to approximate the sequestration potential of finished compost. For both composting methods, it is assumed that -0.10 tCO<sub>2</sub>e/tonne serves as a GHG benefit.

Based on the assumed properties of the Remainder, as developed in Section 2.3 – *Remaining Wastes*, the GHG implications of landfilling, incineration and recycling are also developed. Disposal at Cache Creek (-0.033 tCO<sub>2</sub>e/tonne) is nearly equivalent to combustion at the Burnaby Incinerator (-0.037 tCO<sub>2</sub>e/tonne). With the higher decay rate assumed for the Vancouver Landfill, an emission factor of 0.10 tCO<sub>2</sub>e/tonne is estimated. Recycling of the remainder causes a GHG benefit of 0 tCO<sub>2</sub>e/tonne.

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<sup>3</sup> This is surprising result when considering that this author's original interest in this subject came from an attempt to demonstrate the GHG benefits of backyard composting over landfilling. Initially, incineration was not included as a waste management alternative.

The importance of transportation and equipment-related emissions to waste management is a relatively minor issue for landfilling and incineration. This research has found that methane, sequestration, energy benefits or nitrous oxide issues are of much greater value when calculating on a per tonne of waste basis. This fact can be effectively illustrated by sub-dividing some of the calculated emission factors in Table 3-2 into five distinct groups: Transport, Future Methane, Energy Utilization, Carbon Sequestration and Nitrous Oxide. The Transport group contains emissions resulting from curbside collection, transfer station equipment, transport to disposal facility and landfill equipment while the other groups are specific to landfilling or incineration. Using absolute values, all emissions are converted to positive numbers, it is possible to compare the percentage importance of these factors. Two examples are provided below. The first figure compares newsprint disposal at the Cache Creek Landfill, the Vancouver Landfill or at the Burnaby Incinerator. The second figure compares food waste disposal also at the Cache Creek Landfill, the Vancouver Landfill or at the Burnaby Incinerator.

Figure 3-1: Relative Importance of Emissions to Newsprint Disposal

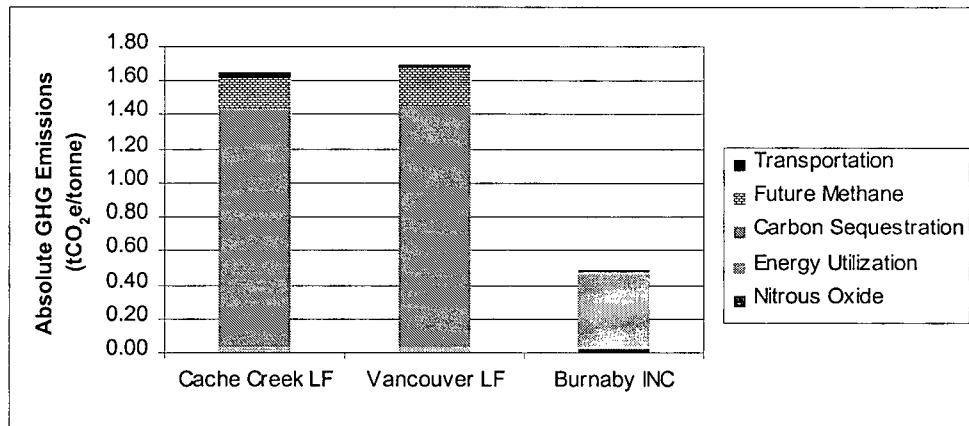
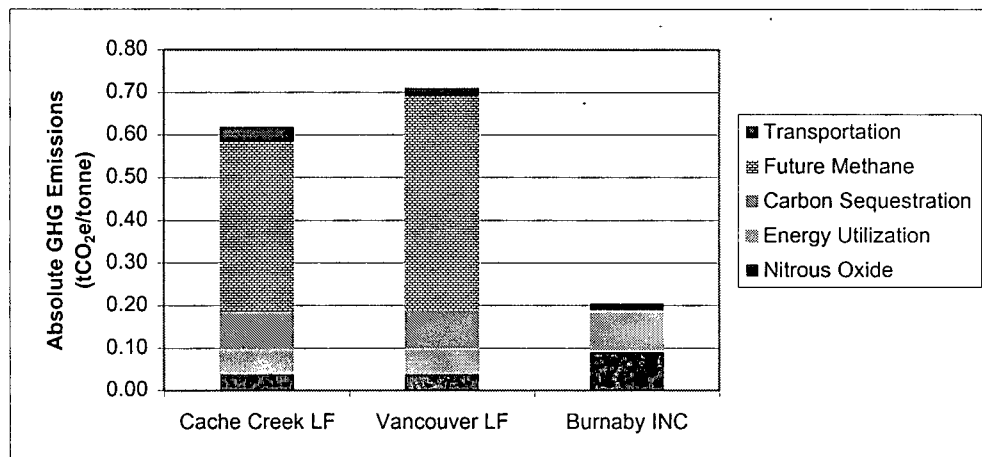


Figure 3-2: Relative Importance of Emissions to Food Waste Disposal



For newsprint disposal, transportation only represents 2% of the absolute GHG emissions at the Cache Creek Landfill, only 1% at the Vancouver Landfill and 3% of emissions at the Burnaby Incinerator. Carbon sequestration is of dominant importance at Cache Creek (86%) and at Vancouver (83%) while energy generation is of greatest importance at the Burnaby Incinerator (95%). During food waste disposal, transportation only represents 6%, 3% or 8% at the Creek Cache Landfill, the Vancouver Landfill or the Burnaby Incinerator. With food waste, future methane is of greatest value during landfilling (64% at Cache Creek and 71% at Vancouver) and energy utilization is the largest percentage during incineration (50%).

Carbon taxation of diesel fuel and other fossil fuels is a very real possibility in 5 or 10 years and could have an impact on the economics of waste transportation. To stave off any surprises, it would be in the GVRD's best interest to assess the unknown effect increased fuel costs could have on the system. However, the GVRD should be more concerned with future taxation on landfill methane emissions or the uncertain nitrous oxide releases for these have much greater quantities.



The Waste Mass Estimates of Table 3-1 are multiplied by the GHG Emission Factors of Table 3-2 to determine the GHG Emissions in Table 3-3 below.

Table 3-3: GHG Emissions from the City of Vancouver (tCO<sub>2</sub>e)

	Cache Creek	Vancouver	Burnaby		Backyard	Centralized	
	Landfill	Landfill	Incinerator	Recycling	Composting	Composting	TOTAL
Newsprint	-5800	-22000	-1500				-29,300
Office Paper	1100	5800	-500				6,400
Metal	160	340	-4300	-40000			-43,800
Glass	96	210	35	-2000			-1,659
HDPE	31	68	1500	-3600			-2,001
LDPE	80	170	3900	-11000			-6,850
Food Scraps	2400	12000	56		110	2100	16,666
Yard Trimmings	-660	-2400	58		-130	1500	-1,632
Remainder	-1200	13000	-580				11,220
<b>TOTAL</b>	<b>-3,793</b>	<b>7,188</b>	<b>-1,331</b>	<b>-56,600</b>	<b>-20</b>	<b>3,600</b>	<b>-50,956</b>

The City of Vancouver's waste management in 1998 is estimated to have a GHG emission of -50,956 tCO<sub>2</sub>e, or a GHG benefit of about -51,000 tCO<sub>2</sub>e. However, there is a range between +54,000 tCO<sub>2</sub>e for the high estimate and -106,000 tCO<sub>2</sub>e for the low estimate. The lion's share of the emission reduction is contributed by recycling operations -56,600 tCO<sub>2</sub>e during the management of 155,414 tonnes of material. Of particular note is the fact that while 236,091 tonnes of waste was disposed at the Vancouver Landfill in 1998, only 7,188 tCO<sub>2</sub>e is estimated to be emitted as greenhouse gases in the next 20 years. In fact, for the 61,290 tonnes of waste disposed at Cache Creek in 1998, a GHG benefit of -3,800 tCO<sub>2</sub>e is estimated and for the 49,641 tonnes combusted at the Burnaby Incinerator, a GHG benefit of -1,300 tCO<sub>2</sub>e occurs. Contrary to conventional understanding, the Cache Creek Landfill actually helps reduce the atmospheric concentrations of greenhouse gases rather than contribute to their increases (except if full decomposition with low gas collection is modelled). Backyard composting is estimated to result in -20 tCO<sub>2</sub>e during the management of 5,950 tonnes of food and yard waste. Centralized composting results in 3,600 tCO<sub>2</sub>e during the processing of 44,949 tonnes of food and yard waste. It is important to recognize that centralized composting is estimated to be a GHG contributor while the Cache Creek Landfill and the Burnaby Incinerator are actually of GHG benefit.

The total GHG emission estimates for all of the 20 municipalities analyzed are presented in the following table.

Table 3-4: GHG Emissions for the GVRD (tCO<sub>2</sub>e)

	Cache Creek Landfill	Vancouver Landfill	Burnaby Incinerator	Recycling	Backyard Composting	Centralized Composting	TOTAL
City of Abbotsford	-3000	1.0	0	-4600	-5.0	210	-7,394
City of Burnaby	-1,200	52	-1600	-20,000	-5.0	1,100	-21,653
City of Coquitlam	-5,600	130	-21	-3,100	-2.0	270	-8,323
Corporation of Delta	-350	370	-2.2	-5,700	-5.4	320	-5,368
City of Langley	-880	10	-0.32	-1,000	-0.3	39	-1,832
Township of Langley	-2,300	-5.0	40	-6,500	-2.4	240	-8,527
D. of Maple Ridge	-1,500	6.0	1.5	-3,100	-2.3	150	-4,445
New Westminster	-770	13	-210	-4,900	-1.2	190	-5,678
C. of North Vancouver	-500	-1.6	40	-4,800	-1.4	290	-4,973
D. of North Vancouver	-1,400	55	-620	-3,100	-4.5	470	-4,599
D. of Pitt Meadows	-560	-7.4	-0.46	-240	-0.4	10	-799
City of Port Coquitlam	-590	32	-1.6	-3,500	-3.1	170	-3,893
City of Port Moody	-780	-9.1	0.07	-1,300	0.0	110	-1,979
City of Richmond	-300	1,500	-140	-24,000	-4.3	1,400	-21,544
City of Surrey	-12,000	-550	11	-19,000	-3.7	940	-30,603
City of Vancouver	-3,800	7,400	-1300	-57,000	-13	3,600	-51,113
D. of West Vancouver	-310	8.3	-23	-1,900	-1.7	230	-1,996
City of White Rock	-14	320	0.03	-420	-1.1	20	-95
Electoral Area A	0.0	170	0.0	-890	0.0	38	-682
Electoral Area C	-97	-0.9	19	-29	0.0	0.4	-108
<b>TOTAL</b>	<b>-35,951</b>	<b>9,493</b>	<b>-3,807</b>	<b>-165,079</b>	<b>-57</b>	<b>9,797</b>	<b>-185,604</b>

The overall contribution of the GVRD's waste management system to Global Climate Change is a best-guess GHG emission of -184,970 tCO<sub>2</sub>e, or about -180,000 tCO<sub>2</sub>e, for the wastes of 1998. The high estimate for the GVRD is +116,000 tCO<sub>2</sub>e and the low estimate is -325,000 tCO<sub>2</sub>e. The overall total in the table above (-185,604) sums up the values for which only two significant figures are provided – this causes a slight difference. The system actually reduced GHG emissions by 180,000 tCO<sub>2</sub>e in 1998. Of course this estimate is highly dependant on where the boundaries of the investigation are drawn and what assumptions are made. The GHG benefits (the negative emissions) are largely a result of the utilization of recyclables to offset virgin production by industry, landfill carbon sequestration and energy generation during incineration. These benefits more than compensate the landfill methane, nitrous oxide or diesel fuel-transportation emissions. Furthermore, installing electricity generation at the Burnaby Incinerator or increasing the gas collection at landfills (two of many possible examples), could even increase these GHG benefits.

There are important caveats to the GVRD estimate presented above which require addressing. The future methane generation included in the previous table does not represent the ultimate decomposition of the organic materials but rather a time-dependent estimate for the 20 years after disposal. Based on the decay rate used, the Model calculates that just over half of the CAAD of the paper products and that just over three-

quarters of the CAAD of food and yard waste decomposes in 20 years. As a result, there is a strong potential for methane emissions to occur after 20 years, thus causing the Model to underestimate the complete future impact. Another caveat regards the valuable contribution of recycling to the GVRD system. The GHG benefit of recycling at the GVRD was estimated at  $-165,079 \text{ tCO}_2\text{e}$ . One could argue that this benefit is outside the authority of the GVRD (it is realized by industry) and as such should not be included here. Without recycling acting as a strong counteracting force to  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , transportation- $\text{CO}_2$  and others, the importance of these emissions increases. These caveats serve as an excellent transition to the next section, *Scenarios*. In response to the first caveat an ultimate decomposition scenario is presented and because of the second issue, another scenario removes the GHG implications of recycling from the Model.

### 3.2 SCENARIOS

The results of eight scenarios which can be programmed into the Model are presented in this section. The first five scenarios represent what could be future changes to the existing waste management system. These include such things as improvements in landfill methane collection, improvements in energy generation during incineration and allowing incineration to replace landfill disposal. The remaining scenarios demonstrate the response of the Model to changes in three controversial aspects of the GHG emission estimates. These aspects include allowing complete decomposition of the Carbon Available for Anaerobic Decomposition (CAAD), the removal of landfill carbon sequestration from the Model and the removal of any GHG benefits from recycling activities from the Model. Each of these scenarios are presented and discussed in detail in this section. All of these scenarios are discussed by comparing them to the existing system which was estimated to have an overall GHG impact of  $-180,000 \text{ tCO}_2\text{e}$ . However, the spreadsheet carries all values forward (not just significant figures) so the overall GHG emissions used for the existing system is actually  $-184,970 \text{ tCO}_2\text{e}$ . This existing system is the base-case against which the scenarios need to be analyzed so as to determine if the changes increase or decrease emissions. Units discussed in this section are  $\text{tCO}_2\text{e/yr}$  – while emissions were calculated for the wastes of 1998. By assuming that successive years have much the same masses and characteristics it is possible to extrapolate the emissions to future years as well. The actual programming changes necessary for the Model to determine these scenarios are described in Section 2.8.3 – *Modelling Scenarios*.

Landfill gas collection for flaring or energy utilization is of vital importance from the perspective of methane gas emissions to the atmosphere. While the spreadsheet estimates the GHG emissions of GVRD waste management in 1998, it is necessary to model the future methane emissions resulting from anaerobic decomposition at the landfills. Not only is the estimated future methane generation important but so is the question of what happens to gas collection in the future. The Model assumes that gas collection, either for flaring or energy utilization, will increase over the current rate and that an increasing fraction is used for energy. This is a safe assumption given the current provincial and federal regulatory interest in LFG to cause reductions in the national GHG emissions

inventory. This increasing gas collection may be in response to new legislation or to avoid paying new GHG emission taxes. Currently, the Cache Creek Landfill collects and flares an estimated 43% of generated methane and the Vancouver Landfill collects and flares an estimated 22%. Both of these facilities are assumed in the Model to linearly increase their collection so that by the year 2020, 75% of generated methane is captured and used for energy. What happens if these assumed improvements do not actually occur? Letting the current collection efficiency remain constant for the next 20 years is Scenario #1.

Scenario #1 results in +109,000 tCO<sub>2</sub>e/yr, a difference of 290,000 tCO<sub>2</sub>e just for the waste of one year, 1998. These are the emissions potentially available for emissions trading if the GVRD was to implement the LFG collection improvements as assumed in the Model. As indicated in Section 1.4, trading of emission reduction credits can be available to any organization that voluntarily reduces its own GHG emissions, i.e. it was not instructed to reduce by legislation. Assuming \$5 will be the average market value for a tonne of CO<sub>2</sub>e over the next two decades, there could be almost \$1.5 million available each year when an outside party purchases the emission credits of the GVRD. This could be a significant source of revenue to finance the actual LFG improvements.

A very real modification to this 290,000 tCO<sub>2</sub>e/yr credit for emission trading would be in the situation where legislation only goes part of the way to the methane collection improvements assumed. In this case, crediting would only be available to the voluntary emission reductions over and above that stipulated by regulations. This 290,000 tCO<sub>2</sub>e/yr credit would be appropriately decreased by the LFG improvements already necessary by legislation.

The second scenario, decreasing the fraction of steam sent to CPL from the current 56% to 37%, results from the fact that CPL has informed the GVRD that they will have a reduced need for steam in the future. Less steam used by CPL means reduced GHG benefits because this steam will no longer be displacing natural gas consumption. This scenario causes the total GVRD emissions to become -161,000 tCO<sub>2</sub>e/yr, an increase of 24,000 tCO<sub>2</sub>e/yr. Less steam offsetting the natural gas consumption at CPL logically removes part of the GHG benefit this Model had originally identified.

The GVRD together with Montenay Inc., the organization contracted to operate the Burnaby Incinerator, is exploring the potential for electricity generation at the Incinerator. This includes installing a turbo-generator and improving the boiler efficiency by raising the steam temperature from the current 250°C to 400°C. Scenario #3 demonstrates the significant GHG ramifications of this electricity generation since it offsets low efficiency natural gas electricity generation by the Burrard Thermal facility of BC Hydro. Using the new steam utilization by CPL of 37% and assuming about 6% of steam is used internally for plant operation, there is a remaining 57% of the steam available to make electricity. This improvement results in the overall GVRD emissions becoming -216,000 tCO<sub>2</sub>e/yr, a reduction of 55,000 tCO<sub>2</sub>e/yr when compared to the -161,000 tCO<sub>2</sub>e/yr GVRD emissions when 37% of steam went to CPL but no steam was used for electricity generation (Scenario #2). This entire emission reduction, 55,000

tCO<sub>2</sub>e/yr, could all be claimed as a credit, for it resulted from a voluntary project. Assuming once again that these credits would be sold at \$5/tCO<sub>2</sub>, about \$275,000 in revenue could be generated annually by implementing this project.

While extensive modelling of 8 waste management components and the Remainder was performed to estimate this 55,000 tCO<sub>2</sub>e/yr emission reduction, it is also possible to back calculate this amount as an effective check. About 820,000 tonnes of steam is generated annually at the Burnaby Incinerator with an energy content of 2.85 GJ/tonne steam for a total energy production of 2,337,000 GJ (Pers. comm. Richard Holt). Allowing 57% of this steam to be converted to electrical energy, at an efficiency of 32%, as an offset against Burrard Thermal (with a GHG emission intensity of 0.147 tCO<sub>2</sub>e/GJ), results in a GHG benefit of 62,661 tCO<sub>2</sub>e. The Model estimates the GHG benefit of generating electricity at the Incinerator as 55,000 tCO<sub>2</sub>e while the back-calculation determines a slightly greater GHG benefit of 63,000 tCO<sub>2</sub>e, an increase of 15%. Assuming that all the efficiencies at the Incinerator are correct, it is likely the energy content of the waste which is slightly off. The Model must be slightly underestimating the electrical energy which can be made at the Incinerator and therefore underestimating the GHG benefit. It is unclear where this energy content is being underestimated. This author hopes that future research will be able to tighten up these numbers so as to reduce any inaccuracies. For this thesis it will suffice to state that energy benefits of incineration may be slightly underestimated and could be larger in reality.

The fourth scenario is also a potential management change for the future. This scenario entails replacing all landfilling with incineration. This scenario uses a hypothetical Burnaby Incinerator as the disposal method even though the current facility is operating at capacity and could not accept any additional waste. The assumption that only 37% of steam is used by CPL and no steam is used to make electricity has an important effect on this scenario. The GVRD emissions become -67,000 tCO<sub>2</sub>e/yr when this scenario is implemented; an increase of 118,000 tCO<sub>2</sub>e/yr from the base-case. As the GHG emissions respond by increasing when incineration replaces landfilling, it would appear that landfill disposal is the preferred management method. However, the landfill methane is only estimated for 20 years and does not model the full impact of potential methane. By modelling the ultimate (complete) decomposition of the CAAD, essentially Scenario #6, it is possible to estimate the life-cycle impacts of landfilling. (Though this discussion is jumping ahead, it will suffice to state that ultimate decomposition in the existing GVRD system causes overall emissions of +147,000 tCO<sub>2</sub>e/yr.) Now the difference between -67,000 tCO<sub>2</sub>e/yr and +147,000 tCO<sub>2</sub>e/yr is a substantial GHG increase of 214,000 tCO<sub>2</sub>e/yr. As a result, switching from landfilling to incineration could result in a GHG benefit of 214,000 tCO<sub>2</sub>e/yr. Furthermore, this is incineration in which only 37% of the steam is used for energy; 6% is assumed to be used internally and 57% of the steam is unutilized. What happens to the emissions when greater energy generation occurs? Scenario #5 demonstrates the answer.

While still hypothetically having incineration replace landfilling and 37% of steam going to Crown, Scenario #5 includes allowing 57% of the steam to generate electricity. The overall GHG emissions drastically decrease to -303,000 tCO<sub>2</sub>e/yr; this is an emission

reduction of 118,000 tCO<sub>2</sub>e/yr from the existing GVRD system and an emission reduction of 450,000 tCO<sub>2</sub>e/yr from the ultimate decomposition variant discussed above. Both Scenarios #4 & #5 represent emissions trading opportunities well worth investigating. Depending on the baseline to compare against and still assuming \$5/tCO<sub>2</sub>e, Scenario #5 could realize between \$1.3 million and \$2.5 million each year just in credit trading revenue.

While the result of Scenario #6 has already been used for comparison purposes, this scenario has not been properly discussed. Landfill methane generation is a highly uncertain issue to accurately model. A 20 year time period was arbitrarily chosen so that appreciable quantities of methane would result while still staying within what could be a foreseeable future. During this reference time period not all of the Carbon Available for Anaerobic Decomposition (CAAD) will be realized. Thus, a limitation of this modeling is that it doesn't represent the complete impact of landfill disposal. Whereas incineration, composting and recycling are essentially immediate activities, the ultimate GHG implications of landfilling are not even ascertained after estimating 20 years of methane generation. Anaerobic decomposition of the organic waste, and methane/GHG emissions can result well beyond 20 years after disposal. To determine the complete life-cycle impact of landfilling, the decay rate constant needs to be increased so that all of the CAAD decomposes within the 20 years. This is Scenario #6; using the same assumed improvements in the LFG collection effectiveness at Cache Creek and Vancouver, it is estimated that the GVRD emissions are +147,000 tCO<sub>2</sub>e/yr. This is an increase of 330,000 tCO<sub>2</sub>e/yr over the existing system and demonstrates a possible complete impact of landfilling. While in the base-case, the Cache Creek Landfill pathway resulted in overall emissions of -36,000 tCO<sub>2</sub>e/yr and the Vancouver Landfill pathway resulted in overall emissions of +9,500 tCO<sub>2</sub>e/yr, under complete decomposition these emissions significantly increase. Disposal at the Cache Creek Landfill causes GHG emissions of +180,000 tCO<sub>2</sub>e/yr and disposal at the Vancouver Landfill causes GHG emissions of +120,000 tCO<sub>2</sub>e/yr. The GVRD organization has complete freedom to model methane in whichever manner it deems appropriate. However, consideration is required when trying to claim credits for all the prevented future methane emissions (as the future is obviously highly uncertain). This author has become acutely aware of this important issue after being exposed to individuals attempting to claim GHG credits by the diversion of organic waste from landfill disposal. While preventing future methane emissions will indeed occur, potential abuse can be a problem because overestimating methane, and thus overestimating the GHG benefits of diversion, is easily performed.

Scenario #7 is concerned with demonstrating the importance of the controversial landfill carbon sequestration issue to this model. If the GVRD was to decide that landfill carbon sequestration was an unacceptable GHG benefit to be included in the Model, it could be removed for the calculation of the GVRD's overall impact on the atmosphere. It requires noting that landfill carbon sequestration is still necessary to appropriately partition the organic-carbon into the fraction that can anaerobically decompose, the CAAD. Removing sequestration as a GHG benefit causes the GVRD system to have a GHG emission of 109,000 tCO<sub>2</sub>e/yr. Thus emissions increase by 294,000 tCO<sub>2</sub>e/yr; the Cache Creek Landfill goes from a previous -36,000 tCO<sub>2</sub>e/yr to 130,000 tCO<sub>2</sub>e/yr and the

Vancouver Landfill goes from 9,500 tCO<sub>2</sub>e/yr to 140,000 tCO<sub>2</sub>e/yr. Landfill carbon sequestration and recycling (as demonstrated in the last scenario) are extremely important in enabling the GVRD waste management system to be a net negative emitter of greenhouse gases.

The last scenario, Scenario #8, demonstrates the removal of any recycling GHG benefits from the Model. One could argue that emissions differences by manufacturing industries as a result of material choices are outside the authority of the GVRD waste management system. As a result, allowing the Model to include this GHG benefit to counteract such positive emissions like CH<sub>4</sub>, N<sub>2</sub>O or transportation-CO<sub>2</sub>, would be inappropriate. Removing this benefit, just as with landfill carbon sequestration, has a tremendous effect on the overall GVRD emissions. The emission of the system becomes -21,000 tCO<sub>2</sub>e/yr for an increase of 164,000 tCO<sub>2</sub>e/yr. Allowing a recycling benefit to be claimed by the organization which allowed it to become a reality is entirely valid, in this author's opinion. In fact, aggressive expansion of the existing recycling activities would result in GHG benefits which the GVRD should attempt to claim ownership of. This trading could partially or fully offset the cost for the recycling expansion.

A number of conclusions and recommendations result from these eight scenarios. These are provided in the next chapter.

## ***CONCLUSIONS & RECOMMENDATIONS***

The GVRD waste management system is not a net emitter of greenhouse gases to the atmosphere. In fact, this research has estimated that the wastes of 1998 prevented 180,000 tCO<sub>2</sub>e emissions. This can also be interpreted as a GHG benefit of 180,000 tCO<sub>2</sub>e. This benefit largely results from landfill carbon sequestration and recycling activities with some benefit from energy generation at the Burnaby Incinerator. Important GHG emissions identified by this research include landfill CH<sub>4</sub>, CO<sub>2</sub> released during the combustion of diesel fuel and plastics, and N<sub>2</sub>O emissions. The scenarios of the previous chapter demonstrate the critical importance that future management changes can have on the overall GVRD emissions. This is of particular relevance when analyzed from the perspective of emissions trading. The conclusions derived from the scenarios are the following.

- The difference between pursuing improvements in LFG collection and doing nothing could be almost 300,000 tCO<sub>2</sub>e/yr – an enormous amount if all available for trading.
- The initiation of electricity generation could reduce emissions by 55,000 tCO<sub>2</sub>e/yr. There is no question about whether this can be claimed as a credit because the benefits result from a voluntary project. At \$5/tCO<sub>2</sub>e, this project could bring in nearly \$300,000 annually just in credit trading; not to mention the value of the electricity when sold to BC Hydro. Furthermore, the Model may actually be slightly underestimating these benefits.
- Considering incineration as a replacement for landfill disposal could bring in credits of 140,000 tCO<sub>2</sub>e/yr when electricity generation is provided. Trading revenue well over \$1 million each year is a very real possibility.
- The future methane liability of landfilling requires extensive consideration, for when ultimate decomposition is modeled for the future, the full life-cycle environmental cost of landfill disposal is significant; an emission increase of over 300,000 tCO<sub>2</sub>e/yr was estimated from ultimate decomposition.
- Landfill carbon sequestration and recycling enable the GVRD to be a negative emitter of greenhouse gases but the former is controversial and the latter can be argued as an inappropriate for the GVRD to claim credit for.

A final product of this research is a spreadsheet model to quantify the GHG emissions from GVRD solid waste management. This is a flexible Model which can illustrate the positive or negative impacts that management changes can have on GHG emissions to the atmosphere. The Model could be of great value in helping to identify emissions trading opportunities.



The following are a number of recommendations for the GVRD which result from this research.

- To strongly encourage the GVRD to begin actively participating in emissions trading to generate revenue or to bank credits in anticipation of future regulatory requirements.
- To investigate improving the LFG collection system at the Cache Creek Landfill (Engineers at the City of Vancouver are currently in the process of upgrading collection at the Vancouver Landfill) and claiming emissions credits for the voluntary portion of this project.
- To investigate electricity generation at the Burnaby Incinerator to generate revenue from emissions trading and from the sale of energy.
- To consider the transition away from landfill disposal, because of the long-term methane liability, and towards incineration, because of the bioenergy potential (this transition can also be facilitated by trading).
- To expand the recycling of metal, glass and plastic materials of the waste stream. This could be funded by claiming the GHG credits from the emission benefits (while current recycling activities occurred without any GHG considerations, expansion of the activity is a fair opportunity to claim GHG credits).
- To expand the backyard composting of food waste when landfilling is the disposal alternative. This is of particular relevance to municipalities such as the City of Vancouver and the City of Coquitlam where a high percentage of waste is historically landfilled. Expansion of the existing participation in backyard composting would also be available for trading.
- To reevaluate the current emphasis on paper recycling. From a strictly GHG perspective, the Model has estimated that newsprint disposal or incineration is preferable to recycling and that the incineration of office paper is also preferable to recycling. The combustion of paper products for bioenergy generation or the landfill sequestering of newsprint maybe more valuable than recycling.
- To assess other components of the MSW stream, such as corrugated cardboard or mixed paper, so as to decrease the size of the Remainder.
- To initiate research on the potential for N<sub>2</sub>O emissions at the wastewater treatment plants managing landfill leachate and the potential for thermal N<sub>2</sub>O formation during waste incineration. (In a side point, an investigation of the GVRD wastewater treatment plants for N<sub>2</sub>O emissions and for potential bioenergy generation from the anaerobic digestors would also be valuable.)
- To initiate research in landfill carbon sequestration to increase the understanding of the local situation.
- To evaluate what impact the carbon taxation of diesel fuel will have on the current economics of waste transport.
- To consider bringing in new staff to identify and implement GHG reducing projects. Combined with emissions trading, these individuals could conceivably pay for themselves while resulting in environmental benefits.
- To assess the aerobic digestion, anaerobic digestion and the new ethanol synthesis technologies as solid waste management alternatives to landfilling or incineration.

A final recommendation results from the author's opinion that the GVRD should remain cautious about selling valuable GHG credits too cheaply. Enormous potential exists for

these credits to drastically increase in value. While the trading value of CO<sub>2</sub> currently languishes at about \$1 per tonne, it could rapidly rise to \$5, \$10 or even \$20 once scarcity hits this new commodity. Extensive consideration should be given to the banking of these credits for future use and for limiting the length of trading contracts so as not to be locked in at a low price.

In closing, it is important to recognize that there is uncertainty in the modelling performed for this research. The understanding of many of the issues in this report is its infancy. Research is necessary to decrease the uncertainty. It is hoped that a combination of future effort by the GVRD, university researchers, consultants and members of federal and provincial departments will expand upon these ideas. The environmental and economic benefits could be considerable indeed.

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## **APPENDIX A: GENERAL CALCULATIONS**

This appendix contains the general calculations and parameters which are not specific to any municipality or to any waste material. This includes the fuel consumption estimates for waste transferred to transfer stations, subsequent transport to disposal facilities and the operation of equipment at the Vancouver or Cache Creek Landfill. These estimates also include the fuel consumption for equipment at recycling or composting facilities. These calculations are the same utilized in Worksheet #5 – *General Parameters* to estimate emission factors necessary for the model. This appendix can be separated into 8 separate sections:

- Waste Delivered to the Coquitlam Transfer Station
- Waste Delivered to the North Shore Transfer Station
- Waste Delivered to the Vancouver Transfer Station
- Waste Delivered to the Matsqui Transfer Station
- Waste Delivered to the Langley Transfer Station
- Waste Delivered to the Maple Ridge Transfer Station
- Recycling Equipment
- Centralized Composting Equipment
- Diesel Fuel Combustion Emissions

Emission factors for these 8 alternatives are developed in turn.

An exception to the description above occurs in Worksheet #5 – General Parameters which represents this very appendix in the spreadsheet model. This worksheet contains all the waste flow data for 1998 as provided by the GVRD. These are all the masses of waste collected at the member municipalities and delivered to transfer stations and transferred to final disposal destinations. This data is necessary to determine the quantities of waste disposed at the Cache Creek Landfill, the Vancouver Landfill or the Burnaby Incinerator for each municipality. These tables are presented in the Worksheet #5 and are not provided in this appendix.

So as to facilitate the explanations and calculations in the following sections, a number of abbreviations have been employed. These are listed below:

CCLF – Cache Creek Landfill  
VLF – Vancouver Landfill  
BI – Burnaby Incinerator  
NSTS – North Shore Transfer Station  
CTS – Coquitlam Transfer Station  
VTS – Vancouver Transfer Station  
LTS – Langley Transfer Station  
MTS – Matsqui Transfer Station  
MRTS – Maple Ridge Transfer Station  
FutLF – Future Landfill

While this research has attempted to obtain fuel consumption data from as many sources as possible, the sheer number of potential transportation requirements causes assumptions to be necessary. These include that a typical heavy-duty diesel vehicle has a diesel fuel consumption of 45.0L per 100km, as published by Environment Canada (1997), and that each of these trucks has a capacity of 20 tonnes. Also, to assign fuel consumption to the appropriate transportation, it is also necessary to know whether the vehicle returns to the original location, therefore necessitating fuel for the entire round-trip, or whether the vehicle provided another task on the return trip, thereby necessitating fuel only for this a one-way distance.

## WASTE DELIVERED TO THE COQUITLAM TRANSFER STATION

### 1. Diesel Fuel Consumption by Transfer Station Equipment:

At the CTS approximately 279,495 litres of diesel fuel was consumed in 1998 for the processing of 319,651 tonnes of waste (Pers. comm. Louie DeVent).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( \frac{2.854 \text{ kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(279,495)(2.854)}{(319,651) \cdot 1000} = 0.0025 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0025 \text{ tCO}_2\text{e/tonne}$$

### 2. Diesel Fuel Consumption for Transport to the Cache Creek Landfill:

Tractor trailers transport waste the approximate 300 km distance from the GVRD to the Cache Creek Landfill (GVRD 1993b). A recent GVRD report has estimated the GHG emissions associated with this transport (GVRD 1999b). The total diesel fuel used in 1997 (both ways) was 4,440,000 L; of which half was estimated to be the responsibility of the GVRD (woodchips are transported to the Lower Mainland on the return trip). In 1998, 8,112 trips were taken from the CTS to the CCLF for the disposal of 303,608 tonnes of waste. Each tractor trailer trip consumes about 200 litres (one way) (Pers. comm. Louie DeVent). The average emission factor for this transport is:

$$\frac{\text{Mass Hauled}}{\text{Trip}} = \frac{303,608 \text{ tonnes}}{8,112 \text{ trips}} = 37.4 \text{ tonnes/trip}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/trip}) \left( \frac{2.854 \text{ kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes/trip})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(200)(2.854)}{(37.4) \cdot 1000} = 0.015 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.015 \text{ tCO}_2\text{e/tonne}$$

### 3. Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:

The diesel fuel combusted by equipment at the Cache Creek Landfill in 1998 was 812,499L. During this same time period, 474,873 tonnes of waste was disposed (Pers. comm. Louie DeVent). The average emission factor is:

$$\frac{\text{GHG-Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( \frac{2.854 \text{ kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(812,499)(2.854)}{(474,873) \cdot 1000} = 0.0049 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.0049 tCO<sub>2</sub>e/tonne

#### 4. Diesel Fuel Consumption for Transport to the Vancouver Landfill:

Approximately 339 tractor-trailer trips were required to transport 8,189 tonnes of waste from the CTS to the VLF. The necessitated the consumption of 45 litres of diesel fuel per trip (Pers. comm. Louie DeVent).

$$\frac{\text{Mass Hauled}}{\text{Trip}} = \frac{8,189 \text{ tonnes}}{339 \text{ trips}} = 24.2 \text{ tonnes/trip}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \text{Fuel Consumption, L/trip} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne/1000 kg} \right)}{\left( \text{tonnes/trip} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(45)(2.854)}{(24.2) \cdot 1000} = 0.0053 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.0053 tCO<sub>2</sub>e/tonne

#### 5. Diesel Fuel Consumption by Equipment at the Vancouver Landfill:

In 1998, approximately 335,000 litres was consumed by City operations (a small part of this also includes the composting equipment but cannot be differentiated) and 144,000 litres was consumed by a private contractor supplying cover materials. During this same time period, a total of 379,554 tonnes of waste was disposed at this site (Pers. comm. Kevin Van Vliet).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \text{Fuel Consumption, L} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne/1000 kg} \right)}{\left( \text{tonnes} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(335,000 + 144,000)(2.854)}{(379,554) \cdot 1000} = 0.0036 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.0036 tCO<sub>2</sub>e/tonne

#### 6. Diesel Fuel Consumption for Transport to the Burnaby Incinerator:

Trucks transport waste from the Coquitlam Transfer Station to the Burnaby Incinerator and return empty. In 1998, 176 trips delivered 3,981 tonnes of waste to the Incinerator and consumed 23 litres per trip in the process (Pers. comm. Louie DeVent).

$$\frac{\text{Mass Hauled}}{\text{Trip}} = \frac{3,981 \text{ tonnes}}{176 \text{ trips}} = 22.6 \text{ tonnes/trip}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \text{Fuel Consumption, L/trip} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne/1000 kg} \right)}{\left( \text{tonnes/trip} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(23)(2.854)}{(22.6) \cdot 1000} = 0.0029 \text{ tCO}_2\text{e/tonne}$$

GHG emission = 0.0029 tCO<sub>2</sub>e/tonne

### WASTE DELIVERED TO THE NORTH SHORE TRANSFER STATION

#### 1. Diesel Fuel Consumption by Transfer Station Equipment:

At the NSTS, 87,918 litres was consumed by equipment for the processing of 194,755 tonnes of waste (Pers. comm. Louie DeVent).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \text{Fuel Consumption, L} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne/1000 kg} \right)}{\left( \text{tonnes} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(87,918)(2.854)}{(194,755) \cdot 1000} = 0.0013 \text{ tCO}_2\text{e/tonne}$$

GHG Emissions = 0.0013 tCO<sub>2</sub>e/tonne

## 2. Diesel Fuel Consumption for Transport to the Cache Creek Landfill:

Tractor trailers transport waste the approximate 300 km distance from the GVRD to the Cache Creek Landfill (GVRD 1993b). A recent GVRD report has estimated the GHG emissions associated with this transport (GVRD 1999b). The total diesel fuel used in 1997 (both ways) was 4,440,000 L; of which half was estimated to be the responsibility of the GVRD (woodchips are transported to the Lower Mainland on the return trip). In 1998, 2,283 trips were taken from the NSTS to the CCLF for the disposal of 82,930 tonnes of waste. Each tractor trailer trip consumes about 215 litres (one way) (Pers. comm. Louie DeVent). The average emission factor for this transport is:

$$\begin{aligned}\frac{\text{Mass Hauled}}{\text{Trip}} &= \frac{82,930 \text{ tonnes}}{2,283 \text{ trips}} = 36.3 \text{ tonnes/trip} \\ \frac{\text{GHG Emissions}}{\text{tonne}} &= \frac{\left( \text{Fuel Consumption, L/trip} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne}/1000 \text{ kg} \right)}{\left( \text{tonnes/trip} \right)} = \text{tCO}_2\text{e/tonne} \\ \frac{\text{GHG Emissions}}{\text{tonne}} &= \frac{(215)(2.854)}{(36.3) \cdot 1000} = 0.017 \text{ tCO}_2\text{e/tonne} \\ \text{GHG Emission} &= 0.017 \text{ tCO}_2\text{e/tonne}\end{aligned}$$

## 3. Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:

The diesel fuel combusted by equipment at the Cache Creek Landfill in 1998 was 812,499 L. During this same time period, 474,873 tonnes of waste was disposed (Pers. comm. Louie DeVent). The average emission factor is:

$$\begin{aligned}\frac{\text{GHG Emissions}}{\text{tonne}} &= \frac{\left( \text{Fuel Consumption, L} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne}/1000 \text{ kg} \right)}{\left( \text{tonnes} \right)} = \text{tCO}_2\text{e/tonne} \\ \frac{\text{GHG Emissions}}{\text{tonne}} &= \frac{(812,499)(2.854)}{(474,873) \cdot 1000} = 0.0049 \text{ tCO}_2\text{e/tonne} \\ \text{GHG Emission} &= 0.0049 \text{ tCO}_2\text{e/tonne}\end{aligned}$$

## 4. Diesel Fuel Consumption for Transport to the Vancouver Landfill:

A small percentage (less than 1%) of the waste delivered to the NSTS was disposed at the VLF in 1998 (GVRD 1999a). The trucks return empty. In this year, 71 trips delivered 1,754 tonnes and consumed 45 litres per trip (Pers. comm. Louie DeVent).

$$\begin{aligned}\frac{\text{Mass Hauled}}{\text{Trip}} &= \frac{1,754 \text{ tonnes}}{71 \text{ trips}} = 24.7 \text{ tonnes/trip} \\ \frac{\text{GHG Emissions}}{\text{tonne}} &= \frac{\left( \text{Fuel Consumption, L/trip} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne}/1000 \text{ kg} \right)}{\left( \text{tonnes/trip} \right)} = \text{tCO}_2\text{e/tonne} \\ \frac{\text{GHG Emissions}}{\text{tonne}} &= \frac{(45)(2.854)}{(24.7) \cdot 1000} = 0.0052 \text{ tCO}_2\text{e/tonne} \\ \text{GHG emissions} &= 0.0052 \text{ tCO}_2\text{e/tonne}\end{aligned}$$

## 5. Diesel Fuel Consumption by Equipment at the Vancouver Landfill:

In 1998, approximately 335,000 litres was consumed by City operations (a small part of this also includes the composting equipment but cannot be differentiated) and 144,000 litres was consumed by a private contractor supplying cover materials. During this same time period, a total of 379,554 tonnes of waste was disposed at this site (Pers. comm. Kevin Van Vliet).

$$\begin{aligned}\frac{\text{GHG-Emissions}}{\text{tonne}} &= \frac{\left( \text{Fuel Consumption, L} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne}/1000 \text{ kg} \right)}{\left( \text{tonnes} \right)} = \text{tCO}_2\text{e/tonne} \\ \frac{\text{GHG-Emissions}}{\text{tonne}} &= \frac{(335,000 + 144,000)(2.854)}{(379,554) \cdot 1000} = 0.0036 \text{ tCO}_2\text{e/tonne} \\ \text{GHG Emission} &= 0.0036 \text{ tCO}_2\text{e/tonne}\end{aligned}$$

## 6. Diesel Fuel Consumption for Transport to the Burnaby Incinerator:

Trucks transport waste from the NSTS to the BI and return empty. In 1998, 3,609 trucks trips delivered 89,942 tonnes of waste and used 23 litres per trip (Pers. comm. Louie DeVent).

$$\frac{\text{Mass Hauled}}{\text{Trip}} = \frac{89,942 \text{ tonnes}}{3,609 \text{ trips}} = 24.9 \text{ tonnes/trip}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \text{Fuel Consumption, L/trip} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne/1000 kg} \right)}{\left( \text{tonnes/trip} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(23)(2.854)}{(24.9) * 1000} = 0.0026 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0026 \text{ tCO}_2\text{e/tonne}$$

## WASTE DELIVERED TO THE VANCOUVER TRANSFER STATION

### 1. Diesel Fuel Consumption by Transfer Station Equipment:

At the Vancouver Transfer Station approximately 87,650 litres of diesel fuel was consumed in 1998 for the transfer of 273,691 tonnes of waste (Pers. comm. Kevin Van Vliet). The resulting emission factor is:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \text{Fuel Consumption, L} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne/1000 kg} \right)}{\left( \text{tonnes} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(87,650)(2.854)}{(273,691) * 1000} = 0.0009 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0009 \text{ tCO}_2\text{e/tonne}$$

### 2. Diesel Fuel Consumption for Transport to the Cache Creek Landfill:

Tractor trailers transport waste the approximate 300 km distance from the GVRD to the CCLF (GVRD 1993b). A recent GVRD report has estimated the GHG emissions associated with this transport (GVRD 1999b). The total diesel fuel used in 1997 (both ways) was 4,440,000 L; of which half was estimated to be the responsibility of the GVRD (woodchips are transported to the Lower Mainland on the return trip). In 1998, no waste was transferred from the VTS to the CCLF. However, the inspection of a street map of Vancouver has determined the NSTS to be an approximate estimate for the hypothetical transfer from the VTS. In 1998, 2,283 trips were taken from the NSTS to the CCLF for the disposal of 82,930 tonnes of waste. Each tractor trailer trip consumes about 215 litres (one way) (Pers. comm. Louie DeVent).

$$\frac{\text{Mass Hauled}}{\text{Trip}} = \frac{82,930 \text{ tonnes}}{2,283 \text{ trips}} = 36.3 \text{ tonnes/trip}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \text{Fuel Consumption, L/trip} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne/1000 kg} \right)}{\left( \text{tonnes/trip} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(215)(2.854)}{(36.3) * 1000} = 0.017 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.017 \text{ tCO}_2\text{e/tonne}$$

### 3. Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:

The diesel fuel combusted by equipment at the Cache Creek Landfill in 1998 was 812,499L. During this same time period, 474,873 tonnes of waste was disposed (Pers. comm. Louie DeVent). The average emission factor is:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(812,499)(2.854)}{(474,873) * 1000} = 0.0049 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.0049 tCO<sub>2</sub>e/tonne

#### 4. Diesel Fuel Consumption for Transport to the Vancouver Landfill:

Approximately 12,500 tractor-trailer trips were required to transport 271,431 tonnes of waste and 16,500 tonnes of yard trimmings from the VTS to the VLF. This necessitated the consumption of 334,000 litres of diesel fuel (Pers. comm. Kevin Van Vliet).

$$\frac{\text{Mass Hauled}}{\text{Trip}} = \frac{271,431 \text{ tonnes}}{12,500 \text{ trips}} = 23.0 \text{ tonnes/trip}$$

$$\frac{\text{Fuel Consumption}}{\text{Trip}} = \frac{334,000 \text{ tonnes}}{12,500 \text{ trips}} = 26.7 \text{ L/trip}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/trip}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes/trip})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(26.7)(2.854)}{(23.0) * 1000} = 0.0033 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.0033 tCO<sub>2</sub>e/tonne

#### 5. Diesel Fuel Consumption by Equipment at the Vancouver Landfill:

In 1998, approximately 335,000 litres was consumed by City operations (a small part of this also includes the composting equipment but cannot be differentiated) and 144,000 litres was consumed by a private contractor supplying cover materials. During this same time period, a total of 379,554 tonnes of waste was disposed at this site (Pers. comm. Kevin Van Vliet).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(335,000 + 144,000)(2.854)}{(379,554) * 1000} = 0.0036 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.0036 tCO<sub>2</sub>e/tonne

#### 6. Diesel Fuel Consumption for Transport to the Burnaby Incinerator:

No waste was transferred from the VTS to the BI in 1998. However, a hypothetical assumption is calculated. By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 22 km (estimated from map), the emission would be:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km}) (\text{Distance, km}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes/trip})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(45/100)(22)(2.854)}{(20) * 1000} = 0.0014 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.0083 tCO<sub>2</sub>e/tonne

## WASTE DELIVERED TO THE MATSQUI TRANSFER STATION

### 1. Diesel Fuel Consumption by Transfer Station Equipment:

At the MTS approximately 33,280 litres of diesel fuel was consumed in 1998 for the processing of 75,850 tonnes of waste (Pers. comm. Louie DeVent). The resulting emission factor is:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(33,280)(2.854)}{(75,850) \cdot 1000} = 0.0013 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0013 \text{ tCO}_2\text{e/tonne}$$

### 2. Diesel Fuel Consumption for Transport to the Cache Creek Landfill:

Tractor trailers transport waste the approximate 300 km distance from the GVRD to the CCLF (GVRD 1993b). A recent GVRD report has estimated the GHG emissions associated with this transport (GVRD 1999b). The total diesel fuel used in 1997 (both ways) was 4,440,000 L; of which half was estimated to be the responsibility of the GVRD (woodchips are transported to the Lower Mainland on the return trip). In 1998, 2104 trips were taken from the MTS to the CCLF for the disposal of 73,169 tonnes of waste. Each tractor trailer trip consumes about 185 litres (one way) (Pers. comm. Louie DeVent).

$$\frac{\text{Mass Hauled}}{\text{Trip}} = \frac{73,169 \text{ tonnes}}{2,104 \text{ trips}} = 34.8 \text{ tonnes/trip}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/trip}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes/trip})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(185)(2.854)}{(34.8) \cdot 1000} = 0.014 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.014 \text{ tCO}_2\text{e/tonne}$$

### 3. Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:

The diesel fuel combusted by equipment at the Cache Creek Landfill in 1998 was 812,499L. During this same time period, 474,873 tonnes of waste was disposed (Pers. comm. Louie DeVent). The average emission factor is:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(812,499)(2.854)}{(474,873) \cdot 1000} = 0.0049 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0049 \text{ tCO}_2\text{e/tonne}$$

### 4. Diesel Fuel Consumption for Transport to the Vancouver Landfill:

No waste was transferred from the MTS to the VLF in 1998. This hypothetical emission factor is estimated by assuming 20 tonnes is hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 130 km (estimated from map).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km}) (\text{Distance, km}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes/trip})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(45/100)(130)(2.854)}{(20) \cdot 1000} = 0.0083 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0083 \text{ tCO}_2\text{e/tonne}$$



### 5. Diesel Fuel Consumption by Equipment at the Vancouver Landfill:

In 1998, approximately 335,000 litres was consumed by City operations (a small part of this also includes the composting equipment but cannot be differentiated) and 144,000 litres was consumed by a private contractor supplying cover materials. During this same time period, a total of 379,554 tonnes of waste was disposed at this site (Pers. comm. Kevin Van Vliet).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(335,000 + 144,000)(2.854)}{(379,554) \cdot 1000} = 0.0036 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0036 \text{ tCO}_2\text{e/tonne}$$

### 6. Diesel Fuel Consumption for Transport to the Burnaby Incinerator:

No waste is transferred from the MTS to the BI in 1998. By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 120 km (estimated from map), the emission would be :

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km}) (\text{Distance, km}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{\left( \frac{\text{tonnes}}{\text{trip}} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \frac{45}{100} \right) (120) (2.854)}{(20) \cdot 1000} = 0.0077 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0077 \text{ tCO}_2\text{e/tonne}$$

## WASTE DELIVERED TO THE LANGLEY TRANSFER STATION

Most of the waste dropped off at the LTS in 1998 was subsequently transferred to the MTS. This majority was 87% of total waste. The remaining 12% was transferred to the CTS. Both the MTS and the CTS transferred most of their waste to the CCLF. As the MTS is the most important pathway, it will be used as representative of waste disposed in the CCLF which originated at the LTS. However, the hypothetical disposal of waste disposed at the VLF or the BI will be assumed to have been transferred there from the LTS.

### 1. Diesel Fuel Consumption by Transfer Station Equipment:

Analysis of other transfer stations have allowed estimates for waste processing:

North Shore Transfer Station = 0.0013 tCO<sub>2</sub>e/tonne

Coquitlam Transfer Station = 0.0025 tCO<sub>2</sub>e/tonne

Vancouver Transfer Station = 0.0009 tCO<sub>2</sub>e/tonne

Matsqui Transfer Station = 0.0013 tCO<sub>2</sub>e/tonne

An average of these four estimates will be used here for the LTS.

$$\text{GHG Emission} = 0.0015 \text{ tCO}_2\text{e/tonne}$$

### 2. Diesel Fuel Consumption for Transport to the Cache Creek Landfill:

The majority of waste delivered to LTS is subsequently transported to the MTS. From the MTS, waste is disposed in the CCLF. Therefore, the transport from the LTS to the

MTS, processing at the MTS and finally transport to the CCLF must be included here. By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 40 km, the emission would be:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km})(\text{Distance, km}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{\left( \frac{\text{tonnes}}{\text{trip}} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \frac{45}{100} \right) (40) (2.854)}{(20) \cdot 1000} = 0.0026 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0026 \text{ tCO}_2\text{e/tonne}$$

At the Matsqui Transfer Station approximately 33,280 litres of diesel fuel was consumed in 1998 for the processing of 75,850 tonnes of waste (Pers. comm. Louie DeVent). The resulting emission factor is:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(33,280)(2.854)}{(75,850) \cdot 1000} = 0.0013 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0013 \text{ tCO}_2\text{e/tonne}$$

Tractor trailers transport waste the approximate 300 km distance from the GVRD to the Cache Creek Landfill (GVRD 1993b). A recent GVRD report has estimated the GHG emissions associated with this transport (GVRD 1999b). The total diesel fuel used in 1997 (both ways) was 4,440,000 L; of which half was estimated to be the responsibility of the GVRD (woodchips are transported to the Lower Mainland on the return trip). In 1998, 2104 trips were taken from the Matsqui Transfer Station to the Cache Creek Landfill for the disposal of 73,169 tonnes of waste. Each tractor trailer trip consumes about 185 litres (one way) (Pers. comm. Louie DeVent).

$$\frac{\text{Mass Hauled}}{\text{Trip}} = \frac{73,169 \text{ tonnes}}{2,104 \text{ trips}} = 34.8 \frac{\text{tonnes}}{\text{trip}}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/trip}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{\left( \frac{\text{tonnes}}{\text{trip}} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(185)(2.854)}{(34.8) \cdot 1000} = 0.014 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.014 \text{ tCO}_2\text{e/tonne}$$

$$\text{Total GHG Emission} = 0.0026 + 0.0013 + 0.014 = 0.018 \text{ tCO}_2\text{e/tonne}$$

### 3. Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:

The diesel fuel combusted by equipment at the Cache Creek Landfill in 1998 was 812,499L. During this same time period, 474,873 tonnes of waste was disposed (Pers. comm. Louie DeVent). The average emission factor is:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(812,499)(2.854)}{(474,873) \cdot 1000} = 0.0049 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0049 \text{ tCO}_2\text{e/tonne}$$

#### 4. Diesel Fuel Consumption for Transport to the Vancouver Landfill:

No waste was transferred from the LTS to the VLF in 1998. This hypothetical emission factor is estimated by assuming 20 tonnes is hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 85 km (estimated from map).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km})(\text{Distance, km}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{\left( \frac{\text{tonnes}}{\text{trip}} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \frac{45}{100} \right) (85) (2.854)}{(20) * 1000} = 0.0055 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0055 \text{ tCO}_2\text{e/tonne}$$

#### 5. Diesel Fuel Consumption by Equipment at the Vancouver Landfill:

In 1998, approximately 335,000 litres was consumed by City operations (a small part of this also includes the composting equipment but cannot be differentiated) and 144,000 litres was consumed by a private contractor supplying cover materials. During this same time period, a total of 379,554 tonnes of waste was disposed at this site (Pers. comm. Kevin Van Vliet).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(335,000 + 144,000) (2.854)}{(379,554) * 1000} = 0.0036 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0036 \text{ tCO}_2\text{e/tonne}$$

#### 6. Diesel Fuel Consumption for Transport to the Burnaby Incinerator:

No waste is transferred from the MRTS to the BI in 1998. By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 90 km (estimated from map), the emission would be :

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km})(\text{Distance, km}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{\left( \frac{\text{tonnes}}{\text{trip}} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \frac{45}{100} \right) (90) (2.854)}{(20) * 1000} = 0.0058 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0058 \text{ tCO}_2\text{e/tonne}$$

### WASTE DELIVERED TO THE MAPLE RIDGE TRANSFER STATION

Most of the waste dropped off at the MRTS in 1998 was subsequently transferred to the MTS. This majority was 83% of total waste. The remaining 17% was transferred to the CTS. Both the MTS and the CTS transferred most of their waste to the CCLF. As the MTS is the most important pathway, it will be used as representative of waste disposed in the CCLF which originated at the MRTS. However, the hypothetical disposal of waste disposed at the VLF or the BI will be assumed to have been transferred there from the MRTS.

#### 7. Diesel Fuel Consumption by Transfer Station Equipment:

Analysis of other transfer stations have allowed estimates for waste processing:

$$\text{North Shore Transfer Station} = 0.0013 \text{ tCO}_2\text{e/tonne}$$

Coquitlam Transfer Station = 0.0025 tCO<sub>2</sub>e/tonne  
 Vancouver Transfer Station = 0.0009 tCO<sub>2</sub>e/tonne  
 Matsqui Transfer Station = 0.0013 tCO<sub>2</sub>e/tonne

An average of these four estimates will be used here for the MRTS.  
 GHG Emission = 0.0015 tCO<sub>2</sub>e/tonne

#### 8. Diesel Fuel Consumption for Transport to the Cache Creek Landfill:

The majority of waste originating in the District of Maple Ridge is processed at the MRTS and subsequently transported to the MTS. From the MTS, waste is disposed in the CCLF. Therefore, the transport from MRTS to MTS, processing at MTS and finally transport to the CCLF must be included here. By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 60 km, the emission would be:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}/100\text{km})(\text{Distance, km})(2.854 \text{ kgCO}_2\text{e/L})(1 \text{ tonne}/1000 \text{ kg})}{(\text{tonnes}/\text{trip})} = \text{tCO}_2\text{e}/\text{tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(45/100)(60)(2.854)}{(20) \cdot 1000} = 0.0039 \text{ tCO}_2\text{e}/\text{tonne}$$

GHG Emission = 0.0039 tCO<sub>2</sub>e/tonne

At the Matsqui Transfer Station approximately 33,280 litres of diesel fuel was consumed in 1998 for the processing of 75,850 tonnes of waste (Pers. comm. Louie DeVent). The resulting emission factor is:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L})(2.854 \text{ kgCO}_2\text{e/L})(1 \text{ tonne}/1000 \text{ kg})}{(\text{tonnes})} = \text{tCO}_2\text{e}/\text{tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(33,280)(2.854)}{(75,850) \cdot 1000} = 0.0013 \text{ tCO}_2\text{e}/\text{tonne}$$

GHG Emission = 0.0013 tCO<sub>2</sub>e/tonne

Tractor trailers transport waste the approximate 300 km distance from the GVRD to the Cache Creek Landfill (GVRD 1993b). A recent GVRD report has estimated the GHG emissions associated with this transport (GVRD 1999b). The total diesel fuel used in 1997 (both ways) was 4,440,000 L; of which half was estimated to be the responsibility of the GVRD (woodchips are transported to the Lower Mainland on the return trip). In 1998, 2104 trips were taken from the Matsqui Transfer Station to the Cache Creek Landfill for the disposal of 73,169 tonnes of waste. Each tractor trailer trip consumes about 185 litres (one way) (Pers. comm. Louie DeVent).

$$\frac{\text{Mass Hauled}}{\text{Trip}} = \frac{73,169 \text{ tonnes}}{2,104 \text{ trips}} = 34.8 \text{ tonnes}/\text{trip}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}/\text{trip})(2.854 \text{ kgCO}_2\text{e/L})(1 \text{ tonne}/1000 \text{ kg})}{(\text{tonnes}/\text{trip})} = \text{tCO}_2\text{e}/\text{tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(185)(2.854)}{(34.8) \cdot 1000} = 0.014 \text{ tCO}_2\text{e}/\text{tonne}$$

GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

Total GHG Emission = 0.0039 + 0.0013 + 0.014 = 0.019 tCO<sub>2</sub>e/tonne

**9. Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:**

The diesel fuel combusted by equipment at the Cache Creek Landfill in 1998 was 812,499L. During this same time period, 474,873 tonnes of waste was disposed (Pers. comm. Louie DeVent). The average emission factor is:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(812,499)(2.854)}{(474,873) * 1000} = 0.0049 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0049 \text{ tCO}_2\text{e/tonne}$$

**10. Diesel Fuel Consumption for Transport to the Vancouver Landfill:**

No waste was transferred from the MRTS to the VLF in 1998. This hypothetical emission factor is estimated by assuming 20 tonnes is hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 110 km (estimated from map).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km}) (\text{Distance, km}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{\left( \frac{\text{tonnes}}{\text{trip}} \right)} = \text{tCO}_2\text{e/tonne}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \frac{45}{100} \right) (110) (2.854)}{(20) * 1000} = 0.0071 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0071 \text{ tCO}_2\text{e/tonne}$$

**11. Diesel Fuel Consumption by Equipment at the Vancouver Landfill:**

In 1998, approximately 335,000 litres was consumed by City operations (a small part of this also includes the composting equipment but cannot be differentiated) and 144,000 litres was consumed by a private contractor supplying cover materials. During this same time period, a total of 379,554 tonnes of waste was disposed at this site (Pers. comm. Kevin Van Vliet).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(335,000 + 144,000)(2.854)}{(379,554) * 1000} = 0.0036 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0036 \text{ tCO}_2\text{e/tonne}$$

**12. Diesel Fuel Consumption for Transport to the Burnaby Incinerator:**

No waste is transferred from the MRTS to the BI in 1998. By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 75 km (estimated from map), the emission would be :

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km}) (\text{Distance, km}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{\left( \frac{\text{tonnes}}{\text{trip}} \right)} = \text{tCO}_2\text{e/tonne}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \frac{45}{100} \right) (75) (2.854)}{(20) * 1000} = 0.0048 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0048 \text{ tCO}_2\text{e/tonne}$$

## RECYCLING EQUIPMENT

### Fossil Fuel Consumption by Equipment at Recycling Facilities:

Electricity and fossil fuels are required by equipment at recycling facilities. The low greenhouse gas emission intensity for electricity in this province (because of the predominance of hydroelectric generation) allows the electricity to be ignored. However, propane is required by forklifts and 'bobcat-like' loaders at the recycling depot in Surrey operated by ETL Recycling Services. Data was obtained for this organization and will be used as to represent all recycling depots in the GVRD. In 1998, the ETL facility consumed 0.45L of propane per tonne of materials recycled (Pers. comm. Brian Carrow). Propane has a greenhouse gas emission factor of 1.53 kgCO<sub>2</sub>/L combusted (Env Can 1999).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \left( \frac{0.45 \text{ L propane}}{\text{tonne Recyclables}} \right) \left( \frac{1.53 \text{ kgCO}_2}{\text{L propane}} \right) \left( \frac{\text{tonne}}{1000 \text{ kg}} \right) = 0.0007 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.0007 tCO<sub>2</sub>e/tonne

## CENTRALIZED COMPOSTING EQUIPMENT

### Diesel Fuel Consumption by Equipment at Composting Facilities:

Data cannot be obtained for the diesel consumed by the composting equipment at either Fraser Richmond Bio-Cycle or the composting facility at the Vancouver Landfill since this consumption cannot be separated from other equipment. As a result, the diesel consumed by composting equipment will have to be estimated from available literature. Franklin Associates, in a 1994 report, estimated that 221,000 BTUs of energy was required from diesel fuel in order to compost a short ton of yard trimmings and that this fuel results in a greenhouse gas emission of 0.0763 tCO<sub>2</sub>e/million BTUs (Franklin Associates 1994; USEPA 1998).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \left( \frac{221000 \text{ BTU}}{\text{short ton Yard Waste}} \right) \left( \frac{0.0763 \text{ tCO}_2\text{e}}{10^6 \text{ BTU}} \right) \left( \frac{1.102 \text{ short ton}}{\text{metric tonne}} \right) = 0.019 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.019 tCO<sub>2</sub>e/tonne

## DIESEL FUEL COMBUSTION EMISSIONS

There are three greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O) emitted during the combustion of diesel fuel. All three of these gases have different 100 year Global Warming Potentials which can be used to calculate the GHG emission in terms of carbon dioxide.

Heavy duty diesel truck (moderate control) emits (Environment Canada 1997):

2,730 g of CO<sub>2</sub>/L fuel  
0.20 g of CH<sub>4</sub>/L fuel  
0.40 g of N<sub>2</sub>O/L fuel

Global Warming Potentials (GWP) based on a 100 year Timeframe (IPCC 1995):

GWP of CO<sub>2</sub> = 1  
GWP of CH<sub>4</sub> = 21  
GWP of N<sub>2</sub>O = 310

$$\frac{\text{GHG Emissions}}{\text{L of Diesel Fuel}} = \text{g CO}_2/\text{L} * GWP_{\text{CO}_2} + \text{g CH}_4/\text{L} * GWP_{\text{CH}_4} + \text{g N}_2\text{O}/\text{L} * GWP_{\text{N}_2\text{O}} = \text{g CO}_2e/\text{L}$$

$$\frac{\text{GHG Emissions}}{\text{L of Diesel Fuel}} = 2730 \text{ g CO}_2/\text{L} * 1 + 0.20 \text{ g CH}_4/\text{L} * 21 + 0.40 \text{ g N}_2\text{O}/\text{L} * 310 = 2854 \text{ g CO}_2e/\text{L}$$

$$\text{GHG Emission from Diesel Fuel Combustion} = 2.854 \text{ kgCO}_2e/\text{L}$$

## **APPENDIX B:**

### **MUNICIPALITY CALCULATIONS**

This appendix presents all the diesel fuel consumption data necessary for waste transportation issues specific to each municipality. With this data, greenhouse gas emission factors are estimated. While the Waste Mass Estimates, described in Section 2.9, are also specific to municipalities, this is not presented here – it is provided in Worksheet #5 of the spreadsheet. The discussion in Section 2.9 is deemed to be sufficient to provide an understanding of those calculations. All of the data and calculations for the 20 municipalities' Waste Mass Estimates are provided in Appendix L – *Spreadsheet Program*. This also includes the estimates of the masses of different waste components which are disposed or recycled. It was necessary to estimate waste masses specific to individual municipalities because of the highly variable contribution of wastes from ICI sources which are independent of the residential population of that jurisdiction.

It requires noting that this appendix (and as previously discussed, the entire report) assumes that waste from Anmore and Belcarra are essentially from the City of Port Moody and that waste from the Village of Lions Bay can be included with Electoral Area C.

So as to facilitate the explanations and calculations in the following sections, a number of abbreviations have been employed. These are listed below:

CCLF – Cache Creek Landfill  
VLF – Vancouver Landfill  
BI – Burnaby Incinerator  
NSTS – North Shore Transfer Station  
CTS – Coquitlam Transfer Station  
VTS – Vancouver Transfer Station  
LTS – Langley Transfer Station  
MTS – Matsqui Transfer Station  
MRTS – Maple Ridge Transfer Station  
FutLF – Future Landfill  
FutINC – Future Incinerator

When dealing with the curbside collection of waste, recyclables and yard trimmings at the various single and multi-family residential and ICI sources of the materials in the member municipalities, assumptions are necessary. No municipality was able to provide the fuel consumption data for ICI collection as it handled by multiple private contractors with confidential customer lists, but municipalities can easily obtain data for the single-family residential collection and can frequently gather multi-family data. As a result of these complexities, the easily obtainable single-family residential collection has been used as representative of all collections (except where specified).

Substantial effort has been undertaken to collect the necessary information for each municipality, yet much of the data is unavailable. As a result, the data which was



successfully acquired will be used to fill in the gaps where the actual numbers do not exist.

For curbside waste collection, data has been acquired from 5 municipalities. Three municipalities provided fuel data on the curbside collection of recyclables. Data for the separate curbside collection of yard trimmings has been obtained from four municipalities. This emission factors estimated for this collection along with the fuel consumption and total mass of material collected is presented in the table below. An average of these emission factors is used with the municipalities for which data is unavailable.

### Curbside Collection of Waste, Recyclables & Yard Trimmings

	Emission Factor (tCO <sub>2</sub> e/tonne)	Diesel Fuel Consumption (L)	Mass Collected (tonnes)
<b>GENERAL WASTE</b>			
City of Burnaby	0.019	156,000	23,098
Corporation of Delta	0.006	134,000	67,110
City of New Westminster	0.023	50,331	6,309
City of North Vancouver	0.011	16,257	4,175
City of Vancouver	0.012	316,000	76,000
Average =	0.014		
<b>RECYCLABLES</b>			
City of Burnaby	0.045	134,000	8,437
City of New Westminster	0.052	24,604	1,344
City of Vancouver	0.031	190,000	17,500
Average =	0.043		
<b>YARD TRIMMINGS</b>			
City of Burnaby	0.024	58,000	6,798
Corporation of Delta	0.030	23,075	2,227
City of North Vancouver	0.023	10,020	1,223
Average =	0.027		

An extensive analysis of recycling issues is provided in Section 2.6 of this report. Many emission factors developed by the USEPA (1998) and discussed in Section 2.6 are being used in this thesis. As these emission factors already include a transportation component, it is appropriate not to include the curbside collection of recyclables for the table above. Even the recyclable materials which are not using the USEPA estimates, newsprint and office paper, curb-side collection is not included so as to allow recycling to remain zero from a GHG emissions perspective (See 2.6.1 and 2.6.2). While this curbside collection of recyclables is presented in the table above and displayed in the spreadsheet model it is not used and does not have any effect on emission estimates.

The following sections, B.1 through to B.20, are the calculations for the 20 municipalities investigated.

## **B.1 CITY OF ABBOTSFORD**

In 1998, the City of Abbotsford generated 48,949 tonnes of waste which was delivered to the MTS (48,031 tonnes) and to the LTS (162 tonnes) (GVRD 1999a). For this analysis it is assumed that all of the waste was delivered to the MTS. Approximately half of the general waste and recyclables generated in Abbotsford are collected by municipal crews. Their data will be used for all of Abbotsford. There is no separate collection of yard trimmings in this municipality, only residential drop-off. The emissions from residents dropping off yard waste individually will not be considered here. Furthermore, yard trimmings are ground up and used as a soil amendment directly; they are not composted in the traditional manner (Pers. comm. Roger Farrant).

### **1. Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

### **2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

## **B.2 CITY OF BURNABY**

In the City of Burnaby, collected waste was delivered to 3 different locations in 1998, the BI (91,666 tonnes), the CTS (27,081 tonnes) and the NSTS (10,342 tonnes) (GVRD 1999a). These waste flows complicate the modelling of this municipality. For example, waste disposed at the BI could have been directly delivered their by collection vehicles, could have been transferred from the NSTS or could have been transferred from the CTS. Of the total 129,089 tonnes of waste disposed in 1998, 71% was delivered to the Burnaby Incinerator, 21% was delivered to the CTS (96% of which was transferred to the CCLF) and 8% was delivered to the NSTS (51.5% of which was transferred to the BI and 47.5% was transferred to the CCLF). The transportation differences between the CTS and the NSTS are of relatively minor importance. To simplify matters, it is assumed that waste going to a transfer station will be delivered only to the CTS. As a result, it can be assumed that 71% of waste was directly delivered to the Burnaby Incinerator, 15% of waste was delivered to the Burnaby Incinerator via the CTS and 14% of waste was disposed at the CCLF.

The CTS can allow subsequent transfer to the CCLF, the VLF and the BI. Due to the fact that the vast majority of disposed waste is directly delivered to the BI, the emission factor for this transport will have to be corrected to include the portion requiring equipment processing and transfer. These calculations are performed in Worksheet #7 – *City of Burnaby*. The collection of general waste, recyclables and yard trimmings (all separate) are handled by municipal crews. Recyclables are delivered to a recycling depot operated by Crown Packaging Limited and yard trimmings are delivered directly to Fraser Richmond Bio-Cycle (Pers. comm. Lambert Chu).

### **1. Diesel Fuel Consumption for Curbside Waste Collection:**

In 1999, municipal crews collected 23,098 tonnes of waste from single and two family residences and consumed 156,000 litres in the process. Actual fuel consumption data

between January and April was unavailable, therefore the annual fuel consumption data was extrapolated based on the May to December period (Pers. comm. Lambert Chu).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e}/\text{tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(156,000)(2.854)}{(23,098) * 1000} = 0.019 \text{ tCO}_2\text{e}/\text{tonne}$$

$$\text{GHG Emissions} = 0.019 \text{ tCO}_2\text{e}/\text{tonne}$$

## 2. Diesel Fuel Consumption for Curbside Recyclables Collection:

In 1999, municipal crews collected 8,437 tonnes of recyclables from single and multi-family curbside collection and consumed 134,000 litres in the process. Actual fuel consumption data between January and April was unavailable, therefore the annual fuel consumption data was extrapolated based on the May to December period (Pers. comm. Lambert Chu).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e}/\text{tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(134,000)(2.854)}{(8,437) * 1000} = 0.045 \text{ tCO}_2\text{e}/\text{tonne}$$

$$\text{GHG Emissions} = 0.045 \text{ tCO}_2\text{e}/\text{tonne}$$

## 3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

In 1999, municipal crews collected 6,798 tonnes of yard trimmings by curbside collection and consumed 58,000 litres in the process. Actual fuel consumption data between January and April was unavailable, therefore the annual fuel consumption data was extrapolated based on the May to December period (Pers. comm. Lambert Chu).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e}/\text{tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(58,000)(2.854)}{(6,798) * 1000} = 0.024 \text{ tCO}_2\text{e}/\text{tonne}$$

$$\text{GHG Emissions} = 0.024 \text{ tCO}_2\text{e}/\text{tonne}$$

# B.3 CITY OF COQUITLAM

In the City of Coquitlam, 93,925 tonnes of waste was generated and delivered to the CTS in 1998 and 78 tonnes was directly delivered to the BI (GVRD 1999a). It is assumed in this study that all waste originating in the City of Coquitlam is processed at the CTS. All three separate collections of general waste, recyclables and yard trimmings are performed by contract with Canadian Waste. The recyclables are delivered to Best Recycling for processing and the yard trimmings are directly delivered to Fraser Richmond Bio-Cycle depot in Pitt Meadows for subsequent transportation to the Richmond composting facility (Pers. comm. Mike Iviney).

## 1. Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

**2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

**3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

**4. Diesel Fuel Consumption for Yard Trimmings Transport to Fraser Richmond Biocycle:**

The transport of the yard trimmings from the Pitt Meadows depot to the Richmond composting facility is calculated below. By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 60 km (estimated from map), the emission would be :

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km})(\text{Distance, km}) \left( \frac{2.854 \text{ kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes/trip})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(45/100)(60)(2.854)}{(20) * 1000} = 0.0039 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.0039 tCO<sub>2</sub>e/tonne

## **B.4 CORPORATION OF DELTA**

In 1998, the Corporation of Delta generated 69,104 tonnes of waste which was delivered to the VLF (64,428 tonnes), the CTS (3,973 tonnes) and the VTS (703 tonnes) (GVRD 1999a). For this analysis, since the relatively minor amount delivered to the VTS will subsequently be transferred to the VLF, it is assumed that all the waste from this municipality is directly delivered to the VLF (except for waste which goes to the CTS). When assessing the emissions for transferring waste to the BI it will have been assumed to have been directly delivered there and when assessing the emissions from disposing waste at the CCLF it will be assumed to have been transferred from the CTS. A private contractor provides the separate collection of general waste, recyclables and yard trimmings in this municipality. Yard waste is directly delivered to the composting facility at the VLF (Pers. comm. Sharon Horsburgh).

**1. Diesel Fuel Consumption for Curbside Waste Collection:**

The private contractor employed on behalf of this municipality collected 67,110 tonnes of waste in 1999 and consumed 134,000 litres in the process (Pers. comm. Sharon Horsburgh).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( \frac{2.854 \text{ kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(134,000)(2.854)}{(67,110) * 1000} = 0.006 \text{ tCO}_2\text{e/tonne}$$

GHG Emissions = 0.006 tCO<sub>2</sub>e/tonne

**2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

### 3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

The private contractor employed on behalf of this municipality collected 2,227 tonnes of yard trimmings in 1999 and consumed 23,075 litres in the process (Pers. comm. Sharon Horsburgh).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e}/\text{tonne}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(23,075)(2.854)}{(2,227) * 1000} = 0.030 \text{ tCO}_2\text{e}/\text{tonne}$$

GHG Emissions = 0.030 tCO<sub>2</sub>e/tonne

## B.5 CITY OF LANGLEY

In the City of Langley, 13,995 tonnes of waste was generated and delivered to the CTS (10,025 tonnes), the MTS (3,460 tonnes) and the LTS (510 tonnes) (GVRD 1999a). As most of the waste (72%) was delivered to the CTS, this is used as a proxy for all of the waste generated in the City of Langley. Canadian Waste is the private contractor that provides the curbside collection of general waste, recyclables and yard trimmings in this municipality.

### 1. Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

### 2. Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

### 3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

### 4. Diesel Fuel Consumption for Yard Waste Transport to Composting Facility:

As the yard trimmings collected separately is directly delivered to one of the several GVRD approved composting facilities, this emission factor is unnecessary. On any given day, yard trimmings may or may not be deposited at Fraser Richmond Bio-Cycle but is assumed to be for this research.

## B.6 TOWNSHIP OF LANGLEY

In the Township of Langley, 27,521 tonnes of waste was generated in 1998. This was delivered to the LTS (11,744 tonnes), the BI (5,961 tonnes), the CTS (5,501 tonnes) and the MTS (4,315) (GVRD 1993a). Most of the waste delivered to the LTS is transferred to the MTS for subsequent disposal in the CCLF (87% in 1998) and most of the waste delivered to the CTS is transferred for disposal at the CCLF). To simplify these flows, waste to be disposed at the CCLF will be assumed to be delivered to the LTS and transferred to the MTS. In addition, waste disposed at the VLF is assumed to be transferred there from the LTS and waste disposed at the BI is assumed to be directly

delivered there. Canadian Waste is the private contractor that provides the curbside collection of general waste, recyclables and yard trimmings in this municipality.

**1. Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

**2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

**3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

From the perspective of recycling, transport within this municipality would be very similar to the City of Langley. Please refer to Section B.5 for the remaining emission factors.

## **B.7 DISTRICT OF MAPLE RIDGE**

In 1998, the District of Maple Ridge generated 21,355 tonnes of waste which was delivered to the MRTS (12,177 tonnes), the CTS (8,308 tonnes) and the MTS (870 tonnes) (GVRD 1999a). Similar to the LTS, most of the waste at the MRTS (83%) is transferred to MTS, and is ultimately sent to the CCLF. For this analysis, it is therefore assumed that waste disposed in the CCLF was processed at the MRTS and waste disposed at the VLF or combusted at the BI was processed at the CTS.

**1. Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

**2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

**3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

## **B.8 CITY OF NEW WESTMINSTER**

In 1998, the City of New Westminster generated 28,018 tonnes of waste which was delivered to the BI (14,411 tonnes) and to the CTS (13,607 tonnes) (GVRD 1999a). For this analysis, it will be assumed that waste disposed at the CCLF or VLF was processed at the CTS and that all waste combusted at the BI was directly transported there by collection vehicles. In this municipality, general waste and recyclables are collected by municipal crews. There is no separate collection of yard trimmings, however residents can drop off this waste at depots. Yard waste is subsequently transported to the Fraser Richmond BioCycle composting facility in Richmond (Pers. comm. Ron Trewern).

### 1. Diesel Fuel Consumption for Curbside Waste Collection:

In 1999, municipal crews collected 6,309 tonnes of waste from residences and consumed 50,331 litres in the process (Pers. comm. Ron Trewern).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e}/\text{tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(50,331)(2.854)}{(6,309) * 1000} = 0.023 \text{ tCO}_2\text{e}/\text{tonne}$$

$$\text{GHG Emissions} = 0.023 \text{ tCO}_2\text{e}/\text{tonne}$$

### 2. Diesel Fuel Consumption for Curbside Recyclables Collection:

In 1999, municipal crews collected 1,344 tonnes of recyclables from residences and consumed 24,604 litres in the process (Pers. comm. Ron Trewern).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e}/\text{tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(24,604)(2.854)}{(1,344) * 1000} = 0.052 \text{ tCO}_2\text{e}/\text{tonne}$$

$$\text{GHG Emissions} = 0.052 \text{ tCO}_2\text{e}/\text{tonne}$$

### 3. Diesel Fuel Consumption for Yard Trimmings Transport to Fraser Richmond Biocycle:

By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 40 km, the emission would be:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}/100\text{km}) (\text{Distance, km}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( 1 \frac{\text{tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes}/\text{trip})} = \text{tCO}_2\text{e}/\text{tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(45/100)(40)(2.854)}{(20) * 1000} = 0.0026 \text{ tCO}_2\text{e}/\text{tonne}$$

$$\text{GHG Emission} = 0.0026 \text{ tCO}_2\text{e}/\text{tonne}$$

## B.9 CITY OF NORTH VANCOUVER

In the City of North Vancouver, 10,037 tonnes of waste was generated and delivered to the NSTS in 1998. The only other drop off site for waste was the CTS with only 136 tonnes (GVRD 1999a). For this analysis, it is assumed that all of the waste generated in this municipality is deposited at the NSTS. In this municipality, municipal crews provide the curbside collection of general waste and yard trimmings for ground-level residences and small apartments while private haulers provide the waste collection at the large apartment and commercial buildings. While there may be differences between single and multi-family dwellings from the perspective of fuel efficiency, this investigation only uses the data obtained from the municipal crews. Recyclables are collected by contract with International Paper Industries, which also provides the subsequent processing (Pers. comm. Brent Mahood). The separate curbside collection of yard trimmings only started in 1998, so the most recent available data, the calendar year of 1999, is used here.

### 1. Diesel Fuel Consumption for Curbside Waste Collection:

The municipal crews of the City of North Vancouver collected 4,175 tonnes of waste at single-family residences in 1999 and consumed 16,257 litres in the process (Pers. comm. Brent Mahood).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(16,275)(2.854)}{(4,175) \cdot 1000} = 0.011 \text{ tCO}_2\text{e/tonne}$$

GHG Emissions = 0.011 tCO<sub>2</sub>e/tonne

### 2. Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

### 3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

The municipal crews of the City of North Vancouver collected 1,223 tonnes of yard waste at single-family residences in 1999 and consumed 10,020 litres in the process (Pers. comm. Brent Mahood).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(10,020)(2.854)}{(1,223) \cdot 1000} = 0.023 \text{ tCO}_2\text{e/tonne}$$

GHG Emissions = 0.023 tCO<sub>2</sub>e/tonne

### 4. Diesel Fuel Consumption for Yard Trimmings Transport to Fraser Richmond Biocycle:

By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a one-way distance of 20 km (the trucks return to the NSTS with finished compost (Pers. comm. Steve Aujla) and therefore the return trip is not be included under waste management), the emission would be :

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km}) (\text{Distance, km}) \left( 2.854 \frac{\text{kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes/trip})} = \text{tCO}_2\text{e/tonne}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(45/100)(20)(2.854)}{(20) \cdot 1000} = 0.0013 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.0013 tCO<sub>2</sub>e/tonne

## B.10 DISTRICT OF NORTH VANCOUVER

In the District of North Vancouver, 73,521 tonnes of waste was generated and delivered to the NSTS in 1997. The only other drop-off location was the CTS with 379 tonnes (GVRD 1999a). It is assumed in this analysis that all of the waste generated in this municipality is delivered to the NSTS. In this municipality, municipal crews collect general waste and yard trimmings from all the residences (Pers. comm. Daryl Mielty). Recyclables are collected by contract with International Paper Industries, which also provides the subsequent processing.



**1. Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

**2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

**3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

From the perspective of recycling, transport within this municipality would be very similar to the City of North Vancouver. Please refer to Section B.9 for the remaining emission factors.

## **B.11 DISTRICT OF PITT MEADOWS**

In 1998, the District of Pitt Meadows generated 3,821 tonnes of waste which was delivered to the CTS (3,595 tonnes), the MRTS (209 tonnes) and the MTS (17 tonnes) (GVRD 1999a). For this analysis, it is assumed that all waste originating in this municipality is processed at the CTS. In this municipality, the private contractor, Canadian Waste provides the curbside collection of general waste, recyclables and yard trimmings. Recyclables are delivered to Wastech in Coquitlam and yard trimmings are dropped off at the Fraser Richmond Bio-Cycle depot in Pitt Meadows for subsequent transport to the Richmond composting facility (Pers. comm. Greg Cross).

**1. Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

**2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

**3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

**4. Diesel Fuel Consumption for Yard Trimmings Transport to Fraser Richmond Biocycle:**

The transport of the yard trimmings from the Pitt Meadows depot to the Richmond composting facility is calculated below. By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 60 km (estimated from map), the emission would be :

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km}) (\text{Distance, km}) \left( \frac{2.854 \text{ kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{\left( \frac{\text{tonnes}}{\text{trip}} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \frac{45}{100} \right) (60) (2.854)}{(20) * 1000} = 0.0039 \text{ tCO}_2\text{e/tonne}$$

GHG Emission = 0.0039 tCO<sub>2</sub>e/tonne

## **B.12 CITY OF PORT COQUITLAM**

In 1998, the City of Port Coquitlam generated a total of 17,895 tonnes of waste of which 100% was delivered to the CTS (GVRD 1999a).

### **1. Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

### **2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

### **3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

From the perspective of recycling, transport within this municipality would be very similar to the City of Coquitlam. Please refer to Section B.3 for the remaining emission factors.

## **B.13 CITY OF PORT MOODY**

In 1998, the City of Port Moody generated 5,670 tonnes of waste and all of this was delivered to the CTS (GVRD 1999a). As previously discussed, waste generated in Anmore or Belcarra is to be assumed as having originated in the City of Port Moody. In the GVRD's Solid Waste Flow Model for 1998 (GVRD 1999a), this is already assumed as the waste from Anmore & Belcarra is zero (Pers. comm.. Mike Stringer). Canadian Waste is the private contractor which provides the curbside collection of general waste, recyclables and yard trimmings. Recyclables are delivered to Wastech Services in Coquitlam and the yard trimmings are delivered to the Fraser Richmond BioCycle depot in Pitt Meadows for subsequent transport to the Richmond composting facility.

### **1. Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

### **2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

### **3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

### **4. Diesel Fuel Consumption for Yard Trimmings Transport to Fraser Richmond Biocycle:**

The transport of the yard trimmings from the Pitt Meadows depot to the Richmond composting facility is calculated below. By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 60 km (estimated from map), the emission would be :

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \text{Fuel Consumption, L/100km} \right) \left( \text{Distance, km} \right) \left( 2.854 \text{ kgCO}_2\text{e/L} \right) \left( 1 \text{ tonne/1000 kg} \right)}{\left( \text{tonnes/trip} \right)} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{\left( \frac{45}{100} \right) (60) (2.854)}{(20) * 1000} = 0.0039 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0039 \text{ tCO}_2\text{e/tonne}$$

## B.14 CITY OF RICHMOND

In 1998, the City of Richmond generated 64,364 tonnes of waste; most of which was delivered to the VTS (43,609 tonnes), however, waste was also delivered to the VLF (7,508 tonnes), the BI (7,280 tonnes) and the CTS (5,967 tonnes) (GVRD 1999a). For this analysis, it is assumed that waste disposed in the VLF was processed through the VTS, that waste combusted at the BI was delivered directly there and that waste disposed at the CCLF was processed through the CTS. Yard waste is assumed to be directly delivered to Fraser Richmond Biocycle.

### 1. Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

### 2. Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

### 3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

## B.15 CITY OF SURREY

In 1998, the City of Surrey generated 126,130 tonnes of waste which was delivered to the CTS (96,881 tonnes), the BI (21,286 tonnes), the VLF (7,471 tonnes) and the MTS (492 tonnes) (GVRD 1999a). For this analysis, it is assumed that all waste generated in this municipality was processed through the CTS. Also, the curbside collection of waste will deliver to the CTS. Canadian Waste is the private contractor which handles the curbside collection of general waste, recyclables and yard trimmings (Pers. comm. Richard Woo). Recyclables are delivered to the recycling depot operated by ETL Recycling Services.

### 1. Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

### 2. Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

### 3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

#### 4. Diesel Fuel Consumption for Yard Trimmings Transport to Fraser Richmond Biocycle:

By assuming 20 tonnes hauled per trip, a diesel fuel consumption of 45.0L per 100km and a round-trip distance of 60 km (estimated from map), the emission would be :

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/100km})(\text{Distance, km})(2.854 \text{ kgCO}_2\text{e/L})(1 \text{ tonne/1000 kg})}{(\text{tonnes/trip})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(45/100)(40)(2.854)}{(20) \cdot 1000} = 0.0026 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0026 \text{ tCO}_2\text{e/tonne}$$

### B.16 CITY OF VANCOUVER

In 1998, the City of Vancouver generated 346,991 tonnes of waste which was collected and delivered to the VTS (225,740 tonnes), to the NSTS (83,761 tonnes), to the CTS (22,374 tonnes) and directly delivered to the VLF (8,899 tonnes) and the BI (6,217 tonnes) (GVRD 1999a). As 100% of the waste delivered to the VTS is transferred to the VLF, the small amount delivered directly to the VLF is insignificant and is assumed to have been transferred through the VTS. As approximately half of the waste delivered to the NSTS is transferred to the BI and the other half is transferred to the CCLF, and since the 83,761 tonnes at the NSTS is much greater than either the tonnage going to the CTS or BI, it is assumed that waste disposed in the CCLF or combusted at the BI was processed at the NSTS. In this municipality, city crews provide the curbside collection of general waste, recyclables and yard trimmings for ground-level (single family) residences while private contractors provide collection of general waste and recyclable at apartment (multi-family) residences and commercial buildings. Canadian Waste, the largest private hauler, collected nearly as much waste in 1998 (72,900 tonnes) as the city crews did (76,000 tonnes) (Pers. comm. Kevin Van Vliet). As a result, data from this organization was also obtained for comparison. However, as a simplification, only the data for ground-level residences will be used in the greenhouse gas estimates. The collected recyclables were delivered to a recycling depot in south Vancouver operated by Browning Ferris Industries. A separate collection of yard waste was recently been initiated in this municipality. Currently, yard waste is collected and delivered to the VTS for subsequent transport to the composting facility at the VLF.

#### 1. Diesel Fuel Consumption for Curbside Waste Collection:

In 1998, the city crews collected 76,000 tonnes of waste from ground level (single-family) residences and delivered it to the VTS. During this activity approximately 316,000 litres of diesel fuel was consumed (Pers. comm. Kevin Van Vliet).

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L})(2.854 \text{ kgCO}_2\text{e/L})(1 \text{ tonne/1000 kg})}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(316,000)(2.854)}{(76,000) \cdot 1000} = 0.012 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emissions} = 0.012 \text{ tCO}_2\text{e/tonne}$$

## 2. Diesel Fuel Consumption for Curbside Recyclables Collection:

The collection of recyclables from single-family residences (blue boxes) is performed by municipal crews. In the collection of 17,500 tonnes of recyclables in 1998, approximately 190,000 litres of diesel fuel was consumed (Pers. comm. Kevin Van Vliet). The average emission is calculated below:

$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L}) \left( \frac{2.854 \text{ kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes})} = \text{tCO}_2\text{e/tonne}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(190,000)(2.854)}{(17,500) * 1000} = 0.031 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emissions} = 0.031 \text{ tCO}_2\text{e/tonne}$$

## 3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

$$\text{Average GHG Emission} = 0.027 \text{ tCO}_2\text{e/tonne}$$

## 4. Diesel Fuel Consumption for Yard Trimmings Transport to the Vancouver Composting Facility:

Approximately 12,500 tractor-trailer trips were required to transport 271,431 tonnes of waste and 16,500 tonnes of yard trimmings from the VTS to the VLF. This necessitated the consumption of 334,000 litres of diesel fuel (Pers. comm. Kevin Van Vliet).

$$\frac{\text{Mass Hauled}}{\text{Trip}} = \frac{271,431 \text{ tonnes}}{12,500 \text{ trips}} = 23.0 \text{ tonnes/trip}$$
$$\frac{\text{Fuel Consumption}}{\text{Trip}} = \frac{334,000 \text{ litres}}{12,500 \text{ trips}} = 26.7 \text{ L/trip}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(\text{Fuel Consumption, L/trip}) \left( \frac{2.854 \text{ kgCO}_2\text{e}}{\text{L}} \right) \left( \frac{1 \text{ tonne}}{1000 \text{ kg}} \right)}{(\text{tonnes/trip})} = \text{tCO}_2\text{e/tonne}$$
$$\frac{\text{GHG Emissions}}{\text{tonne}} = \frac{(26.7)(2.854)}{(23.0) * 1000} = 0.0033 \text{ tCO}_2\text{e/tonne}$$

$$\text{GHG Emission} = 0.0033 \text{ tCO}_2\text{e/tonne}$$

## B.17 DISTRICT OF WEST VANCOUVER

In the District of West Vancouver, 15,733 tonnes of waste was generated and delivered to the NSTS in 1998 (GVRD 1999a). This is 100% of the waste stream collected that year. International Paper Industries (IPI) is the private contractor which provides the curbside collection of general waste, recyclables and yard trimmings. Recyclables are delivered to the recycling depot near the North Shore Transfer Station which is operated by IPI. Yard trimmings are delivered to the Green Waste Processing Yard at the North Shore Transfer Station for subsequent transport to the Richmond composting facility of Fraser Richmond Bio-Cycle.

### 1. Diesel Fuel Consumption for Curbside Waste Collection:

$$\text{Average GHG Emission} = 0.014 \text{ tCO}_2\text{e/tonne}$$

### 2. Diesel Fuel Consumption for Curbside Recyclables Collection:

$$\text{Average GHG Emission} = 0.043 \text{ tCO}_2\text{e/tonne}$$

### 3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

From the perspective of recycling, transport within this municipality would be very similar to the City of North Vancouver. Please refer to Section B.9 for the remaining emission factors.

### **B.18 CITY OF WHITE ROCK**

In 1998, the City of White Rock generated 8,964 tonnes of waste which was collected and delivered to the VLF (8,635 tonnes), to the CTS (287 tonnes), and to the VTS (42 tonnes) (GVRD 1999a). For this analysis, it is assumed that waste disposed in the VLF was delivered directly there, while waste to the CCLF or the BI was first processed at the CTS.

**1. Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

**2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

**3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

### **B.19 ELECTORAL AREA A (U.B.C. & U.E.L.)**

In 1998, Electoral A generated 3,349 tonnes of waste which was collected and delivered to the VTS (3,283 tonnes) and the VLF (66 tonnes) (GVRD 1999a). For this analysis, it is assumed that all waste generated will be processed through the VTS.

**1. Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

**2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

**3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

**4. Diesel Fuel Consumption for Yard Trimmings Transport to Fraser Richmond Biocycle:**

### **B.20 ELECTORAL AREA C (BOWEN ISLAND & HOWE SOUND)**

In the 1998, Electoral C generated 1,266 tonnes of waste which was collected and delivered to the NSTS (GVRD 1999a). The fuel consumption of the ferries associated with crossing Howe Sound is not included in this analysis. As previously discussed,

waste generated from the Village of Lions Bay is to be assumed as originating from Electoral Area C. In 1998, only a total of 23 tonnes of waste came from Lions Bay to the NSTS (GVRD 1999a). Obviously much of the generated waste is being managed outside of the GVRD and will not be subject to any analysis.

**1. Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG Emission = 0.014 tCO<sub>2</sub>e/tonne

**2. Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG Emission = 0.043 tCO<sub>2</sub>e/tonne

**3. Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG Emission = 0.027 tCO<sub>2</sub>e/tonne

From the perspective of recycling, transport within this municipality would be very similar to the City of North Vancouver. Please refer to Section B.9 for the remaining emission factors.

## **APPENDIX C:**

### **NEWSPRINT WASTE MANAGEMENT**

This appendix provides all the data and calculations to estimate emission factors for the landfilling, incineration or recycling of newsprint generated in the GVRD. The first three sections are devoted to the GHG implications of the Cache Creek Landfill (1-3). The next three sections assess the same implications for the Vancouver Landfill (4-6). Sections 7 and 8, assess the energy generation and GHG emissions from the Burnaby Incinerator. The last two sections of this appendix, 9 and 10, analyze the GHG ramifications of newsprint recycling.

#### **1. Methane & Energy Implications of the Cache Creek Landfill:**

As discussed in Section 2.4, a time-dependant model is used to estimate emissions for the next 20 years. In this model, calculations are used to estimate the future methane emissions from the anaerobic decomposition of disposed newsprint. These calculations estimate the emission for a 20 year period between 1999 and 2018 for waste deposited in the year 1998. As this estimate is strictly limited to these years, and anaerobic decomposition could continue after this period, the actual or total emissions could be greater. At the end of 20 years, the organic-carbon previously deposited in the landfill will have either been emitted as CH<sub>4</sub>, emitted as CO<sub>2</sub>, entered long-term storage or not yet decomposed. The Carbon Storage Factors estimated by Barlaz (and discussed in Section 2.4) are used here and revised to determine the fraction sequestered and the fraction of *Carbon Available for Anaerobic Decomposition*. However, the decay rate will determine how much of the CAAD (carbon not being sequestered) will actually be decomposed during the 20 year time period. As a result, carbon not yet degraded, but not entering storage, will remain at the end of the time period.

The Scholl Canyon Decay Model (EMCON Associates 1980) is recommended by the IPCC (IPCC 1997), and is also used by Environment Canada (1997), for estimating methane emission at landfills. The first order equation for this model is:

$$G_i = kL_oM_i e^{-kt_i}$$

where:  $G_i$  = methane generation rate from waste placed in the  $i^{\text{th}}$  year  
 $k$  = methane generation first order rate constant (year<sup>-1</sup>)  
 $L_o$  = methane generation potential (tCH<sub>4</sub>/tonne waste)  
 $M_i$  = mass of waste placed in the  $i^{\text{th}}$  year (tonnes)  
 $t_i$  = age of the  $i^{\text{th}}$  section (years)

This research uses this model to estimate landfill methane emissions.

The first order decay rate constant used here is 0.04 y<sup>-1</sup> and the assumptions behind it are discussed in Section 2.4 - *Landfill Carbon Sequestration*.

Also of great importance with respect to methane generation, is what fraction of landfill gas escapes collection systems and is emitted to the atmosphere. Personal



communication with Wastech Services (Pers. comm.. Louie DeVent) has informed this author that 2.1 million m<sup>3</sup> of CH<sub>4</sub> gas was collected in 1998 and flared without any energy utilization. However, the GVRD has modelled that 4,931,000 m<sup>3</sup> of CH<sub>4</sub> was generated in this same year (GVRD 1999b). While this generation estimate is by no means certain, when dividing the LFG collection by the LFG generation a landfill gas collection efficiency of 43% can be approximated. While this may be the current situation, it is likely that with the strong federal and provincial interest in stricter landfill gas regulations this efficiency will probably increase in the future. Not only will the collection efficiency be greater but the current flaring could adapt to allow for energy utilization. If utilization occurred, the consumption of landfill gas would be a replacement of fossil-based natural gas; thereby resulting in a GHG benefit. As a result of the potential for increasing regulations to improve landfill gas collection systems, this model will slowly ramp up, year after year, not only the collection efficiency but also the proportion utilized for energy (to replace fossil energy). The energy generation benefits of landfill methane derive from the assumption that they are the CO<sub>2</sub> prevented by the replacement of natural gas. By utilizing landfill gas for energy generation, the consumption of fossil fuel and a GHG emission is prevented.

Lastly, there is also the potential for microorganisms in the cover material of the landfill to cause the oxidation of CH<sub>4</sub> to CO<sub>2</sub>. Research conducted in the U.S. has observed this factor to oxidize about 10% of the methane which had escaped collection (Czepiel et al. 1996). This is the oxidation factor to be used for methane gas which bypassed collection systems.

The calculations for landfill methane emissions and energy generation follow – starting with the Carbon Available for Anaerobic Decomposition (CAAD):

Estimated Methane Yield from Newsprint in reactors = 74.2 ml/dry gram (USEPA 1998)

Assumed Carbon Dioxide Yield from newsprint = 74.2 ml/dry gram

Molar gas constant=22.4 L/mol at standard temperature and pressure

Typical Moisture Content of Newsprint = 6% (Tchobanoglous et al. 1993)

$$\text{Moles of CH}_4 = \frac{74.2 \text{ ml/gram}}{22,400 \text{ ml/mol}} = 0.0033 \text{ mol CH}_4$$

$$\text{Moles of CO}_2 = \frac{74.2 \text{ ml/gram}}{22,400 \text{ ml/mol}} = 0.0033 \text{ mol CO}_2$$

$$\text{Total Moles of C} = 0.0033 + 0.0033 = 0.0066 \text{ mol C}$$

$$\text{Carbon Available for Anaerobic Decomposition} = 0.0066 \text{ mol C} * 12 \frac{\text{g}}{\text{mol}} = 0.0795 \text{ g C / dry gram}$$

$$\text{CAAD(dry)} = 0.0795 \text{ g C / dry gram} = 0.0795 \text{ t C / dry tonne}$$

$$\text{CAAD(wet)} = 0.0795 * (1 - 0.06) = 0.075 \text{ g C / wet gram} = 0.075 \text{ t C / wet tonne}$$

Carbon Content of Dry Newsprint = 49.1% (Barlaz 1998)

RevisedCarbonStorageFactor = InitialCarbon - CAAD = gC / drygram

$$\text{RevisedCarbonStorageFactor} = 0.491 \frac{\text{gC}}{\text{drygram}} - 0.0795 \frac{\text{gC}}{\text{drygram}} = 0.41 \frac{\text{gC}}{\text{drygram}}$$

$$\text{RevisedCarbonStorageFactor} = 0.41 \frac{\text{gC}}{\text{drygram}} = 0.41 \frac{\text{tC}}{\text{drytonne}}$$

This 0.075 tC per wet tonne of newsprint is available for anaerobic decomposition and will be assumed to be evenly split between CH<sub>4</sub> and CO<sub>2</sub>. Remember that since any CO<sub>2</sub> is neutral, it does not have to be considered further.

$$\text{Methane Generation} = \left( \text{Carbon To Decompose} \frac{\text{tC}}{\text{WetTonne}} \right) \left( \text{Methane Fraction} \right) \left( \frac{\text{Molecular Mass of CH}_4}{\text{Molecular Mass of C}} \right) = \frac{\text{tCH}_4}{\text{Wet Tonne}}$$

$$\text{Methane Generation} = (0.075) \left( 0.5 \right) \left( \frac{16}{12} \right) = 0.050 \frac{\text{tCH}_4}{\text{WetTonne}}$$

Methane Generation Potential = 0.050 tCH<sub>4</sub>/tonne of food waste

The calculations below demonstrate the estimate of the methane emissions for the year 1999 and the year 2010 for one tonne of newsprint deposited in the year 1998. The year 1999 is assumed as the first year, year zero, of decomposition.

#### YEAR 2001

Solving for the Methane Generation Rate (G<sub>i</sub>):

methane generation first order rate constant (k) = 0.04 year<sup>-1</sup>

methane generation potential (L<sub>0</sub>) = 0.050 tCH<sub>4</sub>/tonne waste

mass of waste placed in the i<sup>th</sup> year (M<sub>i</sub>) = 1 tonne

age of the i<sup>th</sup> section (t<sub>i</sub>) = 1999-1999 = 0 year

$$G_i = kL_0M_i e^{-kt_i}$$

$$G_i = \left( 0.04 \frac{1}{\text{yr}} \right) \cdot \left( 0.050 \frac{\text{tCH}_4}{\text{tonne}} \right) \cdot (1 \text{ tonne}) \cdot e^{\left( -0.04 \frac{1}{\text{yr}} \right) \cdot (0 \text{ yr})} = 0.00199 \frac{\text{tCH}_4}{\text{yr}}$$

Solving for the Atmospheric Methane Emission:

methane generation rate = 0.00199 tCH<sub>4</sub>/yr

percentage oxidation by cover material = 10%

percentage landfill gas flared = 43%

percentage landfill gas for energy = 0%

$$\text{Methane Emission} = \left( \text{Generation} \right) \left( 1 - \% \text{Flared} - \% \text{Energy} \right) \left( 1 - \text{Oxidation} \right) \left( \text{GWP of CH}_4 \right) = \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\text{Methane Emission} = (0.00199) (1 - 0.43 - 0) (1 - 0.10) (21) = 0.0215 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

Solving for the Energy Generation:

percentage landfill gas for energy = 0%

$$\text{GHG Benefit of Energy Generation} = \left( \text{CH}_4 \text{ Generation} \right) \left( \% \text{Energy} \right) \left( \frac{\text{Molecular Mass of CO}_2}{\text{Molecular Mass of CH}_4} \right) = \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\text{GHG Benefit of Energy Generation} = (0.00199) \left( 0 \right) \left( \frac{44}{16} \right) = 0 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

### YEAR 2010

Solving for the Methane Generation Rate ( $G_i$ ):

methane generation first order rate constant ( $k$ ) =  $0.04 \text{ year}^{-1}$

methane generation potential ( $L_0$ ) =  $0.050 \text{ tCH}_4/\text{tonne waste}$

mass of waste placed in the  $i^{\text{th}}$  year ( $M_i$ ) =  $1 \text{ tonne}$

age of the  $i^{\text{th}}$  section ( $t_i$ ) =  $2010 - 1999 = 11 \text{ year}$

$$G_i = kL_0M_i e^{-kt_i}$$

$$G_i = \left(0.04 \frac{1}{\text{yr}}\right) \cdot \left(0.05 \frac{\text{tCH}_4}{\text{tonne}}\right) \cdot (1 \text{ tonne}) \cdot e^{\left(-0.04 \frac{1}{\text{yr}}\right) \cdot (11 \text{ yr})} = 0.00128 \frac{\text{tCH}_4}{\text{yr}}$$

Solving for the Atmospheric Methane Emission:

methane generation rate =  $0.00128 \text{ tCH}_4/\text{yr}$

percentage oxidation by cover material =  $10\%$

percentage landfill gas flared =  $25\%$

percentage landfill gas for energy =  $50\%$

$$\text{Methane Emission} = (\text{Generation}) \times (1 - \% \text{Flared} - \% \text{Energy}) \times (1 - \text{Oxidation}) \times (\text{GWP of CH}_4) = \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\text{Methane Emission} = (0.00128) \times (1 - 0.25 - 0.50) \times (1 - 0.10) \times (21) = 0.0061 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

Solving for the Energy Generation:

percentage landfill gas for energy =  $50\%$

$$\text{GHG Benefit of Energy Generation} = (\text{CH}_4 \text{ Generation}) \times (\% \text{Energy}) \times \left(\frac{\text{Molecular Mass of CO}_2}{\text{Molecular Mass of CH}_4}\right) = \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\text{GHG Benefit of Energy Generation} = (0.00128) \times (0.50) \times \left(\frac{44}{16}\right) = 0.0019 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

Using these calculations, the model is presented below:

BEST-GUESS:						
YEAR	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-
1999	0.00199	10	43	0	0.0215	0.0000
2000	0.00191	10	50	0	0.0181	0.0000
2001	0.00184	10	50	10	0.0139	0.0005
2002	0.00177	10	50	15	0.0117	0.0007
2003	0.00170	10	45	20	0.0112	0.0009
2004	0.00163	10	40	25	0.0108	0.0011
2005	0.00157	10	35	35	0.0089	0.0015
2006	0.00151	10	30	40	0.0085	0.0017
2007	0.00145	10	25	50	0.0068	0.0020
2008	0.00139	10	25	50	0.0066	0.0019
2009	0.00134	10	20	55	0.0063	0.0020
2010	0.00128	10	20	55	0.0061	0.0019
2011	0.00123	10	15	60	0.0058	0.0020
2012	0.00118	10	15	60	0.0056	0.0020
2013	0.00114	10	10	65	0.0054	0.0020
2014	0.00109	10	10	65	0.0052	0.0020
2015	0.00105	10	5	70	0.0050	0.0020
2016	0.00101	10	5	70	0.0048	0.0019
2017	0.00097	10	0	75	0.0046	0.0020
2018	0.00093	10	0	75	0.0044	0.0019
<b>TOTAL =</b>	<b>0.02799</b>				<b>0.171</b>	<b>0.030</b>

Best-Guess of Atmospheric Methane Emissions= 0.171 tCO<sub>2</sub>e/tonne

Best-Guess of Benefit of Energy Utilization= -0.030 tCO<sub>2</sub>e/tonne

For the 20 year period between 1999 and 2018, it is estimated that 0.028 tCH<sub>4</sub>/tonne would be generated. This represents 56% of the ultimate potential of 0.050 tCH<sub>4</sub>/tonne, the CAAD. This generation corresponds to, minus the collection and oxidation, an emission of 0.171 tCO<sub>2</sub>e/tonne. Furthermore an energy benefit, via the replacement of fossil energy, of 0.030 tCO<sub>2</sub>e/tonne would be realized.

The calculations above are based on best-guess data. However, the first-order decay rate constant, the LFG collection for flaring or energy utilization and the oxidation by landfill cover materials are all uncertain. Rather than simply providing just best-guess estimates, high and low estimates are calculated to demonstrate a likely range for future methane

emissions. These estimates are developed by increasing and decreasing the important parameters involved in calculations above. The high estimate uses a first-order decay rate constant that is increased by 50% while the LFG collection for flaring and energy utilization is decreased to an appropriate level deemed by this author. The oxidation by landfill cover materials is also decreased by 50%. The low estimate uses a first-order decay rate constant that is decreased by 50% with the collection effectiveness increased appropriately. The oxidation by cover materials is also increased by 50% in the low estimate. These calculations presented in Worksheet 26 and the results are below.

Best-Guess of Atmospheric Methane Emissions=	0.171	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.030	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.079	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.020	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.321	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.007	tCO <sub>2</sub> e/tonne

## 2. Long-Term Carbon Sequestration in the Cache Creek Landfill:

Since not all of the cellulose and hemicellulose and only a negligible portion of the lignin from newsprint is expected to anaerobically degrade in a landfill, organic-carbon will remain in long-term storage in the landfill. In this capacity, the organic-carbon, which was originally atmospheric CO<sub>2</sub> but was photosynthesized into biomass, will be sequestered. As a result, organic-carbon can perform a GHG benefit, a negative GHG emission. This issue is discussed in greater detail in Section 2.4 – *Landfill Carbon Sequestration*.

The Carbon Storage Factors, as determined by Barlaz (1998), and also discussed in Eleazer et al. (1997), are used here as representative of long-term storage in the CCLF. These experiments determined that the long-term carbon storage of newsprint in landfills is 0.42 kg C per kg of dry newsprint. The researchers observed that 31% of the cellulose and hemicellulose fraction and only a negligible portion of lignin decomposed. However, these factors were developed with laboratory research of idealized landfill decomposition conditions and are thus highly conservative. As a result, the actual storage in the CCLF could be greater than is indicated by these experiments. While there is great potential for uncertainty with this estimate, it is likely that the uncertainty would be skewed towards a greater value. By using this conservative estimate, the risk of overestimating this factor is probably minimal. For these reasons, only the best-guess estimate will be used in this analysis.

In Section #1 of the Appendix a revised Carbon Storage Factor was developed to attempt to correct inconsistencies in the previous estimates by Barlaz. The new estimate is as follows:

Revised Carbon Storage Factor for newsprint = 0.41 tC/dry tonne newsprint

Typical Moisture Content of Newsprint = 6% (Tchobanoglous et al. 1993)

$$\text{Carbon Sequestration} = \left( \frac{\text{tC}}{\text{Dry newsprint}} \right) (1 - \text{Moisture Content}) \left( \frac{44 \text{gCO}_2 / \text{mol}}{12 \text{gC} / \text{mol}} \right) = \text{tCO}_2 \text{e} / \text{tonne}$$

$$\text{Carbon Sequestration} = (0.41)(1 - 0.06) \left( \frac{44}{12} \right) = 1.41 \text{ tCO}_2 \text{e} / \text{tonne}$$

Long-Term Carbon Sequestration from Newsprint = -1.41 tCO<sub>2</sub>e/tonne

### 3. Immediate & Future N<sub>2</sub>O Emissions from the Cache Creek Landfill

As the nitrogen content of newsprint is negligible (<0.1% in Tchobanoglous (1993)), the potential for nitrous oxide emissions can be ignored.

### 4. Methane & Energy Implications of the Vancouver Landfill:

The only significant difference between this section and Section 1, *Methane & Energy Implications of the Cache Creek Landfill*, is the estimated landfill gas collection efficiency and the first order decay rate constant. While at Cache Creek the current collection efficiency is estimated to be 43%, the current collection efficiency at the Vancouver Landfill is estimated to only be 22% (Pers. comm. Chris Underwood). However, engineers with the City of Vancouver are currently in the process of upgrading the collection equipment. As with the CCLF assessment, the collection efficiency is assumed to increase year after year in response to improving regulations. In this study, the first order decay rate constant used for the VLF in this report, 0.05 yr<sup>-1</sup>, is assumed based on the discussion in Section 2.4 – *Landfill Carbon Sequestration*.

Based on these changes, the model is provided below:

BEST-GUESS:						
YEAR	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-
1999	0.00249	10	22	0	0.0367	0.0000
2000	0.00237	10	30	0	0.0313	0.0000
2001	0.00225	10	35	10	0.0234	0.0006
2002	0.00214	10	40	15	0.0182	0.0009
2003	0.00204	10	45	20	0.0135	0.0011
2004	0.00194	10	40	25	0.0128	0.0013
2005	0.00185	10	30	40	0.0105	0.0020
2006	0.00176	10	30	40	0.0100	0.0019
2007	0.00167	10	25	50	0.0079	0.0023
2008	0.00159	10	25	50	0.0075	0.0022
2009	0.00151	10	20	55	0.0071	0.0023
2010	0.00144	10	20	55	0.0068	0.0022

2011	0.00137	10	15	60	0.0065	0.0023
2012	0.00130	10	15	60	0.0061	0.0021
2013	0.00124	10	10	65	0.0058	0.0022
2014	0.00118	10	10	65	0.0056	0.0021
2015	0.00112	10	5	70	0.0053	0.0022
2016	0.00106	10	5	70	0.0050	0.0020
2017	0.00101	10	0	75	0.0048	0.0021
2018	0.00096	10	0	75	0.0046	0.0020
<b>TOTAL =</b>	<b>0.032</b>				<b>0.229</b>	<b>0.034</b>

Best-Guess of Atmospheric Methane Emissions=	0.229	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.034	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.107	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.023	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.408	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.007	tCO <sub>2</sub> e/tonne

##### **5. Long-Term Carbon Sequestration in the Vancouver Landfill:**

The Revised Carbon Storage Factors is used here as representative of long-term storage in the VLF.

Long-Term Carbon Sequestration from Newsprint = -1.41 tCO<sub>2</sub>e/tonne

##### **6. Immediate & Future N<sub>2</sub>O Emissions from the Vancouver Landfill**

As the nitrogen content of newsprint is negligible (<0.1% in Tchobanoglous (1993)), the potential for nitrous oxide emissions can be ignored.

##### **7. Energy Generation from Waste Incineration at the Burnaby Incinerator:**

At the Burnaby Incinerator, 247,075 tonnes of waste was combusted in 1998 to generate 816,916 tonnes of steam (Montenay Inc. 1999; Pers. comm. Richard Holt). Of this steam produced, 56% was exported to Crown Packaging Ltd. – Paper Mill Division (CPL) for utilization in the pulping of corrugated cardboard into various recycled paper products (the remainder is used internally or condensed for disposal) (Pers. comm. John MacDowell). This steam, when utilized by CPL, offsets the combustion of natural gas which would otherwise be necessary. Of the remaining steam, a small portion is used internally for heating purposes at the Incinerator and the vast majority is condensed for disposal. There is currently no electricity generation at the Incinerator. For these calculations, it is assumed that 40% of the steam is used for electricity generation and the remaining 4% is used internally at the Incinerator. The calculations below determine the greenhouse gas implications of current energy generation at the Burnaby Incinerator and the potential for electricity generation in the future.

One of the most important parameters at a waste-to-energy facility like the Burnaby Incinerator, is the energy efficiency; what percentage of the energy embodied in the combusted waste is represented in the generated steam? This critical parameter is a valuable indication of the effectiveness of the facility in generating energy. After construction in 1988, the boiler efficiency was measured at 71%, but initial test runs this year have indicated that it may have decreased to 69% (Pers. comm. Ron Richter). This is still higher than the typical thermal efficiency reported in literature of 63% for a mass-fired incinerator-boiler (Tchobanoglous 1993). Furthermore, improvements to the boiler will be made in the future to increase this efficiency to between 75 and 77% when a planned turbo generator is installed for electricity generation. For this research, it is assumed that Incinerator currently has a boiler efficiency of 70% (conversion of waste energy to steam energy). The proposed turbo generator at the incinerator, together with improvements to current steam generation, will have a steam to electricity conversion efficiency of 32% (Pers. comm. Ron Richter; it has been calculated by consultants that 24MW could result from the incinerator using all of its steam for electricity generation). To calculate an overall efficiency of waste energy to electrical energy, the two efficiencies, 70% for waste-to-steam and 32% for steam-to-electricity, can be multiplied. This results in an overall efficiency of 23% - slightly greater than the 18% efficiency recently assumed in an EPA analysis (USEPA 1998). This is logical considering that the EPA assumption is an average of the old low-efficiency and modern high efficiency waste-to-energy plants in the U.S.

In order to determine the amount of GHG emissions prevented by this operation the energy produced by combustion in an Incinerator-Boiler to make steam must be determined (1). Next, the emission factor for natural gas that would otherwise be combusted to make steam is necessary (2). These results must then be multiplied to calculate the GHG emissions prevented per tonne of waste by the utilization of steam by CPL (3). In addition, the energy produced by the Incinerator which is used to make electricity needs to be calculated (4) and the emission factor for electricity production in British Columbia needs to be determined (5). Multiplying these two results will find the GHG benefit of replacing electrical generation by the provincial utility, B.C. Hydro (6). Both (3) and (6) are summed to calculate a total GHG emission prevention (7). These calculations are below:

Net Energy Content of Newsprint = 7,950 BTU/lb = 18,435 kJ/kg (USEPA 1998)  
 (7,950 BTU/lb\*1.054 kJ/BTU\*2.20 lb/kg = 18,435 kJ/kg)  
 (wet basis, correction for latent heat of water in this reference is assumed but not directly specified)

From another source (Tchobanoglous et al. 1993):

Gross Energy Content of Newsprint = 7,975 BTU/lb = 18,492 kJ/kg (wet basis)

Typical Moisture Content of Newsprint = 6% (Tchobanoglous et al. 1993)

Latent Heat of Water=2473 kJ/kg (Incropera and DeWitt 1990)

Net Energy Content = [Gross Energy] - [Latent Heat of Vaporization]

$$\text{Net Energy Content} = \left[ 18,492 \frac{\text{kJ}}{\text{kg}} \right] - \left[ \left( 2473 \frac{\text{kJ}}{\text{kg}} \right) (0.06)_{MC} \right] = 18,344 \frac{\text{kJ}}{\text{kg}}$$



An average of these two values will be used as the estimate for the net energy content.

$$\text{Net Energy Content} = \left[ \frac{18,435 + 18,344}{2} \right] = 18,390 \text{ kJ/kg} = 18.4 \text{ GJ/tonne}$$

Best-Guess Estimate of the Net Energy Content of Newsprint = 18.4 GJ/tonne

Steam Energy produced by the combustion of newsprint in an Incinerator-Boiler (1):

Assumed Boiler Efficiency = 70% (Pers. comm. Ron Richter)

Fraction of Steam Utilized by CPL = 56% (Montenay Inc. 1999)

$$\frac{\text{Utilized Energy}}{\text{tonne Newsprint}} = \frac{\text{energy}}{\text{tonne}} * (\text{Thermal Efficiency}) * (\text{Energy Utilization}) = \text{kJ/tonne}$$

$$\frac{\text{Utilized Energy}}{\text{tonne Newsprint}} = \frac{18.4 \text{ GJ}}{\text{tonne}} * (0.70) * (0.56) = 7.21 \text{ GJ/tonne}$$

Utilized Steam Energy per tonne of newsprint, (1) = 7.21 GJ/tonne

Emission factor for natural gas that would otherwise be combusted by CPL (2):

Typical Efficiency of Natural Gas Combustion to generate Steam = 80% (Fryling 1966)

CO<sub>2</sub> Emission from Natural Gas Combustion = 1.88 kg/m<sup>3</sup> (Environment Canada 1997a)

Typical Energy of Natural Gas = 1020 BTU/ft<sup>3</sup> = 37,843 kJ/m<sup>3</sup> (Perry's 1984)

(Energy = 1020 BTU/ft<sup>3</sup> \* 1.054 kJ/BTU \* 35.2 ft<sup>3</sup>/m<sup>3</sup> = 37,843 kJ/m<sup>3</sup>)

$$\text{Emission Factor for Natural Gas} = \frac{\left(1.88 \frac{\text{kg CO}_2}{\text{m}^3}\right) * \left(\frac{\text{tonnes}}{1000 \text{ kg}}\right)}{\left(\text{Natural Gas} \frac{\text{kJ}}{\text{m}^3}\right) * (\text{Efficiency}) * \left(\frac{\text{GJ}}{10^6 \text{ kJ}}\right)} = \text{tCO}_2\text{e/GJ}$$

$$\text{Emission Factor for Natural Gas} = \frac{\left(1.88 \frac{\text{kg CO}_2}{\text{m}^3}\right) * \left(\frac{\text{tonnes}}{1000 \text{ kg}}\right)}{\left(37843 \frac{\text{kJ}}{\text{m}^3}\right) * (0.80) * \left(\frac{\text{GJ}}{10^6 \text{ kJ}}\right)} = 0.062 \text{ tCO}_2\text{e/GJ}$$

Emission Factor for Natural Gas, (2) = 0.062 tCO<sub>2</sub>e/GJ

GHG emission prevented per tonne of newsprint (3):

$$\frac{\text{GHG Emission Prevented}}{\text{tonne newsprint}} = \left( \frac{\text{Utilized Energy}}{\text{tonne Newsprint}} \right) * \left( \text{Emission Factor for Natural Gas, tCO}_2\text{e/GJ} \right) = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne newsprint}} = (7.21 \text{ GJ/tonne}) * (0.062 \text{ tCO}_2\text{e/GJ}) = 0.4477 \text{ tCO}_2\text{e/tonne}$$

GHG Emission Prevented from Natural Gas, (3) = 0.447 tCO<sub>2</sub>e/tonne

Electricity produced by the combustion of newsprint in an Incinerator-Boiler (4):

Assumed Turbo Generator Efficiency = 32% (Pers. comm. Ron Richter)

Steam Fraction for Electricity Generation = 40% (assumed as discussed)

$$\frac{\text{Utilized Energy}}{\text{tonne Newsprint}} = \frac{\text{energy}}{\text{tonne}} * (\text{Boiler Effic}) * (\text{TurboGenerator}) * (\text{Energy Utilization}) = \text{kJ/tonne}$$

$$\frac{\text{Utilized Energy}}{\text{tonne Newsprint}} = \frac{18.4 \text{ GJ}}{\text{tonne}} * (0.70) * (0.32) * (0.40) = 1.65 \text{ GJ/tonne}$$

Utilized Electrical Energy per tonne of newsprint, (4) = 1.65 GJ/tonne

Emission factor for electricity that would otherwise be generated by B.C. Hydro (5):

While electricity generation in British Columbia is predominantly from hydroelectric facilities, there are several thermal generation stations. The GHG emission intensity for

electricity production in this province, 30 tCO<sub>2</sub>e/GWh (BC Hydro 1998), is a fraction of the Canadian average for fossil fuel electricity generation, 960 tCO<sub>2</sub>e/GWh (Environment Canada 1997a). Of considerable note is that the emission intensity for the natural gas power plant, Burrard Thermal, is significantly higher than this BC average also. Burrard Thermal emits 530 tCO<sub>2</sub>e/GWh (BC Hydro 1998), and if the Incinerator can replace this marginal electricity production, the GHG benefit would be much greater. Discussion with a representative of B.C. Hydro has informed this author that any new electricity generation would likely be replacing low-efficiency natural gas generation either at Burrard Thermal or in Washington state (Pers. comm. John Duffy). Thus the emission factor for Burrard Thermal is appropriate for use in these calculations.

Burrard Thermal emission intensity = 530 tCO<sub>2</sub>e/GWh = 0.147 tCO<sub>2</sub>e/GJ  
 [530 tCO<sub>2</sub>e/GWh \* (1/3600 GWh/GJ)=0.147 tCO<sub>2</sub>e/GJ]  
 Emission Factor for Electricity Generation, (5) = 0.147 tCO<sub>2</sub>e/GJ

Electrical GHG emission prevented per tonne of newsprint: (6)

$$\frac{\text{GHG Emission Prevented}}{\text{tonne newsprint}} = \left( \frac{\text{Utilized Energy}}{\text{tonne Newsprint}} \right) * \left( \text{Emission Factor for Electricity, } \frac{\text{tCO}_2\text{e}}{\text{GJ}} \right) = \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne newsprint}} = (1.65 \text{ GJ/tonne}) * (0.147 \frac{\text{tCO}_2\text{e}}{\text{GJ}}) = 0.243 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

GHG Emission Prevented from Electricity, (6) = 0.243 tCO<sub>2</sub>e/tonne

Total GHG Emissions Prevented, (7) = 0.447 + 0.243 = -0.69 tCO<sub>2</sub>e/tonne

## 8. GHG Emissions from Waste Incineration at the Burnaby Incinerator:

At the Burnaby Incinerator, 247,075 tonnes of waste was combusted in 1998. This process required the consumption of 7,516 GJ of natural gas, 16,011 MWh of electricity, and 3,369 tonnes of lime (CaO) and 295 tonnes of ammonia (NH<sub>3</sub>) for acid gas control (Montenay Inc. 1999; Pers. comm. Richard Holt). Greenhouse gas emissions result from municipal solid waste incineration. This includes emissions of carbon dioxide and nitrous oxide during incineration, the consumption of natural gas and electricity, and the consumption of lime for acid gas control (the production of lime from limestone results in CO<sub>2</sub> emissions). Since newsprint is biomass carbon and is therefore carbon-neutral, the CO<sub>2</sub> emissions can be ignored here. Environment Canada estimates that while a small methane emission is measurable during wastewater sewage sludge incineration there is negligible methane emissions during MSW incineration (Environment Canada 1999). That will also be assumed for this investigation.

To begin, the emissions resulting from natural gas and electricity consumption will be equally distributed over the entire solid waste combusted in 1998.

CO<sub>2</sub> Emission from Natural Gas Combustion = 1.88 kg/m<sup>3</sup> (Environment Canada 1997)  
 Typical Energy of Natural Gas = 1020 BTU/ft<sup>3</sup> = 37,843 kJ/m<sup>3</sup> (Perry's 1984)  
 (Energy=1020 BTU/ft<sup>3</sup> \* 1.054 kJ/BTU \* 35.2 ft<sup>3</sup>/m<sup>3</sup> = 37,843 kJ/m<sup>3</sup>)

$$\text{GHG Emissions from Natural Gas} = \frac{(\text{Annual Energy Consumption, GJ}) * \left(1.88 \frac{\text{kg CO}_2}{\text{m}^3}\right) * \left(\frac{\text{tonnes}}{1000 \text{ kg}}\right)}{(\text{Annual Waste Combusted, tonnes}) \left(\text{Natural Gas } \frac{\text{kJ}}{\text{m}^3}\right) * \left(\frac{\text{GJ}}{10^6 \text{ kJ}}\right)} = \text{tCO}_2\text{e/tonne}$$

$$\text{GHG Emissions from Natural Gas} = \frac{(7519 \text{ GJ}) * \left(1.88 \frac{\text{kg CO}_2}{\text{m}^3}\right) * \left(\frac{\text{tonnes}}{1000 \text{ kg}}\right)}{(247075 \text{ tonnes}) \left(37843 \frac{\text{kJ}}{\text{m}^3}\right) * \left(\frac{\text{GJ}}{10^6 \text{ kJ}}\right)} = 0.0015 \text{ tCO}_2\text{e/tonne}$$

GHG Emission from Natural Gas Consumption = 0.0015 tCO<sub>2</sub>e/tonne

Discussion with a representative of B.C. Hydro has informed this author that since the Burnaby Incinerator has been drawing load since the late 1980's it can be assumed to use the provincial average for electricity generation. In other words, the Burnaby Incinerator does not have to be assumed as using marginal electricity generation – it is an established user. Therefore, this analysis will assume the B.C. average for electricity generation.

BC Hydro emission intensity = 30 tCO<sub>2</sub>e/GWh = 0.00833 tCO<sub>2</sub>e/GJ

[30 tCO<sub>2</sub>e/GWh \* (1/3600 GWh/GJ) = 0.00833 tCO<sub>2</sub>e/GJ]

$$\text{GHG Emissions from Electricity} = \frac{(\text{Annual Electricity Consumption, GWh}) * (\text{BC Hydro GHG Average, tCO}_2\text{e/GWh})}{(\text{Annual Waste Combusted, tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\text{GHG Emissions from Electricity} = \frac{(16.0 \text{ GWh}) * (30 \frac{\text{tCO}_2\text{e}}{\text{GWh}})}{(247075 \text{ tonnes})} = 0.0019 \text{ tCO}_2\text{e/tonne}$$

GHG Emission from BC Hydro electricity consumption = 0.0019 tCO<sub>2</sub>e/tonne

Lime (calcium oxide, CaO) is used at the Incinerator during air pollution control to neutralize acid gases which are produced during the combustion of waste. While the consumption of lime at the incinerator does not result in GHG emissions, the production of this material by the lime calcination process does result in emissions. In the production of lime, limestone (CaCO<sub>3</sub>) is heated so that it separates to CaO and CO<sub>2</sub>. In addition to the fossil fuel energy required to perform this reaction there is the non-energy related GHG emission from the liberalization of the unwanted carbon dioxide gas. Environment Canada (1997) has estimated that 0.790 kg of CO<sub>2</sub> is emitted during the production of each kg of lime. It is assumed that the incineration of food waste equally requires the use of lime for the neutralization of acid gases as any other waste.

Therefore:

GHG Emission from CaO Production = 0.790 tCO<sub>2</sub>e/tonne CaO

$$\text{GHG Emissions from Lime} = \left(0.790 \frac{\text{tCO}_2}{\text{tonne CaO}}\right) * \frac{3,369 \text{ tonnes of CaO}}{247,075 \text{ tonnes of waste}} = 0.011 \text{ tCO}_2\text{e/tonne}$$

GHG Emission from lime consumption at Incinerator = 0.011 tCO<sub>2</sub>e/tonne

As a result of the combustion of waste, CO<sub>2</sub> emissions occur. As the waste being investigated here is biogenic in origin (and thus considered “neutral”) the CO<sub>2</sub> emissions need not be considered.

Nitrous oxide emissions from the incineration of newsprint can result in one of the five following pathways.

- Thermal conversion of the N<sub>2</sub> gas in air to N<sub>2</sub>O during combustion (Immediate emis.)
- Thermal conversion of the nitrogen in waste to N<sub>2</sub>O (Immediate emission)

- Thermal conversion of the ammonia injected in the flue gases (Immediate emission)
- Microbial  $\text{N}_2\text{O}$  conversion of  $\text{NO}_x$  emitted and later denitrified (Future emission)
- Microbial  $\text{N}_2\text{O}$  conversion of  $\text{NH}_3$  injected but unreacted (Future emission)

Each of these five pathways are evaluated in the following calculations. Unfortunately, the current lack of understanding in these issues result in much uncertainty associated with the following estimates. An extensive discussion of the issue is provided Section 2.5.5.3.

The first two potential sources of nitrous oxide emissions result from the potential for the nitrogen in waste or the  $\text{N}_2$  gas in air to thermal convert to  $\text{N}_2\text{O}$  during incineration. There is limited and highly variable research of the  $\text{N}_2\text{O}$  emissions resulting from municipal solid waste incineration. Examples of emission estimates being used are:

- |                                       |   |
|---------------------------------------|---|
| • IPCC Compilation (de Soete 1993)    | 11-293 g $\text{N}_2\text{O}$ /tonne of waste |
| • Environment Canada Inventory (1997) | 160 g $\text{N}_2\text{O}$ /tonne of waste    |
| • USEPA National Inventory (1999)     | 30 g $\text{N}_2\text{O}$ /tonne of waste     |
| • USEPA MSW Analysis (1998)           | 130 g $\text{N}_2\text{O}$ /tonne of waste    |

Research in the fluidized bed combustion of coal has determined that  $\text{N}_2\text{O}$  emissions originate mainly from the oxidation of fuel nitrogen (Moritomi 1994), and since coal combustion is similar to that of waste incineration, it can be inferred that  $\text{N}_2\text{O}$  emissions during incineration are likely a factor of the nitrogen content. This hypothesis is reinforced by one study (Tanikawa et al. 1995), and the observation that the incineration of high nitrogen content wastewater sludge produces much higher  $\text{N}_2\text{O}$  emission rates than MSW incinerators (Tanaka et al. 1994). Since newsprint has a negligible nitrogen content ( $<0.1\%$ ), this study will assume that the incineration of newsprint does not have to account for any of the nitrous oxide emissions measured during MSW incineration. However, there is still the possibility of alternative pathways for  $\text{N}_2\text{O}$  emissions.

The incineration of newsprint needs to take responsibility for the  $\text{N}_2\text{O}$  emissions resulting from acid gas ( $\text{NO}_x$ ) control. As the nitrogen oxide releases can be from molecular nitrogen in the air, office paper incineration can contribute to this emission. This study assumes that the emissions from acid gas control should be evenly distributed across the mass of waste combusted. At the Burnaby Incinerator, 295 tonnes of ammonia ( $\text{NH}_3$ ) was used during the combustion of 247,075 tonnes of waste in 1998 to reduce  $\text{NO}_x$  emissions. As a result of the lack of any available research on the propensity for injected ammonia to thermally convert to  $\text{N}_2\text{O}$ , this study will assume the same conversion rate exhibited by the waste-nitrogen upon incineration. (See Appendix I #8) Therefore, approximately 1.7% of injected ammonia, and ranging between 0.3 and 3.1%, will be estimated to convert to nitrous oxide.

Fraction of Injected-Ammonia emitted as  $\text{N}_2\text{O}$  = 1.7 (0.3-3.1) %  
 Annual consumption of ammonia (1998) = 295 tonnes  
 Annual mass of waste combusted (1998) = 247,075 tonnes

$$\text{N}_2\text{O from NH}_3 \text{ Injection} = \frac{(\text{NH}_3 \text{ Injected, tonnes}) \left( \frac{14 \text{ gN/mol}}{17 \text{ g NH}_3/\text{mol}} \right)}{(\text{Waste Combusted, tonnes})} * (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ gN}_2\text{O/mol}}{28 \text{ gN}_2\text{O} - \text{N/mol}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e/tonne}$$

$$\text{N}_2\text{O from NH}_3 \text{ Injection} = \frac{(295) \left( \frac{14}{17} \right)}{(247,075)} * (0.017) \left( \frac{44}{28} \right) (310) = 0.0081 \text{ tCO}_2\text{e/tonne}$$

$$\text{N}_2\text{O Emission resulting from NH}_3 \text{ Injection} = 0.0081 (0.0014 - 0.015) \text{ tCO}_2\text{e/tonne}$$

In addition to the potential for injected  $\text{NH}_3$  to thermally convert to  $\text{N}_2\text{O}$ , there can also be the future denitrification of the nitrogen oxide ( $\text{NO}_x$ ) gases released. It has been estimated that 10-30% of waste-nitrogen is converted to  $\text{NO}_x$  ( $\text{NO} + \text{NO}_2$ ) during combustion (White et al. 1995). This report will evenly distribute  $\text{NO}_x$  emissions across the total mass of waste incinerated even though newsprint has a negligible nitrogen content. Nitrogen oxides are short lived in the atmosphere as they are quickly rained out in the form of nitrate ( $\text{NO}_3^-$ ) or nitric acid ( $\text{HNO}_3$ ). Thus the deposition as  $\text{NO}_3^-$  will eventually require denitrification to  $\text{N}_2$ , resulting in potential leakage of  $\text{N}_2\text{O}$ . The IPCC provides guidelines for these emissions and estimates that 1% of emitted  $\text{NH}_3\text{-N}$  or  $\text{NO}_x\text{-N}$  will be converted to  $\text{N}_2\text{O}$ . However they also provide low and high estimates of 0.2 and 2% respectively. All three of these values are used in this study. In addition to the potential for the microbial conversion of nitrogen oxide to nitrous oxide, nitrogen oxides are suspected to be indirect greenhouse gases for another reason – they deplete the tropospheric concentration of the OH radical, which would otherwise react and destroy  $\text{CH}_4$  (Mackenzie 1995). Thus  $\text{NO}_x$  causes  $\text{CH}_4$  to be a stronger GHG. (As it is too early for any methodology on this issue, it will have to be ignored in this report.) At the Burnaby Incinerator it is estimated that 449 tonnes of  $\text{NO}_x$  was emitted in 1998 (Pers. comm. Chantal Babensee). Nitric oxide ( $\text{NO}$ ) is predominantly the nitrogen oxide formed during incineration (Robinson 1986), and this is assumed in the calculations below.

Best-Guess Estimate for the future  $\text{N}_2\text{O}$  conversion of  $\text{NO}_x = 1\% \text{ N}_2\text{O-N/NO}_x\text{-N}$

Low Estimate for the future  $\text{N}_2\text{O}$  conversion of  $\text{NO}_x = 0.2\% \text{ N}_2\text{O-N/NO}_x\text{-N}$

High Estimate for the future  $\text{N}_2\text{O}$  conversion of  $\text{NO}_x = 2\% \text{ N}_2\text{O-N/NO}_x\text{-N}$

Annual  $\text{NO}_x$  emission (1998) = 449 tonnes

Annual mass of waste combusted (1998) = 247,075 tonnes

$$\text{N}_2\text{O Emission from NO}_x = \frac{(\text{NO}_x \text{ Emission, tonnes}) \left( \frac{14 \text{ gN/mol}}{30 \text{ gNO/mol}} \right)}{(\text{Waste Combusted, tonnes})} * (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ gN}_2\text{O/mol}}{28 \text{ gN}_2\text{O} - \text{N/mol}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e/tonne}$$

$$\text{N}_2\text{O Emission from NO}_x = \frac{(449) \left( \frac{14}{30} \right)}{(247,075)} * (0.01) \left( \frac{44}{28} \right) (310) = 0.004 (0.001 - 0.008) \text{ tCO}_2\text{e/tonne}$$

$$\text{Future N}_2\text{O from NO}_x \text{ Emission} = 0.004 (0.001-0.008) \text{ tCO}_2\text{e/tonne}$$

The last potential  $\text{N}_2\text{O}$  emission from waste incineration could occur when ammonia is injected into the flue gas but is emitted to the atmosphere, the so-called “ammonia slip”. The ammonia will undergo wet or dry deposition to soils downwind where it can nitrify

and denitrify. Communication with the GVRD (Pers. comm. Chantal Babensee) has learned that ammonia slip is virtually negligible at the Incinerator largely because only the minimum amount is injected into the flue gas. As a result, the potential for ammonia slip to result in nitrous oxide emissions can be neglected in this study.

$$\begin{aligned}\text{Total GHG Emissions} &= \text{N}_2\text{O} + \text{Natural Gas} + \text{Electricity} + \text{Lime} = \text{tCO}_2\text{e/tonne} \\ \text{Total Emissions} &= 0.0121 + 0.0015 + 0.0019 + 0.011 \\ &= 0.027 \text{ (0.017-0.037) tCO}_2\text{e/tonne}\end{aligned}$$

#### **9. GHG Emissions of Recycled Newsprint Utilization**

The assumption discussed in Section 2.6.1 – *Newsprint* is that no GHG benefit exists with newsprint recycling.

$$\text{GHG Benefit of Recycled Newsprint Utilization} = 0 \text{ tCO}_2\text{e/tonne}$$

#### **10. Effect of Recycling Newsprint on Forest Carbon Storage**

The assumption discussed in Section 2.6.7 – *Forest Carbon Sequestration* is that no GHG benefit exists with newsprint recycling.

$$\text{GHG Benefit of Recycled Newsprint Utilization} = 0 \text{ tCO}_2\text{e/tonne}$$

## **APPENDIX D: OFFICE PAPER WASTE MANAGEMENT**

This appendix provides all the data and calculations specific to estimating GHG emission factors for the landfilling, incineration or recycling of office paper generated in the GVRD. However, a great deal of the data and calculations are similar to those presented in Appendix C – *Newsprint Waste Management*. As a result, only the important data and calculations which are different from newsprint are presented here. The first three sections are devoted to the GHG implications of the Cache Creek Landfill (1-3). The next three sections assess the same implications for the Vancouver Landfill (4-6). Sections 7 and 8, assess the energy generation and GHG emissions from the Burnaby Incinerator. The last two sections of this appendix, 9 and 10, analyze the GHG ramifications of office paper recycling.

### **1. Methane & Energy Implications of the Cache Creek Landfill:**

The calculations for landfill methane emissions and energy generation follow – starting with the Carbon Available for Anaerobic Decomposition (CAAD):

Estimated Methane Yield from Office Paper in reactors = 346 ml/gram (USEPA 1998)

Assumed Carbon Dioxide Yield from office paper = 346 ml/dry gram

Molar gas constant = 22.4 L/mol at standard temperature and pressure

Typical Moisture Content of Office Paper = 6% (Tchobanoglous et al. 1993)

$$\text{Moles of } CH_4 = \frac{346 \text{ ml/gram}}{22,400 \text{ ml/mol}} = 0.0154 \text{ mol } CH_4$$

$$\text{Moles of } CO_2 = \frac{346 \text{ ml/gram}}{22,400 \text{ ml/mol}} = 0.0154 \text{ mol } CO_2$$

$$\text{Total Moles of C} = 0.0154 + 0.0154 = 0.0309 \text{ mol C}$$

$$\text{Carbon Available for Anaerobic Decomposition} = 0.0309 \text{ mol C} * 12 \text{ g/mol} = 0.371 \text{ gC / drygram}$$

$$\text{CAAD(dry)} = 0.371 \text{ gC / drygram} = 0.371 \text{ tC / drytonne}$$

$$\text{CAAD(wet)} = 0.371 * (1 - 0.06) = 0.348 \text{ gC / wetgram} = 0.348 \text{ tC / wettonne}$$

Carbon Content of Dry Office Paper = 40.3% (Barlaz 1998)

$$\text{Revised Carbon Storage Factor} = \text{Initial Carbon} - \text{CAAD} = \text{gC / drygram}$$

$$\text{Revised Carbon Storage Factor} = 0.403 \text{ gC/drygram} - 0.371 \text{ gC/drygram} = 0.03 \text{ gC / drygram}$$

$$\text{Revised Carbon Storage Factor} = 0.03 \text{ gC / drygram} = 0.03 \text{ tC / drytonne}$$

This 0.348 tC per wet tonne of office paper is available for anaerobic decomposition and will be assumed to be evenly split between  $CH_4$  and  $CO_2$ . Remember that since any  $CO_2$  is neutral, it does not have to be considered further.

$$\text{Methane Generation} = \left( \text{Carbon To Decompose} \frac{\text{tC}}{\text{Wet Tonne}} \right) \left( \text{Methane Fraction} \right) \left( \frac{\text{Molecular Mass of CH}_4}{\text{Molecular Mass of C}} \right) = \frac{\text{tCH}_4}{\text{Wet Tonne}}$$

$$\text{Methane Generation} = (0.348)(0.5) \left( \frac{16}{12} \right) = 0.232 \frac{\text{tCH}_4}{\text{Wet Tonne}}$$

Methane Generation Potential = 0.232 tCH<sub>4</sub>/tonne of office paper

The first order decay rate constant used here is 0.04 y<sup>-1</sup> and the assumptions behind it are discussed in Section 2.4 - *Landfill Carbon Sequestration*.

The calculations in Worksheet # 27, estimate that for the 20 year period between 1999 and 2018, 0.130 tCH<sub>4</sub>/tonne would be generated. This represents only 56% of the ultimate potential of 0.232 tCH<sub>4</sub>/tonne. This generation corresponds to, minus the collection and oxidation, an emission of 0.798 tCO<sub>2</sub>e/tonne. Furthermore an energy benefit, via the replacement of fossil energy, of 0.141 tCO<sub>2</sub>e/tonne would be realized.

Best-Guess of Atmospheric Methane Emissions=	0.798	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.141	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.368	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.091	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	1.498	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.033	tCO <sub>2</sub> e/tonne

## 2. Long-Term Carbon Sequestration in the Cache Creek Landfill:

Since not all of the cellulose and hemicellulose and only a negligible portion of the lignin from office paper is expected to anaerobically degrade in a landfill, organic-carbon will remain in long-term storage in the landfill. In this capacity, the organic-carbon, which was originally atmospheric CO<sub>2</sub> but was photosynthesized into biomass, will be sequestered. As a result, organic-carbon can perform a GHG benefit, a negative GHG emission. This issue is discussed in greater detail in Section 2.4 – *Landfill Carbon Sequestration*.

The Carbon Storage Factors, as determined by Barlaz (1998), and also discussed in Eleazer et al. (1997), are used here as representative of long-term storage in the CCLF. These experiments determined that the long-term carbon storage of office paper in landfills is 0.05 kg C per kg of dry newsprint. The researchers observed that office paper, with a lignin content measured at 2.3% (dry mass), approximately 55% of the cellulose and hemicellulose fraction and a negligible portion of lignin anaerobically decomposed. However, these factors were developed with laboratory research of idealized landfill decomposition conditions and are thus highly conservative. As a result, the actual storage in the CCLF could be greater than is indicated by these experiments. While there is great potential for uncertainty with this estimate, it is likely that the uncertainty would be skewed towards a greater value. By using this conservative estimate, the risk of overestimating this factor is probably minimal. For these reasons, only the best-guess estimate will be used in this analysis.



In Section #1 of the Appendix a revised Carbon Storage Factor was developed to attempt to correct inconsistencies in the previous estimates by Barlaz. The new estimate is as follows:

Revised Carbon Storage Factor for office paper = 0.03 tC/dry tonne

Typical Moisture Content of Office Paper = 6% (Tchobanoglous et al. 1993)

$$\text{Carbon Sequestration} = \left( \frac{\text{kgC}}{\text{Dry Office Paper}} \right) (1 - \text{Moisture Content}) \left( \frac{44 \text{gCO}_2/\text{mol}}{12 \text{gC}/\text{mol}} \right) = \text{tCO}_2\text{e}/\text{tonne}$$

$$\text{Carbon Sequestration} = (0.03)(1 - 0.06) \left( \frac{44}{12} \right) = 0.10 \text{ tCO}_2\text{e}/\text{tonne}$$

Long-Term Carbon Sequestration from Office Paper = -0.10 tCO<sub>2</sub>e/tonne

### 3. Immediate & Future N<sub>2</sub>O Emissions from the Cache Creek Landfill

As the nitrogen content of office paper is negligible, the potential for nitrous oxide emissions can be ignored.

### 4. Methane & Energy Implications of the Vancouver Landfill:

The only significant difference between this section and Section 1, *Methane & Energy Implications of the Cache Creek Landfill*, is the estimated landfill gas collection efficiency and the first order decay rate constant. While at Cache Creek the current collection efficiency is estimated to be 43%, the current collection efficiency at the Vancouver Landfill is estimated to only be 22% (Pers. comm. Chris Underwood). However, engineers with the City of Vancouver are currently in the process of upgrading the collection equipment. As with the CCLF assessment, the collection efficiency is assumed to increase year after year in response to improving regulations. The first order decay rate constant used here is 0.05 y<sup>-1</sup> and the assumptions behind it are discussed in Section 2.4 - *Landfill Carbon Sequestration*.

Worksheet #27 determines that:

Best-Guess of Atmospheric Methane Emissions=	1.070	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.158	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.501	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.107	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	1.903	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.033	tCO <sub>2</sub> e/tonne

### 5. Long-Term Carbon Sequestration in the Vancouver Landfill:

The Revised Carbon Storage Factors is used here as representative of long-term storage in the VLF.

Long-Term Carbon Sequestration from Office Paper = -0.10 tCO<sub>2</sub>e/tonne

## 6. Immediate & Future N<sub>2</sub>O Emissions from the Vancouver Landfill

As the nitrogen content of office paper is negligible, the potential for nitrous oxide emissions can be ignored.

## 7. Energy Generation from Waste Incineration at the Burnaby Incinerator:

Net Energy Content of Office Paper = 6,800 BTU/lb = 15,768 kJ/kg (USEPA 1998)

(6,800 BTU/lb \* 1.054 kJ/BTU \* 2.20 lb/kg = 15,768 kJ/kg)

(wet basis, correction for latent heat of water in this reference is assumed but not directly specified)

From another source (Tchobanoglous et al. 1993):

Gross Energy Content of Office Paper = 6,799 BTU/lb = 15,765 kJ/kg (wet basis)

Typical Moisture Content of Newsprint = 6% (Tchobanoglous et al. 1993)

Latent Heat of Water = 2473 kJ/kg (Incropera and DeWitt 1990)

Net Energy Content = [Gross Energy] - [Latent Heat of Vaporization]

$$\text{Net Energy Content} = \left[ 15,765 \frac{\text{kJ}}{\text{kg}} \right] - \left[ \left( 2473 \frac{\text{kJ}}{\text{kg}} \right) (0.06)_{MC} \right] = 15,616 \frac{\text{kJ}}{\text{kg}}$$

An average of these two values will be used as the estimate for the net energy content.

$$\text{Net Energy Content} = \left[ \frac{15,765 + 15,616}{2} \right] = 15,692 \frac{\text{kJ}}{\text{kg}} = 15.7 \frac{\text{GJ}}{\text{tonne}}$$

Net Energy Content of Office Paper = 15.7 GJ/tonne

Steam Energy produced by the combustion of office paper in an Incinerator-Boiler (1):

Assumed Boiler Efficiency = 70% (Pers. comm. Ron Richter)

Fraction of Steam Utilized by CPL = 56% (Montenay Inc. 1999)

$$\frac{\text{Utilized Energy}}{\text{tonne Office Paper}} = \frac{\text{energy}}{\text{tonne}} * (\text{Thermal Efficiency}) * (\text{Energy Utilization}) = \frac{\text{kJ}}{\text{tonne}}$$

$$\frac{\text{Utilized Energy}}{\text{tonne Office Paper}} = \frac{15.7 \text{ GJ}}{\text{tonne}} * (0.70) * (0.56) = 6.15 \frac{\text{GJ}}{\text{tonne}}$$

Utilized Steam Energy per tonne of office paper, (1) = 6.15 GJ/tonne

GHG emission prevented per tonne of office paper (3):

$$\frac{\text{GHG Emission Prevented}}{\text{tonne office paper}} = \left( \frac{\text{Utilized Energy}}{\text{tonne office paper}} \right) * \left( \text{Emission Factor for Natural Gas, } \frac{\text{tCO}_2\text{e}}{\text{GJ}} \right) = \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne office paper}} = \left( 6.15 \frac{\text{GJ}}{\text{tonne}} \right) * \left( 0.062 \frac{\text{tCO}_2\text{e}}{\text{GJ}} \right) = 0.381 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

GHG Emission Prevented from Natural Gas, (3) = 0.381 tCO<sub>2</sub>e/tonne

Electricity produced by the combustion of office paper in an Incinerator-Boiler (4):

Assumed Turbo Generator Efficiency = 32% (Pers. comm. Ron Richter)

Steam Fraction for Electricity Generation = 40% (assumed as discussed)

$$\frac{\text{Utilized Energy}}{\text{tonne office paper}} = \frac{\text{energy}}{\text{tonne}} * (\text{Boiler Effic}) * (\text{TurboGenerator}) * (\text{Energy Utilization}) = \text{kJ/tonne}$$

$$\frac{\text{Utilized Energy}}{\text{tonne office paper}} = \frac{15.7 \text{ GJ}}{\text{tonne}} * (0.70) * (0.32) * (0.40) = 1.41 \text{ GJ/tonne}$$

Utilized Electrical Energy per tonne of office paper, (4) = 1.41 GJ/tonne

Electrical GHG emission prevented per tonne of office paper: (6)

$$\frac{\text{GHG Emission Prevented}}{\text{tonne office paper}} = \left( \frac{\text{Utilized Energy}}{\text{tonne office paper}} \right) * \left( \text{Emission Factor for Electricity, } \frac{\text{tCO}_2\text{e}}{\text{GJ}} \right) = \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne office paper}} = (1.41 \text{ GJ/tonne}) * (0.147 \frac{\text{tCO}_2\text{e}}{\text{GJ}}) = 0.207 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

GHG Emission Prevented from Electricity, (6) = 0.207 tCO<sub>2</sub>e/tonne

Total GHG Emissions Prevented, (7) = 0.381 + 0.207 = -0.59 tCO<sub>2</sub>e/tonne

#### 8. GHG Emissions from Waste Incineration at the Burnaby Incinerator:

This entire section is identical to the same one in Appendix C- Newsprint Waste Management.

Total GHG Emissions = N<sub>2</sub>O + Natural Gas + Electricity + Lime = tCO<sub>2</sub>e/tonne

Total Emissions = 0.027 (0.017-0.037) tCO<sub>2</sub>e/tonne

#### 9. GHG Emissions of Recycled Office Paper Utilization

The assumption discussed in Section 2.6.2 – *Office Paper* is that no GHG benefit exists with office paper recycling.

GHG Benefit of Recycled Office Paper Utilization = 0 tCO<sub>2</sub>e/tonne

#### 10. Effect of Recycling Office Paper on Forest Carbon Storage

The assumption discussed in Section 2.6.7 – *Forest Carbon Sequestration* is that no GHG benefit exists with office paper recycling.

GHG Benefit of Recycled Office Paper Utilization = 0 tCO<sub>2</sub>e/tonne

## **APPENDIX E:**

### **FERROUS METAL MANAGEMENT**

As ferrous metal is not organic and will not participate in methane emissions at any landfills, the only emission factors required with the disposal of metals are associated with the transportation and processing. The diesel fuel consumption for equipment at the CCLF or at the BBLF is in the section, *General Parameters*, and the transportation emissions are included in the municipality-specific parameters. Only emissions strictly associated with metal are included here.

#### **1. GHG Emissions of Recycled Ferrous Metal Utilization**

The assumption discussed in Section 2.6.3 – *Ferrous Metal* is that a GHG benefit of 2.35 tCO<sub>2</sub>e/tonne exists with the recycling of ferrous metal.

GHG Benefit of Recycled Ferrous Metal Utilization = 2.35 tCO<sub>2</sub>e/tonne

#### **2. GHG Benefit of Ferrous Metal Incineration**

The incineration of metals causes a GHG benefit which does not occur when metals are landfilled. Magnetic separation allows for the recovery of ferrous metal after incineration so that recycling can occur. This increased recycling, separate from curbside recycling initiatives, will also cause reduced GHG emissions by industry for the manufacture of similar products. As a result, it is appropriate for incineration to be assigned a GHG benefit for this additional recycling. The necessary question is: What fraction of metal in waste is captured for recycling? Inspection of WS#3 – *Waste Tonnages* of the spreadsheet model finds that an estimated 16,174 tonnes of ferrous metal is delivered to the Burnaby Incinerator in 1998, the year analyzed. However, GVRD records document that only 7,170 tonnes of metal was recovered from the Incinerator for recycling. Either the capture efficiency is only 44% or the estimated metal incinerated, 16,174 tonnes, is too high as it is likely that the GVRD records are accurate. Lacking more accurate waste metal generation data at the municipalities, this research assumes a 50% capture efficiency of metal at the Incinerator. If more accurate waste mass estimates are developed, users should revise this assumption to increase the accuracy of this issue. To calculate the resulting GHG benefit the metal in wastes incinerated is multiplied by 50% and then by recycling benefit of ferrous metal:

Ferrous Metal Capture Efficiency at Incinerator = 50%

GHG Benefit of Recycled Ferrous Metal Utilization = 2.35 tCO<sub>2</sub>e/tonne

$$\text{Benefit of Incinerating Metal} = 1 \text{ tonne/tonne} * (0.50) * \left( 2.35 \text{ tCO}_2\text{e/tonne} \right) = 1.18 \text{ tCO}_2\text{e/tonne}$$

GHG Benefit of Incinerating Metal-Containing Wastes = 1.18 tCO<sub>2</sub>e/tonne

## ***APPENDIX F:*** **GLASS MANAGEMENT**

As glass is not organic and will not participate in methane emissions, the only emission factors required with the landfill disposal of glass are associated with the transportation and processing. The diesel fuel consumption for equipment at the CCLF or at the BBLF is in the section, *General Parameters*, and the transportation emissions are included in the municipality-specific parameters. Only emissions strictly associated with glass are included here.

### **1. GHG Emissions of Recycled Glass Utilization**

The assumption discussed in Section 2.6.4 – *Glass* is that a GHG benefit of 0.37 tCO<sub>2</sub>e/tonne exists with the recycling of glass.

GHG Benefit of Recycled Glass Utilization = 0.37 tCO<sub>2</sub>e/tonne

## **APPENDIX G:**

### **HIGH-DENSITY POLYETHYLENE MANAGEMENT**

High-density polyethylene (HDPE) is a plastic manufactured from petroleum products. Therefore, HDPE is an organic material which contains fossil-carbon; contrary to paper, food or yard waste which are organic materials but contain atmospheric carbon that was fixed by photosynthesis. High-density polyethylene does not biodegrade therefore it cannot contribute to landfill methane emissions. The only emission factors required with the landfill disposal of HDPE are associated with transportation and processing and are thus not included here. Plastics, being organic, are readily combustible during incineration and generate significant amounts of energy. Importantly, the carbon dioxide emissions from plastics must be treated differently than the neutral carbon dioxide emissions from paper, food or yard trimmings as plastics contain fossil-carbon and any combustion results in greenhouse gas emissions.

This appendix provides all the data and calculations to estimate emission factors for the incineration or recycling of HDPE generated in the GVRD. However, many of these calculations are similar to Appendix C – Newsprint Waste Management. Only the items specific to HDPE are included here. The first section is devoted to the energy generation implications at the Burnaby Incinerator. The next section assesses the GHG emissions of this incineration. The last section of this appendix analyzes the GHG ramifications of HDPE recycling.

#### **1. Energy Generation from Waste Incineration:**

Typical Energy Content of HDPE = 18,687 BTU/lb = 43,331 kJ/kg = 43.3 GJ/tonne  
 (18,687 BTU/lb\*1.054 kJ/BTU\*2.20 lb/kg = 43,331 kJ/kg) (USEPA 1998)  
 (wet basis, correction for latent heat of water in this reference is assumed but not directly specified)

Steam Energy produced by the combustion of HDPE in an Incinerator-Boiler (1):

Assumed Boiler Efficiency = 70% (Pers. comm. Ron Richter)

Fraction of Steam Utilized by CPL = 56% (Montenay Inc. 1999)

$$\frac{\text{Utilized Energy}}{\text{tonne HDPE}} = \frac{\text{energy}}{\text{tonne}} * (\text{Thermal Efficiency}) * (\text{Energy Utilization}) = \text{kJ/tonne}$$

$$\frac{\text{Utilized Energy}}{\text{tonne HDPE}} = \frac{43.3 \text{ GJ}}{\text{tonne}} * (0.70) * (0.56) = 17.0 \text{ GJ/tonne}$$

Utilized Steam Energy per tonne of HDPE, (1) = 17.0 GJ/tonne

GHG emission prevented per tonne of HDPE (3):

$$\frac{\text{GHG Emission Prevented}}{\text{tonne HDPE}} = \left( \frac{\text{Utilized Energy}}{\text{tonne HDPE}} \right) * \left( \text{Emission Factor for Natural Gas, } \frac{\text{tCO}_2\text{e}}{\text{GJ}} \right) = \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne HDPE}} = \left( 17.0 \text{ GJ/tonne} \right) * \left( 0.062 \frac{\text{tCO}_2\text{e}}{\text{GJ}} \right) = 1.05 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

GHG Emission Prevented from Natural Gas, (3) = 1.05 tCO<sub>2</sub>e/tonne

Electricity produced by the combustion of HDPE in an Incinerator-Boiler (4):

Assumed Turbo Generator Efficiency = 32% (Pers. comm. Ron Richter)

Steam Fraction for Electricity Generation = 40% (assumed as discussed)

$$\frac{\text{Utilized Energy}}{\text{tonne HDPE}} = \frac{\text{energy}}{\text{tonne}} * (\text{Boiler Effic}) * (\text{TurboGenerator}) * (\text{Energy Utilization}) = \text{kJ/tonne}$$

$$\frac{\text{Utilized Energy}}{\text{tonneHDPE}} = \frac{43.3\text{GJ}}{\text{tonne}} * (0.70) * (0.32) * (0.40) = 3.88\text{GJ/tonne}$$

Utilized Electrical Energy per tonne of HDPE, (4) = 3.88 GJ/tonne

Electrical GHG emission prevented per tonne of HDPE: (6)

$$\frac{\text{GHG Emission Prevented}}{\text{tonne HDPE}} = \left( \frac{\text{Utilized Energy}}{\text{tonne HDPEr}} \right) * (\text{Emission Factor for Electricity, } \text{tCO}_2\text{e/GJ}) = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne HDPE}} = (3.88\text{GJ/tonne}) * (0.147\text{tCO}_2\text{e/GJ}) = 0.57\text{tCO}_2\text{e/tonne}$$

GHG Emission Prevented from Electricity, (6) = 0.57 tCO<sub>2</sub>e/tonne

Total GHG Emissions Prevented, (7) = 1.05 + 0.57 = -1.62 tCO<sub>2</sub>e/tonne

## 2. GHG Emissions from Waste Incineration:

At the Burnaby Incinerator, 247,075 tonnes of waste was combusted in 1998. This process required the consumption of 7,516 GJ of natural gas, 16,011 MWh of electricity, and 3,369 tonnes of lime (CaO) and 295 tonnes of ammonia (NH<sub>3</sub>) for acid gas control (Montenay Inc. 1999; Pers. comm. Richard Holt). Greenhouse gas emissions result from municipal solid waste incineration. This includes emissions of carbon dioxide and nitrous oxide during incineration, the consumption of natural gas and electricity, and the consumption of lime for acid gas control (the production of lime from limestone results in CO<sub>2</sub> emissions). Since newsprint is biomass carbon and is therefore carbon-neutral, the CO<sub>2</sub> emissions can be ignored here. Environment Canada estimates that while a small methane emission is measurable during wastewater sewage sludge incineration there is negligible methane emissions during MSW incineration (Environment Canada 1999). That will also be assumed for this investigation. In the combustion of HDPE, the greatest GHG emission is associated with the fossil carbon emissions of carbon dioxide. These are calculated first:

The fossil carbon content of HDPE has been assumed to be 83% in one recent report (USEPA 1998). This is the mass of carbon divided by the total mass of the plastic. In a draft report available on the internet, USEPA (2000), the fossil carbon content was assumed to be 86%. This research will assume the fossil carbon content of HDPE as 85% of the total mass of the plastic.

Fossil carbon content of HDPE = 85%

$$\text{CO}_2 \text{ Emissions from HDPE combustion} = (0.85\text{tC/tonne HDPE}) \left( \frac{44\text{gCO}_2/\text{mol}}{12\text{gC/mol}} \right) = 3.12\text{tCO}_2\text{e/tonne}$$

GHG Emission of fossil-carbon from HDPE combustion = 3.12 tCO<sub>2</sub>e/tonne

The emissions resulting from natural gas and electricity consumption will be equally distributed over the entire solid waste combusted in 1998.

Lime (calcium oxide, CaO) is used at the Incinerator during air pollution control to neutralize acid gases which are produced during the combustion of waste. While the consumption of lime at the incinerator does not result in GHG emissions, the production of this material by the lime calcination process does result in emissions. In the production of lime, limestone (CaCO<sub>3</sub>) is heated so that it separates to CaO and CO<sub>2</sub>. In addition to the fossil fuel energy required to perform this reaction there is the non-energy related GHG emission from the liberalization of the unwanted carbon dioxide gas. Environment Canada (1997) has estimated that 0.790 kg of CO<sub>2</sub> is emitted during the production of each kg of lime. It is assumed that the incineration of HDPE equally requires the use of lime for the neutralization of acid gases as any other waste.

Therefore:

GHG Emission from CaO Production = 0.790 tCO<sub>2</sub>e/tonne CaO

$$\text{GHG Emissions from Lime} = \left( 0.790 \frac{\text{tCO}_2}{\text{tonne CaO}} \right) * \frac{3,369 \text{ tonnes of CaO}}{247,075 \text{ tonnes of waste}} = 0.011 \frac{\text{tCO}_2}{\text{tonne}}$$

GHG Emission from lime consumption at Incinerator=0.011 tCO<sub>2</sub>e/tonne

Nitrous oxide emissions from the incineration of HDPE can result in one of the five following pathways.

- Thermal conversion of the N<sub>2</sub> gas in air to N<sub>2</sub>O during combustion (Immediate emis.)
- Thermal conversion of the nitrogen in food waste to N<sub>2</sub>O (Immediate emission)
- Thermal conversion of the ammonia injected in the flue gases (Immediate emission)
- Microbial N<sub>2</sub>O conversion of NO<sub>x</sub> emitted and later denitrified (Future emission)
- Microbial N<sub>2</sub>O conversion of NH<sub>3</sub> injected but unreacted (Future emission)

Each of these five pathways are evaluated in the following calculations. Unfortunately, the current lack of understanding in these issues result in much uncertainty associated with the following estimates. An extensive discussion of the issue is provided Section 2.5.5.3.

The first two potential sources of nitrous oxide emissions result from the potential for the nitrogen in waste or the N<sub>2</sub> gas in air to thermal convert to N<sub>2</sub>O during incineration. There is limited and highly variable research of the N<sub>2</sub>O emissions resulting from municipal solid waste incineration. Examples of emission estimates being used are:

- |                                       |   |
|---------------------------------------|---|
| • IPCC Compilation (de Soete 1993)    | 11-293 gN <sub>2</sub> O/tonne of waste |
| • Environment Canada Inventory (1997) | 160 gN <sub>2</sub> O/tonne of waste    |
| • USEPA National Inventory (1999)     | 30 gN <sub>2</sub> O/tonne of waste     |
| • USEPA MSW Analysis (1998)           | 130 gN <sub>2</sub> O/tonne of waste    |

Research in the fluidized bed combustion of coal has determined that N<sub>2</sub>O emissions originate mainly from the oxidation of fuel nitrogen (Moritomi 1994), and since coal combustion is similar to that of waste incineration, it can be inferred that N<sub>2</sub>O emissions during incineration are likely a factor of the nitrogen content. This hypothesis is reinforced by one study (Tanikawa et al. 1995), and the observation that the incineration of high nitrogen content wastewater sludge produces much higher N<sub>2</sub>O emission rates than MSW incinerators (Tanaka et al. 1994). Since polyethylene has a negligible nitrogen content (<0.1% on a dry weight basis (Tchobanoglous et al. 1993), this study



will assume that the incineration of HDPE does not have to account for any of the nitrous oxide emissions measured during MSW incineration. However, there is still the possibility of alternative pathways for N<sub>2</sub>O emissions.

The incineration of HDPE needs to take responsibility for the N<sub>2</sub>O emissions resulting from acid gas (NO<sub>x</sub>) control. As the nitrogen oxide releases can be from molecular nitrogen in the air, HDPE incineration can contribute to this emission. This study assumes that the emissions from acid gas control should be evenly distributed across the mass of waste combusted. At the Burnaby Incinerator, 295 tonnes of ammonia (NH<sub>3</sub>) was used during the combustion of 247,075 tonnes of waste in 1998 to reduce NO<sub>x</sub> emissions. As a result of the lack of any available research on the propensity for injected ammonia to thermally convert to N<sub>2</sub>O, this study will assume the same conversion rate exhibited by the waste-nitrogen upon incineration. (See Appendix I #8) Therefore, approximately 1.7% of injected ammonia will be estimated to convert to nitrous oxide (only the best-guess estimate is used here as the emission is greatly dominated by the fossil-carbon content).

Fraction of Injected-Ammonia emitted as N<sub>2</sub>O = 1.7%

Annual consumption of ammonia (1998) = 295 tonnes

Annual mass of waste combusted (1998) = 247,075 tonnes

$$\text{N}_2\text{O from NH}_3 \text{ Injection} = \frac{(\text{NH}_3 \text{ Injected, tonnes}) \left( \frac{14\text{gN/mol}}{17\text{gNH}_3/\text{mol}} \right)}{(\text{Waste Combusted, tonnes})} * (\text{N}_2\text{O Conversion}) \left( \frac{44\text{gN}_2\text{O/mol}}{28\text{gN}_2\text{O} - \text{N/mol}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e/tonne}$$

$$\text{N}_2\text{O from NH}_3 \text{ Injection} = \frac{(295) \left( \frac{14}{17} \right)}{(247,075)} * (0.017) \left( \frac{44}{28} \right) (310) = 0.0081 \text{ tCO}_2\text{e/tonne}$$

$$\text{N}_2\text{O Emission resulting from NH}_3 \text{ Injection} = 0.0081 (0.0014 - 0.015) \text{ tCO}_2\text{e/tonne}$$

In addition to the potential for injected NH<sub>3</sub> to thermally convert to N<sub>2</sub>O, there can also be the future denitrification of the nitrogen oxide (NO<sub>x</sub>) gases released. It has been estimated that 10-30% of waste-nitrogen is converted to NO<sub>x</sub> (NO + NO<sub>2</sub>) during combustion (White et al. 1995). This report will evenly distribute NO<sub>x</sub> emissions across the total mass of waste incinerated even though HDPE has a negligible nitrogen content. Nitrogen oxides are short lived in the atmosphere as they are quickly rained out in the form of nitrate (NO<sub>3</sub><sup>-</sup>) or nitric acid (HNO<sub>3</sub>). Thus the deposition as NO<sub>3</sub><sup>-</sup> will eventually require denitrification to N<sub>2</sub>, resulting in potential leakage of N<sub>2</sub>O. The IPCC provides guidelines for these emissions and estimates that 1% of emitted NH<sub>3</sub>-N or NO<sub>x</sub>-N will be converted to N<sub>2</sub>O. This value is used to develop this emission factor (only the best-guess estimate is used here as the emission is greatly dominated by the fossil-carbon content). In addition to the potential for the microbial conversion of nitrogen oxide to nitrous oxide, nitrogen oxides are suspected to be indirect greenhouse gases for another reason – they deplete the tropospheric concentration of the OH radical, which would otherwise react and destroy CH<sub>4</sub> (Mackenzie 1995). Thus NO<sub>x</sub> causes CH<sub>4</sub> to be a stronger GHG. (As it is too early for any methodology on this issue, it will have to be ignored in this report.) At the Burnaby Incinerator it is estimated that 449 tonnes of NO<sub>x</sub> was emitted in 1998 (Pers. comm. Chantal Babensee). Nitric oxide (NO) is predominantly the nitrogen

oxide formed during incineration (Robinson 1986), and is assumed in the calculations below.

Best-Guess Estimate for the future  $N_2O$  conversion of  $NO_x = 1\% N_2O-N/NO_x-N$

Annual  $NO_x$  emission (1998) = 449 tonnes

Annual mass of waste combusted (1998) = 247,075 tonnes

$$N_2O \text{ Emission from } NO_x = \frac{(NO_x \text{ Emission, tonnes}) \left( \frac{14 \text{ gN}}{30 \text{ gNO}} \right)}{(\text{Waste Combusted, tonnes})} * (N_2O \text{ Conversion}) \left( \frac{44 \text{ gN}_2O}{28 \text{ gN}_2O - N} \right) (\text{GWP of } N_2O) = tCO_2e/\text{tonne}$$

$$N_2O \text{ Emission from } NO_x = \frac{(449) \left( \frac{14}{30} \right)}{(247,075)} * (0.01) \left( \frac{44}{28} \right) (310) = 0.004 tCO_2e/\text{tonne}$$

Future  $N_2O$  from  $NO_x$  emission = 0.004  $tCO_2e/\text{tonne}$

The last potential  $N_2O$  emission from waste incineration could occur when ammonia is injected into the flue gas but is emitted to the atmosphere, the so-called "ammonia slip". The ammonia will undergo wet or dry deposition to soils downwind where it can nitrify and denitrify. Communication with the GVRD (Pers. comm. Chantal Babensee) has learned that ammonia slip is virtually negligible at the Incinerator largely because only the minimum amount is injected into the flue gas. As a result, the potential for ammonia slip to result in nitrous oxide emissions can be neglected in this study.

$$\begin{aligned} \text{Total GHG Emissions} &= CO_2 + N_2O + \text{Natural Gas} + \text{Electricity} + \text{Lime} = tCO_2e/\text{tonne} \\ \text{Total Emissions} &= 3.14 tCO_2e/\text{tonne} \end{aligned}$$

### 3. GHG Emissions of Recycled HDPE Utilization

The assumption discussed in Section 2.6.5 – *High-Density Polyethylene* is that a GHG benefit of 1.7  $tCO_2e/\text{tonne}$  exists with the recycling of HDPE.

GHG Benefit of Recycled HDPE Utilization = 1.7  $tCO_2e/\text{tonne}$

## **APPENDIX H:**

### **LOW-DENSITY POLYETHYLENE MANAGEMENT**

Low-density polyethylene (LDPE) is a plastic manufactured from petroleum products. Therefore, LDPE is an organic material which contains fossil-carbon; contrary to paper, food or yard waste which are organic materials but contain atmospheric carbon that was fixed by photosynthesis. Low-density polyethylene does not biodegrade therefore it cannot contribute to landfill methane emissions. The only emission factors required with the landfill disposal of LDPE are associated with transportation and processing and are thus not included here. Plastics, being organic, are readily combustible during incineration and generate significant amounts of energy. Importantly, the carbon dioxide emissions from plastics must be treated differently than the neutral carbon dioxide emissions from paper, food or yard trimmings as plastics contain fossil-carbon and any combustion results in greenhouse gas emissions.

As LDPE exhibits all the same material properties as HDPE from the perspective of GHG emissions, the emission factors are identical for waste incineration. Only the GHG ramifications of LDPE recycling are provided in this Appendix.

#### **1. GHG Emissions of Recycled LDPE Utilization**

The assumption discussed in Section 2.6.6 – *Low-Density Polyethylene* is that a GHG benefit of 2.25 tCO<sub>2</sub>e/tonne exists with the recycling of HDPE.

GHG Benefit of Recycled HDPE Utilization = 2.25 tCO<sub>2</sub>e/tonne

## **APPENDIX I: FOOD WASTE MANAGEMENT**

This appendix only provides the data and calculations specific to estimating the emission factors for the landfilling, incineration or composting of food waste generated in the GVRD. For complete sample calculations, refer to Appendix C – *Newsprint Waste Management*. The first three sections are devoted to the GHG implications of the Cache Creek Landfill (1-3). The next three sections assess the same implications for the Vancouver Landfill (4-6). Sections 7 and 8, assess the energy generation and GHG emissions from the Burnaby Incinerator. The last three sections of this appendix, 9 through 11, analyze the GHG ramifications of the backyard or centralized composting of food waste.

Food waste in this thesis is treated as a single entity yet it is a highly heterogeneous mixture of fruits, vegetables, meats, fats, breads and other components. While all this mixture can be landfilled or incinerated it needs to be recognized that composting does not typically manage meats and fats due to the rodent problems which result. This is a limitation of this research.

### **1. Methane & Energy Implications of the Cache Creek Landfill:**

The calculations for landfill methane emissions and energy generation follow – starting with the Carbon Available for Anaerobic Decomposition (CAAD). However, as discussed in Section 2.4 – Landfill Carbon Sequestration, this CAAD is calculated from the CSF published by Barlaz (1998) and is not revised as the others are. The CAAD for food waste is the difference of the initial carbon content minus the fraction which is assumed to enter long-term storage.

Typical Carbon Content of Dry Food Waste = 48.0% (Tchobanoglous et al. 1993)

Typical Moisture Content of Food Waste = 70% (Tchobanoglous et al. 1993)

Carbon Storage Factor (CSF) = 0.08 kg C/dry kg (Barlaz 1998)

$$= 0.08 * (1 - MC) = 0.08 * (1 - 0.70) = 0.024 \text{ kg C/fresh kg}$$

$$\text{Carbon Available To Decompose} = \left(1 \frac{\text{Wet Tonne}}{\text{Wet Tonne}}\right) \left[ (1 - \text{Moisture Content}) \frac{\text{Dry Tonne}}{\text{Wet Tonne}} \right] \left( \text{Carbon Content Mass C} / \text{Dry Mass} \right) -$$

$$\text{Carbon Available To Decompose} = (1) \left[ (1 - 0.70) \right] (0.48) - 0.024 = 0.120 \text{ tC} / \text{Wet Tonne}$$

This 0.120 tC per wet tonne of food waste is available for anaerobic decomposition and will be assumed to be evenly split between CH<sub>4</sub> and CO<sub>2</sub>. Remember that since any CO<sub>2</sub> is neutral, it does not have to be considered further.

$$\text{Methane Generation} = \left( \text{Carbon To Decompose} \frac{\text{tC}}{\text{Wet Tonne}} \right) \left( \text{Methane Fraction} \right) \left( \frac{\text{Molecular Mass of CH}_4}{\text{Molecular Mass of C}} \right) = \text{tCH}_4 / \text{Wet Tonne}$$

$$\text{Methane Generation} = (0.120) (0.5) \left( \frac{16}{12} \right) = 0.080 \text{ tCH}_4 / \text{Wet Tonne}$$

Methane Generation Potential = 0.080 tCH<sub>4</sub>/tonne of food waste

The first order decay rate constant used here is 0.07 y<sup>-1</sup> and the assumptions behind it are discussed in Section 2.4 - *Landfill Carbon Sequestration*.

The model in Worksheet #32, estimates that for the 20 year period between 1999 and 2018, 0.050 tCH<sub>4</sub>/tonne would be generated. This represents 77% of the ultimate potential of 0.064 tCH<sub>4</sub>/tonne. This generation corresponds to, minus the collection and oxidation, an emission of 0.320 tCO<sub>2</sub>e/tonne. Furthermore an energy benefit, via the replacement of fossil energy, of 0.049 tCO<sub>2</sub>e/tonne was realized.

Estimates are as follows:

Best-Guess of Atmospheric Methane Emissions=	0.320	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.049	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.162	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.037	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.547	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.009	tCO <sub>2</sub> e/tonne

## 2. Long-Term Carbon Sequestration in the Cache Creek Landfill:

Since not all of the cellulose and hemicellulose and only a negligible portion of the lignin from food waste is expected to anaerobically degrade in a landfill, organic-carbon will remain in long-term storage in the landfill. In this capacity, the organic-carbon, which was originally atmospheric CO<sub>2</sub> but was photosynthesized into biomass, will be sequestered. As a result, organic-carbon can perform a GHG benefit, a negative GHG emission. This issue is discussed in greater detail in Section 2.4 – *Landfill Carbon Sequestration*.

The Carbon Storage Factors, as determined by Barlaz (1998), and also discussed in Eleazer et al. (1997), are used here as representative of long-term storage in the CCLF. These researchers observed that food waste, with a measured lignin concentration of 11.4%, exhibited an 84% decomposition of the cellulose, hemicellulose and protein fraction but only a negligible breakdown of the lignin. These experiments determined that the long-term carbon storage of food waste in landfills is 0.08 tC/tonne of dry food waste. However, these factors were developed with laboratory research of idealized landfill decomposition conditions and are thus highly conservative. As a result, the actual storage in the CCLF could be greater than is indicated by these experiments. While there is great potential for uncertainty with this estimate, it is likely that the uncertainty would be skewed towards a greater value. By using this conservative estimate, the risk of overestimating this factor is probably minimal. For these reasons, only the best-guess estimate will be used in this analysis.

In Section #1 of the Appendix a revised Carbon Storage Factor was developed to attempt to correct inconsistencies in the previous estimates by Barlaz. The new estimate is as follows:

Revised Carbon Storage Factor for food waste = 0.19 tC/dry tonne

Typical Moisture Content of Food Waste = 70% (Tchobanoglous et al. 1993)

$$\text{Carbon Sequestration} = \left( \frac{\text{kgC}}{\text{Dry Food Waste}} \right) (1 - \text{Moisture Content}) \left( \frac{44 \text{gCO}_2 / \text{mol}}{12 \text{gC} / \text{mol}} \right) = \text{tCO}_2\text{e} / \text{tonne}$$

$$\text{Carbon Sequestration} = (0.19)(1 - 0.70) \left( \frac{44}{12} \right) = 0.209 \text{ tCO}_2\text{e} / \text{tonne}$$

$$\text{Long-Term Carbon Sequestration from Food Waste} = -0.209 \text{ tCO}_2\text{e} / \text{tonne}$$

### 3. Immediate & Future N<sub>2</sub>O Emissions from the Cache Creek Landfill

The organic-nitrogen in food waste is predominantly anthropogenic in origin – almost all of the nitrogen was derived from synthetic fertilizers or the human-induced cultivation of legumes which perform biological nitrogen fixation. When disposed in landfills, most of the food waste undergoes anaerobic decomposition to CO<sub>2</sub> and CH<sub>4</sub> and at this point the organic-nitrogen is transformed to ammonia (NH<sub>3</sub>) or ammonium (NH<sub>4</sub><sup>+</sup>). When in this form, the nitrogen is free to undergo nitrification and denitrification to be leached by water percolating through the fill or to be volatilized and vented with the landfill gas. However, as a result of the anaerobic conditions (specifically the lack of electron acceptors), there is likely very little opportunity for nitrification to occur and thus very little opportunity for denitrification or nitrous oxide emissions to occur. Therefore, nitrous oxide emissions from solubilized ammonia in the landfill leachate or volatilized ammonia in the landfill gas. An extensive discussion of this issue is provided in Section 2.5.5.1.

It is assumed in this analysis that the anaerobic conditions present in landfills do not present the opportunity for ammonia compounds to nitrify to nitrate (this also prevents any denitrification). As a result, there is no potential for immediate nitrous oxide emissions at the landfill site. It is also assumed that all of the nitrogen contained in food waste which decomposes will eventually be solubilized and exit the landfill as leachate or vented gas. (This may be an overestimate due to the potential for Nitrogen Sequestration – discussed in Section 2.5.5.1) Since this leachate will be transferred to a wastewater treatment plant and the vented landfill gas is the emission of reactive nitrogen to the atmosphere, the IPCC estimates for these potential N<sub>2</sub>O sources are appropriate here. Therefore N<sub>2</sub>O emissions estimated from nitrogen in food waste will be future emissions at the treatment plant managing the landfill leachate or the subsequent nitrification and denitrification of wet or dry deposited ammonia or nitrogen oxide gas. As a result of the uncertainty associated with the IPCC estimate, the high and low estimates provided by the IPCC will also be used here. While not all food waste will anaerobically decompose, the lignin fraction will resist decomposition, it will be assumed that the nitrogen is predominantly from the protein fraction of food waste and thus all nitrogen will be available for solubilization.

There is no appreciable leachate at the Cache Creek Landfill due to the dry climatic conditions. Any leachate which is collected is spread on the active face to return the leachate back to the fill (Pers. comm.. Louie DeVent). As a result, it is assumed that ammonia only exits the landfill in the vented gas.

Best-Guess Estimate of the N<sub>2</sub>O from vented nitrogen = 1.0% N<sub>2</sub>O/emitted NH<sub>3</sub> or NO<sub>x</sub>

Low Estimate of the N<sub>2</sub>O from vented nitrogen = 0.2% N<sub>2</sub>O/emitted NH<sub>3</sub> or NO<sub>x</sub>  
 High Estimate of the N<sub>2</sub>O from vented nitrogen = 2.0% N<sub>2</sub>O/emitted NH<sub>3</sub> or NO<sub>x</sub>  
 Typical moisture content of food waste = 70% (Tchobanoglous et al. 1993)  
 Nitrogen content of dry food waste = 2.6% N (Tchobanoglous et al. 1993)

$$\text{Nitrogen Content of Wet Food Waste} = \left( \text{Dry N Content} \frac{\text{kg N}}{\text{kg dry food}} \right) (1 - \text{Moisture Content})$$

$$\text{Nitrogen Content of Wet Food Waste} = (0.026)(1 - 0.70) = 0.0078 = 0.8\% \text{ N}$$

$$\text{N}_2\text{O Emission} = \left( \text{Mass} \frac{\text{tonne}}{\text{tonne}} \right) (\text{N Content}) (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ gN}_2\text{O} / \text{mol}}{28 \text{ gN}_2\text{O} - \text{N} / \text{mol}} \right) (\text{GWP of N}_2\text{O})$$

$$\text{N}_2\text{O Emission} = \left( 1 \frac{\text{tonne}}{\text{tonne}} \right) (0.008) (0.01) \left( \frac{44}{28} \right) (310) = 0.038 \text{ tCO}_2\text{e} / \text{tonne}$$

$$\text{Immediate \& Future N}_2\text{O Emissions} = 0.038 \text{ (0.008-0.076) tCO}_2\text{e/tonne}$$

#### 4. Methane & Energy Implications of the Vancouver Landfill:

The only significant difference between this section and Section 1, *Methane & Energy Implications of the Cache Creek Landfill*, is the estimated landfill gas collection efficiency and the first order decay rate constant. While at Cache Creek the current collection efficiency is estimated to be 43%, the current collection efficiency at the Vancouver Landfill is estimated to only be 22% (Pers. comm. Chris Underwood). However, engineers with the City of Vancouver are currently in the process of upgrading the collection equipment. As with the CCLF assessment, the collection efficiency is assumed to increase year after year in response to improving regulations. The first order decay rate constant used here is 0.08 yr<sup>-1</sup> and the assumptions behind it are discussed in Section 2.4 - *Landfill Carbon Sequestration*.

From Worksheet #32:

Best-Guess of Atmospheric Methane Emissions=	0.404	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.050	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.203	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.040	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.665	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.008	tCO <sub>2</sub> e/tonne

#### 5. Long-Term Carbon Sequestration in the Vancouver Landfill:

The Revised Carbon Storage Factors is used here as representative of long-term storage in the VLF.

$$\text{Long-Term Carbon Sequestration from Food Waste} = -0.209 \text{ tCO}_2\text{e/tonne}$$

## 6. Immediate & Future N<sub>2</sub>O Emissions from the Vancouver Landfill:

The potential for nitrous oxide emissions at the Vancouver Landfill differ from the Cache Creek Landfill in that they are assumed to result from the solubilized ammonia in the leachate instead of the volatilized ammonia gas. It is assumed that all of the nitrogen contained in food waste which decomposes will eventually be solubilized and exit the landfill as leachate. (This may be an overestimate due to the potential for Nitrogen Sequestration – discussed in Section 2.5.5.1) The calculations for this emission are below:

Best-Guess Estimate of the N<sub>2</sub>O from wastewater nitrogen = 1.0% N<sub>2</sub>O/influent-N

Low Estimate of the N<sub>2</sub>O from wastewater nitrogen = 0.2% N<sub>2</sub>O/ influent-N

High Estimate of the N<sub>2</sub>O from wastewater nitrogen = 2.0% N<sub>2</sub>O/ influent-N

Typical moisture content of food waste = 70% (Tchobanoglous et al. 1993)

Nitrogen content of dry food waste = 2.6% N (Tchobanoglous et al. 1993)

$$\text{Nitrogen Content of Wet Food Waste} = \left( \text{Dry N Content} \frac{\text{kg N}}{\text{kg dry food}} \right) (1 - \text{Moisture Content})$$

$$\text{Nitrogen Content of Wet Food Waste} = (0.026)(1 - 0.70) = 0.0078 = 0.8\% \text{N}$$

$$\text{N}_2\text{O Emission} = \left( \text{Mass} \frac{\text{tonne}}{\text{tonne}} \right) (\text{N Content}) (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ gN}_2\text{O} / \text{mol}}{28 \text{ gN}_2\text{O} \cdot \text{N} / \text{mol}} \right) (\text{GWP of N}_2\text{O})$$

$$\text{N}_2\text{O Emission} = \left( 1 \frac{\text{tonne}}{\text{tonne}} \right) (0.008) (0.01) \left( \frac{44}{28} \right) (310) = 0.039 \text{ tCO}_2\text{e} / \text{tonne}$$

$$\text{Total Immediate \& Future N}_2\text{O Emissions} = 0.039 (0.008-0.078) \text{ tCO}_2\text{e/tonne}$$

## 7. Energy Generation from Waste Incineration at the Burnaby Incinerator:

Net Energy Content of Food Waste = 2,370 BTU/lb = 5,496 kJ/kg (USEPA 1998)

(2,370 BTU/lb \* 1.054 kJ/BTU \* 2.20 lb/kg = 5,496 kJ/kg)

(wet basis, correction for latent heat of water in this reference is assumed but not directly specified)

From another source (Tchobanoglous et al. 1993):

Gross Energy Content of Food Waste = 1,797 BTU/lb = 4,167 kJ/kg (wet basis)

Typical Moisture Content of Food Waste = 70% (Tchobanoglous et al. 1993)

Latent Heat of Water = 2473 kJ/kg (Incropera and DeWitt 1990)

$$\text{Net Energy Content} = [\text{Gross Energy}] - [\text{Latent Heat of Vaporization}]$$

$$\text{Net Energy Content} = \left[ 4,167 \frac{\text{kJ}}{\text{kg}} \right] - \left[ \left( 2473 \frac{\text{kJ}}{\text{kg}} \right) (0.70)_{MC} \right] = 2,436 \frac{\text{kJ}}{\text{kg}}$$

Because of the variation between these values, the average will be used as the best-guess estimate while the high and low estimates will be the high and low values respectively.

$$\text{Net Energy Content} = \left[ \frac{5496 + 2436}{2} \right] = 3,966 \frac{\text{kJ}}{\text{kg}} = 4.0 \text{ GJ} / \text{tonne}$$

Best-Guess Estimate of the Net Energy Content of Food Waste = 4.0 GJ/tonne

Low Estimate of the Net Energy Content of Food Waste = 2.4 GJ/tonne

High Estimate of the Net Energy Content of Food Waste = 5.5 GJ/tonne



Steam Energy produced by the combustion of food waste in an Incinerator-Boiler (1):  
 Assumed Boiler Efficiency = 70% (Pers. comm. Ron Richter)  
 Fraction of Steam Utilized by CPL = 56% (Montenay Inc. 1999)

$$\frac{\text{Utilized Energy}}{\text{tonne Food Waste}} = \frac{\text{energy}}{\text{tonne}} * (\text{Thermal Efficiency}) * (\text{Energy Utilization}) = \text{kJ/tonne}$$

$$\frac{\text{Utilized Energy}}{\text{tonne Food Waste}} = \frac{4.0 \text{ GJ}}{\text{tonne}} * (0.70) * (0.56) = 1.57 \text{ GJ/tonne}$$

Utilized Steam Energy per tonne of food waste, (1) = 1.57 (0.94-2.16) GJ/tonne

GHG emission prevented per tonne of food waste (3):

$$\frac{\text{GHG Emission Prevented}}{\text{tonne food waste}} = \left( \frac{\text{Utilized Energy}}{\text{tonne Newsprint}} \right) * \left( \text{Emission Factor for Natural Gas, } \text{tCO}_2\text{e/GJ} \right) = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne food waste}} = (1.57 \text{ GJ/tonne}) * (0.062 \text{ tCO}_2\text{e/GJ}) = 0.097 \text{ tCO}_2\text{e/tonne}$$

GHG Emission Prevented from Natural Gas, (3) = 0.097 (0.058-0.134) tCO<sub>2</sub>e/tonne

Electricity produced by the combustion of food waste in an Incinerator-Boiler (4):

Assumed Turbo Generator Efficiency = 32% (Pers. comm. Ron Richter)

Steam Fraction for Electricity Generation = 40% (assumed as discussed)

$$\frac{\text{Utilized Energy}}{\text{tonne Food Waste}} = \frac{\text{energy}}{\text{tonne}} * (\text{Boiler Effic}) * (\text{TurboGenerator}) * (\text{Energy Utilization}) = \text{kJ/tonne}$$

$$\frac{\text{Utilized Energy}}{\text{tonne Food Waste}} = \frac{4.0 \text{ GJ}}{\text{tonne}} * (0.70) * (0.32) * (0.40) = 0.36 \text{ GJ/tonne}$$

Utilized Electrical Energy per tonne of food waste, (4) = 0.36 (0.22-0.49) GJ/tonne

Electrical GHG emission prevented per tonne of food waste: (6)

$$\frac{\text{GHG Emission Prevented}}{\text{tonne food waste}} = \left( \frac{\text{Utilized Energy}}{\text{tonne food waste}} \right) * \left( \text{Emission Factor for Electricity, } \text{tCO}_2\text{e/GJ} \right) = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne food waste}} = (0.36 \text{ GJ/tonne}) * (0.147 \text{ tCO}_2\text{e/GJ}) = 0.053 \text{ tCO}_2\text{e/tonne}$$

GHG Emission Prevented from Electricity, (6) = 0.053 (0.032-0.072) tCO<sub>2</sub>e/tonne

Total GHG Emissions Prevented, (7) = 0.097 + 0.053 = -0.15 (0.09-0.21) tCO<sub>2</sub>e/tonne

## 8. Greenhouse Gas Emissions from Waste Incineration:

At the Burnaby Incinerator, 247,075 tonnes of waste was combusted in 1998. This process required the consumption of 7,516 GJ of natural gas, 16,011 MWh of electricity, and 3,369 tonnes of lime (CaO) and 295 tonnes of ammonia (NH<sub>3</sub>) for acid gas control (Montenay Inc. 1999; Pers. comm. Richard Holt). Greenhouse gas emissions result from municipal solid waste incineration. This includes emissions of carbon dioxide and nitrous oxide during incineration, the consumption of natural gas and electricity, and the consumption of lime for acid gas control (the production of lime from limestone results in CO<sub>2</sub> emissions). Since food waste is biomass carbon and is therefore carbon-neutral, the CO<sub>2</sub> emissions can be ignored here. Environment Canada estimates that while a small methane emission is measurable during wastewater sewage sludge incineration there is negligible methane emissions during MSW incineration (Environment Canada 1999). That will also be assumed for this investigation.

The most important greenhouse gas emission associated with the incineration of food waste, and also the most uncertain, is the potential for significant nitrous oxide releases. This can result from one of five pathways:

- Thermal conversion of the  $N_2$  gas in air to  $N_2O$  during combustion (Immediate emis.)
- Thermal conversion of the nitrogen in food waste to  $N_2O$  (Immediate emission)
- Thermal conversion of the ammonia injected in the flue gases (Immediate emission)
- Microbial  $N_2O$  conversion of  $NO_x$  emitted and later denitrified (Future emission)
- Microbial  $N_2O$  conversion of  $NH_3$  injected but unreacted (Future emission)

Each of these five pathways are evaluated in the following calculations. Unfortunately, the current lack of understanding in these issues result in much uncertainty associated with the following estimates. An extensive discussion of the issue is provided Section 2.5.5.3.

The first two potential sources of nitrous oxide emissions result from the potential for the nitrogen in waste or the  $N_2$  gas in air to thermal convert to  $N_2O$  during incineration. There is limited and highly variable research of the  $N_2O$  emissions resulting from municipal solid waste incineration. Examples of emission estimates being used are:

- |                                       |                                 |
|---------------------------------------|---------------------------------|
| • IPCC Compilation (de Soete 1993)    | 11-293 g $N_2O$ /tonne of waste |
| • Environment Canada Inventory (1997) | 160 g $N_2O$ /tonne of waste    |
| • USEPA National Inventory (1999)     | 30 g $N_2O$ /tonne of waste     |
| • USEPA MSW Analysis (1998)           | 130 g $N_2O$ /tonne of waste    |

Research in the fluidized bed combustion of coal has determined that  $N_2O$  emissions originate mainly from the oxidation of fuel nitrogen (Moritomi 1994), and since coal combustion is similar to that of waste incineration, it can be inferred that  $N_2O$  emissions during incineration are likely a factor of the nitrogen content. This hypothesis is reinforced by one study (Tanikawa et al. 1995), and the observation that the incineration of high nitrogen content wastewater sludge produces much higher  $N_2O$  emission rates than MSW incinerators (Tanaka et al. 1994). For this research, it is deemed appropriate for food waste to account for its proportionate share of nitrous oxide rather than distribute it across a typical municipal solid waste, the individual components of which (excluding food) may be low in nitrogen. As a result, the immediate  $N_2O$  emissions measured during incineration will be assumed to be entirely a contribution of the nitrogen content and not the  $N_2$  gas in air. These estimates below first determine the nitrogen emission during incineration as nitrous oxide and then determine the nitrogen of municipal solid waste. By dividing these two results it is possible to estimate the expected nitrous oxide conversion of waste-nitrogen, an important emission factor. For these calculations, the Environment Canada (1997) estimate will be used as the best-guess value (160 g $N_2O$ /tonne). The IPCC compilation (de Soete 1993) will be used as the high estimate (300 g $N_2O$ /tonne) and the USEPA national inventory (1999) will be used as the low estimate (30 g $N_2O$ /tonne).

Best-Guess Estimate for  $N_2O$  Emissions from Incineration = 160 g $N_2O$ /tonne of MSW  
Low Estimate for  $N_2O$  Emissions from Incineration = 30 g $N_2O$ /tonne of MSW

High Estimate for  $N_2O$  Emissions from Incineration = 300 g $N_2O$ /tonne of MSW

Nitrogen Content of MSW = 0.8% N/dry tonne (Environment Canada 1978)

Moisture Content of MSW = 24% (Environment Canada 1978)

$$N_2O \text{ Emission} = \left( N_2O \text{ from Incineration } \frac{g N_2O}{\text{tonne MSW}} \right) \left( \frac{28 \frac{g N_2O - N}{\text{mol}}}{44 \frac{g N_2O - N}{\text{mol}}} \right) = \frac{g N_2O - N}{\text{tonne MSW}}$$

$$N_2O \text{ Emission} = (160) \left( \frac{28}{44} \right) = 102 \text{ (19-191) } \frac{g N_2O - N}{\text{tonne MSW}}$$

$$\text{Nitrogen in MSW incinerated} = \left( 1000 \frac{kg}{\text{tonne}} \right) \left( \text{Nitrogen Content } \frac{N}{\text{Dry Waste}} \right) \left[ (1 - \text{Moisture Content})^{\text{dry/wet}} \right] = \frac{kg N}{\text{tonne MSW}}$$

$$\text{Nitrogen in MSW incinerated} = \left( 10^6 \frac{g}{\text{tonne}} \right) (0.008) \left[ (1 - 0.24)^{\text{dry/wet}} \right] = 6080 \frac{g N}{\text{tonne MSW}}$$

$$\text{Percentage of Waste Nitrogen Emitted as } N_2O - N = \frac{102 \frac{g N_2O - N}{\text{tonne MSW}}}{6080 \frac{g N}{\text{tonne MSW}}} = 0.017 \frac{g N_2O - N}{g N} = 1.7\% \text{ Conversion of Nitrogen to } N_2O$$

Fraction of Waste-Nitrogen emitted as  $N_2O$  = 1.7 (0.3-3.1) %

Therefore, it has been estimated that approximately 1.7% of the nitrogen in waste is emitted as  $N_2O$  during incineration but could likely range between 0.3 and 3.1%. The immediate  $N_2O$  emission from the conversion of food-nitrogen during combustion can now be estimated:

Nitrogen Content of food waste = 0.8% N (wet basis) – see #3

$$\text{Immediate } N_2O \text{ Emission} = \left( \text{Mass } \frac{\text{tonne}}{\text{tonne}} \right) \left( N \text{ Content} \right) \left( N_2O \text{ Emission} \right) \left( \frac{44 \frac{g N_2O}{\text{mol}}}{28 \frac{g N_2O - N}{\text{mol}}} \right) \left( \text{GWPOf } N_2O \right) = \frac{tCO_2e}{\text{tonne}}$$

$$\text{Immediate } N_2O \text{ Emission} = (1) (0.008) (0.017) \left( \frac{44}{28} \right) (310) = 0.066 (0.012 - 0.13) \frac{tCO_2e}{\text{tonne}}$$

$$\text{Immediate } N_2O \text{ Emission} = 0.065 (0.011 - 0.12) \frac{tCO_2e}{\text{tonne}}$$

The next potential pathway for  $N_2O$  emissions could result from the injection of ammonia into the flue gas to reduce  $NO_x$  gases. Remember that at the Burnaby Incinerator, 295 tonnes of ammonia ( $NH_3$ ) was used during the combustion of 247,075 tonnes of waste in 1998 to reduce  $NO_x$  emissions. As a result of the lack of any available research on the propensity for injected ammonia to thermally convert to  $N_2O$ , this study will assume the same conversion rate exhibited by the waste-nitrogen upon incineration. Therefore, approximately 1.8% of injected ammonia, and ranging between 0.3 and 3.4%, will be estimated to convert to nitrous oxide. There is a complicating factor which requires discussion. Does the  $NO_x$  acid gases which require treatment by ammonia injection result from the incineration of nitrogen-rich materials or from municipal solid waste in general? If the former is true, food waste would need to take responsibility for its proportionate share of  $NO_x/NH_3$  while if the latter is true these emissions could be evenly divided among the waste incinerated. This is a difficult question to answer and for simplicity this investigation assumes that  $NO_x/NH_3$  is equally contributed by all waste. In the event that  $NO_x/NH_3$  is a function of nitrogen content, the results here would be underestimating the contribution of food waste.

Fraction of Waste-Nitrogen emitted as  $N_2O$  = 1.7 (0.3-3.1) %

Annual consumption of ammonia (1998) = 295 tonnes

Annual mass of waste combusted (1998) = 247,075 tonnes

$$\text{N}_2\text{O from NH}_3 \text{ Injection} = \frac{(\text{NH}_3 \text{ Injected, tonnes}) \left( \frac{14 \text{ gN}}{17 \text{ g NH}_3} \right)}{(\text{Waste Combusted, tonnes})} * (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ gN}_2\text{O}}{28 \text{ gN}_2\text{O} - \text{N}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e/tonne}$$

$$\text{N}_2\text{O from NH}_3 \text{ Injection} = \frac{(295) \left( \frac{14}{17} \right)}{(247,075)} * (0.017) \left( \frac{44}{28} \right) (310) = 0.0081 \text{ tCO}_2\text{e/tonne}$$

N<sub>2</sub>O Emission resulting from NH<sub>3</sub> Injection = 0.0081 (0.0014 – 0.015) tCO<sub>2</sub>e/tonne

In addition to the potential for injected NH<sub>3</sub> to thermally convert to N<sub>2</sub>O, there can also be the future denitrification of the nitrogen oxide (NO<sub>x</sub>) gases released. It has been estimated that 10-30% of waste-nitrogen is converted to NO<sub>x</sub> (NO + NO<sub>2</sub>) during combustion (White et al. 1995). Nitrogen oxides are short lived in the atmosphere as they are quickly rained out in the form of nitrate (NO<sub>3</sub><sup>-</sup>) or nitric acid (HNO<sub>3</sub>). Thus the deposition as NO<sub>3</sub><sup>-</sup> will eventually require denitrification to N<sub>2</sub>, resulting in potential leakage of N<sub>2</sub>O. The IPCC provides guidelines for these emissions and estimates that 1% of emitted NH<sub>3</sub>-N or NO<sub>x</sub>-N will be converted to N<sub>2</sub>O. However they also provide low and high estimates of 0.2 and 2% respectively. All three of these values are used in this study. In addition to the potential for the microbial conversion of nitrogen oxide to nitrous oxide, nitrogen oxides are suspected to be indirect greenhouse gases for another reason – they deplete the tropospheric concentration of the OH radical, which would otherwise react and destroy CH<sub>4</sub> (Mackenzie 1995). Thus NO<sub>x</sub> causes CH<sub>4</sub> to be a stronger GHG. (As it is too early for any methodology on this issue, it will have to be ignored in this report.) At the Burnaby Incinerator it is estimated that 449 tonnes of NO<sub>x</sub> was emitted in 1998 (Pers. comm. Chantal Babensee). Nitric oxide (NO) is predominantly the nitrogen oxide formed during incineration (Robinson 1986), and is assumed in the calculations below.

Best-Guess Estimate for the future N<sub>2</sub>O conversion of NO<sub>x</sub> = 1% N<sub>2</sub>O-N/NO<sub>x</sub>-N

Low Estimate for the future N<sub>2</sub>O conversion of NO<sub>x</sub> = 0.2% N<sub>2</sub>O-N/NO<sub>x</sub>-N

High Estimate for the future N<sub>2</sub>O conversion of NO<sub>x</sub> = 2% N<sub>2</sub>O-N/NO<sub>x</sub>-N

Annual NO<sub>x</sub> emission (1998) = 449 tonnes

Annual mass of waste combusted (1998) = 247,075 tonnes

$$\text{N}_2\text{O Emission from NO}_x = \frac{(\text{NO}_x \text{ Emission, tonnes}) \left( \frac{14 \text{ gN}}{30 \text{ gNO}} \right)}{(\text{Waste Combusted, tonnes})} * (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ gN}_2\text{O}}{28 \text{ gN}_2\text{O} - \text{N}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e/tonne}$$

$$\text{N}_2\text{O Emission from NO}_x = \frac{(449) \left( \frac{14}{30} \right)}{(247,075)} * (0.01) \left( \frac{44}{28} \right) (310) = 0.004 (0.001 - 0.008) \text{ tCO}_2\text{e/tonne}$$

N<sub>2</sub>O from NH<sub>3</sub> Injection = 0.004 (0.001-0.008) tCO<sub>2</sub>e/tonne

The last potential N<sub>2</sub>O emission from waste incineration could occur when ammonia is injected into the flue gas but is emitted to the atmosphere, the so-called “ammonia slip”. The ammonia will undergo wet or dry deposition to soils downwind where it can nitrify

and denitrify. Communication with the GVRD (Pers. comm. Chantal Babensee) has learned that ammonia slip is virtually negligible at the Incinerator largely because only the minimum amount is injected into the flue gas. As a result, the potential for ammonia slip to result in nitrous oxide emissions can be neglected in this study.

The remaining greenhouse gas emissions during waste combustion result from the consumption of natural gas, electricity and lime by the Incinerator. This analysis will assume that the emissions resulting from natural gas, electricity and lime consumption will be equally distributed over the entire solid waste combusted in 1998. These estimates are below:

Natural gas consumption (1998) = 7516 GJ

CO<sub>2</sub> Emission from Natural Gas Combustion = 1.88 kg/m<sup>3</sup> (Environment Canada 1997)

Typical Energy of Natural Gas = 1020 BTU/ft<sup>3</sup> = 37,843 kJ/m<sup>3</sup> (Perry's 1984)

(Energy = 1020 BTU/ft<sup>3</sup> \* 1.054 kJ/BTU \* 35.2 ft<sup>3</sup>/m<sup>3</sup> = 37,843 kJ/m<sup>3</sup>)

$$\text{GHG Emissions from Natural Gas} = \frac{(\text{Annual Energy Consumption, GJ}) * \left(1.88 \frac{\text{kg CO}_2}{\text{m}^3}\right) * \left(\frac{\text{tonnes}}{1000 \text{ kg}}\right)}{(\text{Annual Waste Combusted, tonnes}) * \left(37843 \frac{\text{kJ}}{\text{m}^3}\right) * \left(\frac{\text{GJ}}{10^6 \text{ kJ}}\right)} = \text{tCO}_2\text{e/tonne}$$

$$\text{GHG Emissions from Natural Gas} = \frac{(7516 \text{ GJ}) * \left(1.88 \frac{\text{kg CO}_2}{\text{m}^3}\right) * \left(\frac{\text{tonnes}}{1000 \text{ kg}}\right)}{(247075 \text{ tonnes}) * \left(37843 \frac{\text{kJ}}{\text{m}^3}\right) * \left(\frac{\text{GJ}}{10^6 \text{ kJ}}\right)} = 0.0015 \text{ tCO}_2\text{e/tonne}$$

GHG Emission from Natural Gas Consumption = 0.0015 tCO<sub>2</sub>e/tonne

Electricity consumption (1998) = 16011 MWh

While up for debate, this analysis will assume the B.C. average for electricity.

BC Hydro emission intensity = 30 tCO<sub>2</sub>e/GWh = 0.00833 tCO<sub>2</sub>e/GJ

[30 tCO<sub>2</sub>e/GWh \* (1/3600 GWh/GJ) = 0.00833 tCO<sub>2</sub>e/GJ]

$$\text{GHG Emissions from Electricity} = \frac{(\text{Annual Electricity Consumption, GWh}) * (\text{BC Hydro GHG Average, tCO}_2\text{e/GWh})}{(\text{Annual Waste Combusted, tonnes})} = \text{tCO}_2\text{e/tonne}$$

$$\text{GHG Emissions from Electricity} = \frac{(16.0 \text{ GWh}) * (30 \text{ tCO}_2\text{e/GWh})}{(247075 \text{ tonnes})} = 0.0019 \text{ tCO}_2\text{e/tonne}$$

GHG Emission from BC Hydro electricity consumption = 0.0019 tCO<sub>2</sub>e/tonne

Lime (calcium oxide, CaO) is used at the Incinerator during air pollution control to neutralize acid gases which are produced during the combustion of waste. While the consumption of lime at the incinerator does not result in GHG emissions, the production of this material by the lime calcination process does result in emissions. In the production of lime, limestone (CaCO<sub>3</sub>) is heated so that it separates to CaO and CO<sub>2</sub>. In addition to the fossil fuel energy required to perform this reaction there is the non-energy related GHG emission from the liberalization of the unwanted carbon dioxide gas. Environment Canada (1997) has estimated that 0.790 kg of CO<sub>2</sub> is emitted during the production of each kg of lime. It is assumed that the incineration of food waste equally requires the use of lime for the neutralization of acid gases as any other waste.

Therefore:

GHG Emission from CaO Production = 0.790 tCO<sub>2</sub>e/tonne CaO

$$\text{GHG Emissions from Lime} = \left( 0.790 \text{ tCO}_2 / \text{tonne CaO} \right) * \frac{3369 \text{ tonnes of CaO}}{247075 \text{ tonnes of waste}} = 0.011 \text{ tCO}_2 / \text{tonne}$$

The total greenhouse gas emissions resulting from the incineration of food waste are summed below. While there is little uncertainty with the emissions from natural gas, electricity and lime consumption, the nitrous oxide emissions are uncertain and cause the provision of best-guess, high and low estimates. The high and low estimates are the total of all the high and low estimates, respectively.

Total GHG Emissions = N<sub>2</sub>O + Natural Gas + Electricity + Lime = tCO<sub>2</sub>e/tonne  
 Total Emissions = 0.092 (0.028 – 0.16) tCO<sub>2</sub>e/tonne

## 9. Greenhouse Gas Emissions from Backyard Composting:

The backyard composting of food waste together with yard trimmings at ground-level dwellings is quite common in the GVRD. The participation has been strongly encouraged by the GVRD and others and can even exceed 25% of the single-family residences in some of the member municipalities. This section will evaluate the greenhouse gas implications of the backyard composting of food waste by residents.

Research has observed emissions of carbon dioxide, methane and nitrous oxide during composting. As food waste is photosynthetic in origin, any carbon dioxide emissions resulting during the composting process are considered neutral and therefore do not have to be considered as greenhouse gas emissions. However, methane emissions can occur from inadequately aerated composting piles. While the carbon in methane is originally from atmospheric carbon dioxide, returning the carbon as methane, with its Global Warming Potential 21 times that of CO<sub>2</sub>, has important greenhouse gas implications.

The Office of Solid Waste of the U.S. Environmental Protection Agency (1998) investigated the extent to which composting might result in methane emissions by conducting a literature search of articles published between 1991 and 1995 and by contacting several researchers at universities and the U.S. Department of Agriculture. Their literature search was unproductive and the researchers contacted stated that well-managed compost operations usually do not generate methane because they typically maintain an aerobic environment with proper moisture content to encourage aerobic decomposition of the materials. "...even if methane is generated in anaerobic pockets in the center of the compost pile, the methane is most likely oxidized when it reaches the oxygen-rich surface of the pile." As a result it was concluded from the available information that methane generation from composting is likely negligible.

Contrary to this conclusion was that of consultants in a recent Environment Canada report (Proctor & Redfern Ltd. 1995). It was concluded by Proctor & Redfern, in association with Ortech International, that while no methane emissions result from mechanized composting, a small amount does result from backyard composting. They estimated that 7.3 kg of CH<sub>4</sub> is emitted for every tonne of waste backyard composted. These consultants concluded that without mechanical mixing, the process is partially

anaerobic and results in some CH<sub>4</sub> production. It is not stated in this summary report how this value was determined.

For this investigation, a literature search of any research which had quantified any methane emissions from composting operations was also conducted. Five research papers were found during this search. In a German study (Hellebrand 1998), 14.8 tonnes of green waste from land maintenance was passively composted in trapezoidal heaps for 194 days with turning at 32 and 70 days. They found that of 4.3 tonnes of initial carbon, 3.5 tonnes was lost as CO<sub>2</sub> and 75 kg as CH<sub>4</sub>, or a methane emission of 1.7% of the initial carbon. Sommer and Dahl (1999) only observed methane emissions from the compressed and unmixed treatments of their experimental dairy litter compost heaps between the 30 and 40 day period of a 197 composting duration. The highest emission observed was 40 g of CH<sub>4</sub>-C per day. Jackson and Line (1998), from the University of Tasmania, reported that at no time during the windrow composting of pulp and paper mill sludge was methane detected. This was despite the fact that tests indicated that the compost piles were oxygen starved for most of the trial. In a British study (Lopez-Real and Baptista 1996) of the composting of cattle manure and straw, the researchers found that the passive composting method produced high levels of methane (> 4 percent) while both the windrowing (mechanical turning) and the forced aeration method "drastically reduced methane output." Samples taken from the top of the passive composting, windrow and forced aeration piles at 14 days into the 36 day experiment had CH<sub>4</sub> concentrations of 48,675±25,949, 39.6±39.4 and 3.69±0.38 parts per million volume, respectively. An investigation of the biosolids composting facilities (aerated static piles of biosolids + woodchips; 1:1 by weight) operated in conjunction with the City of Philadelphia's wastewater treatment plants has observed methane emissions (Hentz et al. 1996). They reported emissions of 42,060 lbs of CH<sub>4</sub>/yr from the compost piles, 15,180 lbs of CH<sub>4</sub>/yr from the biofilters and 1,700 lbs of CH<sub>4</sub>/yr from the curing piles. Unfortunately it is not stated in this paper what was the annual throughput of organic wastes so as to convert these methane emissions into a percentage of decomposed carbon.

Methanogenic bacteria are very sensitive to oxygen, pH and temperature and even when conditions are optimum, can still be quite problematic to culture. These methanogenic bacteria have to be in conditions completely devoid of oxygen, within a narrow pH range of 6.6 to 7.6 and a temperature of 30 to 38°C (Metcalf & Eddy Inc 1991). Though some of the composting studies demonstrated methane emissions, these were from compost heaps much larger in size, with a greater potential for anaerobic zones to develop, than a relatively small (200-250L) backyard composter. As a result, it will be assumed that CH<sub>4</sub> emissions from backyard composting are negligible or non-existent. In the event that future research demonstrates the existence of CH<sub>4</sub> emissions, this assumption will be an underestimate of actual GHG emissions.

During composting, seven research papers have been obtained which document immediate emissions of nitrous oxide during the composting of various organic wastes. These emissions are N<sub>2</sub>O leaking from microorganisms during the nitrification and denitrification of reactive N in these wastes. These researchers have observed a

conversion of reactive N to N<sub>2</sub>O ranging from 0.00005 to 2.2%. An extensive review of this issue is provided in Section 2.5.5.2.

As a result of the available literature, this analysis will use a best-guess estimate that 0.8% of the initial nitrogen in the compost was converted to N<sub>2</sub>O during the composting process. This study will assume high and low estimates of 2% and 0.2%. This data, while important, is not the full picture of N<sub>2</sub>O emissions from composting. These research findings above are only the immediate releases of N<sub>2</sub>O; there will also be future releases of N<sub>2</sub>O resulting from the future nitrification and denitrification of the ammonia or nitric oxide emissions during composting and from the future decomposition of the nitrogen contained in finished compost. These future emissions must also be assessed, thereby necessitating a nitrogen balance.

The immediate N<sub>2</sub>O emissions observed during composting were a result of nitrification and denitrification of the initial nitrogen present in the organic materials to be composted. It is therefore important to know what portion of the initial nitrogen underwent nitrification and denitrification to cause the observed N<sub>2</sub>O emissions. This investigation assumes that 30% of the initial nitrogen actually decomposed. This assumption is uncertain and as a result, low and high estimates of 10 and 50% are utilized. Because of the assumption that 30% of the initial nitrogen actually decomposed, it is conversely assumed that 70% of the initial nitrogen present in the compost escaped nitrification/denitrification. This majority of the compost which did not nitrify or denitrify may have volatilized from the compost pile in the form of ammonia emissions (and been subject to downwind deposition), may have leached from the compost pile as ammonia, organic-nitrogen or nitrate, or may be contained in the finished compost. This nitrogen will be subject to future nitrification and denitrification and can therefore result in future emissions of N<sub>2</sub>O.

The potential for these future N<sub>2</sub>O emissions are estimated using the IPCC guidelines for NH<sub>3</sub> or NO<sub>x</sub> emitted as gases (IPCC 1997). It is estimated that 1% of emitted NH<sub>3</sub>-N or NO<sub>x</sub>-N will eventually be converted to N<sub>2</sub>O-N with low and high estimates of 0.2 and 2% respectively.

Nitrogen Content of food waste = 0.8% N (wet basis) – see #3

Best-Guess Estimate of the Immediate N<sub>2</sub>O Emission = 0.8% of initial N

Low Estimate of the Immediate N<sub>2</sub>O Emission = 0.2% of initial N

High Estimate of the Immediate N<sub>2</sub>O Emission = 2.0% of initial N

$$\text{Immediate N}_2\text{O Emission} = \left( \text{Mass } \frac{\text{tonne}}{\text{tonne}} \right) (\text{N Content}) (\text{N}_2\text{O Emission}) \left( \frac{44 \text{ g N}_2\text{O} / \text{mol}}{28 \text{ g N}_2\text{O} - \text{N} / \text{mol}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e} / \text{tonne}$$

$$\text{Immediate N}_2\text{O Emission} = (1) (0.008) (0.008) \left( \frac{44}{28} \right) (310) = 0.030 \text{ tCO}_2\text{e} / \text{tonne}$$

$$\text{Immediate N}_2\text{O Emission} = 0.030 (0.008-0.076) \text{ tCO}_2\text{e} / \text{tonne}$$

Nitrogen Content of food waste = 0.8% N (wet basis) – see #3

Best-Guess Estimate of Fraction Undergoing Future N<sub>2</sub>O Emissions = 70%

Low Estimate of Fraction Undergoing Future N<sub>2</sub>O Emissions = 50%



High Estimate of Fraction Undergoing Future N<sub>2</sub>O Emissions = 90%

Best-Guess Estimate for the future N<sub>2</sub>O conversion = 1% N<sub>2</sub>O-N/NO<sub>x</sub>-N

Low Estimate for the future N<sub>2</sub>O conversion = 0.2% N<sub>2</sub>O-N/NO<sub>x</sub>-N

High Estimate for the future N<sub>2</sub>O conversion = 2% N<sub>2</sub>O-N/NO<sub>x</sub>-N

Mass of Nitrogen Available for Future N<sub>2</sub>O = (Mass tonne/tonne)(N Content)(Future N Fraction) = Mass of Future N/tonne food waste

Mass of Nitrogen Available for Future N<sub>2</sub>O = (1)(0.008)(0.70) = 0.0056 (0.0039 - 0.0070) tonne Future N/tonne food waste

Future N<sub>2</sub>O Emission = (Mass of Future N)(N<sub>2</sub>O Conversion)  $\left( \frac{44 \text{ g N}_2\text{O/mol}}{28 \text{ g N}_2\text{O-N/mol}} \right)$  (GWP of N<sub>2</sub>O) = tCO<sub>2</sub>e/tonne

Future N<sub>2</sub>O Emission = (0.0056)(0.01)  $\left( \frac{44}{28} \right)$  (310) = 0.027 (0.004 - 0.068) tCO<sub>2</sub>e/tonne

Future N<sub>2</sub>O Emission = 0.027 (0.004-0.068) tCO<sub>2</sub>e/tonne

Since the carbon dioxide emissions from composting can be ignored (GHG neutrality) and this study assumes that methane emissions from backyard composters are nonexistent, the only GHG emissions resulting from backyard composting of food waste is nitrous oxide. The potential for immediate and future N<sub>2</sub>O best-guess emission estimates are totalled below together with the total of the low and high estimates respectively.

Total GHG Emissions from Backyard Composting = 0.057 (0.011-0.144) tCO<sub>2</sub>e/tonne

#### 10. Greenhouse Gas Emissions from Centralized Composting:

The centralized composting of food waste does not currently occur in the GVRD, but is actively pursued in other jurisdictions such as Edmonton or Halifax. However, the centralized composting of yard trimmings collected from residents is performed at Fraser-Richmond Biocycle (FRBC) and at other composting facilities in the GVRD. FRBC uses passively aerated windrows and handles the yard trimmings for the three municipalities of the North Shore, Burnaby, Delta, Surrey, New Westminster, Port Coquitlam, Coquitlam, Maple Ridge and Pitt Meadows (Pers. comm. Steve Aujla). These windrows are roughly triangular in profile, about 25 feet in height, having a base of about 40 feet and several hundred feet in length. The composting process in these windrows is 4 to 5 months in duration. During this process, the windrows are turned 12 to 14 times to provide aeration for the decomposition (Pers. comm. Steve Aujla).

This investigation assumes that centralized composting of food waste will occur in the same manner as is currently being performed at FRBC for yard trimmings. The important difference between backyard and centralized composting is the potential for methane emissions to occur (carbon dioxide emissions from food waste are greenhouse gas neutral [see Section 2.3 – *Biomass Decomposition/Combustion*] and there should be little difference between centralized and backyard composting from the perspective of nitrous oxide emissions). As discussed in the previous section, five research papers investigated methane emissions. Two of these papers reported methane being emitted during passive aerating composting with turning. In the German study (Hellebrand 1998)

it was observed that 1.7% of the initial carbon was emitted as methane and in the British study (Lopez-Real and Baptista 1996), the researchers found that the passive composting method produced high levels of methane (> 4 percent of initial carbon) while both the windrowing (mechanical turning) and the forced aeration method “drastically reduced methane output.” FRBC also performs windrow composting with turning every week or every two weeks, thus the intervals between turning can result in anaerobic conditions in the center of these large windrows. This author believes that methane emissions are a possibility. Given the scarcity of data, but the potential, this investigation will assume that 0.5% of the initial carbon in food waste will be emitting as methane during centralized composting. In addition, high and low estimates of 0.1% and 1% of initial carbon will also be utilized because of the uncertainty involved.

Best-Guess Estimate of the Methane Emission = 0.5% of initial carbon

Low Estimate of the Methane Emission = 0.1% of initial carbon

High Estimate of the Methane Emission = 1.0% of initial carbon

Typical Carbon Content of Food Waste = 48.0% (dry basis) (Tchobanoglous et al. 1993)

Typical Moisture Content of Food Waste = 70% (Tchobanoglous et al. 1993)

$$\text{Methane Emission} = \left( \text{Mass } \frac{\text{tonne}}{\text{tonne}} \right) (\text{C Content}) (1 - \text{Moisture Content}) (\text{CH}_4 \text{ Emission}) \left( \frac{16 \frac{\text{gCH}_4}{\text{mol}}}{12 \frac{\text{gC}}{\text{mol}}} \right) (\text{GWP of CH}_4) = \text{tCO}_2\text{e} / \text{tonne}$$

$$\text{Methane Emission} = (1)(0.48)(1 - 0.70)(0.005) \left( \frac{16}{12} \right) (21) = 0.020 (0.004 - 0.040) \text{ tCO}_2\text{e} / \text{tonne}$$

$$\text{Methane Emission from Centralized Composting} = 0.020 (0.004 - 0.040) \text{ tCO}_2\text{e/tonne}$$

The methane emission above needs to be combined with the nitrous oxide emissions previously estimated for backyard composting:

$$\text{Total GHG Emissions from Centralized Composting} = 0.077 (0.015 - 0.185) \text{ tCO}_2\text{e/tonne}$$

## 11. Long-Term Carbon Sequestration of Compost:

In a similar study to this one, the EPA assumed that the backyard composting of food scraps converts all of the carbon to CO<sub>2</sub> and that none of the carbon becomes sequestered as humic substances (food waste has been demonstrated to be readily degradable to CO<sub>2</sub>) (USEPA 1998). The same assumption is used here. It was previously discussed that 84% of the non-lignin fraction of food waste anaerobically decomposes in landfills (Barlaz 1998), therefore it is likely a valid assumption that 100% of food waste would aerobically decompose during composting. In this thesis, it is necessary to be consistent with the time frame used for Global Warming Potentials, a 100 year reference period. Therefore, this assumption of no carbon sequestered from food-waste-derived-compost after a 100 period is likely valid. The backyard composting of food scraps and yard trimmings probably results in primarily yard waste remaining in the finished compost. (It will be discussed in the next appendix what proportion of this finished compost, largely consisting of yard waste, will contribute to long-term carbon sequestration.) As a result, the potential for food waste to undergo long-term sequestration as compost will be assumed to be negligible.

$$\text{Carbon Sequestration of Composted Food Waste} = 0 \text{ tCO}_2\text{e/tonne}$$

## **APPENDIX J:**

### **YARD TRIMMINGS MANAGEMENT**

This appendix provides only the data and calculations specific to estimating the emission factors for the landfilling, incineration or composting of yard trimmings generated in the GVRD. Refer to Appendix C – *Newsprint Waste Management* for the full sample calculations. The first three sections are devoted to the GHG implications of the Cache Creek Landfill (1-3). The next three sections assess the same implications for the Vancouver Landfill (4-6). Sections 7 and 8, assess the energy generation and GHG emissions from the Burnaby Incinerator. The last three sections of this appendix, 9 through 11, analyze the GHG ramifications of the backyard or centralized composting of yard trimmings.

While this appendix contains many similarities with Appendix I, Food Waste Management, the distinctiveness of the three main components of yard waste (grass, leaves and branches) cause several differences. Each of these three main components of typical 'yard trimmings' have varying lignin concentrations and hence exhibit different responses to anaerobic decomposition. For the purpose of this investigation, it will be assumed that typical yard trimmings in the GVRD consists of 50% grass, 25% leaves and 25% branches by mass. This distribution was used in a similar EPA analysis (USEPA 1998). However, when assessing the potential landfill methane emissions and landfill carbon sequestration implications of yard waste, these three components are analyzed individually. When not specified by one of the three components, readers can assume that yard waste is being treated as a total entity.

#### **1. Methane & Energy Implications of the Cache Creek Landfill:**

The calculations for landfill methane emissions and energy generation follow – starting with the Carbon Available for Anaerobic Decomposition (CAAD):

##### Grass:

Estimated Methane Yield from Grass in reactors = 144.3 ml/gram (USEPA 1998)

Assumed Carbon Dioxide Yield from grass = 144.3 ml/gram

Molar gas constant=22.4 L/mol at standard temperature and pressure

Typical Moisture Content of Grass= 60% (USEPA 1998)

$$\text{Moles of } CH_4 = \frac{144.3 \text{ ml/gram}}{22,400 \text{ ml/mol}} = 0.0064 \text{ mol } CH_4$$

$$\text{Moles of } CO_2 = \frac{144.3 \text{ ml/gram}}{22,400 \text{ ml/mol}} = 0.0064 \text{ mol } CO_2$$

$$\text{Total Moles of } C = 0.0064 + 0.0064 = 0.0129 \text{ mol } C$$

$$\text{Carbon Available for Anaerobic Decomposition} = 0.0129 \text{ mol } C * 12 \frac{\text{g}}{\text{mol}} = 0.155 \text{ g } C / \text{ drygram}$$

$$\text{CAAD(dry)} = 0.155 \text{ g } C / \text{ drygram} = 0.155 \text{ t } C / \text{ drytonne}$$

$$\text{CAAD(wet)} = 0.155 * (1 - 0.60) = 0.055 \text{ g } C / \text{ wetgram} = 0.055 \text{ t } C / \text{ wettonne}$$

Carbon Content of Dry Grass = 44.9% (Barlaz 1998)

Revised Carbon Storage Factor = Initial Carbon - CAAD = gC / drygram

Revised Carbon Storage Factor =  $0.449 \frac{\text{gC}}{\text{drygram}} - 0.155 \frac{\text{gC}}{\text{drygram}} = 0.32 \frac{\text{gC}}{\text{drygram}}$

Revised Carbon Storage Factor =  $0.32 \frac{\text{gC}}{\text{drygram}} = 0.32 \text{ tC / drytonne}$

#### Leaves:

Estimated Methane Yield of Leaves from Barlaz = 56 ml/gram (USEPA 1998)

Assumed Carbon Dioxide Yield from leaves = 56 ml/gram

Molar gas constant = 22.4 L/mol at standard temperature and pressure

Typical Moisture Content of leaves = 20% (USEPA 1998)

Carbon Content of Dry Leaves = 44.9% (Barlaz 1998)

With the same calculations above:

Carbon Available for Anaerobic Decomposition (dry) = 0.060 tC/dry tonne

Revised Carbon Storage Factor = 0.43 tC/dry tonne

#### Branches:

Estimated Methane Yield from Branches in reactors = 76.3 ml/gram (USEPA 1998)

Assumed Carbon Dioxide Yield from branches = 76.3 ml/gram

Molar gas constant = 22.4 L/mol at standard temperature and pressure

Typical Moisture Content of branches = 40% (USEPA 1998)

Carbon Content of Dry Branches = 49.4% (Barlaz 1998)

With the same calculations above:

Carbon Available for Anaerobic Decomposition (dry) = 0.082 tC/dry tonne

Revised Carbon Storage Factor = 0.41 tC/dry tonne

Mass averages can now be calculated for CAAD and CSF for yard waste as an entity:

$\text{MassAverageCAAD} = (\% * \text{CAAD} * [1 - \text{MC}])_{\text{GRASS}} + (\% * \text{CAAD} * [1 - \text{MC}])_{\text{LEAVES}} + (\% * \text{CAAD} * [1 - \text{MC}])_{\text{BRANCHES}}$

$\text{MassAverageCAAD} = (0.50 * 0.155 * [1 - 0.60]) + (0.25 * 0.060 * [1 - 0.20]) + (0.25 * 0.082 * [1 - 0.40])$

$\text{MassAverageCAAD(wet)} = 0.055 \frac{\text{tC}}{\text{wettonne}}$

$\text{MassAverageCSF} = (\% * \text{CSF} * [1 - \text{MC}])_{\text{GRASS}} + (\% * \text{CSF} * [1 - \text{MC}])_{\text{LEAVES}} + (\% * \text{CSF} * [1 - \text{MC}])_{\text{BRANCHES}}$

$\text{MassAverageCSF} = (0.50 * 0.29 * [1 - 0.60])_{\text{GRASS}} + (0.25 * 0.43 * [1 - 0.20])_{\text{LEAVES}} + (0.25 * 0.41 * [1 - 0.40])_{\text{BRANCHES}}$

$\text{MassAverageCSF} = 0.206 \frac{\text{tC}}{\text{wettonne}}$

This 0.055 tC per wet tonne of yard trimmings is available for anaerobic decomposition and will be assumed to be evenly split between CH<sub>4</sub> and CO<sub>2</sub>. Remember that since any CO<sub>2</sub> is neutral, it does not have to be considered further.

$\text{MethaneGeneration} = \left( \text{Carbon To Decompose} \frac{\text{tC}}{\text{WetTonne}} \right) \left( \text{MethaneFraction} \left( \frac{\text{MolecularMassofCH}_4}{\text{MolecularMassofC}} \right) \right) = \frac{\text{tCH}_4}{\text{WetTonne}} \text{Methan}$

$\text{MethaneGeneration} = (0.055) \left( 0.5 \right) \left( \frac{16}{12} \right) = 0.037 \frac{\text{tCH}_4}{\text{WetTonne}}$

Methane Generation Potential = 0.037 tCH<sub>4</sub>/tonne of yard trimmings

The first order decay rate constant used here is 0.07 y<sup>-1</sup> and the assumptions behind it are discussed in Section 2.4 - *Landfill Carbon Sequestration*.

From the model in Worksheet #33:

Best-Guess of Atmospheric Methane Emissions=	0.183	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.028	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.092	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.021	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.313	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.005	tCO <sub>2</sub> e/tonne

## 2. Long-Term Carbon Sequestration in the Cache Creek Landfill:

Since not all of the cellulose and hemicellulose and only a negligible portion of the lignin from yard trimmings is expected to anaerobically degrade in a landfill, organic-carbon will remain in long-term storage in the landfill. In this capacity, the organic-carbon, which was originally atmospheric CO<sub>2</sub> but was photosynthesized into biomass, will be sequestered. As a result, organic-carbon can perform a GHG benefit, a negative GHG emission. This issue is discussed in greater detail in Section 2.4 – *Landfill Carbon Sequestration*.

The Carbon Storage Factors, as determined by Barlaz (1998), and also discussed in Eleazer et al. (1997), are used here as representative of long-term storage in the CCLF. These researchers observed that grass, with a lignin concentration measured at 28%, exhibited a 94% decomposition of the cellulose plus hemicellulose fraction and resulted in a carbon storage factor estimated at 0.32 kgC per dry kg. They also observed that leaves, with a 44% lignin content, exhibited a 28% decomposition of the cellulose plus hemicellulose fraction and resulted in carbon storage factor of 0.54 kgC per dry kg. These researchers also tested branches as well; branches, with a lignin content of 33%, exhibited a 28% decomposition of the cellulose plus hemicellulose fraction and resulted in a carbon storage factor 0.38 kg C per dry kg. However, these factors were developed with laboratory research of idealized landfill decomposition conditions and are thus highly conservative. As a result, the actual storage in the CCLF could be greater than is indicated by these experiments. While there is great potential for uncertainty with this estimate, it is likely that the uncertainty would be skewed towards a greater value. By using this conservative estimate, the risk of overestimating this factor is probably minimal. For these reasons, only the best-guess estimate will be used in this analysis.

In Section #1 of the Appendix a revised Carbon Storage Factor was developed to attempt to correct inconsistencies in the previous estimates by Barlaz. The new estimate is as follows:

Revised Carbon Storage Factor for yard waste = 0.206 tC/wet tonne

$$\text{Carbon Sequestration} = \left( \frac{\text{kgC}}{\text{Wet Yard Trimmings}} \right) \left( \frac{44\text{gCO}_2/\text{mol}}{12\text{gC}/\text{mol}} \right) = \text{tCO}_2\text{e}/\text{tonne}$$

$$\text{Carbon Sequestration} = (0.206) \left( \frac{44}{12} \right) = 0.75 \text{ tCO}_2\text{e}/\text{tonne}$$

Long-Term Carbon Sequestration from Yard Trimmings = -0.75 tCO<sub>2</sub>e/tonne

### 3. Immediate & Future N<sub>2</sub>O Emissions from the Cache Creek Landfill

What portion of the reactive nitrogen contained in yard wastes is anthropogenic in origin? While the nitrogen portion that was fixed by human activity can contribute nitrous oxide emissions, the nitrogen portion that was fixed by nature can be considered as part of natural cycling and thus GHG neutral. Given that urban green spaces are frequently applied with fertilizers, compost or animal manures, it is probably safe to assume that most of the nitrogen is anthropogenic. Furthermore, the NO<sub>x</sub> released from automobile exhausts, also anthropogenic, probably serves as another nitrogen source for this urban vegetation. This report will assume that the reactive nitrogen in yard wastes are predominantly anthropogenic in origin; thus nitrous oxide emissions from this nitrogen are GHG emissions.

When yard wastes are disposed in landfills, this material is available for anaerobic decomposition. If decomposed, the organic-nitrogen is transformed to ammonia (NH<sub>3</sub>) or ammonium (NH<sub>4</sub><sup>+</sup>). When in this form, the nitrogen is free to undergo nitrification and denitrification to be leached by water percolating through the fill or to be volatilized and vented with the landfill gas. However, as a result of the anaerobic conditions (specifically the lack of electron acceptors), there is likely very little opportunity for nitrification to occur and thus very little opportunity for denitrification or nitrous oxide emissions to occur. Therefore, nitrous oxide emissions likely only result from solubilized ammonia in the landfill leachate or volatilized ammonia in the landfill gas. An extensive discussion of this issue is provided in Section 2.5.5.1.

It is assumed in this analysis that the anaerobic conditions present in landfills do not present the opportunity for ammonia compounds to nitrify to nitrate (this also prevents any denitrification). As a result, there is no potential for immediate nitrous oxide emissions at the landfill site. It is also assumed that all of the nitrogen contained in the yard trimmings which decompose will eventually be solubilized and exit the landfill as leachate or vented gas. (This may be an overestimate due to the potential for Nitrogen Sequestration – discussed in Section 2.5.5.1) Since this leachate will be transferred to a wastewater treatment plant and the vented landfill gas is the emission of reactive nitrogen to the atmosphere, the IPCC estimates for these potential N<sub>2</sub>O sources are appropriate here. Therefore N<sub>2</sub>O emissions estimated from nitrogen in yard waste will be future emissions at the treatment plant managing the landfill leachate or the subsequent nitrification and denitrification resulting from wet or dry deposition of NH<sub>3</sub> or NO<sub>x</sub>. As a result of the uncertainty associated with the IPCC estimate, the high and low estimates provided by the IPCC will also be used here. Since not all yard waste can be expected to anaerobically decompose, thus not all of the nitrogen can be expected to be released, a percentage decomposition factor is used to approximate the fraction of nitrogen converted to NH<sub>3</sub>.

There is no appreciable leachate at the Cache Creek Landfill due to the dry climatic conditions. Any leachate which is collected is spread on the active face to return the leachate back to the fill (Pers. comm.. Louie DeVent). As a result, it is assumed that ammonia only exits the landfill in the vented gas.

Best-Guess Estimate of the N<sub>2</sub>O from vented nitrogen = 1.0% N<sub>2</sub>O/emitted NH<sub>3</sub> or NO<sub>x</sub>  
 Low Estimate of the N<sub>2</sub>O from vented nitrogen = 0.2% N<sub>2</sub>O/emitted NH<sub>3</sub> or NO<sub>x</sub>  
 High Estimate of the N<sub>2</sub>O from vented nitrogen = 2.0% N<sub>2</sub>O/emitted NH<sub>3</sub> or NO<sub>x</sub>  
 Typical moisture content of yard trimmings = 45% (Tchobanoglous et al. 1993)  
 Nitrogen content of dry yard trimmings = 3.4% N (Tchobanoglous et al. 1993)  
 Percentage Decomposition to be expected from yard trimmings=34% (Barlaz 1998)  
 (mass weighted decomposition=grass+leaves+branches=35\*0.5+37\*0.25+28\*0.25=34%)

$$\text{Nitrogen Content of Wet Yard Trimmings} = \left( \text{Dry N Content} \frac{\text{kg N}}{\text{kg dry food}} \right) (1 - \text{Moisture Content})$$

$$\text{Nitrogen Content of Wet Food Waste} = (0.034)(1 - 0.45) = 0.019 = 1.9\% \text{ N}$$

$$\text{N}_2\text{O Emission} = \left( \text{Mass} \frac{\text{tonne}}{\text{tonne}} \right) (\text{N Content}) (\text{Decomposition}) (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ g N}_2\text{O} / \text{mol}}{28 \text{ g N}_2\text{O} - \text{N} / \text{mol}} \right) (\text{GWP of N}_2\text{O})$$

$$\text{N}_2\text{O Emission} = \left( 1 \frac{\text{tonne}}{\text{tonne}} \right) (0.019) (0.34) (0.01) \left( \frac{44}{28} \right) (310) = 0.031 \text{ tCO}_2\text{e} / \text{tonne}$$

$$\text{Immediate \& Future N}_2\text{O Emissions} = 0.031 \text{ (0.006-0.063) tCO}_2\text{e/tonne}$$

#### 4. Methane & Energy Implications of the Vancouver Landfill:

The only significant difference between this section and Section 1, *Methane & Energy Implications of the Cache Creek Landfill*, is the estimated landfill gas collection efficiency and the first order decay rate constant. While at Cache Creek the current collection efficiency is estimated to be 43%, the current collection efficiency at the Vancouver Landfill is estimated to only be 22% (Pers. comm. Chris Underwood). However, engineers with the City of Vancouver are currently in the process of upgrading the collection equipment. As with the CCLF assessment, the collection efficiency is assumed to increase year after year in response to improving regulations. The first order decay rate constant used here is 0.08 yr<sup>-1</sup> and the assumptions behind it are discussed in Section 2.4 - *Landfill Carbon Sequestration*.

Best-Guess of Atmospheric Methane Emissions=	0.231	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.029	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.116	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.023	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.381	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.005	tCO <sub>2</sub> e/tonne

#### 5. Long-Term Carbon Sequestration in the Vancouver Landfill:

The Revised Carbon Storage Factors is used here as representative of long-term storage in the VLF.

$$\text{Long-Term Carbon Sequestration from Yard Waste} = -0.75 \text{ tCO}_2\text{e/tonne}$$

## 6. Immediate & Future N<sub>2</sub>O Emissions from the Vancouver Landfill:

The potential for nitrous oxide emissions at the Vancouver Landfill differ from the Cache Creek Landfill in that they are assumed to result from the solubilized ammonia in the leachate instead of the volatilized ammonia gas. It is assumed that all of the nitrogen contained in yard waste which decomposes will eventually be solubilized and exit the landfill as leachate. (This may be an overestimate due to the potential for Nitrogen Sequestration – discussed in Section 2.5.5.1) The calculations for this emission are below:

Best-Guess Estimate of the N<sub>2</sub>O from wastewater nitrogen = 1.0% N<sub>2</sub>O/influent-N

Low Estimate of the N<sub>2</sub>O from wastewater nitrogen = 0.2% N<sub>2</sub>O/ influent-N

High Estimate of the N<sub>2</sub>O from wastewater nitrogen = 2.0% N<sub>2</sub>O/ influent-N

Typical moisture content of yard trimmings = 45% (Tchobanoglous et al. 1993)

Nitrogen content of dry yard trimmings = 3.4% N (Tchobanoglous et al. 1993)

Percentage Decomposition to be expected from yard trimmings=34% (Barlaz 1998)

(mass weighted decomposition=grass+leaves+branches=35\*0.5+37\*0.25+28\*0.25=34%)

Nitrogen Content of Wet Yard Trimmings =  $\left( \text{Dry N Content} \frac{\text{kg N}}{\text{kg dry food}} \right) (1 - \text{Moisture Content})$

Nitrogen Content of Wet Food Waste =  $(0.034)(1 - 0.45) = 0.019 = 1.9\%N$

N<sub>2</sub>O Emission =  $\left( \text{Mass} \frac{\text{tonne}}{\text{tonne}} \right) (N \text{ Content}) (Decomposition) (N_2O \text{ Conversion}) \left( \frac{44 \text{ gN}_2\text{O}}{28 \text{ gN}_2\text{O} - N} \frac{\text{mol}}{\text{mol}} \right) (\text{GWP of N}_2\text{O})$

N<sub>2</sub>O Emission =  $\left( 1 \frac{\text{tonne}}{\text{tonne}} \right) (0.019) (0.34) (0.01) \left( \frac{44}{28} \right) (310) = 0.031 \text{ tCO}_2\text{e} / \text{tonne}$

Immediate & Future N<sub>2</sub>O Emissions = 0.031 (0.006-0.063) tCO<sub>2</sub>e/tonne

## 7. Energy Generation from Waste Incineration:

Net Energy Content of Yard Trimmings = 2,800 BTU/lb = 6,493 kJ/kg (USEPA 1998)

(2,800 BTU/lb\*1.054 kJ/BTU\*2.20 lb/kg = 6,493 kJ/kg)

(wet basis, correction for latent heat of water in this reference is assumed but not directly specified)

From another source (Tchobanoglous et al. 1993):

Gross Energy Content of yard trimmings = 2,601 BTU/lb = 6,031 kJ/kg (wet basis)

Typical Moisture Content of Yard Trimmings = 45% (CALCS ABOVE?????)

Latent Heat of Water=2473 kJ/kg (Incropera and DeWitt 1990)

Net Energy Content = [Gross Energy] – [Latent Heat of Vaporization]

Net Energy Content =  $\left[ 6,031 \frac{\text{kJ}}{\text{kg}} \right] - \left[ \left( 2473 \frac{\text{kJ}}{\text{kg}} \right) (0.45)_{MC} \right] = 4,918 \frac{\text{kJ}}{\text{kg}}$

Because of the variation between these values, the average will be used as the estimate.

Net Energy Content =  $\left[ \frac{6493 + 4918}{2} \right] = 5706 \frac{\text{kJ}}{\text{kg}} = 5.7 \text{ GJ} / \text{tonne}$

Estimate of the Net Energy Content of Wet Yard Waste = 5.7 GJ/tonne



Steam Energy produced by the combustion of yard waste in an Incinerator-Boiler (1):  
 Assumed Boiler Efficiency = 70% (Pers. comm. Ron Richter)  
 Fraction of Steam Utilized by CPL = 56% (Montenay Inc. 1999)

$$\frac{\text{Utilized Energy}}{\text{tonne Yard Waste}} = \frac{\text{energy}}{\text{tonne}} * (\text{Thermal Efficiency}) * (\text{Energy Utilization}) = \text{kJ/tonne}$$

$$\frac{\text{Utilized Energy}}{\text{tonne Yard Waste}} = \frac{5.7 \text{ GJ}}{\text{tonne}} * (0.70) * (0.56) = 2.23 \text{ GJ/tonne}$$

Utilized Steam Energy per tonne of yard waste, (1) = 2.23 GJ/tonne

GHG emission prevented per tonne of food waste (3):

$$\frac{\text{GHG Emission Prevented}}{\text{tonne yard waste}} = \left( \frac{\text{Utilized Energy}}{\text{tonne yard waste}} \right) * \left( \text{Emission Factor for Natural Gas, } \frac{\text{tCO}_2\text{e}}{\text{GJ}} \right) = \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne yard waste}} = (2.23 \text{ GJ/tonne}) * (0.062 \frac{\text{tCO}_2\text{e}}{\text{GJ}}) = 0.139 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

GHG Emission Prevented from Natural Gas, (3) = 0.139 tCO<sub>2</sub>e/tonne

Electricity produced by the combustion of yard waste in an Incinerator-Boiler (4):

Assumed Turbo Generator Efficiency = 32% (Pers. comm. Ron Richter)

Steam Fraction for Electricity Generation = 40% (assumed as discussed)

$$\frac{\text{Utilized Energy}}{\text{tonne Yard Waste}} = \frac{\text{energy}}{\text{tonne}} * (\text{Boiler Effic}) * (\text{Turbo Generator}) * (\text{Energy Utilization}) = \text{kJ/tonne}$$

$$\frac{\text{Utilized Energy}}{\text{tonne Yard Waste}} = \frac{5.7 \text{ GJ}}{\text{tonne}} * (0.70) * (0.32) * (0.40) = 0.51 \text{ GJ/tonne}$$

Utilized Electrical Energy per tonne of yard waste, (4) = 0.51 GJ/tonne

Electrical GHG emission prevented per tonne of yard waste: (6)

$$\frac{\text{GHG Emission Prevented}}{\text{tonne yard waste}} = \left( \frac{\text{Utilized Energy}}{\text{tonne yard waste}} \right) * \left( \text{Emission Factor for Electricity, } \frac{\text{tCO}_2\text{e}}{\text{GJ}} \right) = \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne yard waste}} = (0.51 \text{ GJ/tonne}) * (0.147 \frac{\text{tCO}_2\text{e}}{\text{GJ}}) = 0.075 \frac{\text{tCO}_2\text{e}}{\text{tonne}}$$

GHG Emission Prevented from Electricity, (6) = 0.075 tCO<sub>2</sub>e/tonne

Total GHG Emissions Prevented, (7) = 0.139 + 0.075 = -0.214 tCO<sub>2</sub>e/tonne

## 8. Greenhouse Gas Emissions from Waste Incineration:

At the Burnaby Incinerator, 247,075 tonnes of waste was combusted in 1998. This process required the consumption of 7,516 GJ of natural gas, 16,011 MWh of electricity, and 3,369 tonnes of lime (CaO) and 295 tonnes of ammonia (NH<sub>3</sub>) for acid gas control (Montenay Inc. 1999; Pers. comm. Richard Holt). Greenhouse gas emissions result from municipal solid waste incineration. This includes emissions of carbon dioxide and nitrous oxide during incineration, the consumption of natural gas and electricity, and the consumption of lime for acid gas control (the production of lime from limestone results in CO<sub>2</sub> emissions). Since yard waste is biomass carbon and is therefore carbon-neutral, the CO<sub>2</sub> emissions can be ignored here. Environment Canada estimates that while a small methane emission is measurable during wastewater sewage sludge incineration there is negligible methane emissions during MSW incineration (Environment Canada 1999). That will also be assumed for this investigation.

The most important greenhouse gas emission associated with the incineration of yard waste, and also the most uncertain, is the potential for significant nitrous oxide releases. This can result from one of five pathways:

- Thermal conversion of the  $N_2$  gas in air to  $N_2O$  during combustion (Immediate emis.)
- Thermal conversion of the nitrogen in food waste to  $N_2O$  (Immediate emission)
- Thermal conversion of the ammonia injected in the flue gases (Immediate emission)
- Microbial  $N_2O$  conversion of  $NO_x$  emitted and later denitrified (Future emission)
- Microbial  $N_2O$  conversion of  $NH_3$  injected but unreacted (Future emission)

Each of these five pathways are evaluated in the following calculations. Unfortunately, the current lack of understanding in these issues result in much uncertainty associated with the following estimates. An extensive discussion of the issue is provided Section 2.5.5.3.

The first two potential sources of nitrous oxide emissions result from the potential for the nitrogen in waste or the  $N_2$  gas in air to thermal convert to  $N_2O$  during incineration. There is limited and highly variable research of the  $N_2O$  emissions resulting from municipal solid waste incineration. Examples of emission estimates being used are:

- |                                       |                                 |
|---------------------------------------|---------------------------------|
| • IPCC Compilation (de Soete 1993)    | 11-293 g $N_2O$ /tonne of waste |
| • Environment Canada Inventory (1997) | 160 g $N_2O$ /tonne of waste    |
| • USEPA National Inventory (1999)     | 30 g $N_2O$ /tonne of waste     |
| • USEPA MSW Analysis (1998)           | 130 g $N_2O$ /tonne of waste    |

Research in the fluidized bed combustion of coal has determined that  $N_2O$  emissions originate mainly from the oxidation of fuel nitrogen (Moritomi 1994), and since coal combustion is similar to that of waste incineration, it can be inferred that  $N_2O$  emissions during incineration are likely a factor of the nitrogen content. This hypothesis is reinforced by one study (Tanikawa et al. 1995), and the observation that the incineration of high nitrogen content wastewater sludge produces much higher  $N_2O$  emission rates than MSW incinerators (Tanaka et al. 1994). For this research, it is deemed appropriate for yard waste to account for its proportionate share of nitrous oxide rather than distribute it across a typical municipal solid waste, the individual components of which (excluding yard waste) may be low in nitrogen. As a result, the immediate  $N_2O$  emissions measured during incineration will be assumed to be entirely a contribution of the nitrogen content and not the  $N_2$  gas in air. These estimates below first determine the nitrogen emission during incineration as nitrous oxide and then determine the nitrogen of municipal solid waste. By dividing these two results it is possible to estimate the expected nitrous oxide conversion of waste-nitrogen, an important emission factor. For these calculations, the Environment Canada (1997) estimate will be used as the best-guess value (160 g $N_2O$ /tonne). The IPCC compilation (de Soete 1993) will be used as the high estimate (300 g $N_2O$ /tonne) and the USEPA national inventory (1999) will be used as the low estimate (30 g $N_2O$ /tonne).

Best-Guess Estimate for  $N_2O$  Emissions from Incineration = 160 g $N_2O$ /tonne of MSW  
Low Estimate for  $N_2O$  Emissions from Incineration = 30 g $N_2O$ /tonne of MSW

High Estimate for N<sub>2</sub>O Emissions from Incineration = 300 gN<sub>2</sub>O/tonne of MSW

Nitrogen Content of MSW = 0.8% N/dry tonne (Environment Canada 1978)

Moisture Content of MSW = 24% (Environment Canada 1978)

$$N_2O \text{ Emission} = \left( N_2O \text{ from Incineration } \frac{g N_2O}{\text{tonne MSW}} \right) \left( \frac{28 \frac{g N_2O - N}{\text{mol}}}{44 \frac{g N_2O - N}{\text{mol}}} \right) = \frac{g N_2O - N}{\text{tonne MSW}}$$

$$N_2O \text{ Emission} = (160) \left( \frac{28}{44} \right) = 102 \text{ (19-191) } \frac{g N_2O - N}{\text{tonne MSW}}$$

$$\text{Nitrogen in MSW incinerated} = \left( 1000 \frac{kg}{\text{tonne}} \right) \left( \text{Nitrogen Content } \frac{N}{\text{Dry Waste}} \right) \left[ (1 - \text{Moisture Content}) \frac{\text{dry}}{\text{wet}} \right] = \frac{kg N}{\text{tonne MSW}}$$

$$\text{Nitrogen in MSW incinerated} = \left( 10^6 \frac{g}{\text{tonne}} \right) (0.008) \left[ (1 - 0.24) \frac{\text{dry}}{\text{wet}} \right] = 6080 \frac{g N}{\text{tonne MSW}}$$

$$\text{Percentage of Waste Nitrogen Emitted as } N_2O - N = \frac{102 \frac{g N_2O - N}{\text{tonne MSW}}}{6080 \frac{g N}{\text{tonne MSW}}} = 0.017 \frac{g N_2O - N}{g N} = 1.7\% \text{ Conversion of Nitrogen to } N_2O$$

Fraction of Waste-Nitrogen emitted as N<sub>2</sub>O = 1.7 (0.3-3.1) %

Therefore, it has been estimated that approximately 1.7% of the nitrogen in waste is emitted as N<sub>2</sub>O during incineration but could likely range between 0.3 and 3.1%. The immediate N<sub>2</sub>O emission from the conversion of food-nitrogen during combustion can now be estimated:

Nitrogen Content of wet yard waste = 1.9% N (wet basis) – see #3

$$\text{Immediate } N_2O \text{ Emission} = \left( \text{Mass } \frac{\text{tonne}}{\text{tonne}} \right) \left( N \text{ Content} \right) \left( N_2O \text{ Emission} \right) \left( \frac{44 \frac{g N_2O}{\text{mol}}}{28 \frac{g N_2O - N}{\text{mol}}} \right) \left( \text{GWP of } N_2O \right) = \frac{tCO_2e}{\text{tonne}}$$

$$\text{Immediate } N_2O \text{ Emission} = (1) (0.019) (0.017) \left( \frac{44}{28} \right) (310) = 0.157 \frac{tCO_2e}{\text{tonne}}$$

Immediate N<sub>2</sub>O Emission = 0.157 (0.028-0.29) tCO<sub>2</sub>e/tonne

The next potential pathway for N<sub>2</sub>O emissions could result from the injection of ammonia into the flue gas to reduce NO<sub>x</sub> gases. Remember that at the Burnaby Incinerator, 295 tonnes of ammonia (NH<sub>3</sub>) was used during the combustion of 247,075 tonnes of waste in 1998 to reduce NO<sub>x</sub> emissions. As a result of the lack of any available research on the propensity for injected ammonia to thermally convert to N<sub>2</sub>O, this study will assume the same conversion rate exhibited by the waste-nitrogen upon incineration. Therefore, approximately 1.7% of injected ammonia, and ranging between 0.3 and 3.1%, will be estimated to convert to nitrous oxide. There is a complicating factor which requires discussion. Does the NO<sub>x</sub> acid gases which require treatment by ammonia injection result from the incineration of nitrogen-rich materials or from municipal solid waste in general? If the former is true, yard waste would need to take responsibility for its proportionate share of NO<sub>x</sub>/NH<sub>3</sub> while if the latter is true these emissions could be evenly divided among the waste incinerated. This is a difficult question to answer and for simplicity this investigation assumes that NO<sub>x</sub>/NH<sub>3</sub> is equally contributed by all waste. In the event that NO<sub>x</sub>/NH<sub>3</sub> is a function of nitrogen content, the results here would be underestimating the contribution from yard waste.

Fraction of Injected-Ammonia emitted as N<sub>2</sub>O = 1.7 (0.3-3.1) %

Annual consumption of ammonia (1998) = 295 tonnes

Annual mass of waste combusted (1998) = 247,075 tonnes

$$\text{N}_2\text{O from NH}_3 \text{ Injection} = \frac{(\text{NH}_3 \text{ Injected, tonnes}) \left( \frac{14 \text{ gN/mol}}{17 \text{ g NH}_3/\text{mol}} \right)}{(\text{Waste Combusted, tonnes})} * (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ gN}_2\text{O/mol}}{28 \text{ gN}_2\text{O} - \text{N/mol}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e/tonne}$$

$$\text{N}_2\text{O from NH}_3 \text{ Injection} = \frac{(295) \left( \frac{14}{17} \right)}{(247,075)} * (0.017) \left( \frac{44}{28} \right) (310) = 0.0081 \text{ tCO}_2\text{e/tonne}$$

N<sub>2</sub>O Emission resulting from NH<sub>3</sub> Injection = 0.0081 (0.0014 – 0.015) tCO<sub>2</sub>e/tonne

In addition to the potential for injected NH<sub>3</sub> to thermally convert to N<sub>2</sub>O, there can also be the future denitrification of the nitrogen oxide (NO<sub>x</sub>) gases released. It has been estimated that 10-30% of waste-nitrogen is converted to NO<sub>x</sub> (NO + NO<sub>2</sub>) during combustion (White et al. 1995). Nitrogen oxides are short lived in the atmosphere as they are quickly rained out in the form of nitrate (NO<sub>3</sub><sup>-</sup>) or nitric acid (HNO<sub>3</sub>). Thus the deposition as NO<sub>3</sub><sup>-</sup> will eventually require denitrification to N<sub>2</sub>, resulting in potential leakage of N<sub>2</sub>O. The IPCC provides guidelines for these emissions and estimates that 1% of emitted NH<sub>3</sub>-N or NO<sub>x</sub>-N will be converted to N<sub>2</sub>O. However they also provide low and high estimates of 0.2 and 2% respectively. All three of these values are used in this study. In addition to the potential for the microbial conversion of nitrogen oxide to nitrous oxide, nitrogen oxides are suspected to be indirect greenhouse gases for another reason – they deplete the tropospheric concentration of the OH radical, which would otherwise react and destroy CH<sub>4</sub> (Mackenzie 1995). Thus NO<sub>x</sub> causes CH<sub>4</sub> to be a stronger GHG. (As it is too early for any methodology on this issue, it will have to be ignored in this report.) At the Burnaby Incinerator it is estimated that 449 tonnes of NO<sub>x</sub> was emitted in 1998 (Pers. comm. Chantal Babensee). Nitric oxide (NO) is predominantly the nitrogen oxide formed during incineration (Robinson 1986), and is assumed in the calculations below.

Best-Guess Estimate for the future N<sub>2</sub>O conversion of NO<sub>x</sub> = 1% N<sub>2</sub>O-N/NO<sub>x</sub>-N

Low Estimate for the future N<sub>2</sub>O conversion of NO<sub>x</sub> = 0.2% N<sub>2</sub>O-N/NO<sub>x</sub>-N

High Estimate for the future N<sub>2</sub>O conversion of NO<sub>x</sub> = 2% N<sub>2</sub>O-N/NO<sub>x</sub>-N

Annual NO<sub>x</sub> emission (1998) = 449 tonnes

Annual mass of waste combusted (1998) = 247,075 tonnes

$$\text{N}_2\text{O Emission from NO}_x = \frac{(\text{NO}_x \text{ Emission, tonnes}) \left( \frac{14 \text{ gN/mol}}{30 \text{ gNO/mol}} \right)}{(\text{Waste Combusted, tonnes})} * (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ gN}_2\text{O/mol}}{28 \text{ gN}_2\text{O} - \text{N/mol}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e/tonne}$$

$$\text{N}_2\text{O Emission from NO}_x = \frac{(449) \left( \frac{14}{30} \right)}{(247,075)} * (0.01) \left( \frac{44}{28} \right) (310) = 0.0074 (0.0012 - 0.014) \text{ tCO}_2\text{e/tonne}$$

N<sub>2</sub>O from NH<sub>3</sub> Injection = 0.004 (0.001-0.008) tCO<sub>2</sub>e/tonne

The last potential N<sub>2</sub>O emission from waste incineration could occur when ammonia is injected into the flue gas but is emitted to the atmosphere, the so-called “ammonia slip”. The ammonia will undergo wet or dry deposition to soils downwind where it can nitrify

and denitrify. Communication with the GVRD (Pers. comm. Chantal Babensee) has learned that ammonia slip is virtually negligible at the Incinerator largely because only the minimum amount is injected into the flue gas. As a result, the potential for ammonia slip to result in nitrous oxide emissions is neglected in this study.

The remaining greenhouse gas emissions during waste combustion result from the consumption of natural gas, electricity and lime by the Incinerator. This analysis will assume that the emissions resulting from natural gas, electricity and lime consumption will be equally distributed over the entire solid waste combusted in 1998. These estimates are in Appendix C – *Newsprint Waste Management*.

The total greenhouse gas emissions resulting from the incineration of yard trimmings are summed below. While there is little uncertainty with the emissions from natural gas, electricity and lime consumption, the nitrous oxide emissions are uncertain and cause the provision of best-guess, high and low estimates. The high and low estimates are the total of all the high and low estimates, respectively.

Total GHG Emissions =  $N_2O$  + Natural Gas + Electricity + Lime = tCO<sub>2</sub>e/tonne  
Total Emissions = 0.18 (0.045-0.33) tCO<sub>2</sub>e/tonne

#### **9. Greenhouse Gas Emissions from Backyard Composting:**

The backyard composting of yard trimmings together with food waste at ground-level dwellings is quite common in the GVRD. The participation has been strongly encouraged by the GVRD and others and can even exceed 25% of the single-family residences in some of the member municipalities. This section will evaluate the greenhouse gas implications of the backyard composting of food waste by residents.

Research has observed emissions of carbon dioxide, methane and nitrous oxide during composting. As food waste is photosynthetic in origin, any carbon dioxide emissions resulting during the composting process are considered neutral and therefore do not have to be considered as greenhouse gas emissions. However, methane emissions can occur from inadequately aerated composting piles. While the carbon in methane is originally from atmospheric carbon dioxide, returning the carbon as methane, with its Global Warming Potential 21 times that of CO<sub>2</sub>, has important greenhouse gas implications.

The potential for methane emissions during composting is reviewed in Appendix I – *Food Waste Management*.

Though some of the composting studies demonstrated methane emissions, these were from compost heaps much larger in size, with a greater potential for anaerobic zones to develop, than a relatively small (200-250L) backyard composter. As a result, it will be assumed that CH<sub>4</sub> emissions from backyard composting are negligible or non-existent. In the event that future research demonstrates the existence of CH<sub>4</sub> emissions, this assumption will be an underestimate of actual GHG emissions.

During composting, seven research papers have been obtained which document immediate emissions of nitrous oxide during the composting of various organic wastes. These emissions are  $\text{N}_2\text{O}$  leaking from microorganisms during the nitrification and denitrification of reactive N in these wastes. These researchers have observed a conversion of reactive N to  $\text{N}_2\text{O}$  ranging from 0.00005 to 2.2%. An extensive review of this issue is provided in Section 2.5.5.2.

As a result of the available literature, this analysis will use a best-guess estimate that 0.8% of the initial nitrogen in the compost was converted to  $\text{N}_2\text{O}$  during the composting process. This study will assume high and low estimates of 2% and 0.2%. This data, while important, is not the full picture of  $\text{N}_2\text{O}$  emissions from composting. These research findings above are only the immediate releases of  $\text{N}_2\text{O}$ ; there will also be future releases of  $\text{N}_2\text{O}$  resulting from the future nitrification and denitrification of the ammonia or nitric oxide emissions during composting and from the future decomposition of the nitrogen contained in finished compost. These future emissions must also be assessed, thereby necessitating a nitrogen balance.

The immediate  $\text{N}_2\text{O}$  emissions observed during composting were a result of nitrification and denitrification of the initial nitrogen present in the organic materials to be composted. It is therefore important to know what portion of the initial nitrogen underwent nitrification and denitrification to cause the observed  $\text{N}_2\text{O}$  emissions. This investigation assumes that 30% of the initial nitrogen actually decomposed. This assumption is uncertain and as a result, low and high estimates of 10 and 50% are utilized. Because of the assumption that 30% of the initial nitrogen actually decomposed, it is conversely assumed that 70% of the initial nitrogen present in the compost escaped nitrification/denitrification. This majority of the compost which did not nitrify or denitrify may have volatilized from the compost pile in the form of ammonia emissions (and been subject to downwind deposition), may have leached from the compost pile as ammonia, organic-nitrogen or nitrate, or may be contained in the finished compost. This nitrogen will be subject to future nitrification and denitrification and can therefore result in future emissions of  $\text{N}_2\text{O}$ .

The last important consideration when assessing the potential for  $\text{N}_2\text{O}$  emissions from yard waste is the anthropogenic/natural nitrogen complication. What are the relative fractions of the anthropogenic reactive nitrogen and natural reactive nitrogen in yard waste to be nitrified and denitrified? This question is also discussed in Section 2.5.5.2. Due to the inherent difficulty in separating chemical fertilizer-based reactive nitrogen from the naturally reactive existing in yard wastes contained in a community, this research assumes a 50:50 split. Therefore 50% of the nitrogen is assumed to be human-induced and the remaining 50% would exist regardless of human interference. This assumption results in only half of the actual  $\text{N}_2\text{O}$  emitted to be considered as a GHG emission to the atmosphere – the natural nitrogen is simply participating in natural  $\text{N}_2\text{O}$  cycling.

The potential for these future N<sub>2</sub>O emissions are estimated using the IPCC guidelines for NH<sub>3</sub> or NO<sub>x</sub> emitted as gases (IPCC 1997). It is estimated that 1% of emitted NH<sub>3</sub>-N or NO<sub>x</sub>-N will eventually be converted to N<sub>2</sub>O-N with low and high estimates of 0.2 and 2% respectively.

Nitrogen Content of yard waste = 1.9% N (wet basis) – see #3

Anthropogenic Fraction of the Nitrogen Content = 50%

Anthropogenic Nitrogen Content of Yard Waste = 1.9% \* 0.50 = 0.95% Anthro N

Best-Guess Estimate of the Immediate N<sub>2</sub>O Emission = 0.8% of initial N

Low Estimate of the Immediate N<sub>2</sub>O Emission = 0.2% of initial N

High Estimate of the Immediate N<sub>2</sub>O Emission = 2.0% of initial N

$$\text{Immediate N}_2\text{O Emission} = (\text{Mass tonne/tonne}) (\text{N Content}) (\text{N}_2\text{O Emission}) \left( \frac{44 \text{ g N}_2\text{O/mol}}{28 \text{ g N}_2\text{O} - \text{N/mol}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e/tonne}$$

$$\text{Immediate N}_2\text{O Emission} = (1)(0.0095)(0.008) \left( \frac{44}{28} \right) (310) = 0.036 \text{ tCO}_2\text{e/tonne}$$

$$\text{Immediate N}_2\text{O Emission} = 0.036 (0.009-0.091) \text{ tCO}_2\text{e/tonne}$$

Anthropogenic Nitrogen Content of Yard Waste = 0.95% N (wet basis)

Best-Guess Estimate of Fraction Undergoing Future N<sub>2</sub>O Emissions = 70%

Low Estimate of Fraction Undergoing Future N<sub>2</sub>O Emissions = 50%

High Estimate of Fraction Undergoing Future N<sub>2</sub>O Emissions = 90%

Best-Guess Estimate for the future N<sub>2</sub>O conversion = 1% N<sub>2</sub>O-N/NO<sub>x</sub>-N

Low Estimate for the future N<sub>2</sub>O conversion = 0.2% N<sub>2</sub>O-N/NO<sub>x</sub>-N

High Estimate for the future N<sub>2</sub>O conversion = 2% N<sub>2</sub>O-N/NO<sub>x</sub>-N

$$\text{Mass of Nitrogen Available for Future N}_2\text{O} = (\text{Mass tonne/tonne}) (\text{N Content}) (\text{Future N Fraction}) = \text{Mass of Future N/tonne food waste}$$

$$\text{Mass of Nitrogen Available for Future N}_2\text{O} = (1)(0.0095)(0.70) = 0.0065 (0.0047 - 0.0084) \text{ tonne Future N/tonne food waste}$$

$$\text{Future N}_2\text{O Emission} = (\text{Mass of Future N}) (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ g N}_2\text{O/mol}}{28 \text{ g N}_2\text{O} - \text{N/mol}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e/tonne}$$

$$\text{Future N}_2\text{O Emission} = (0.0065)(0.01) \left( \frac{44}{28} \right) (310) = 0.032 \text{ tCO}_2\text{e/tonne}$$

$$\text{Future N}_2\text{O Emission} = 0.032 (0.0005-0.082) \text{ tCO}_2\text{e/tonne}$$

Since the carbon dioxide emissions from composting can be ignored (GHG neutrality) and this study assumes that methane emissions from backyard composters are nonexistent, the only GHG emissions resulting from backyard composting of yard waste is nitrous oxide. The potential for immediate and future N<sub>2</sub>O best-guess emission estimates are totalled below together with the total of the low and high estimates respectively.

$$\text{Total GHG Emissions from Backyard Composting} = 0.068 (0.014-0.173) \text{ tCO}_2\text{e/tonne}$$

#### 10. Greenhouse Gas Emissions from Centralized Composting:

The centralized composting of food waste does not currently occur in the GVRD, but is actively pursued in other jurisdictions such as Edmonton or Halifax. However, the centralized composting of yard trimmings collected from residents is performed at Fraser-Richmond Biocycle (FRBC) and at other composting facilities in the GVRD. FRBC uses passively aerated windrows and handles the yard trimmings for the three municipalities of the North Shore, Burnaby, Delta, Surrey, New Westminster, Port Coquitlam, Coquitlam, Maple Ridge and Pitt Meadows (Pers. comm. Steve Aujla). These windrows are roughly triangular in profile, about 25 feet in height, having a base of about 40 feet and several hundred feet in length. The composting process in these windrows is 4 to 5 months in duration. During this process, the windrows are turned 12 to 14 times to provide aeration for the decomposition (Pers. comm. Steve Aujla).

The important difference between backyard and centralized composting of yard wastes is the potential for methane emissions to occur (carbon dioxide emissions from yard wastes are greenhouse gas neutral [see Section 2.3 – *Biomass Decomposition/Combustion*] and there should be little difference between centralized and backyard composting from the perspective of nitrous oxide emissions). As discussed in Appendix I, five research papers have investigated methane emissions with mixed results being reported. In the German study (Hellebrand 1998) it was observed that 1.7% of the initial carbon was emitted as methane and in the British study (Lopez-Real and Baptista 1996), the researchers found that the passive composting method produced high levels of methane (> 4 percent of initial carbon) while both the windrowing (mechanical turning) and the forced aeration method “drastically reduced methane output.” FRBC also performs windrow composting with turning every week or every two weeks, thus the intervals between turning can result in anaerobic conditions in the center of these large windrows. This author believes that methane emissions are a possibility. Given the scarcity of data, but the potential, this investigation will assume that 0.5% of the initial carbon in food waste will be emitting as methane during centralized composting. In addition, high and low estimates of 0.1% and 1% of initial carbon will also be utilized because of the uncertainty involved.

Best-Guess Estimate of the Methane Emission = 0.5% of initial carbon

Low Estimate of the Methane Emission = 0.1% of initial carbon

High Estimate of the Methane Emission = 1.0% of initial carbon

Typical Carbon Content of Yard Waste = 47.0% (dry basis) (Tchobanoglous et al. 1993)

Typical Moisture Content of Yard Waste = 45% (Tchobanoglous et al. 1993)

$$\text{Methane Emission} = \left( \text{Mass } \frac{\text{tonne}}{\text{tonne}} \right) (\text{C Content}) (1 - \text{Moisture Content}) (\text{CH}_4 \text{ Emission}) \left( \frac{16 \text{ gCH}_4 / \text{mol}}{12 \text{ gC} / \text{mol}} \right) (\text{GWP of CH}_4) = \text{tCO}_2\text{e} / \text{tonne}$$

$$\text{Methane Emission} = (1) (0.47) (1 - 0.45) (0.005) \left( \frac{16}{12} \right) (21) = 0.036 \text{ tCO}_2\text{e} / \text{tonne}$$

Methane Emission from Centralized Composting = 0.036 (0.007-0.072) tCO<sub>2</sub>e/tonne

The methane emission above needs to be combined with the nitrous oxide emissions previously estimated for backyard composting:

Total GHG Emissions from Centralized Composting = 0.105 (0.021-0.245) tCO<sub>2</sub>e/tonne



### **11. Long-Term Carbon Sequestration of Compost:**

The U.S. Environmental Protection Agency (1998) developed an estimate that between 0.004 and 0.20 tCO<sub>2</sub>e/tonne yard waste is sequestered when yard trimmings are managed by centralized composting. This is believed to result because “the heat generated within the compost piles favors “thermophilic” (heat-loving) bacteria, which tend to produce a greater proportion of stable, long-chain carbon compounds than do bacteria that predominate at ambient surface temperatures.” These humic substances provide carbon sequestration in excess of yard trimmings left directly on the ground to naturally rot. The USEPA did not consider the alternative backyard composting of yard wastes. Due to the lack of research in these issues and the high degree of uncertainty which exists, the USEPA report identifies this as an area which could benefit from further study.

The estimates developed by the USEPA, 0.004 and 0.20 tCO<sub>2</sub>e/tonne yard waste, are used in this thesis as high and low estimates of the carbon sequestration resulting from the centralized composting of yard waste. The average of these values, 0.10 tCO<sub>2</sub>e/tonne, is used as the best-guess estimate. Since the backyard composting of yard waste (individually or together with food scraps) does not typically reach the high temperatures observed during centralized operations, the conditions are likely not conducive to the formation of the humic substances important for carbon sequestration. As a result, this thesis assumes that no carbon sequestration occurs when yard waste is backyard composted.

Best-Guess Estimate of Carbon Sequestration of Centralized Composted Yard Waste = 0.10 tCO<sub>2</sub>e/tonne

Low Estimate of Carbon Sequestration of Centralized Composted Yard Waste = 0.004 tCO<sub>2</sub>e/tonne

High Estimate of Carbon Sequestration of Centralized Composted Yard Waste = 0.20 tCO<sub>2</sub>e/tonne

Estimate of Carbon Sequestration of Backyard Composted Yard Waste = 0 tCO<sub>2</sub>e/tonne

## **APPENDIX K:**

### **REMAINDER WASTE MANAGEMENT**

This appendix provides all the data and calculations to estimate emission factors for the landfilling or incineration of the Remainder. The first three sections are devoted to the GHG implications of the Cache Creek Landfill (1-3). The next three sections assess the same implications for the Vancouver Landfill (4-6). Sections 7 and 8, assess the energy generation and GHG emissions from the Burnaby Incinerator. The issues surrounding the Remainder are extensively discussed in Section 2.10 and readers are encouraged to examine that section prior to this appendix. The following data are developed in that section and are used in the calculations:

Carbon Storage Factor for wet Remainder = 0.09 tC/wet tonne Remainder  
 Carbon Content of Biodegradable Organic Carbon in Remainder = 50%  
 Biodegradable Fraction of Remainder = 70%  
 Moisture Content of Biodegradable Carbon in Remainder = 30%  
 Net Energy Content of Remainder = 11,600 kJ/kg  
 Fossil Carbon Content of Remainder = 0.060 tC/tonnes Remainder  
 Nitrogen Content of Remainder = 0 %

#### **1. Methane & Energy Implications of the Cache Creek Landfill:**

Biodegradable Carbon Content of Remainder = 50%  
 Moisture Content of Biodegradable Carbon in Remainder = 30%  
 Carbon Storage Factor for wet Remainder = 0.09 tC/wet tonne Remainder

$$\text{Carbon To Decompose} = \left( \frac{1 \text{ Wet Tonne}}{\text{Wet Tonne}} \right) (\text{Biodegradable Fraction}) \left[ (1 - \text{MC}) \frac{\text{Dry}}{\text{Wet}} \right] \left( \text{Carbon Content} \frac{\text{Mass C}}{\text{Dry Mass}} \right) - \text{CSF}$$

$$\text{Carbon To Decompose} = (1)(0.70)(1 - 0.30)(0.50) - 0.09 = 0.155 \frac{\text{tC}}{\text{Wet Tonne}}$$

This 0.155 tC per wet tonne of Remainder is available for anaerobic decomposition and will be assumed to be evenly split between CH<sub>4</sub> and CO<sub>2</sub>. Remember that since any CO<sub>2</sub> is neutral, it does not have to be considered further.

$$\text{Methane Generation} = \left( \text{Carbon To Decompose} \frac{\text{tC}}{\text{Wet Tonne}} \right) (\text{Methane Fraction}) \left( \frac{\text{Molecular Mass of CH}_4}{\text{Molecular Mass of C}} \right) = \frac{\text{tCH}_4}{\text{Wet Tonne}}$$

$$\text{Methane Generation} = (0.155)(0.5) \left( \frac{16}{12} \right) = 0.103 \frac{\text{tCH}_4}{\text{Wet Tonne}}$$

Methane Generation Potential = 0.103 tCH<sub>4</sub>/tonne of food waste

The first order decay rate constant used here is 0.04 yr<sup>-1</sup> and the assumptions behind it are discussed in Section 2.4 - *Landfill Carbon Sequestration*.

From Worksheet #34:

Best-Guess of Atmospheric Methane Emissions=	0.312	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.050	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.164	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.041	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.666	tCO <sub>2</sub> e/tonne

High Estimate of Benefit of Energy Utilization=

-0.014 tCO<sub>2</sub>e/tonne

## **2. Long-Term Carbon Sequestration in the Cache Creek Landfill:**

As discussed in Section 2.10 – *Remaining Wastes*, the Carbon Storage Factor used for Remainder in this thesis will be that for mixed MSW published in USEPA (1998). This CSF is 0.18 tonnes of carbon sequestered per wet tonne of MSW.

## **3. Immediate & Future N<sub>2</sub>O Emissions from the Cache Creek Landfill**

The nitrogen content of the Remainder is assumed to be negligible, therefore there is no potential for N<sub>2</sub>O emissions.

## **4. Methane & Energy Implications of the Vancouver Landfill:**

The only significant difference between this section and Section 1, *Methane & Energy Implications of the Cache Creek Landfill*, is the estimated landfill gas collection efficiency and the first order decay rate constant. While at Cache Creek the current collection efficiency is estimated to be 43%, the current collection efficiency at the Vancouver Landfill is estimated to only be 22% (Pers. comm. Chris Underwood). However, engineers with the City of Vancouver are currently in the process of upgrading the collection equipment. As with the CCLF assessment, the collection efficiency is assumed to increase year after year in response to improving regulations. The first order decay rate constant used here is 0.05 yr<sup>-1</sup> and the assumptions behind it are discussed in Section 2.4 - *Landfill Carbon Sequestration*.

From Worksheet #34:

Best-Guess of Atmospheric Methane Emissions=	0.476	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.070	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.223	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.048	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.846	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.015	tCO <sub>2</sub> e/tonne

## **5. Long-Term Carbon Sequestration in the Vancouver Landfill:**

As discussed in Section 2.10 – *Remaining Wastes*, the Carbon Storage Factor used for Remainder in this thesis will be that for mixed MSW published in USEPA (1998). This CSF is 0.18 tonnes of carbon sequestered per wet tonne of MSW.

## **6. Immediate & Future N<sub>2</sub>O Emissions from the Vancouver Landfill:**

The nitrogen content of the Remainder is assumed to be negligible, therefore there is no potential for N<sub>2</sub>O emissions.

## 7. Energy Generation from Waste Incineration at the Burnaby Incinerator:

Net Energy Content of Remainder = 11.6 GJ/tonne

Steam Energy produced by the combustion of Remainder in an Incinerator-Boiler (1):

Assumed Boiler Efficiency = 70% (Pers. comm. Ron Richter)

Fraction of Steam Utilized by CPL = 56% (Montenay Inc. 1999)

$$\frac{\text{Utilized Energy}}{\text{tonne Remainder}} = \frac{\text{energy}}{\text{tonne}} * (\text{Thermal Efficiency}) * (\text{Energy Utilization}) = \text{kJ/tonne}$$

$$\frac{\text{Utilized Energy}}{\text{tonne Remainder}} = \frac{11.6 \text{ GJ}}{\text{tonne}} * (0.70) * (0.56) = 4.54 \text{ GJ/tonne}$$

Utilized Steam Energy per tonne of Remainder, (1) = 4.54 GJ/tonne

GHG emission prevented per tonne of Remainder (3):

$$\frac{\text{GHG Emission Prevented}}{\text{tonne Remainder}} = \left( \frac{\text{Utilized Energy}}{\text{tonne Newsprint}} \right) * \left( \text{Emission Factor for Natural Gas, } \text{tCO}_2\text{e/GJ} \right) = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne Remainder}} = (4.54 \text{ GJ/tonne}) * (0.062 \text{ tCO}_2\text{e/GJ}) = 0.281 \text{ tCO}_2\text{e/tonne}$$

GHG Emission Prevented from Natural Gas, (3) = 0.281 tCO<sub>2</sub>e/tonne

Electricity produced by the combustion of Remainder in an Incinerator-Boiler (4):

Assumed Turbo Generator Efficiency = 32% (Pers. comm. Ron Richter)

Steam Fraction for Electricity Generation = 40% (assumed as discussed)

$$\frac{\text{Utilized Energy}}{\text{tonne Remainder}} = \frac{\text{energy}}{\text{tonne}} * (\text{Boiler Effic}) * (\text{TurboGenerator}) * (\text{Energy Utilization}) = \text{kJ/tonne}$$

$$\frac{\text{Utilized Energy}}{\text{tonne Remainder}} = \frac{11.6 \text{ GJ}}{\text{tonne}} * (0.70) * (0.32) * (0.40) = 1.04 \text{ GJ/tonne}$$

Utilized Electrical Energy per tonne of Remainder, (4) = 1.04 GJ/tonne

Electrical GHG emission prevented per tonne of Remainder: (6)

$$\frac{\text{GHG Emission Prevented}}{\text{tonne Remainder}} = \left( \frac{\text{Utilized Energy}}{\text{tonne Remainder}} \right) * \left( \text{Emission Factor for Electricity, } \text{tCO}_2\text{e/GJ} \right) = \text{tCO}_2\text{e/tonne}$$

$$\frac{\text{GHG Emission Prevented}}{\text{tonne Remainder}} = (1.04 \text{ GJ/tonne}) * (0.147 \text{ tCO}_2\text{e/GJ}) = 0.153 \text{ tCO}_2\text{e/tonne}$$

GHG Emission Prevented from Electricity, (6) = 0.153 tCO<sub>2</sub>e/tonne

Total GHG Emissions Prevented, (7) = 0.281 + 0.153 = -0.434 tCO<sub>2</sub>e/tonne

## 8. Greenhouse Gas Emissions from Waste Incineration:

At the Burnaby Incinerator, 247,075 tonnes of waste was combusted in 1998. This process required the consumption of 7,516 GJ of natural gas, 16,011 MWh of electricity, and 3,369 tonnes of lime (CaO) and 295 tonnes of ammonia (NH<sub>3</sub>) for acid gas control (Montenay Inc. 1999; Pers. comm. Richard Holt). Greenhouse gas emissions result from municipal solid waste incineration. This includes emissions of carbon dioxide and nitrous oxide during incineration, the consumption of natural gas and electricity, and the consumption of lime for acid gas control (the production of lime from limestone results in CO<sub>2</sub> emissions). Part of Remainder is fossil carbon and is therefore important from a

GHG perspective when combusted and must be assessed. However, the biomass carbon fraction is carbon-neutral, and is ignored

From Section 2.10:

Fossil Carbon Emissions during Incineration of Remainder = 0.060 tC/tonnes Remainder

$$\text{CO}_2 \text{ Emissions from Remainder combustion} = \left(0.060 \text{ tC/tonne} \times \left(\frac{44 \text{ gCO}_2/\text{mol}}{12 \text{ gC/mol}}\right)\right) = 0.22 \text{ tCO}_2\text{e/tonne}$$

GHG Emission of fossil-carbon from Remainder combustion = 0.22 tCO<sub>2</sub>e/tonne

The emissions resulting from natural gas and electricity consumption will be equally distributed over the entire solid waste combusted in 1998.

Lime (calcium oxide, CaO) is used at the Incinerator during air pollution control to neutralize acid gases which are produced during the combustion of waste. While the consumption of lime at the incinerator does not result in GHG emissions, the production of this material by the lime calcination process does result in emissions. In the production of lime, limestone (CaCO<sub>3</sub>) is heated so that it separates to CaO and CO<sub>2</sub>. In addition to the fossil fuel energy required to perform this reaction there is the non-energy related GHG emission from the liberalization of the unwanted carbon dioxide gas. Environment Canada (1997) has estimated that 0.790 kg of CO<sub>2</sub> is emitted during the production of each kg of lime. It is assumed that the incineration of HDPE equally requires the use of lime for the neutralization of acid gases as any other waste.

Therefore:

GHG Emission from CaO Production = 0.790 tCO<sub>2</sub>e/tonne CaO

$$\text{GHG Emissions from Lime} = \left(0.790 \text{ tCO}_2/\text{tonne CaO}\right) \times \frac{3,369 \text{ tonnes of CaO}}{247,075 \text{ tonnes of waste}} = 0.011 \text{ tCO}_2/\text{tonne}$$

GHG Emission from lime consumption at Incinerator=0.011 tCO<sub>2</sub>e/tonne

Nitrous oxide emissions from the incineration of Remainder can result in one of the five following pathways.

- Thermal conversion of the N<sub>2</sub> gas in air to N<sub>2</sub>O during combustion (Immediate emis.)
- Thermal conversion of the nitrogen in food waste to N<sub>2</sub>O (Immediate emission)
- Thermal conversion of the ammonia injected in the flue gases (Immediate emission)
- Microbial N<sub>2</sub>O conversion of NO<sub>x</sub> emitted and later denitrified (Future emission)
- Microbial N<sub>2</sub>O conversion of NH<sub>3</sub> injected but unreacted (Future emission)

Each of these five pathways are evaluated in the following calculations. Unfortunately, the current lack of understanding in these issues result in much uncertainty associated with the following estimates. An extensive discussion of the issue is provided Section 2.5.5.3.

The first two potential sources of nitrous oxide emissions result from the potential for the nitrogen in waste or the N<sub>2</sub> gas in air to thermal convert to N<sub>2</sub>O during incineration. There is limited and highly variable research of the N<sub>2</sub>O emissions resulting from municipal solid waste incineration. Examples of emission estimates being used are:

- IPCC Compilation (de Soete 1993) 11-293 gN<sub>2</sub>O/tonne of waste
- Environment Canada Inventory (1997) 160 gN<sub>2</sub>O/tonne of waste
- USEPA National Inventory (1999) 30 gN<sub>2</sub>O/tonne of waste
- USEPA MSW Analysis (1998) 130 gN<sub>2</sub>O/tonne of waste

Research in the fluidized bed combustion of coal has determined that N<sub>2</sub>O emissions originate mainly from the oxidation of fuel nitrogen (Moritomi 1994), and since coal combustion is similar to that of waste incineration, it can be inferred that N<sub>2</sub>O emissions during incineration are likely a factor of the nitrogen content. This hypothesis is reinforced by one study (Tanikawa et al. 1995), and the observation that the incineration of high nitrogen content wastewater sludge produces much higher N<sub>2</sub>O emission rates than MSW incinerators (Tanaka et al. 1994). Since Remainder is assumed to have a negligible nitrogen content, this study will assume that this incineration does not have to account for any of the nitrous oxide emissions measured during MSW incineration. However, there is still the possibility of alternative pathways for N<sub>2</sub>O emissions.

The incineration of Remainder needs to take responsibility for the N<sub>2</sub>O emissions resulting from acid gas (NO<sub>x</sub>) control. As the nitrogen oxide releases can be from molecular nitrogen in the air, Remainder incineration can contribute to this emission. This study assumes that the emissions from acid gas control should be evenly distributed across the mass of waste combusted. At the Burnaby Incinerator, 295 tonnes of ammonia (NH<sub>3</sub>) was used during the combustion of 247,075 tonnes of waste in 1998 to reduce NO<sub>x</sub> emissions. As a result of the lack of any available research on the propensity for injected ammonia to thermally convert to N<sub>2</sub>O, this study will assume the same conversion rate exhibited by the waste-nitrogen upon incineration. (See Appendix I #8) Therefore, approximately 1.7% of injected ammonia, and ranging between 0.3 and 3.1%, will be estimated to convert to nitrous oxide.

Fraction of Injected-Ammonia emitted as N<sub>2</sub>O = 1.7 (0.3-3.1) %

Annual consumption of ammonia (1998) = 295 tonnes

Annual mass of waste combusted (1998) = 247,075 tonnes

$$\text{N}_2\text{O from NH}_3 \text{ Injection} = \frac{(\text{NH}_3 \text{ Injected, tonnes}) \left( \frac{14 \text{ gN/mol}}{17 \text{ g NH}_3/\text{mol}} \right)}{(\text{Waste Combusted, tonnes})} * (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ gN}_2\text{O/mol}}{28 \text{ gN}_2\text{O} - \text{N/mol}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e/tonne}$$

$$\text{N}_2\text{O from NH}_3 \text{ Injection} = \frac{(295) \left( \frac{14}{17} \right)}{(247,075)} * (0.017) \left( \frac{44}{28} \right) (310) = 0.0081 \text{ tCO}_2\text{e/tonne}$$

N<sub>2</sub>O Emission resulting from NH<sub>3</sub> Injection = 0.0081 (0.0014 – 0.015) tCO<sub>2</sub>e/tonne

In addition to the potential for injected NH<sub>3</sub> to thermally convert to N<sub>2</sub>O, there can also be the future denitrification of the nitrogen oxide (NO<sub>x</sub>) gases released. It has been estimated that 10-30% of waste-nitrogen is converted to NO<sub>x</sub> (NO + NO<sub>2</sub>) during combustion (White et al. 1995). This report will evenly distribute NO<sub>x</sub> emissions across the total mass of waste incinerated even though Remainder has a negligible nitrogen content. Nitrogen oxides are short lived in the atmosphere as they are quickly rained out in the form of nitrate (NO<sub>3</sub><sup>-</sup>) or nitric acid (HNO<sub>3</sub>). Thus the deposition as NO<sub>3</sub><sup>-</sup> will

eventually require denitrification to N<sub>2</sub>, resulting in potential leakage of N<sub>2</sub>O. The IPCC provides guidelines for these emissions and estimates that 1% of emitted NH<sub>3</sub>-N or NO<sub>x</sub>-N will be converted to N<sub>2</sub>O. However they also provide low and high estimates of 0.2 and 2% respectively. All three of these values are used in this study. In addition to the potential for the microbial conversion of nitrogen oxide to nitrous oxide, nitrogen oxides are suspected to be indirect greenhouse gases for another reason – they deplete the tropospheric concentration of the OH radical, which would otherwise react and destroy CH<sub>4</sub> (Mackenzie 1995). Thus NO<sub>x</sub> causes CH<sub>4</sub> to be a stronger GHG. (As it is too early for any methodology on this issue, it will have to be ignored in this report.) At the Burnaby Incinerator it is estimated that 449 tonnes of NO<sub>x</sub> was emitted in 1998 (Pers. comm. Chantal Babensee). Nitric oxide (NO) is predominantly the nitrogen oxide formed during incineration (Robinson 1986), and is assumed in the calculations below.

Best-Guess Estimate for the future N<sub>2</sub>O conversion of NO<sub>x</sub> = 1% N<sub>2</sub>O-N/NO<sub>x</sub>-N

Low Estimate for the future N<sub>2</sub>O conversion of NO<sub>x</sub> = 0.2% N<sub>2</sub>O-N/NO<sub>x</sub>-N

High Estimate for the future N<sub>2</sub>O conversion of NO<sub>x</sub> = 2% N<sub>2</sub>O-N/NO<sub>x</sub>-N

Annual NO<sub>x</sub> emission (1998) = 449 tonnes

Annual mass of waste combusted (1998) = 247,075 tonnes

$$\text{N}_2\text{O Emission from NO}_x = \frac{(\text{NO}_x \text{ Emission, tonnes}) \left( \frac{14 \text{ gN/mol}}{30 \text{ gNO/mol}} \right)}{(\text{Waste Combusted, tonnes})} * (\text{N}_2\text{O Conversion}) \left( \frac{44 \text{ gN}_2\text{O/mol}}{28 \text{ gN}_2\text{O} - \text{N/mol}} \right) (\text{GWP of N}_2\text{O}) = \text{tCO}_2\text{e/tonne}$$

$$\text{N}_2\text{O Emission from NO}_x = \frac{(449) \left( \frac{14}{30} \right)}{(247,075)} * (0.01) \left( \frac{44}{28} \right) (310) = 0.0074 (0.0012 - 0.014) \text{ tCO}_2\text{e/tonne}$$

Future N<sub>2</sub>O from NO<sub>x</sub> emission = 0.004 (0.001-0.008) tCO<sub>2</sub>e/tonne

The last potential N<sub>2</sub>O emission from waste incineration could occur when ammonia is injected into the flue gas but is emitted to the atmosphere, the so-called “ammonia slip”. The ammonia will undergo wet or dry deposition to soils downwind where it can nitrify and denitrify. Communication with the GVRD (Pers. comm. Chantal Babensee) has learned that ammonia slip is virtually negligible at the Incinerator largely because only the minimum amount is injected into the flue gas. As a result, the potential for ammonia slip to result in nitrous oxide emissions can be neglected in this study.

The remaining greenhouse gas emissions during waste combustion result from the consumption of natural gas, electricity and lime by the Incinerator. This analysis will assume that the emissions resulting from natural gas, electricity and lime consumption will be equally distributed over the entire solid waste combusted in 1998. These estimates are in Appendix C – *Newsprint Waste Management*.

$$\begin{aligned} \text{Total GHG Emissions} &= \text{CO}_2 + \text{N}_2\text{O} + \text{Natural Gas} + \text{Electricity} + \text{Lime} = \text{tCO}_2\text{e/tonne} \\ \text{Total Emissions} &= 0.25 (0.24-0.26) \text{ tCO}_2\text{e/tonne} \end{aligned}$$

## 9. GHG Emissions of Recycled Remainder Utilization:

The assumption discussed in Section 2.10 – *Remaining Wastes* is that a GHG benefit of 0 tCO<sub>2</sub>e/tonne exists with the recycling of Remainder.

GHG Benefit of Recycled Remainder Utilization = 0 tCO<sub>2</sub>e/tonne

**10. Effect of Recycling Remainder on Forest Carbon Storage**

The assumption discussed in Section 2.6.7 – *Forest Carbon Sequestration* is that no GHG benefit exists with Remainder recycling.

GHG Benefit of Recycled Remainder Utilization = 0 tCO<sub>2</sub>e/tonne



## **APPENDIX L: SPREADSHEET PROGRAM**

The appendix contains print-outs of each of the 34 worksheets which create the spreadsheet model. These worksheets are presented in the following pages in the same order they are on the spreadsheet and as listed in Table 2-5 : List of Worksheets. This table is reprinted below along with the page numbers where these worksheets can be found.

### List of Worksheets

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[illegible]

	Best	Low	High
<b>GVRO TOTAL=</b>	<b>-18497.09</b>	<b>-32494.2</b>	<b>116455.2</b>
Catch Creek Landfill Totals	36143.4	-97930.2	117075.9
Vancouver Landfill Totals	9494.8	-64096.4	114524.8
Future Landfill Totals	0.0	0.0	0.0
Burnaby Incinerator Totals	-3800.5	-7086.4	-290.4
Future Incinerator Totals	0.0	0.0	0.0
Recycling Totals	-164340.0	-164340.0	-164340.0
Backyard Composting Totals	-528.9	328.2	1157.5
<b>Future Totals</b>	<b>-164340.0</b>	<b>-164340.0</b>	<b>-164340.0</b>

[illegible]

1998 WASTE TONNAGES (wet tonne)

	City of Abbots	City of Burnaby	City of Coquitlam	City of Langley	City of Langley	T. of Langley	City of Maple Ridge	New West	City of N. Van.	City of N. Van.	Port Moody	City of Richmond	City of Surrey	City of Van.	West Van.	White Rock	Elect. A (U.E.L.)	Elect. C (Bowen HS)	TOTAL		
<b>Newsprint</b>																					
Cache Creek Landfill	3,700.4	2,011.3	4,764.3	253.7	650.8	2,141.9	1,095.9	1,038.2	664.3	1,419.3	478.7	1,095.8	748.0	566.4	7,979.7	4,669.4	12.4	0.0	77.9		
Vancouver Landfill	1.5	52.4	128.5	5,014.9	12.5	18.3	23.2	27.7	14.2	30.1	12.2	28.6	20.2	5,061.9	650.8	17,984.4	12.2	388.8	171.8		
Future Landfill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6		
Burnaby Incinerator	0.7	6,325.5	66.5	3.9	6.1	608.6	11.3	1,146.1	701.4	1,523.6	6.0	14.4	9.8	726.2	1,918.0	3,781.9	628.0	0.2	84.5		
Future Incinerator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
Recycling	3,412.2	5,940.7	2,836.7	2,831.3	616.7	3,100.4	1,828.0	1,513.5	2,165.3	4,225.5	326.7	1,159.4	354.9	7,214.8	9,073.1	15,177.9	2,647.5	510.7	200.2	65.102	
<b>Office Paper</b>																					
Cheche Creek Landfill	1,379.5	850.1	1,284.7	72.9	336.3	685.8	731.6	460.2	194.4	606.0	125.8	678.3	285.6	219.4	2,742.0	1,812.5	215.4	6.4	0.0	12.907	
Vancouver Landfill	0.6	22.1	34.7	1,244.8	6.5	7.6	12.4	12.4	4.1	12.9	3.2	16.8	7.7	1,951.5	282.3	4,531.0	4.6	202.6	0.0	10.817	
Future Landfill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Burnaby Incinerator	0.3	2,573.6	18.0	1.0	3.2	251.7	4.6	513.0	205.2	650.5	1.6	8.9	3.7	280.0	659.1	1,468.0	233.6	0.1	0.0	6.988	
Future Incinerator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Recycling	320.1	1,880.7	433.8	624.9	107.7	450.2	194.3	459.2	434.7	402.3	54.3	312.6	153.1	2,113.3	1,909.6	5,293.8	234.3	134.0	184.0	15.692	
<b>Metal</b>																					
Cheche Creek Landfill	2,099.7	2,066.2	2,845.7	173.4	733.6	1,618.6	1,151.3	987.0	260.4	1,381.6	334.4	1,354.4	432.0	594.5	5,447.3	4,531.0	483.7	16.7	0.0	18.5	
Vancouver Landfill	0.9	53.8	79.5	2,960.9	14.1	13.9	14.7	26.6	5.5	29.3	6.6	33.8	11.7	5,224.1	590.8	17,451.4	10.2	525.2	178.8	0.0	27.224
Future Landfill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Burnaby Incinerator	0.4	6,498.1	41.2	2.3	6.9	486.2	7.2	1,100.2	274.9	1,483.1	4.2	16.4	5.7	748.4	1,369.3	3,669.8	524.6	0.2	0.0	16.174	
Future Incinerator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Recycling	1,101.3	5,825.0	779.9	1,555.1	281.6	1,854.3	1,034.6	1,484.0	1,428.5	898.4	71.9	1,056.2	361.7	6,589.5	5,216.2	17,137.4	549.9	123.4	285.7	48.156	
<b>Glass</b>																					
Cheche Creek Landfill	1,557.0	1,056.0	2,181.2	97.5	323.2	628.7	784.9	568.4	421.1	977.0	223.1	480.5	136.1	586.6	3,261.1	2,710.8	493.6	12.9	0.0	25.3	
Vancouver Landfill	0.6	27.5	38.6	1,965.8	0.2	0.1	0.3	0.3	0.0	0.0	0.0	0.0	0.0	3,023.0	350.6	10,552.2	405.6	10.0	0.0	16.537	
Future Landfill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Burnaby Incinerator	0.3	3,321.1	30.5	1.3	3.0	235.5	4.8	633.6	444.6	1,048.8	2.8	6.3	1.8	472.5	798.7	2,219.8	535.3	0.2	0.0	9.778	
Future Incinerator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Recycling	596.1	1,653.6	837.6	1,622.2	153.2	1,070.9	485.0	350.4	470.8	386.7	26.1	432.6	303.8	2,014.7	2,928.0	5,516.0	252.2	56.5	107.5	18.847	
<b>HDPE</b>																					
Cheche Creek Landfill	538.3	398.4	651.5	26.3	138.9	368.1	323.2	165.4	80.5	287.4	66.4	232.9	109.2	107.8	1,266.4	880.9	130.1	3.7	0.0	5.795	
Vancouver Landfill	0.2	10.4	17.6	443.9	2.7	3.1	4.1	4.5	1.7	6.1	1.7	6.3	2.9	963.0	135.0	3,431.3	2.8	115.0	48.9	0.2	5.201
Future Landfill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Burnaby Incinerator	0.1	1,252.8	9.1	0.3	1.3	104.6	2.0	184.4	85.0	308.5	0.8	3.1	1.4	138.2	304.4	721.6	141.1	0.0	0.0	3.268	
Future Incinerator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Recycling	596.1	633.7	169.5	220.0	41.4	220.5	77.4	135.0	173.7	113.0	7.8	94.5	49.7	709.6	759.5	2,111.6	52.3	16.6	26.9	6.247	
<b>LDPE</b>																					
Cheche Creek Landfill	1,702.2	1,127.6	1,828.3	100.2	447.5	1,158.2	921.3	557.4	256.7	780.2	200.9	780.9	306.5	330.3	3,766.4	2,284.9	296.1	10.3	0.0	16.862	
Vancouver Landfill	0.7	29.4	49.3	1,710.8	8.6	9.9	11.8	15.0	5.5	16.5	5.1	21.1	8.3	2,951.6	401.6	9,000.5	6.3	323.3	147.0	0.6	14.523
Future Landfill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Burnaby Incinerator	0.3	3,546.4	25.6	1.3	4.2	328.5	5.7	621.4	271.1	837.6	2.5	10.2	4.0	423.4	953.3	1,650.6	321.1	0.1	0.0	9.189	
Future Incinerator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Recycling	352.2	1,337.7	255.0	541.9	94.3	556.7	170.3	442.4	439.0	271.0	19.8	331.1	127.3	2,334.1	1,703.4	5,053.4	142.9	37.9	59.1	14.908	
<b>Food Scraps</b>																					
Cheche Creek Landfill	5,190.3	3,290.9	5,684.1	273.9	1,474.4	3,573.2	2,926.3	1,707.6	776.9	2,277.1	618.2	1,850.8	999.7	925.4	12,568.8	7,319.2	1,090.1	32.3	0.0	52.643	
Vancouver Landfill	2.1	65.7	133.6	4,677.9	26.4	30.6	37.5	58.1	0.4	0.0	0.0	0.0	0.0	8,700.4	1,568.6	28,711.1	1,58.6	58.7	0.0	44.959	
Future Landfill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Burnaby Incinerator	1.0	10,350.0	79.5	3.6	13.8	1,015.3	18.2	1,903.4	844.0	2,444.4	7.7	24.3	13.1	1,186.4	3,020.6	5,528.0	1,182.3	0.4	0.0	25.106	
Future Incinerator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Centralized Composting	1,130.4	744.3	289.8	794.7	36.6	357.8	340.3	182.6	211.5	661.7	53.1	456.5	283.4	6,198.0	5,478.6	15,786.6	246.9	159.4	0.0	8.439	
Yard Trimmings	1,130.4	5,510.7	626.1	1,744.2	264.9	1,680.3	677.8	1,343.8	1,451.4	864.7	66.3	752.5	283.4	6,198.0	5,478.6	15,786.6	246.9	159.4	0.0	45.217	
<b>Cheche Creek Landfill</b>																					
Vancouver Landfill	0.0	18.7	756.7	32.2	1,031.5	2,362.8	869.0	570.3	0.0	0.0	450.2	0.0	622.8	0.0	13,529.5	1,235.4	0.0	17.3	0.0	21.707	
Future Landfill	0.0	0.5	20.4	549.4	19.8	20.4	11.4	15.4	0.0	0.0	11.5	0.0	16.8	0.0	1,453.1	4,758.3	0.0	543.6	90.7	1.5	7.513
Burnaby Incinerator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Future Incinerator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Centralized Composting	1,494.1	1,497.7	583.0	1,599.0	77.7	719.9	684.7	367.4	425.5	1,313.3	106.9	916.5	0.0	1,273.7	3,980.9	4,968.8	320.8	0.0	0.0	5.765	
Remainder	2,434.0	5,125.4	17,118.1	10,977.1	5,367.3	12,944.4	8,202.0	10,977.1	9,369.7	7,122.8	23.1	1,485.5	1,280.1	13,023.8	5,052.2	28,111.7	2,769.8	54.2	283.1	16.990	
<b>Cheche Creek Landfill</b>																					
Vancouver Landfill	13.5	524.3	1,693.3	46,865.5	162.8	71.3	146.5	169.8	47.9	594.4	30.3	282.2	48.9	23,555.3	4,960.2	137,907.2	68.5	5,163.6	2,096.2	290.773	
Future Landfill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Burnaby Incinerator	6.6	63,307.9	981.1	36.1	79.2	2,367.9	71.2	7,844.8	2,375.0	29,575.7	14.7	142.0	23.8	3,379.1	10,326.0	29,006.2	4,537.4	2.2	0.0	0.0	
Future Incinerator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Recycling	2,434.0	5,125.4	17,118.1	10,977.1	5,367.3	12,944.4	8,202.0	10,977.1	9,369.7	7,122.8	23.1	1,485.5	1,280.1	13,023.8	5,052.2	28,111.7	2,769.8	54.2	283.1	373.597	
<b>TOTAL</b>	84,340	216,615	121,319	93,358	2,1204	51,125	36,347	46,862	26,911	99,354	6,003	26,435	11,392	138,004	221,487	555,374	33,900	12,981	5,554	1,494	

TOTAL

Cheche Creek Landfill Tot

1998 EMISSION FACTORS (CO<sub>2</sub>e/wet tonne)

	City of Abbotsford		City of Burnaby		City of Coquitlam		Corporation of Delta		City of Langley		Township of Langley		District of Maple Ridge		City of New Westminster		City of North Vancouver		City of North Vancouver		District	
	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low	High	Best
<b>Newsprint</b>																						
Cheche Creek Landfill	-1.24	-1.32	-1.06	-1.23	-1.31	-1.06	-1.24	-1.32	-1.07	-1.24	-1.32	-1.06	-1.23	-1.31	-1.06	-1.23	-1.31	-1.06	-1.24	-1.32	-1.06	-1.24
Vancouver Landfill	-1.19	-1.30	-0.98	-1.19	-1.30	-0.98	-1.21	-1.32	-1.01	-1.18	-1.30	-0.99	-1.25	-1.35	-1.05	-1.25	-1.35	-1.05	-1.19	-1.30	-0.98	-1.19
Future Landfill	-1.26	-1.36	-1.16	-1.26	-1.36	-1.16	-1.28	-1.38	-1.18	-1.28	-1.38	-1.18	-1.30	-1.40	-1.20	-1.30	-1.40	-1.20	-1.26	-1.36	-1.16	-1.26
Burnaby Incinerator	-1.26	-1.36	-1.16	-1.26	-1.36	-1.16	-1.28	-1.38	-1.18	-1.28	-1.38	-1.18	-1.30	-1.40	-1.20	-1.30	-1.40	-1.20	-1.26	-1.36	-1.16	-1.26
Future Incinerator	-0.41	-0.42	-0.39	-0.40	-0.41	-0.39	-0.40	-0.41	-0.40	-0.40	-0.41	-0.40	-0.40	-0.41	-0.39	-0.40	-0.41	-0.39	-0.41	-0.42	-0.39	-0.41
Recycling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Office Paper</b>																						
Cheche Creek Landfill	0.59	0.21	1.40	0.59	0.22	1.40	0.58	0.20	1.39	0.59	0.21	1.40	0.59	0.21	1.40	0.59	0.21	1.40	0.59	0.21	1.40	0.59
Vancouver Landfill	0.84	0.32	1.79	0.84	0.32	1.79	0.83	0.32	1.77	0.83	0.31	1.79	0.83	0.32	1.79	0.83	0.31	1.79	0.83	0.31	1.79	0.83
Future Landfill	0.57	0.19	1.38	0.58	0.19	1.38	0.56	0.19	1.37	0.57	0.19	1.38	0.57	0.19	1.38	0.57	0.19	1.37	0.57	0.19	1.38	0.57
Burnaby Incinerator	-0.33	-0.34	-0.32	-0.34	-0.35	-0.33	-0.34	-0.35	-0.36	-0.34	-0.35	-0.33	-0.34	-0.35	-0.33	-0.33	-0.34	-0.35	-0.34	-0.35	-0.33	-0.34
Future Incinerator	-0.34	-0.35	-0.33	-0.34	-0.35	-0.33	-0.35	-0.36	-0.34	-0.35	-0.33	-0.34	-0.35	-0.33	-0.34	-0.35	-0.33	-0.34	-0.35	-0.33	-0.34	-0.35
Recycling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Metal</b>																						
Cheche Creek Landfill	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.03	0.03	0.04	0.04	0.04	0.04
Vancouver Landfill	0.03	0.03	0.03	0.03	0.03	0.03	0.01	0.01	0.01	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.04	0.04	0.04	0.04
Future Landfill	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02
Burnaby Incinerator	-1.15	-1.15	-1.15	-1.15	-1.15	-1.16	-1.17	-1.17	-1.17	-1.16	-1.16	-1.16	-1.16	-1.16	-1.15	-1.15	-1.16	-1.16	-1.16	-1.16	-1.16	-1.16
Future Incinerator	-1.16	-1.16	-1.15	-1.15	-1.15	-1.16	-1.17	-1.17	-1.17	-1.16	-1.16	-1.16	-1.16	-1.16	-1.15	-1.15	-1.16	-1.16	-1.16	-1.16	-1.16	-1.16
Recycling	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35	-2.35
<b>Glass</b>																						
Cheche Creek Landfill	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.03	0.03	0.04	0.04	0.04	0.04
Vancouver Landfill	0.03	0.03	0.03	0.03	0.03	0.03	0.01	0.01	0.01	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.04	0.04	0.04	0.04
Future Landfill	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02
Burnaby Incinerator	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02
Future Incinerator	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02
Recycling	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37
<b>HDPE</b>																						
Cheche Creek Landfill	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.03	0.03	0.04	0.04	0.04	0.04
Vancouver Landfill	0.03	0.03	0.03	0.03	0.03	0.03	0.01	0.01	0.01	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.04	0.04	0.04	0.04
Future Landfill	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02
Burnaby Incinerator	2.11	2.11	2.11	2.11	2.11	2.11	2.09	2.09	2.09	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.10	2.10	2.11	2.11	2.11	2.11
Future Incinerator	2.10	2.10	2.11	2.11	2.11	2.11	2.09	2.09	2.09	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.10	2.10	2.11	2.11	2.11	2.11
Recycling	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70	-1.70
<b>LDPE</b>																						
Cheche Creek Landfill	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.03	0.03	0.04	0.04	0.04	0.04
Vancouver Landfill	0.03	0.03	0.03	0.03	0.03	0.03	0.01	0.01	0.01	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.04	0.04	0.04	0.04
Future Landfill	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02
Burnaby Incinerator	2.11	2.11	2.11	2.11	2.11	2.11	2.09	2.09	2.09	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.10	2.10	2.11	2.11	2.11	2.11
Future Incinerator	2.10	2.10	2.11	2.11	2.11	2.11	2.09	2.09	2.09	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.10	2.10	2.11	2.11	2.11	2.11
Recycling	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25	-2.25
<b>Food Scraps</b>																						
Cheche Creek Landfill	0.32	0.11	0.69	0.33	0.12	0.70	0.32	0.11	0.69	0.32	0.11	0.69	0.33	0.12	0.70	0.33	0.12	0.70	0.32	0.11	0.69	0.32
Vancouver Landfill	0.30	0.15	0.67	0.31	0.10	0.68	0.30	0.15	0.67	0.30	0.15	0.67	0.30	0.15	0.67	0.31	0.10	0.68	0.30	0.15	0.67	0.30
Future Landfill	0.26	0.08	0.67	0.27	0.09	0.68	0.26	0.09	0.67	0.26	0.09	0.67	0.26	0.09	0.67	0.27	0.09	0.68	0.26	0.09	0.67	0.26
Burnaby Incinerator	0.02	-0.01	0.04	0.01	-0.01	0.04	0.00	-0.02	0.03	0.01	-0.01	0.04	0.01	-0.01	0.04	0.02	-0.01	0.04	0.01	-0.01	0.04	0.01
Future Incinerator	0.01	-0.02	0.04	0.02	-0.01	0.04	0.01	-0.01	0.04	0.01	-0.02	0.04	0.01	-0.01	0.04	0.02	-0.01	0.04	0.01	-0.02	0.04	0.01
Backyard Composting	0.06	0.01	0.14	0.06	0.01	0.14	0.06	0.01	0.14	0.06	0.01	0.14	0.06	0.01	0.14	0.06	0.01	0.14	0.06	0.01	0.14	0.06
Centralized Composting	0.10	0.03	0.20	0.12	0.06	0.23	0.13	0.06	0.23	0.12	0.06	0.23	0.12	0.06	0.23	0.10	0.04	0.21	0.12	0.06	0.23	0.13
<b>Yard Trimmings</b>																						
Cheche Creek Landfill	-0.53	-0.64	-0.35	-0.53	-0.63	-0.34	-0.54	-0.65	-0.35	-0.53	-0.64	-0.35	-0.53	-0.64	-0.34	-0.52	-0.63	-0.35	-0.53	-0.64	-0.35	-0.53
Vancouver Landfill	-0.49	-0.63	-0.29	-0.49	-0.62	-0.28	-0.51	-0.65	-0.31	-0.49	-0.63	-0.29	-0.49	-0.63	-0.29	-0.49	-0.63	-0.29	-0.50	-0.63	-0.29	-0.49
Future Landfill	-0.55	-0.66	-0.37	-0.55	-0.66	-0.37	-0.56	-0.67	-0.37	-0.55	-0.66	-0.37	-0.55	-0.66	-0.37	-0.54	-0.65	-0.36	-0.55	-0.66	-0.37	-0.55
Burnaby Incinerator	0.07	-0.07	0.20	0.06	-0.08	0.20	0.06	-0.08	0.19	0.06	-0.08	0.20	0.06	-0.08	0.20	0.07	-0.07	0.20	0.06	-0.08	0.20	0.06
Future Incinerator	0.06	-0.08	0.20	0.06	-0.07	0.20	0.06	-0.08	0.19	0.06	-0.08	0.20	0.06	-0.08	0.20	0.06	-0.08	0.19	0.06	-0.08	0.20	0.06
Backyard Composting	-0.03	0.01	0.17	-0.03	0.01	0.17	-0.03	0.01	0.17	-0.03	0.01	0.17	-0.03	0.01	0.17	-0.03	0.01	0.17	-0.03	0.01	0.17	-0.03
Centralized Composting	0.02	0.04	0.06	0.05	0.06	0.09	0.05	0.07	0.09	0.05	0.06	0.09	0.05	0.06	0.09	0.05	0.06	0.09	0.05	0.06	0.09	0.05
<b>Remainder</b>																						
Cheche Creek Landfill	-0.03	-0.17	0.36	-0.03	-0.17	0.36	-0.04	-0.18	0.35	-0.03	-0.17	0.36	-0.03	-0.17	0.36	-0.02	-0.16	0.37	-0.03	-0.17	0.36	-0.03
Vancouver Landfill	0.10	-0.13	0.53	0.10</																		



[illegible][illegible]

[illegible]



# GENERAL PARAMETERS:

## 1998 Waste Flow

### DIRECT HAUL (TONNES):

	Cache Creek Landfill	Vancouver Landfill	Future Landfill	Burnaby Incinerator	Future Incinerator	Coquitlam TS	North Shore TS	Vancouver TS	Matsqui TS	Langley TS	Maple Ridge TS	TOTAL:
Abbotsford	0	0	0	0	0	756	0	0	48,031	162	0	48,949
Burnaby	0	0	0	91,666	0	27,081	10,342	0	0	0	0	129,089
Coquitlam	0	0	0	78	0	93,925	0	0	0	0	0	94,003
Della	0	64,428	0	0	0	3,973	0	703	0	0	0	69,104
Langley (City)	0	0	0	0	0	10,025	0	0	3,460	510	0	13,995
Langley (Town)	0	0	0	5,961	0	5,501	0	0	4,315	11,744	0	27,521
Maple Ridge	0	0	0	0	0	8,308	0	0	870	0	12,177	21,355
New Westminster	0	0	0	14,411	0	13,607	0	0	0	0	0	28,018
N. Van. (City)	0	0	0	0	0	136	10,037	0	0	0	0	10,173
N. Van. (District)	0	0	0	0	0	379	73,521	0	0	0	0	73,900
Pitt Meadows	0	0	0	0	0	3,595	0	0	17	0	209	3,821
Port Coquitlam	0	0	0	0	0	17,895	0	0	0	0	0	17,895
Port Moody	0	0	0	0	0	5,670	0	0	0	0	0	5,670
Richmond	0	7,508	0	7,280	0	5,967	0	43,609	0	0	0	64,364
Surrey	0	7,471	0	21,286	0	96,881	0	492	0	0	0	128,130
Vancouver	0	8,899	0	6,217	0	22,374	83,761	225,740	0	0	0	348,991
West Vancouver	0	0	0	0	0	0	15,733	0	0	0	0	15,733
White Rock	0	8,635	0	0	0	287	0	42	0	0	0	8,964
Elect A (U.E.L.)	0	66	0	0	0	0	0	3,283	0	0	0	3,349
Elect C (Bowen)	0	0	0	0	0	0	1,289	0	0	0	0	1,289
TOTAL:	0	97,007	0	146,899	0	316,360	194,683	273,377	57,185	12,416	12,386	

### TRANSFER FLOWS (TONNES)

	Cache Creek Landfill	Vancouver Landfill	Future Landfill	Burnaby Incinerator	Future Incinerator	Coquitlam TS	Matsqui TS	TOTAL:
transfers to --)								
Coquitlam TS	303,608	8,189	0	3,981	0	0	0	315,778
North Shore TS	82,930	1,754	0	89,942	0	0	0	174,626
Vancouver TS	0	271,431	0	0	0	0	0	271,431
Matsqui TS	73,169	0	0	0	0	0	0	73,169
Langley TS	0	0	0	0	0	1,217	8,172	9,389
Maple Ridge TS	0	0	0	0	0	2,030	10,070	12,100
TOTAL=	459,707	281,374	0	93,923	0	3,247	18,242	

### TRANSFER FLOWS (PERCENTAGES)

	Cache Creek Landfill	Vancouver Landfill	Future Landfill	Burnaby Incinerator	Future Incinerator	TOTAL
transfers to --)						
Coquitlam TS	96.1	2.6	0.0	1.3	0.0	100.0
North Shore TS	47.5	1.0	0.0	51.5	0.0	100.0
Vancouver TS	0.0	100.0	0.0	0.0	0.0	100.0
Matsqui TS	100.0	0.0	0.0	0.0	0.0	100.0
Langley TS	99.5	0.3	0.0	0.2	0.0	100.0
Maple Ridge TS	99.4	0.4	0.0	0.2	0.0	100.0

### TOTAL MASS FLOWS (TONNES)

	Cache Creek Landfill	Vancouver Landfill	Future Landfill	Burnaby Incinerator	Future Incinerator	TOTAL
Abbotsford	48,918	20	0	10	0	48,949
Burnaby	30,949	806	0	97,334	0	129,089
Coquitlam	90,305	2,436	0	1,262	0	94,003
Della	3,820	65,234	0	50	0	69,104
Langley (City)	13,606	262	0	127	0	13,995
Langley (Town)	21,289	182	0	6,060	0	27,521
Maple Ridge	20,956	268	0	130	0	21,355
New Westminster	13,083	353	0	14,583	0	28,018
N. Van. (City)	4,897	104	0	5,171	0	10,173
N. Van. (District)	35,280	748	0	37,872	0	73,900
Pitt Meadows	3,681	94	0	46	0	3,821
Port Coquitlam	17,205	464	0	226	0	17,895
Port Moody	5,451	147	0	71	0	5,670
Richmond	5,737	51,272	0	7,355	0	64,364
Surrey	93,639	9,983	0	22,507	0	128,130
Vancouver	61,200	236,081	0	49,641	0	346,991
West Vancouver	7,472	158	0	8,103	0	15,733
White Rock	278	8,684	0	4	0	8,964
Elect A (U.E.L.)	0	3,349	0	0	0	3,349
Elect C (Bowen)	612	13	0	664	0	1,289
TOTAL:	478,468	380,639	0	251,206	0	

### PERCENTAGE DISTRIBUTION OF WASTE DISPOSAL

	Cache Creek Landfill	Vancouver Landfill	Future Landfill	Burnaby Incinerator	Future Incinerator	TOTAL
Abbotsford	99.9	0.0	0.0	0.0	0.0	100
Burnaby	24.0	0.6	0.0	75.4	0.0	100
Coquitlam	96.1	2.6	0.0	1.3	0.0	100
Della	5.5	94.4	0.0	0.1	0.0	100
Langley (City)	97.2	1.9	0.0	0.9	0.0	100
Langley (Town)	77.4	0.7	0.0	22.0	0.0	100
Maple Ridge	98.1	1.3	0.0	0.6	0.0	100
New Westminster	46.7	1.3	0.0	52.0	0.0	100
N. Van. (City)	48.1	1.0	0.0	50.8	0.0	100
N. Van. (District)	47.7	1.0	0.0	51.2	0.0	100
Pitt Meadows	96.3	2.5	0.0	1.2	0.0	100
Port Coquitlam	96.1	2.6	0.0	1.3	0.0	100
Port Moody	96.1	2.6	0.0	1.3	0.0	100
Richmond	8.9	79.7	0.0	11.4	0.0	100
Surrey	74.2	7.9	0.0	17.8	0.0	100
Vancouver	17.7	68.0	0.0	14.3	0.0	100
West Vancouver	47.5	1.0	0.0	51.5	0.0	100
White Rock	3.1	96.9	0.0	0.0	0.0	100
Elect A (U.E.L.)	0.0	100.0	0.0	0.0	0.0	100
Elect C (Bowen)	47.5	1.0	0.0	51.5	0.0	100

### PHYSICAL CONSTANTS & DATA FROM LITERATURE:

Global Warming Potential of CH <sub>4</sub> =	21
Global Warming Potential of N <sub>2</sub> O=	310
Molecular mass of methane (CH <sub>4</sub> )=	16 g/mol
Molecular mass of carbon (C)=	12 g/mol
Molecular mass of carbon dioxide (CO <sub>2</sub> )=	44 g/mol
Molecular mass of nitrous oxide (N <sub>2</sub> O)=	44 g/mol
Molecular mass of nitrogen in nitrous oxide (N <sub>2</sub> O-N)=	28 g/mol
Molecular mass of ammonia (NH <sub>3</sub> )=	17 g/mol
Molecular mass of nitrogen in ammonia (NH <sub>3</sub> -N)=	14 g/mol
Molecular mass of nitric oxide (NO)=	30 g/mol
Molecular mass of nitrogen in nitric oxide (NO-N)=	14 g/mol
Latent heat of water=	2,473 kJ/kg
Fraction of anaerobically decomposed carbon to be CH <sub>4</sub> =	50 %
CO <sub>2</sub> emission from natural gas combustion	1.88 kgCO <sub>2</sub> /m <sup>3</sup>
Energy of natural gas (typically) =	37,843 kJ/m <sup>3</sup>
GHG emission from diesel fuel combustion=	2.854 kgCO <sub>2</sub> e/L
GHG emission from diesel fuel combustion=	0.076 tCO <sub>2</sub> e/10 <sup>6</sup> BTU
GHG emission from propane combustion=	1.530 kgCO <sub>2</sub> e/L

### DATA FOR THE CACHE CREEK LANDFILL:

YEAR	BEST-GUESS			LOW-ESTIMATE			HIGH-ESTIMATE		
	Oxidation by Cover Material (%)	% LFG Flared (%)	% LFG Energy (%)	Oxidation by Cover Material (%)	% LFG Flared (%)	% LFG Energy (%)	Oxidation by Cover Material (%)	% LFG Flared (%)	% LFG Energy (%)
1998	-	-	-	-	-	-	-	-	-
1999	10	43	0	15	43	0	5	43	0
2000	10	50	0	15	50	0	5	50	0
2001	10	50	10	15	50	10	5	50	0
2002	10	50	15	15	55	15	5	50	0
2003	10	45	20	15	55	20	5	50	0
2004	10	40	25	15	50	25	5	55	0
2005	10	35	35	15	40	35	5	55	0

2006	10	30	40	15	35	40	5	55	5
2007	10	25	50	15	25	50	5	55	5
2008	10	25	50	15	30	50	5	50	10
2009	10	20	55	15	25	55	5	50	10
2010	10	20	55	15	25	55	5	50	10
2011	10	15	60	15	20	60	5	45	15
2012	10	15	60	15	20	60	5	45	15
2013	10	10	65	15	15	65	5	45	15
2014	10	10	65	15	15	65	5	40	20
2015	10	5	70	15	10	70	5	40	20
2016	10	5	70	15	10	70	5	35	25
2017	10	0	75	15	0	85	5	35	25
2018	10	0	75	15	0	85	5	35	25

#### DATA FOR THE VANCOUVER LANDFILL:

YEAR	BEST-GUESS			LOW-ESTIMATE			HIGH-ESTIMATE		
	Oxidation by Cover Material (%)	% LFG Flared (%)	% LFG Energy (%)	Oxidation by Cover Material (%)	% LFG Flared (%)	% LFG Energy (%)	Oxidation by Cover Material (%)	% LFG Flared (%)	% LFG Energy (%)
1998	-	-	-	-	-	-	-	-	-
1999	10	22	0	15	22	0	5	22	0
2000	10	30	0	15	35	0	5	30	0
2001	10	35	10	15	40	10	5	35	0
2002	10	40	15	15	45	15	5	40	0
2003	10	45	20	15	55	20	5	50	0
2004	10	40	25	15	50	25	5	55	0
2005	10	30	40	15	40	35	5	55	0
2006	10	30	40	15	35	40	5	55	5
2007	10	25	50	15	25	50	5	55	5
2008	10	25	50	15	30	50	5	50	10
2009	10	20	55	15	25	55	5	50	10
2010	10	20	55	15	25	55	5	50	10
2011	10	15	60	15	20	60	5	45	15
2012	10	15	60	15	20	60	5	45	15
2013	10	10	65	15	15	65	5	45	15
2014	10	10	65	15	15	65	5	40	20
2015	10	5	70	15	10	70	5	40	20
2016	10	5	70	15	10	70	5	35	25
2017	10	0	75	15	0	85	5	35	25
2018	10	0	75	15	0	85	5	35	25

#### DATA FOR A FUTURE LANDFILL:

YEAR	BEST-GUESS			LOW-ESTIMATE			HIGH-ESTIMATE		
	Oxidation by Cover Material (%)	% LFG Flared (%)	% LFG Energy (%)	Oxidation by Cover Material (%)	% LFG Flared (%)	% LFG Energy (%)	Oxidation by Cover Material (%)	% LFG Flared (%)	% LFG Energy (%)
1998	-	-	-	-	-	-	-	-	-
1999	10	43	0	15	43	0	5	43	0
2000	10	50	0	15	50	0	5	50	0
2001	10	50	10	15	50	10	5	50	0
2002	10	50	15	15	55	15	5	50	0
2003	10	45	20	15	55	20	5	50	0
2004	10	40	25	15	50	25	5	55	0
2005	10	35	35	15	40	35	5	55	0
2006	10	30	40	15	35	40	5	55	5
2007	10	25	50	15	25	50	5	55	5
2008	10	25	50	15	30	50	5	50	10
2009	10	20	55	15	25	55	5	50	10
2010	10	20	55	15	25	55	5	50	10
2011	10	15	60	15	20	60	5	45	15
2012	10	15	60	15	20	60	5	45	15
2013	10	10	65	15	15	65	5	45	15
2014	10	10	65	15	15	65	5	40	20
2015	10	5	70	15	10	70	5	40	20
2016	10	5	70	15	10	70	5	35	25
2017	10	0	75	15	0	85	5	35	25
2018	10	0	75	15	0	85	5	35	25

#### DATA & CALCULATIONS FOR THE BURNABY INCINERATOR:

Mass of waste combusted (1998) =	247,075 tonnes of MSW
Fraction of steam sold to Crown Paperboard =	56 %
Fraction of steam to generate electricity in Turbogenerator =	0 %
Thermal efficiency of a mass-fired incinerator-boiler =	70 %
Electric efficiency of a turbo-generator =	32 %
Efficiency of natural gas combustion to generate steam =	80 %
Emission factor for natural gas consumption at Crown =	0.0621 tCO <sub>2</sub> e/GJ
Burrard Thermal Emission Average for Electricity Generation =	0.147 tCO <sub>2</sub> e/GJ
Best-guess estimate of fraction of waste-nitrogen emitted as N <sub>2</sub> O =	1.7 %N <sub>2</sub> O/waste-nitrogen
Low estimate of fraction of waste-nitrogen emitted as N <sub>2</sub> O =	0.3 %N <sub>2</sub> O/waste-nitrogen
High estimate of fraction of waste-nitrogen emitted as N <sub>2</sub> O =	3.1 %N <sub>2</sub> O/waste-nitrogen
Ammonia injected into flue gases (1998) =	295 tonnes NH <sub>3</sub>
Best-guess estimate immediate N <sub>2</sub> O emission from NH <sub>3</sub> =	0.0081 tCO <sub>2</sub> e/tonne
Low estimate immediate N <sub>2</sub> O emission from NH <sub>3</sub> =	0.0014 tCO <sub>2</sub> e/tonne
High estimate immediate N <sub>2</sub> O emission from NH <sub>3</sub> =	0.015 tCO <sub>2</sub> e/tonne
Best-Guess Estimate of the N <sub>2</sub> O from vented nitrogen =	1.0 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
Low Estimate of the N <sub>2</sub> O from vented nitrogen =	0.2 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
High Estimate of the N <sub>2</sub> O from vented nitrogen =	2.0 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
Nitrogen oxide (NO <sub>x</sub> ) emission (1998) =	449 tonnes NO
Best-guess estimate for future N <sub>2</sub> O conversion of NO <sub>x</sub> =	0.0041 tCO <sub>2</sub> e/tonne
Low estimate for future N <sub>2</sub> O conversion of NO <sub>x</sub> =	0.0008 tCO <sub>2</sub> e/tonne
High estimate for future N <sub>2</sub> O conversion of NO <sub>x</sub> =	0.0083 tCO <sub>2</sub> e/tonne
Natural gas consumption (1998) =	7516 GJ

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CO <sub>2</sub> emission from natural gas consumption=	0.0015 tCO <sub>2</sub> e/tonne
BC Hydro electricity consumption (1998)=	16011 MWh
Provincial average of BC Hydro emission intensity=	30 tCO <sub>2</sub> e/GWh
CO <sub>2</sub> emission from electricity consumption=	0.0019 tCO <sub>2</sub> e/tonne
Lime consumption (1998)=	3369 tonnes CaO
GHG emission from industrial CaO (lime) production=	0.790 tCO <sub>2</sub> e/tonne CaO
GHG emission from incinerator lime consumption=	0.011 tCO <sub>2</sub> e/tonne

#### DATA & CALCULATIONS FOR A FUTURE INCINERATOR:

Mass of waste combusted (1998) =	247,075 tonnes of MSW
Fraction of steam sold to Crown Paperboard=	56 %
Fraction of steam to generate electricity in Turbogenerator=	0 %
Thermal efficiency of a mass-fired incinerator-boiler=	70 %
Electric efficiency of a turbo-generator =	88 %
Efficiency of natural gas combustion to generate steam=	80 %
Emission factor for natural gas consumption at Crown=	0.0621 tCO <sub>2</sub> e/GJ
Burrard Thermal Emission Average for Electricity Generation=	0.147 tCO <sub>2</sub> e/GJ
Best-guess estimate of fraction of waste-nitrogen emitted as N <sub>2</sub> O=	1.7 %N <sub>2</sub> O/waste-nitrogen
Low estimate of fraction of waste-nitrogen emitted as N <sub>2</sub> O=	0.3 %N <sub>2</sub> O/waste-nitrogen
High estimate of fraction of waste-nitrogen emitted as N <sub>2</sub> O=	3.1 %N <sub>2</sub> O/waste-nitrogen
Ammonia injected into flue gases (1998) =	295 tonnes NH <sub>3</sub>
Best-guess estimate immediate N <sub>2</sub> O emission from NH <sub>3</sub> =	0.0081 tCO <sub>2</sub> e/tonne
Low estimate immediate N <sub>2</sub> O emission from NH <sub>3</sub> =	0.0014 tCO <sub>2</sub> e/tonne
High estimate immediate N <sub>2</sub> O emission from NH <sub>3</sub> =	0.015 tCO <sub>2</sub> e/tonne
Best-Guess Estimate of the N <sub>2</sub> O from vented nitrogen=	1.0 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
Low Estimate of the N <sub>2</sub> O from vented nitrogen=	0.2 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
High Estimate of the N <sub>2</sub> O from vented nitrogen=	2.0 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
Nitrogen oxide (NO <sub>x</sub> ) emission (1998) =	449 tonnes NO
Best-guess estimate for future N <sub>2</sub> O conversion of NO <sub>x</sub> =	0.0041 tCO <sub>2</sub> e/tonne
Low estimate for future N <sub>2</sub> O conversion of NO <sub>x</sub> =	0.0008 tCO <sub>2</sub> e/tonne
High estimate for future N <sub>2</sub> O conversion of NO <sub>x</sub> =	0.0083 tCO <sub>2</sub> e/tonne
Natural gas consumption (1998)=	7516 GJ
CO <sub>2</sub> emission from natural gas consumption=	0.0015 tCO <sub>2</sub> e/tonne
BC Hydro electricity consumption (1998)=	16011 MWh
Provincial average of BC Hydro emission intensity=	30 tCO <sub>2</sub> e/GWh
CO <sub>2</sub> emission from electricity consumption=	0.0019 tCO <sub>2</sub> e/tonne
Lime consumption (1998)=	3369 tonnes CaO
GHG emission from industrial CaO (lime) production=	0.790 tCO <sub>2</sub> e/tonne CaO
GHG emission from incinerator lime consumption=	0.011 tCO <sub>2</sub> e/tonne

#### WASTE DELIVERED TO THE COQUITLAM TRANSFER STATION

- Diesel Fuel Consumption by Transfer Station Equipment:**

Diesel fuel consumption by equipment (1998)=	279,495 L
Mass of waste managed (1998)=	319,651 tonnes
GHG emission from equipment =	0.0025 tCO <sub>2</sub> e/tonne
- Diesel Fuel Consumption for Transport to the Cache Creek Landfill:**

Diesel fuel consumption per trip (only one way)=	200 L
# of round trips in 1998=	8112 trips
Mass of waste transported (1998)=	303,608 tonnes
Average mass of waste transported=	37.4 tonnes/trip
GHG emission from waste transport =	0.015 tCO <sub>2</sub> e/tonne
- Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:**

Diesel fuel consumption during disposal (1998)=	812,499 L
Mass collected during this consumption (1998)=	474,873 tonnes
GHG emission from waste collection =	0.0049 tCO <sub>2</sub> e/tonne
- Diesel Fuel Consumption for Transport to the Vancouver Landfill:**

Diesel fuel consumption per trip (round-trip)=	45 L
# of round trips in 1998=	339 trips
Mass of waste transported (1998)=	8,189 tonnes
Average mass of waste transported =	24.2 tonnes/trip
GHG emission from waste transport =	0.0053 tCO <sub>2</sub> e/tonne
- Diesel Fuel Consumption by Equipment at the Vancouver Landfill:**

Diesel fuel consumption during disposal (1998)=	479,000 L
Mass collected during this consumption (1998)=	379,554 tonnes
GHG emission from waste collection =	0.0036 tCO <sub>2</sub> e/tonne
- Diesel Fuel Consumption for Transport to a Future Landfill:**

Diesel fuel consumption per trip (round-trip)=	0 L
# of round trips in 1998=	1 trips
Mass of waste transported (1998)=	1 tonnes
Average mass of waste transported =	1.0 tonnes/trip
GHG emission from waste transport =	0.0000 tCO <sub>2</sub> e/tonne
- Diesel Fuel Consumption by Equipment at a Future Landfill:**

Diesel fuel consumption during disposal (1998)=	0 L
Mass collected during this consumption (1998)=	1 tonnes
GHG emission from waste collection =	0.0000 tCO <sub>2</sub> e/tonne

8 Diesel Fuel Consumption for Transport to the Burnaby Incinerator:  
 Diesel fuel consumption per round trip= 23 L  
 # of round trips in 1998= 176 trips  
 Mass of waste transported (1998)= 3,981 tonnes  
 Average mass of waste transported= 22.6 tonnes/trip  
 GHG emission from waste transport = 0.0029 tCO<sub>2</sub>e/tonne

9 Diesel Fuel Consumption for Transport to a Future Incinerator:  
 Diesel fuel consumption per round trip= 0 L  
 # of round trips in 1998= 1 trips  
 Mass of waste transported (1998)= 1 tonnes  
 Average mass of waste transported= 1.0 tonnes/trip  
 GHG emission from waste transport = 0.0000 tCO<sub>2</sub>e/tonne

Total for Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne  
 Total for Waste Disposed at the Vancouver Landfill= 0.0114 tCO<sub>2</sub>e/tonne  
 Total for Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne  
 Total for Waste Disposed at the Burnaby Incinerator= 0.0054 tCO<sub>2</sub>e/tonne  
 Total for Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

#### WASTE DELIVERED TO THE NORTH SHORE TRANSFER STATION

1 Diesel Fuel Consumption by Transfer Station Equipment:  
 Diesel fuel consumption by equipment (1998)= 87,918 L  
 Mass of waste managed (1998)= 194,755 tonnes  
 GHG emission from equipment = 0.0013 tCO<sub>2</sub>e/tonne

2 Diesel Fuel Consumption for Transport to the Cache Creek Landfill:  
 Diesel fuel consumption per trip (only one way)= 215 L  
 # of round trips in 1998= 2,283 trips  
 Mass of waste transported (1998)= 82,830 tonnes  
 Average mass of waste transported= 36.3 tonnes/trip  
 GHG emission from waste transport = 0.017 tCO<sub>2</sub>e/tonne

3 Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:  
 Diesel fuel consumption during disposal (1998)= 812,499 L  
 Mass collected during this consumption (1998)= 474,873 tonnes  
 GHG emission from waste collection = 0.0049 tCO<sub>2</sub>e/tonne

4 Diesel Fuel Consumption for Transport to the Vancouver Landfill:  
 Diesel fuel consumption per trip (round-trip)= 45 L  
 # of round trips in 1998= 71 trips  
 Mass of waste transported (1998)= 1,754 tonnes  
 Average mass of waste transported = 24.7 tonnes/trip  
 GHG emission from waste transport = 0.0052 tCO<sub>2</sub>e/tonne

5 Diesel Fuel Consumption by Equipment at the Vancouver Landfill:  
 Diesel fuel consumption during disposal (1998)= 479,000 L  
 Mass collected during this consumption (1998)= 379,554 tonnes  
 GHG emission from waste collection = 0.0036 tCO<sub>2</sub>e/tonne

6 Diesel Fuel Consumption for Transport to a Future Landfill:  
 Diesel fuel consumption per trip (round-trip)= 0 L  
 # of round trips in 1998= 1 trips  
 Mass of waste transported (1998)= 1 tonnes  
 Average mass of waste transported = 1.0 tonnes/trip  
 GHG emission from waste transport = 0.0000 tCO<sub>2</sub>e/tonne

7 Diesel Fuel Consumption by Equipment at a Future Landfill:  
 Diesel fuel consumption during disposal (1998)= 0 L  
 Mass collected during this consumption (1998)= 1 tonnes  
 GHG emission from waste collection = 0.0000 tCO<sub>2</sub>e/tonne

8 Diesel Fuel Consumption for Transport to the Burnaby Incinerator:  
 Diesel fuel consumption per round trip= 23 L  
 # of round trips in 1998= 3609 trips  
 Mass of waste transported (1998)= 89,942 tonnes  
 Average mass of waste transported= 24.9 tonnes/trip  
 GHG emission from waste transport = 0.0026 tCO<sub>2</sub>e/tonne

9 Diesel Fuel Consumption for Transport to a Future Incinerator:  
 Diesel fuel consumption per round trip= 0 L  
 # of round trips in 1998= 1 trips  
 Mass of waste transported (1998)= 1 tonnes  
 Average mass of waste transported= 1.0 tonnes/trip  
 GHG emission from waste transport = 0.0000 tCO<sub>2</sub>e/tonne

Total for Waste Disposed at the Cache Creek Landfill= 0.0231 tCO<sub>2</sub>e/tonne  
 Total for Waste Disposed at the Vancouver Landfill= 0.0101 tCO<sub>2</sub>e/tonne  
 Total for Waste Disposed at a Future Landfill= 0.0013 tCO<sub>2</sub>e/tonne  
 Total for Waste Disposed at the Burnaby Incinerator= 0.0039 tCO<sub>2</sub>e/tonne  
 Total for Waste Disposed at a Future Incinerator= 0.0013 tCO<sub>2</sub>e/tonne

# WASTE DELIVERED TO THE VANCOUVER TRANSFER STATION

<b>1 Diesel Fuel Consumption by Transfer Station Equipment:</b>	
Diesel fuel consumption by equipment (1998)=	87,650 L
Mass of waste managed (1998)=	273,691 tonnes
GHG emission from equipment =	0.0009 tCO <sub>2</sub> e/tonne
<b>2 Diesel Fuel Consumption for Transport to the Cache Creek Landfill:</b>	
Diesel fuel consumption per trip (only one way)=	215 L
# of round trips in 1998=	2,283 trips
Mass of waste transported (1998)=	82,930 tonnes
Average mass of waste transported=	36.3 tonnes/trip
GHG emission from waste transport =	0.017 tCO <sub>2</sub> e/tonne
<b>3 Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	812,499 L
Mass collected during this consumption (1998)=	474,873 tonnes
GHG emission from waste collection =	0.0049 tCO <sub>2</sub> e/tonne
<b>4 Diesel Fuel Consumption for Transport to the Vancouver Landfill:</b>	
Total diesel fuel consumption =	334,000 L
# of round trips in 1998=	12,500 trips
Mass of waste transported (1998)=	287,931 tonnes
Average mass of waste transported =	23.0 tonnes/trip
Average fuel consumption per trip =	26.7 L/trip
GHG emission from waste transport =	0.0033 tCO <sub>2</sub> e/tonne
<b>5 Diesel Fuel Consumption by Equipment at the Vancouver Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	479,000 L
Mass collected during this consumption (1998)=	379,554 tonnes
GHG emission from waste collection =	0.0036 tCO <sub>2</sub> e/tonne
<b>6 Diesel Fuel Consumption for Transport to a Future Landfill:</b>	
Total diesel fuel consumption =	0 L
# of round trips in 1998=	1 trips
Mass of waste transported (1998)=	1 tonnes
Average mass of waste transported =	1.0 tonnes/trip
Average fuel consumption per trip =	0.0 L/trip
GHG emission from waste transport =	0.0000 tCO <sub>2</sub> e/tonne
<b>7 Diesel Fuel Consumption by Equipment at a Future Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	0 L
Mass collected during this consumption (1998)=	1 tonnes
GHG emission from waste collection =	0.0000 tCO <sub>2</sub> e/tonne
<b>8 Diesel Fuel Consumption for Transport to the Burnaby Incinerator:</b>	
Tonnes hauled per trip =	20 tonnes/trip
Distance per trip =	22 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0014 tCO <sub>2</sub> e/tonne
<b>9 Diesel Fuel Consumption for Transport to a Future Incinerator:</b>	
Tonnes hauled per trip =	1 tonnes/trip
Distance per trip =	0 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0000 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at the Cache Creek Landfill=	0.0227 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at the Vancouver Landfill=	0.0076 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at a Future Landfill=	0.0009 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at the Burnaby Incinerator=	0.0023 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at a Future Incinerator=	0.0009 tCO <sub>2</sub> e/tonne

# WASTE DELIVERED TO THE MATSQUI TRANSFER STATION

<b>1 Diesel Fuel Consumption by Transfer Station Equipment:</b>	
Diesel fuel consumption by equipment (1998)=	33,280 L
Mass of waste managed (1998)=	75,850 tonnes
GHG emission from equipment =	0.0013 tCO <sub>2</sub> e/tonne
<b>2 Diesel Fuel Consumption for Transport to the Cache Creek Landfill:</b>	
Diesel fuel consumption per trip (only one way)=	185 L
# of round trips in 1998=	2,104 trips
Mass of waste transported (1998)=	73,169 tonnes
Average mass of waste transported=	34.8 tonnes/trip
GHG emission from waste transport =	0.015 tCO <sub>2</sub> e/tonne
<b>3 Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	812,499 L
Mass collected during this consumption (1998)=	474,873 tonnes
GHG emission from waste collection =	0.0049 tCO <sub>2</sub> e/tonne
<b>4 Diesel Fuel Consumption for Transport to the Vancouver Landfill:</b>	
Tonnes hauled per trip =	20 tonnes/trip
Distance per trip =	130 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0083 tCO <sub>2</sub> e/tonne

<b>5 Diesel Fuel Consumption by Equipment at the Vancouver Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	479,000 L
Mass collected during this consumption (1998)=	379,554 tonnes
GHG emission from waste collection =	0.0036 tCO <sub>2</sub> e/tonne
<b>6 Diesel Fuel Consumption for Transport to a Future Landfill:</b>	
Total diesel fuel consumption =	0 L
# of round trips in 1998=	1 trips
Mass of waste transported (1998)=	1 tonnes
Average mass of waste transported =	1.0 tonnes/trip
Average fuel consumption per trip =	0.0 L/trip
GHG emission from waste transport =	0.0000 tCO <sub>2</sub> e/tonne
<b>7 Diesel Fuel Consumption by Equipment at a Future Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	0 L
Mass collected during this consumption (1998)=	1 tonnes
GHG emission from waste collection =	0.0000 tCO <sub>2</sub> e/tonne
<b>8 Diesel Fuel Consumption for Transport to the Burnaby Incinerator:</b>	
Tonnes hauled per trip =	20 tonnes/trip
Distance per trip =	120 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0077 tCO <sub>2</sub> e/tonne
<b>9 Diesel Fuel Consumption for Transport to a Future Incinerator:</b>	
Tonnes hauled per trip =	1 tonnes/trip
Distance per trip =	0 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0000 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at the Cache Creek Landfill=	0.0213 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at the Vancouver Landfill=	0.0132 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at a Future Landfill=	0.0013 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at the Burnaby Incinerator=	0.0090 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at a Future Incinerator=	0.0013 tCO <sub>2</sub> e/tonne

#### WASTE DELIVERED TO THE LANGLEY TRANSFER STATION

<b>1 Diesel Fuel Consumption by Transfer Station Equipment:</b>	
Average GHG emission from equipment =	0.0015 tCO <sub>2</sub> e/tonne
<b>2 Diesel Fuel Consumption for Transport to the Cache Creek Landfill:</b>	
Transfer to the Matsqui Transfer Station	
Tonnes hauled per trip =	20 tonnes/trip
Distance per trip =	40 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0026 tCO <sub>2</sub> e/tonne
Processing at the Matsqui Transfer Station	
Diesel fuel consumption by equipment (1998)=	33,280 L
Mass of waste managed (1998)=	75,850 tonnes
GHG emission from equipment =	0.0013 tCO <sub>2</sub> e/tonne
Transfer to the Cache Creek Landfill	
Diesel fuel consumption per trip (only one way)=	185 L
# of round trips in 1998=	2,104 trips
Mass of waste transported (1998)=	73,169 tonnes
Average mass of waste transported=	34.8 tonnes/trip
GHG emission from waste transport =	0.015 tCO <sub>2</sub> e/tonne
<b>3 Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	812,499 L
Mass collected during this consumption (1998)=	474,873 tonnes
GHG emission from waste collection =	0.0049 tCO <sub>2</sub> e/tonne
<b>4 Diesel Fuel Consumption for Transport to the Vancouver Landfill:</b>	
Tonnes hauled per trip =	20 tonnes/trip
Distance per trip =	85 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0055 tCO <sub>2</sub> e/tonne
<b>5 Diesel Fuel Consumption by Equipment at the Vancouver Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	479,000 L
Mass collected during this consumption (1998)=	379,554 tonnes
GHG emission from waste collection =	0.0036 tCO <sub>2</sub> e/tonne
<b>6 Diesel Fuel Consumption for Transport to a Future Landfill:</b>	
Total diesel fuel consumption =	0 L
# of round trips in 1998=	1 trips
Mass of waste transported (1998)=	1 tonnes
Average mass of waste transported =	1.0 tonnes/trip
Average fuel consumption per trip =	0.0 L/trip
GHG emission from waste transport =	0.0000 tCO <sub>2</sub> e/tonne

<b>7 Diesel Fuel Consumption by Equipment at a Future Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	0 L
Mass collected during this consumption (1998)=	1 tonnes
GHG emission from waste collection =	0.0000 tCO <sub>2</sub> e/tonne
<b>8 Diesel Fuel Consumption for Transport to the Burnaby Incinerator:</b>	
Tonnes hauled per trip =	20 tonnes/trip
Distance per trip =	90 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0058 tCO <sub>2</sub> e/tonne
<b>9 Diesel Fuel Consumption for Transport to a Future Incinerator:</b>	
Tonnes hauled per trip =	1 tonnes/trip
Distance per trip =	0 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0000 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at the Cache Creek Landfill=	0.0254 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at the Vancouver Landfill=	0.0106 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at a Future Landfill=	0.0015 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at the Burnaby Incinerator=	0.0073 tCO <sub>2</sub> e/tonne
Total for Waste Disposed at a Future Incinerator=	0.0015 tCO <sub>2</sub> e/tonne

#### WASTE DELIVERED TO THE MAPLE RIDGE TRANSFER STATION

<b>1 Diesel Fuel Consumption by Transfer Station Equipment:</b>	
Average GHG emission from equipment =	0.0015 tCO <sub>2</sub> e/tonne
<b>2 Diesel Fuel Consumption for Transport to the Cache Creek Landfill:</b>	
Transfer to the Matsqui Transfer Station	
Tonnes hauled per trip =	20 tonnes/trip
Distance per trip =	60 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0039 tCO <sub>2</sub> e/tonne
Processing at the Matsqui Transfer Station	
Diesel fuel consumption by equipment (1998)=	33,280 L
Mass of waste managed (1998)=	75,850 tonnes
GHG emission from equipment =	0.0013 tCO <sub>2</sub> e/tonne
Transfer to the Cache Creek Landfill	
Diesel fuel consumption per trip (only one way)=	185 L
# of round trips in 1998=	2,104 trips
Mass of waste transported (1998)=	73,169 tonnes
Average mass of waste transported=	34.8 tonnes/trip
GHG emission from waste transport =	0.015 tCO <sub>2</sub> e/tonne
<b>3 Diesel Fuel Consumption by Equipment at the Cache Creek Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	812,499 L
Mass collected during this consumption (1998)=	474,873 tonnes
GHG emission from waste collection =	0.0049 tCO <sub>2</sub> e/tonne
<b>4 Diesel Fuel Consumption for Transport to the Vancouver Landfill:</b>	
Tonnes hauled per trip =	20 tonnes/trip
Distance per trip =	110 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0071 tCO <sub>2</sub> e/tonne
<b>5 Diesel Fuel Consumption by Equipment at the Vancouver Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	479,000 L
Mass collected during this consumption (1998)=	379,554 tonnes
GHG emission from waste collection =	0.0038 tCO <sub>2</sub> e/tonne
<b>6 Diesel Fuel Consumption for Transport to a Future Landfill:</b>	
Total diesel fuel consumption =	0 L
# of round trips in 1998=	1 trips
Mass of waste transported (1998)=	1 tonnes
Average mass of waste transported =	1.0 tonnes/trip
Average fuel consumption per trip =	0.0 L/trip
GHG emission from waste transport =	0.0000 tCO <sub>2</sub> e/tonne
<b>7 Diesel Fuel Consumption by Equipment at a Future Landfill:</b>	
Diesel fuel consumption during disposal (1998)=	0 L
Mass collected during this consumption (1998)=	1 tonnes
GHG emission from waste collection =	0.0000 tCO <sub>2</sub> e/tonne
<b>8 Diesel Fuel Consumption for Transport to the Burnaby Incinerator:</b>	
Tonnes hauled per trip =	20 tonnes/trip
Distance per trip =	75 km
Diesel Fuel Consumption =	45.0 L/100 km
GHG emission =	0.0048 tCO <sub>2</sub> e/tonne
<b>9 Diesel Fuel Consumption for Transport to a Future Incinerator:</b>	
Tonnes hauled per trip =	1 tonnes/trip
Distance per trip =	0 km

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Diesel Fuel Consumption = 45.0 L/100 km  
GHG emission = 0.0000 tCO<sub>2</sub>e/tonne

Total for Waste Disposed at the Cache Creek Landfill= 0.0267 tCO<sub>2</sub>e/tonne  
Total for Waste Disposed at the Vancouver Landfill= 0.0122 tCO<sub>2</sub>e/tonne  
Total for Waste Disposed at a Future Landfill= 0.0015 tCO<sub>2</sub>e/tonne  
Total for Waste Disposed at the Burnaby Incinerator= 0.0063 tCO<sub>2</sub>e/tonne  
Total for Waste Disposed at a Future Incinerator= 0.0015 tCO<sub>2</sub>e/tonne

#### RECYCLING EQUIPMENT

Diesel Fuel Consumption by Equipment at Recycling Facilities:  
Propane fuel consumption during processing (1998)= 0.45 L/tonne recyclables  
GHG emission from waste collection = 0.0007 tCO<sub>2</sub>e/tonne

#### CENTRALIZED COMPOSTING EQUIPMENT

Diesel Fuel Consumption by Equipment at Composting Facilities:  
Diesel fuel consumption composting= 221,000 BTU/short ton of yard trimmings  
GHG emission from waste collection = 0.019 tCO<sub>2</sub>e/tonne



# CITY OF ABBOTSFORD:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	4,737	585	84,687	56	7	113,375	6342	783	7125
Mixed Paper	5,782	3,291	84,687			113,375			
Office Paper	809	461	84,687	10	5	113,375	1084	617	1701
Ferrous Metal	493	1,899	84,687	6	22	113,375	660	2542	3202
Glass	1,081	528	84,687	13	6	113,375	1447	707	2154
HDPE	297	222	84,687	4	3	113,375	398	297	695
Mixed Plastics	2,084	1,333	84,687			113,375			
LDPE	938	600	84,687	11	7	113,375	1255	803	2059
Food Waste	3,110	2,146	84,687	37	25	113,375	4164	2873	7036
Yard Waste	2,537	791	84,687	30	9	113,375	3396	1059	4455

Total ICI waste generated in 1998= 55,397 tonnes

Total ICI waste recycled in 1998= 21,797 tonnes

ICI Recycling Rate= 39 %

# of backyard composters = 8,947

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	6,342	783	3,104			308	3,412		
Mixed Paper			553						
Office Paper	1,084	617	77			243	320		
Metal			202						
Ferrous Metal	660	2,542	101			1,000	1,101		
Glass	1,447	707	318			278	596		
Plastics			119						
HDPE	398	297	39			117	156		
LDPE	1,255	803	39			316	355		
Food Waste	4,164	2,873		743	0	1,130		743	1,130
Yard Waste	3,396	1,059		1,494	3,780	417		1,494	4,197

Total waste disposed in 1998= 48,949 tonnes

Total waste recycled in 1998= 34,959 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF (%)	% OF M <sub>DIS</sub> to VLF (%)	% OF M <sub>DIS</sub> to FutLF (%)	% OF M <sub>DIS</sub> to Burlnc (%)	% OF M <sub>DIS</sub> to FutInc (%)	Disposal 1998 CCLF (tonnes)	Disposal 1998 VLF (tonnes)	Disposal 1998 FutLF (tonnes)	Disposal 1998 Burlnc (tonnes)	Disposal 1998 FutInc (tonnes)
Newsprint	7125	3,412	3,713	99.9	0.0	0.0	0.0	0.0	3,710	2	0	1	0
Office Paper	1701	320	1,380	99.9	0.0	0.0	0.0	0.0	1,380	1	0	0	0
Ferrous Metal	3202	1,101	2,101	99.9	0.0	0.0	0.0	0.0	2,100	1	0	0	0
Glass	2154	596	1,558	99.9	0.0	0.0	0.0	0.0	1,557	1	0	0	0
HDPE	695	156	539	99.9	0.0	0.0	0.0	0.0	538	0	0	0	0
LDPE	2059	355	1,703	99.9	0.0	0.0	0.0	0.0	1,702	1	0	0	0
Food Waste	7036	1,873	5,163	99.9	0.0	0.0	0.0	0.0	5,160	2	0	1	0
Yard Waste	4455	5,691	0	99.9	0.0	0.0	0.0	0.0	0	0	0	0	0
Remainder		21,454	32,792	99.9	0.0	0.0	0.0	0.0	32,772	13	0	7	0
TOTAL=									48,919	20	0	10	0

## EMISSION FACTORS:

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection =

0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection =

0.043 tCO<sub>2</sub>e/tonne

### 3 Emission Factor for Waste Disposal:

All waste is assumed to be delivered to the Matsqui Transfer Station.

Waste Disposed at the Cache Creek Landfill=

0.0213 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill=

0.0132 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill=

0.0013 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator=

0.0090 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator=

0.0013 tCO<sub>2</sub>e/tonne

# CITY OF BURNABY:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	esidenti eneration 1991	ICI eneration 1991	opulation o Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	opulation o Municipality 1998	Residential Generation 1998	ICI Generation 1998	Total Generation 1998
	(tonnes)	(tonnes)	(tonnes)				(tonnes)	(tonnes)	(tonnes)
Newsprint	8,279	3,602	158,858	52	23	191,600	9885	4344	14330
Mixed Paper	13,025	19,112	158,858			191,600			0
Office Pap	1,824	2,676	158,858	11	17	191,600	2199	3227	5426
Ferrous Met	1,061	10,914	158,858		69	191,600	1280	13163	14443
Glass	2,069	2,979	158,858	13	19	191,600	2495	3593	6088
HDPE	690	1,213	158,858	4	8	191,600	832	1463	2295
Mixed Plasti	3,695	8,541	158,858			191,600			
LDPE	1,663	3,843	158,858	10	24	191,600	2005	4636	6641
Food Waste	5,451	11,116	158,858	34	70	191,600	6574	13407	19982
Yard Waste	5,433	4,261	158,858	34	27	191,600	6553	5139	11692

Total ICI waste generated in 1998= 164,172 tonnes

Total ICI waste recycled in 1998= 67,479 tonnes

ICI Recycling Rate= 41 %

# of backyard composters = 8,968

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	esidenti eneration 1998	ICI eneration 1998	Residential Recycling 1998	Backyard Compostin 1998	Centralize Compostin 1998	ICI Recycling 1998	Total Recycling 1998	Backyard Compostin 1998	Centralized Composting 1998
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
Newsprint	9,985	4,344	4,155			1,786	5,941		
Mixed Paper			3,959						
Office Pap	2,199	3,227	554			1,326	1,881		
Metal			829						
Ferrous M	1,280	13,163	415			5,411	5,825		
Glass	2,495	3,593	207			1,477	1,684		
Plastics			98						
HDPE	832	1,463	32			801	634		
LDPE	2,005	4,636	32			1,905	1,938		
Food Waste	6,574	13,407		744	0	5,511		744	5,511
Yard Waste	6,553	5,139		1,498	8,004	2,112		1,498	10,118

Total waste disposed in 1998= 129,089 tonnes

Total waste recycled in 1998= 87,526 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total eneration 1998	Total Recycling 1998	Waste Disposal 1998	% OF M <sub>DIS</sub> to CCLF 1998	% OF M <sub>DIS</sub> to VLF 1998	% OF M <sub>DIS</sub> to FuLF 1998	% OF M <sub>DIS</sub> to Burlnc 1998	% OF M <sub>DIS</sub> to FutInc 1998	Disposal CCLF 1998	Dispos VLF 1998	Dispos FuLF 1998	Dispos Burlnc 1998	Dispos FutInc 1998
	(tonnes)	(tonnes)	(tonnes)	(%)	(%)	(%)	(%)	(%)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
Newsprint	14330	5,941	8,389	24.0	0.6	0.0	75.4	0.0	2,011	52	0	6,325	0
Office Paper	5426	1,881	3,546	24.0	0.6	0.0	75.4	0.0	850	22	0	2,674	0
Ferrous Met	14443	5,825	8,618	24.0	0.6	0.0	75.4	0.0	2,068	54	0	6,498	0
Glass	6088	1,684	4,405	24.0	0.6	0.0	75.4	0.0	1,056	28	0	3,321	0
HDPE	2295	634	1,662	24.0	0.6	0.0	75.4	0.0	398	10	0	1,253	0
LDPE	6641	1,938	4,703	24.0	0.6	0.0	75.4	0.0	1,128	29	0	3,546	0
Food Waste	19982	6,255	13,727	24.0	0.6	0.0	75.4	0.0	3,291	86	0	10,350	0
Yard Waste	11692	11,614	78	24.0	0.6	0.0	75.4	0.0	19	0	0	59	0
Remainder	51,755	83,962		24.0	0.6	0.0	75.4	0.0	20,130	524	0	63,308	0
TOTAL=									30,949	806	0	97,334	0

## EMISSION FACTORS:

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Diesel fuel consumption during collection (1998)= 156,000 L  
 Mass collected during this consumption (1998)= 23,098 tonnes  
 GHG emission from waste collection = 0.019 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Diesel fuel consumption during collection (1998)= 134,000 L  
 Mass collected during this consumption (1998)= 8,437 tonnes  
 GHG emission from waste collection = 0.045 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Diesel fuel consumption during collection (1998)= 58,000 L  
 Mass collected during this consumption (1998)= 6,798 tonnes  
 GHG emission from waste collection = 0.024 tCO<sub>2</sub>e/tonne

### 3 Emission Factor for Waste Disposal:

Most waste to the Burnaby Incinerator is directly delivered, however a portion is assumed to pass through the Coquitlam Transfer Station. This requires a correction of the emission factor for the Burnaby Incinerator. Waste disposed at the CCLF, the VLF, a Future LF or Future Incinerator is assumed to pass through the CTS.

Assumed Percentage of Waste Directly Delivered to the BI= 71 %  
 Assumed Percentage of Waste Transferred to the BI from CTS= 15 %  
 Assumed Percentage of Waste Transferred to the CCLF from the  
 Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne  
 Waste Disposed at the Vancouver Landfill= 0.0114 tCO<sub>2</sub>e/tonne  
 Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne  
 Waste Disposed at the Burnaby Incinerator= 0.0009 tCO<sub>2</sub>e/tonne  
 Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

# CITY OF COQUITLAM:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	5,138	794	84,021	61	9	110,423	6753	1043	7796
Mixed Paper	5,724	3,902	84,021			110,423			
Office Paper	801	546	84,021	10	7	110,423	1053	718	1771
Ferrous Metal	597	2,332	84,021	7	28	110,423	785	3065	3849
Glass	1,674	691	84,021	20	8	110,423	2200	908	3108
HDPE	315	330	84,021	4	4	110,423	414	434	848
Mixed Plastics	2,087	1,613	84,021		19	110,423		2120	
LDPE	939	726	84,021	11	9	110,423	1234	954	2188
Food Waste	3,061	2,146	84,021	36	26	110,423	4023	2820	6843
Yard Waste	2,902	791	84,021	35	9	110,423	3814	1040	4853

Total ICI waste generated in 1998= 80,849 tonnes

Total ICI waste recycled in 1998= 17,949 tonnes

ICI Recycling Rate= 22 %

# of backyard composters = 3,491

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	entralized composting 1998 (tonnes)
Newsprint	6,753	1,043	2,605			232	2,837		
Mixed Paper			1,960						
Office Paper	1,053	718	274			159	434		
Metal			199						
Ferrous Metal	785	3,065	100			680	780		
Glass	2,200	908	636			202	838		
Plastics			222						
HDPE	414	434	73			96	170		
LDPE	1,234	954	73			212	285		
Food Waste	4,023	2,820		290	0	626		290	626
Yard Waste	3,814	1,040		583	3,252	231		583	3,483

Total waste disposed in 1998= 94,003 tonnes

Total waste recycled in 1998= 27,816 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF (%)	% OF M <sub>DIS</sub> to VLF (%)	% OF M <sub>DIS</sub> to FutLF (%)	% OF M <sub>DIS</sub> to Burlnc (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal 1998 CCLF (tonnes)	Disposal 1998 VLF (tonnes)	Disposal 1998 FutLF (tonnes)	Disposal 1998 Burlnc (tonnes)	Disposal 1998 FutInc (tonnes)
Newsprint	7796	2,837	4,959	96.1	2.6	0.0	1.3	0.0	4,764	129	0	67	0
Office Paper	1771	434	1,337	96.1	2.6	0.0	1.3	0.0	1,285	35	0	18	0
Ferrous Metal	3849	780	3,069	96.1	2.6	0.0	1.3	0.0	2,949	80	0	41	0
Glass	3108	838	2,271	96.1	2.6	0.0	1.3	0.0	2,181	59	0	30	0
HDPE	848	170	678	96.1	2.6	0.0	1.3	0.0	651	18	0	9	0
LDPE	2188	285	1,903	96.1	2.6	0.0	1.3	0.0	1,828	49	0	26	0
Food Waste	6843	916	5,927	96.1	2.6	0.0	1.3	0.0	5,694	154	0	80	0
Yard Waste	4853	4,066	788	96.1	2.6	0.0	1.3	0.0	757	20	0	11	0
Remainder		17,492	73,070	96.1	2.6	0.0	1.3	0.0	70,196	1,893	0	981	0
TOTAL=									90,305	2,436	0	1,262	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

All waste is assumed to be delivered to the Coquitlam Transfer Station.

Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0114 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0054 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

### 5 Diesel Fuel Consumption for Yard Trimmings Transport to Fraser-Richmond BioCycle:

Tonnes hauled per trip = 20 tonnes/trip

Distance per trip = 60 km

Diesel Fuel Consumption = 45.0 L/100 km

GHG emission = 0.004 tCO<sub>2</sub>e/tonne

# CORPORATION OF DELTA:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	5,987	1,010	88,978	67	11	101,018	6797	1147	7944
Mixed Paper	6,138	6,090	88,978			101,018			0
Office Paper	859	853	88,978	10	10	101,018	976	968	1944
Ferrous Metal	770	3,366	88,978	9	38	101,018	874	3821	4696
Glass	1,680	898	88,978	19	10	101,018	1907	1020	2927
HDPE	306	302	88,978	3	3	101,018	347	343	690
Mixed Plastics	2,037	2,571	88,978			101,018			
LDPE	917	1,157	88,978	10	13	101,018	1041	1314	2354
Food Waste	2,981	3,118	88,978	34	35	101,018	3384	3540	6924
Yard Waste	3,554	1,247	88,978	40	14	101,018	4035	1416	5451

Total ICI waste generated in 1998= 35,704 tonnes

Total ICI waste recycled in 1998= 11,843 tonnes

ICI Recycling Rate= 33 %

# of backyard composters = 9,575

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	6,797	1,147	2,251			380	2,631		
Mixed Paper			2,170						
Office Paper	976	968	304			321	625		
Metal			583						
Ferrous Metal	874	3,821	292			1,268	1,559		
Glass	1,907	1,020	824			338	1,162		
Plastics			322						
HDPE	347	343	106			114	220		
LDPE	1,041	1,314	106			436	542		
Food Waste	3,384	3,540		795	0	1,174		795	1,174
Yard Waste	4,035	1,416		1,599	2,800	470		1,599	3,270

Total waste disposed in 1998= 69,104 tonnes

Total waste recycled in 1998= 24,254 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to Burlnc 1998 (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal CCLF 1998 (tonnes)	Disposal VLF 1998 (tonnes)	Disposal FutLF 1998 (tonnes)	Disposal Burlnc 1998 (tonnes)	Disposal FutInc 1998 (tonnes)
Newsprint	7944	2,631	5,312	5.5	94.4	0.0	0.1	0.0	294	5,015	0	4	0
Office Paper	1944	625	1,319	5.5	94.4	0.0	0.1	0.0	73	1,245	0	1	0
Ferrous Metal	4696	1,559	3,137	5.5	94.4	0.0	0.1	0.0	173	2,961	0	2	0
Glass	2927	1,162	1,765	5.5	94.4	0.0	0.1	0.0	98	1,666	0	1	0
HDPE	690	220	470	5.5	94.4	0.0	0.1	0.0	26	444	0	0	0
LDPE	2354	542	1,812	5.5	94.4	0.0	0.1	0.0	100	1,711	0	1	0
Food Waste	6924	1,969	4,955	5.5	94.4	0.0	0.1	0.0	274	4,678	0	4	0
Yard Waste	5451	4,869	582	5.5	94.4	0.0	0.1	0.0	32	549	0	0	0
Remainder		10,677	49,752	5.5	94.4	0.0	0.1	0.0	2,750	46,965	0	36	0
TOTAL=									3,820	65,234	0	50	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Diesel fuel consumption during collection (1998)=

134,000 L

Mass collected during this consumption (1998)=

67,110 tonnes

GHG emission from waste collection =

0.006 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection =

0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Diesel fuel consumption during collection (1998)=

23,075 L

Mass collected during this consumption (1998)=

2,227 tonnes

GHG emission from waste collection =

0.030 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

Waste is directly delivered to the VLF and the BI.

Emission factors are only for the CCLF, FutLF and FutInc which all go through the CTS.

Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0000 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0000 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

# CITY OF LANGLEY:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	838	217	19,765	42	11	24,094	1022	265	1286
Mixed Paper	1,502	1,168	19,765			24,094			
Office Paper	210	164	19,765	11	8	24,094	256	199	456
Ferrous Metal	115	735	19,765	6	37	24,094	140	896	1036
Glass	238	185	19,765	12	9	24,094	290	226	516
HDPE	74	78	19,765	4	4	24,094	90	95	185
Mixed Plastics	507	505	19,765			24,094			
LDPE	228	227	19,765	12	11	24,094	278	277	555
Food Waste	753	740	19,765	38	37	24,094	918	902	1820
Yard Waste	779	266	19,765	39	13	24,094	950	324	1274

Total ICI waste generated in 1998= 18,835 tonnes

Total ICI waste recycled in 1998= 5,530 tonnes

ICI Recycling Rate= 29 %

# of backyard composters = 465

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	1,022	265	539			78	617		
Mixed Paper			351						
Office Paper	256	199	49			59	108		
Metal			37						
Ferrous Metal	140	896	19			263	282		
Glass	290	226	117			66	183		
Plastics			41						
HDPE	90	95	14			28	41		
LDPE	278	277	14			81	95		
Food Waste	918	902		39	0	265		39	265
Yard Waste	950	324		78	40	95		78	135

Total waste disposed in 1998= 13,995 tonnes

Total waste recycled in 1998= 7,209 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to Burlnc 1998 (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal CCLF 1998 (tonnes)	Disposal VLF 1998 (tonnes)	Disposal FutLF 1998 (tonnes)	Disposal Burlnc 1998 (tonnes)	Disposal FutInc 1998 (tonnes)
Newsprint	1286	617	669	97.2	1.9	0.0	0.9	0.0	651	13	0	6	0
Office Paper	456	108	348	97.2	1.9	0.0	0.9	0.0	338	7	0	3	0
Ferrous Metal	1036	282	755	97.2	1.9	0.0	0.9	0.0	734	14	0	7	0
Glass	516	183	332	97.2	1.9	0.0	0.9	0.0	323	6	0	3	0
HDPE	185	41	144	97.2	1.9	0.0	0.9	0.0	140	3	0	1	0
LDPE	555	95	460	97.2	1.9	0.0	0.9	0.0	447	9	0	4	0
Food Waste	1820	303	1,517	97.2	1.9	0.0	0.9	0.0	1,474	28	0	14	0
Yard Waste	1274	213	1,061	97.2	1.9	0.0	0.9	0.0	1,032	20	0	10	0
Remainder		5,367	8,709	97.2	1.9	0.0	0.9	0.0	8,467	163	0	79	0
TOTAL=									13,606	262	0	127	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

All waste is assumed to be delivered to the Coquitlam Transfer Station.

Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0114 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0054 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

# TOWNSHIP OF LANGLEY:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	3,697	728	66,040	56	11	87,595	4904	966	5869
Mixed Paper	4,680	3,911	66,040			87,595			
Office Paper	655	548	66,040	10	8	87,595	869	726	1595
Ferrous Metal	522	2,462	66,040	8	37	87,595	692	3266	3958
Glass	997	618	66,040	15	9	87,595	1322	820	2142
HDPE	263	262	66,040	4	4	87,595	349	348	696
Mixed Plastics	1,749	1,691	66,040			87,595			
LDPE	787	761	66,040	12	12	87,595	1044	1009	2053
Food Waste	2,540	2,479	66,040	38	38	87,595	3369	3288	6657
Yard Waste	2,456	889	66,040	37	13	87,595	3258	1179	4437

Total ICI waste generated in 1998= 34,277 tonnes

Total ICI waste recycled in 1998= 17,516 tonnes

ICI Recycling Rate= 51 %

# of backyard composters = 4,311

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	4,904	966	2,607			493	3,100		
Mixed Paper			565						
Office Paper	869	726	79			371	450		
Metal			391						
Ferrous Metal	692	3,266	196			1,669	1,864		
Glass	1,322	820	652			419	1,071		
Plastics			130						
HDPE	349	348	43			178	220		
LDPE	1,044	1,009	43			516	559		
Food Waste	3,369	3,288		358	0	1,680		358	1,680
Yard Waste	3,258	1,179		720	34	603		720	637

Total waste disposed in 1998= 27,521 tonnes

Total waste recycled in 1998= 23,604 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to BurInc 1998 (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal 1998 CCLF (tonnes)	Disposal 1998 VLF (tonnes)	Disposal 1998 FutLF (tonnes)	Disposal 1998 BurInc (tonnes)	Disposal 1998 FutInc (tonnes)
Newsprint	5869	3,100	2,769	77.4	0.7	0.0	22.0	0.0	2,142	18	0	609	0
Office Paper	1595	450	1,145	77.4	0.7	0.0	22.0	0.0	886	8	0	252	0
Ferrous Metal	3958	1,864	2,094	77.4	0.7	0.0	22.0	0.0	1,620	14	0	460	0
Glass	2142	1,071	1,071	77.4	0.7	0.0	22.0	0.0	829	7	0	235	0
HDPE	696	220	476	77.4	0.7	0.0	22.0	0.0	368	3	0	105	0
LDPE	2053	559	1,495	77.4	0.7	0.0	22.0	0.0	1,156	10	0	329	0
Food Waste	6657	2,038	4,619	77.4	0.7	0.0	22.0	0.0	3,573	31	0	1,015	0
Yard Waste	4437	1,357	3,080	77.4	0.7	0.0	22.0	0.0	2,383	20	0	677	0
Remainder	12,944	10,772		77.4	0.7	0.0	22.0	0.0	8,333	71	0	2,368	0
TOTAL=									21,289	182	0	6,050	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

Waste to the CCLF is first delivered to the LTS and transferred to the MTS.

Waste disposed at the VLF, FutLF or FutInc is transferred through the LTS.

Waste disposed at the BI is directly delivered there (thus no emission factor below).

Waste Disposed at the Cache Creek Landfill= 0.0254 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0106 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0015 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0000 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0015 tCO<sub>2</sub>e/tonne

Refer to City of Langley for recycling transportation issues.

# DISTRICT OF MAPLE RIDGE:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	2,524	391	48,422	52	8	60,987	3179	492	3671
Mixed Paper	3,371	1,959	48,422			60,987			
Office Paper	472	274	48,422	10	6	60,987	594	345	940
Ferrous Metal	580	1,173	48,422	12	24	60,987	731	1477	2208
Glass	681	323	48,422	14	7	60,987	858	407	1265
HDPE	176	147	48,422	4	3	60,987	222	185	407
Mixed Plastics	1,192	765	48,422			60,987			
LDPE	536	344	48,422	11	7	60,987	676	434	1109
Food Waste	1,736	1,440	48,422	36	30	60,987	2186	1814	4000
Yard Waste	1,772	517	48,422	37	11	60,987	2232	651	2883

Total ICI waste generated in 1998= 15,661 tonnes

Total ICI waste recycled in 1998= 5,853 tonnes

ICI Recycling Rate= 37 %

# of backyard composters = 4,100

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Compostin 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	3,179	492	1,644			184	1,828		
Mixed Paper			466						
Office Paper	594	345	65			129	194		
Metal			965						
Ferrous Metal	731	1,477	483			552	1,035		
Glass	858	407	333			152	485		
Plastics			25						
HDPE	222	185	8			69	77		
LDPE	676	434	8			162	170		
Food Waste	2,186	1,814		340	0	678		340	678
Yard Waste	2,232	651		685	1,049	243		685	1,292

Total waste disposed in 1998= 21,355 tonnes

Total waste recycled in 1998= 14,992 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to Burlnc 1998 (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal CCLF 1998 (tonnes)	Disposal VLF 1998 (tonnes)	Disposal FutLF 1998 (tonnes)	Disposal Burlnc 1998 (tonnes)	Disposal FutInc 1998 (tonnes)
Newsprint	3671	1,828	1,843	98.1	1.3	0.0	0.6	0.0	1,809	23	0	11	0
Office Paper	940	194	745	98.1	1.3	0.0	0.6	0.0	732	9	0	5	0
Ferrous Metal	2208	1,035	1,173	98.1	1.3	0.0	0.6	0.0	1,151	15	0	7	0
Glass	1265	485	779	98.1	1.3	0.0	0.6	0.0	765	10	0	5	0
HDPE	407	77	329	98.1	1.3	0.0	0.6	0.0	323	4	0	2	0
LDPE	1109	170	939	98.1	1.3	0.0	0.6	0.0	921	12	0	6	0
Food Waste	4000	1,018	2,982	98.1	1.3	0.0	0.6	0.0	2,926	37	0	18	0
Yard Waste	2883	1,977	906	98.1	1.3	0.0	0.6	0.0	889	11	0	6	0
Remainder		8,207	11,657	98.1	1.3	0.0	0.6	0.0	11,439	147	0	71	0
TOTAL=									20,956	268	0	130	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

Waste to the CCLF is first delivered to the MRTS and transferred to the MTS.

Waste disposed at the VLF, BI, FutLF or FutI is transferred through the CTS.

Waste Disposed at the Cache Creek Landfill= 0.0267 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0114 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0054 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

### 5 Diesel Fuel Consumption for Yard Trimmings Transport to Fraser-Richmond BioCycle:

Tonnes hauled per trip = 20 tonnes/trip

Distance per trip = 0 km

Diesel Fuel Consumption = 45.0 L/100 km

GHG emission = 0.000 tCO<sub>2</sub>e/tonne

# CITY OF NEW WESTMINSTER:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	2,184	920	43,585	50	21	53,575	2685	1131	3815
Mixed Paper	3,050	5,346	43,585			53,575			
Office Paper	427	748	43,585	10	17	53,575	525	920	1445
Ferrous Metal	212	2,715	43,585	5	62	53,575	261	3337	3598
Glass	548	760	43,585	13	17	53,575	674	934	1608
HDPE	126	272	43,585	3	6	53,575	155	334	489
Mixed Plastics	917	2,041	43,585			53,575			
LDPE	413	918	43,585	9	21	53,575	507	1129	1636
Food Waste	1,391	2,826	43,585	32	65	53,575	1710	3474	5184
Yard Waste	2,018	1,140	43,585	46	26	53,575	2481	1401	3882

Total ICI waste generated in 1998= 36,117 tonnes

Total ICI waste recycled in 1998= 13,972 tonnes

ICI Recycling Rate= 39 %

# of backyard composters = 2,200

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Compostin 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	2,685	1,131	1,176			437	1,613		
Mixed Paper			738						
Office Paper	525	920	103			356	459		
Metal			386						
Ferrous Metal	261	3,337	193			1,291	1,484		
Glass	674	934	29			361	390		
Plastics			17						
HDPE	155	334	6			129	135		
LDPE	507	1,129	6			437	442		
Food Waste	1,710	3,474		183	0	1,344		183	1,344
Yard Waste	2,481	1,401		367	1,751	542		367	2,293

Total waste disposed in 1998= 28,018 tonnes

Total waste recycled in 1998= 18,784 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to Burlnc 1998 (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal CCLF 1998 (tonnes)	Disposal VLF 1998 (tonnes)	Disposal FutLF 1998 (tonnes)	Disposal Burlnc 1998 (tonnes)	Disposal FutInc 1998 (tonnes)
Newsprint	3815	1,613	2,202	46.7	1.3	0.0	52.0	0.0	1,028	28	0	1,146	0
Office Paper	1445	459	986	46.7	1.3	0.0	52.0	0.0	460	12	0	513	0
Ferrous Metal	3598	1,484	2,114	46.7	1.3	0.0	52.0	0.0	987	27	0	1,100	0
Glass	1608	390	1,217	46.7	1.3	0.0	52.0	0.0	568	15	0	634	0
HDPE	489	135	354	46.7	1.3	0.0	52.0	0.0	165	4	0	184	0
LDPE	1636	442	1,194	46.7	1.3	0.0	52.0	0.0	557	15	0	621	0
Food Waste	5184	1,526	3,657	46.7	1.3	0.0	52.0	0.0	1,708	46	0	1,903	0
Yard Waste	3882	2,660	1,221	46.7	1.3	0.0	52.0	0.0	570	15	0	636	0
Remainder		10,073	15,073	46.7	1.3	0.0	52.0	0.0	7,038	190	0	7,845	0
TOTAL=									13,083	353	0	14,583	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Diesel fuel consumption during collection (1998)= 50,331 L  
 Mass collected during this consumption (1998)= 6,309 tonnes  
 GHG emission from waste collection = 0.023 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Diesel fuel consumption during collection (1998)= 24,604 L  
 Mass collected during this consumption (1998)= 1,344 tonnes  
 GHG emission from waste collection = 0.052 tCO<sub>2</sub>e/tonne

### 3 Emission Factor for Waste Disposal:

Waste to the CCLF, VLF, FutLF or FutI is transferred through the CTS,  
 Waste disposed at the BI is directly delivered there (thus no emission factor below).  
 Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne  
 Waste Disposed at the Vancouver Landfill= 0.0114 tCO<sub>2</sub>e/tonne  
 Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne  
 Waste Disposed at the Burnaby Incinerator= 0.0000 tCO<sub>2</sub>e/tonne  
 Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

### 4 Diesel Fuel Consumption for Yard Trimmings Transport to Fraser-Richmond BioCycle:

Tonnes hauled per trip = 20 tonnes/trip  
 Distance per trip = 40 km  
 Diesel Fuel Consumption = 45.0 L/100 km  
 GHG emission = 0.003 tCO<sub>2</sub>e/tonne



# CITY OF NORTH VANCOUVER:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	2,572	495	38,436	67	13	44,428	2973	572	3545
Mixed Paper	2,483	2,698	38,436			44,428			
Office Paper	348	378	38,436	9	10	44,428	402	437	838
Ferrous Metal	230	1,472	38,436	6	38	44,428	266	1701	1967
Glass	736	428	38,436	19	11	44,428	851	495	1345
HDPE	118	177	38,436	3	5	44,428	136	205	341
Mixed Plastics	854	1,015	38,436			44,428			
LDPE	384	457	38,436	10	12	44,428	444	528	972
Food Waste	1,293	1,531	38,436	34	40	44,428	1495	1770	3264
Yard Waste	1,113	540	38,436	29	14	44,428	1287	624	1911

Total ICI waste generated in 1998= 14,108 tonnes  
Total ICI waste recycled in 1998= 11,571 tonnes  
ICI Recycling Rate= 82 %  
# of backyard composters = 2,548

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	2,973	572	1,696			469	2,165		
Mixed Paper			547						
Office Paper	402	437	77			358	435		
Metal			62						
Ferrous Metal	266	1,701	31			1,396	1,427		
Glass	851	495	65			406	471		
Plastics			18						
HDPE	136	205	6			168	174		
LDPE	444	528	6			433	439		
Food Waste	1,495	1,770		211	0	1,451		211	1,451
Yard Waste	1,287	624		426	1,990	512		426	2,502

Total waste disposed in 1998= 10,173 tonnes  
Total waste recycled in 1998= 16,738 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to Burlnc 1998 (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal CCLF 1998 (tonnes)	Disposal VLF 1998 (tonnes)	Disposal FutLF 1998 (tonnes)	Disposal Burlnc 1998 (tonnes)	Disposal FutInc 1998 (tonnes)
Newsprint	3545	2,165	1,380	48.1	1.0	0.0	50.8	0.0	664	14	0	701	0
Office Paper	838	435	404	48.1	1.0	0.0	50.8	0.0	194	4	0	205	0
Ferrous Metal	1967	1,427	541	48.1	1.0	0.0	50.8	0.0	260	6	0	275	0
Glass	1345	471	875	48.1	1.0	0.0	50.8	0.0	421	9	0	445	0
HDPE	341	174	167	48.1	1.0	0.0	50.8	0.0	81	2	0	85	0
LDPE	972	439	533	48.1	1.0	0.0	50.8	0.0	257	5	0	271	0
Food Waste	3264	1,663	1,601	48.1	1.0	0.0	50.8	0.0	771	16	0	814	0
Yard Waste	1911	2,927	0	48.1	1.0	0.0	50.8	0.0	0	0	0	0	0
Remainder	7,038	4,672		48.1	1.0	0.0	50.8	0.0	2,249	48	0	2,375	0
TOTAL=									4,897	104	0	5,171	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Diesel fuel consumption during collection (1999)= 16,257 L  
Mass collected during this consumption (1999)= 4,175 tonnes  
GHG emission from waste collection = 0.011 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Diesel fuel consumption during collection (1999)= 10,020 L  
Mass collected during this consumption (1999)= 1,223 tonnes  
GHG emission from waste collection = 0.023 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Diesel fuel consumption during collection (1999)= 10,020 L  
Mass collected during this consumption (1999)= 1,223 tonnes  
GHG emission from waste collection = 0.023 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

All waste through the NSTS:  
Waste Disposed at the Cache Creek Landfill= 0.0231 tCO<sub>2</sub>e/tonne  
Waste Disposed at the Vancouver Landfill= 0.0101 tCO<sub>2</sub>e/tonne  
Waste Disposed at a Future Landfill= 0.0013 tCO<sub>2</sub>e/tonne  
Waste Disposed at the Burnaby Incinerator= 0.0039 tCO<sub>2</sub>e/tonne  
Waste Disposed at a Future Incinerator= 0.0013 tCO<sub>2</sub>e/tonne

### 5 Diesel Fuel Consumption for Yard Trimmings Transport to Fraser-Richmond BioCycle:

Tonnes hauled per trip = 20 tonnes/trip  
Distance per trip = 20 km  
Diesel Fuel Consumption = 45.0 L/100 km  
GHG emission = 0.001 tCO<sub>2</sub>e/tonne

# DISTRICT OF NORTH VANCOUVER:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	5,391	961	75,157	72	13	85,292	6118	1091	7209
Mixed Paper	5,283	5,238	75,157			85,292			
Office Paper	740	733	75,157	10	10	85,292	839	832	1672
Ferrous Metal	483	2,857	75,157	6	38	85,292	548	3242	3790
Glass	1,313	831	75,157	17	11	85,292	1490	943	2433
HDPE	287	343	75,157	4	5	85,292	326	389	715
Mixed Plastics	1,761	1,970	75,157			85,292			
LDPE	792	887	75,157	11	12	85,292	899	1006	1905
Food Waste	2,575	2,973	75,157	34	40	85,292	2922	3374	6296
Yard Waste	2,984	1,048	75,157	40	14	85,292	3386	1189	4576

Total ICI waste generated in 1998= 42,579 tonnes

Total ICI waste recycled in 1998= 10,912 tonnes

ICI Recycling Rate= 26 %

# of backyard composters = 7,972

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	6,118	1,091	3,956			279	4,235		
Mixed Paper			1,350						
Office Paper	839	832	189			213	402		
Metal			131						
Ferrous Metal	548	3,242	66			831	896		
Glass	1,490	943	145			242	387		
Plastics			40						
HDPE	326	389	13			100	113		
LDPE	899	1,006	13			258	271		
Food Waste	2,922	3,374		662	0	865		662	865
Yard Waste	3,386	1,189		1,331	6,818	305		1,331	7,123

Total waste disposed in 1998= 73,900 tonnes

Total waste recycled in 1998= 25,654 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to Burlnc 1998 (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal CCLF 1998 (tonnes)	Disposal VLF 1998 (tonnes)	Disposal FutLF 1998 (tonnes)	Disposal Burlnc 1998 (tonnes)	Disposal FutInc 1998 (tonnes)
Newsprint	7209	4,235	2,973	47.7	1.0	0.0	51.2	0.0	1,419	30	0	1,524	0
Office Paper	1672	402	1,269	47.7	1.0	0.0	51.2	0.0	606	13	0	650	0
Ferrous Metal	3790	896	2,894	47.7	1.0	0.0	51.2	0.0	1,382	29	0	1,483	0
Glass	2433	387	2,046	47.7	1.0	0.0	51.2	0.0	977	21	0	1,049	0
HDPE	715	113	602	47.7	1.0	0.0	51.2	0.0	287	6	0	309	0
LDPE	1905	271	1,634	47.7	1.0	0.0	51.2	0.0	780	17	0	838	0
Food Waste	6296	1,526	4,770	47.7	1.0	0.0	51.2	0.0	2,277	48	0	2,444	0
Yard Waste	4576	8,454	0	47.7	1.0	0.0	51.2	0.0	0	0	0	0	0
Remainder		9,369	57,711	47.7	1.0	0.0	51.2	0.0	27,551	584	0	29,576	0
TOTAL=									35,280	748	0	37,872	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

All waste through the NSTS.

Waste Disposed at the Cache Creek Landfill= 0.0231 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0101 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0013 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0039 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0013 tCO<sub>2</sub>e/tonne

Refer to the City of North Vancouver for recycling transportation issues.

# DISTRICT OF PITT MEADOWS:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	581	52	11,147	52	5	14,504	756	68	824
Mixed Paper	766	249	11,147			14,504			
Office Paper	107	35	11,147	10	3	14,504	140	45	185
Ferrous Metal	135	187	11,147	12	17	14,504	176	243	419
Glass	159	39	11,147	14	3	14,504	207	51	258
HDPE	40	19	11,147	4	2	14,504	52	25	77
Mixed Plastics	274	116	11,147			14,504			
LDPE	123	52	11,147	11	5	14,504	160	68	228
Food Waste	401	184	11,147	36	17	14,504	522	239	761
Yard Waste	395	64	11,147	35	6	14,504	514	83	597

Total ICI waste generated in 1998= 4,953 tonnes

Total ICI waste recycled in 1998= 1,372 tonnes

ICI Recycling Rate= 28 %

# of backyard composters = 640

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	756	68	308			19	327		
Mixed Paper			298						
Office Paper	140	45	42			13	54		
Metal			9						
Ferrous Metal	176	243	5			67	72		
Glass	207	51	12			14	26		
Plastics			3						
HDPE	52	25	1			7	8		
LDPE	160	68	1			19	20		
Food Waste	522	239		53	0	66		53	66
Yard Waste	514	83		107	0	23		107	23

Total waste disposed in 1998= 3,821 tonnes

Total waste recycled in 1998= 2,182 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to Burlnc 1998 (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal CCLF 1998 (tonnes)	Disposal VLF 1998 (tonnes)	Disposal FutLF 1998 (tonnes)	Disposal Burlnc 1998 (tonnes)	Disposal FutInc 1998 (tonnes)
Newsprint	824	327	497	96.3	2.5	0.0	1.2	0.0	479	12	0	6	0
Office Paper	185	54	131	96.3	2.5	0.0	1.2	0.0	126	3	0	2	0
Ferrous Metal	419	72	347	96.3	2.5	0.0	1.2	0.0	334	9	0	4	0
Glass	258	26	232	96.3	2.5	0.0	1.2	0.0	223	6	0	3	0
HDPE	77	8	69	96.3	2.5	0.0	1.2	0.0	66	2	0	1	0
LDPE	228	20	209	96.3	2.5	0.0	1.2	0.0	201	5	0	2	0
Food Waste	761	119	642	96.3	2.5	0.0	1.2	0.0	618	16	0	8	0
Yard Waste	597	130	467	96.3	2.5	0.0	1.2	0.0	450	12	0	6	0
Remainder		1,426	1,228	96.3	2.5	0.0	1.2	0.0	1,183	30	0	15	0
TOTAL=									3,681	94	0	46	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

All waste through the CTS.

Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0114 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0054 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

### 5 Diesel Fuel Consumption for Yard Trimmings Transport to Fraser-Richmond BioCycle:

Tonnes hauled per trip = 20 tonnes/trip

Distance per trip = 60 km

Diesel Fuel Consumption = 45.0 L/100 km

GHG emission = 0.004 tCO<sub>2</sub>e/tonne

# CITY OF PORT COQUITLAM:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	1,470	653	36,773	40	18	39,823	1592	707	2299
Mixed Paper	3,105	3,600	36,773			39,823			
Office Paper	435	504	36,773	12	14	39,823	471	546	1017
Ferrous Metal	217	1,963	36,773	6	53	39,823	235	2126	2361
Glass	381	480	36,773	10	13	39,823	413	520	932
HDPE	156	155	36,773	4	4	39,823	169	168	337
Mixed Plastics	953	1,393	36,773			39,823			
LDPE	429	627	36,773	12	17	39,823	464	679	1143
Food Waste	1,393	1,501	36,773	38	41	39,823	1509	1625	3134
Yard Waste	1,619	600	36,773	44	16	39,823	1753	650	2403

Total ICI waste generated in 1998= 13,038 tonnes

Total ICI waste recycled in 1998= 6,036 tonnes

ICI Recycling Rate= 46 %

# of backyard composters = 5,500

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Recycling 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	1,592	707	832			327	1,159		
Mixed Paper			428						
Office Paper	471	546	60			253	313		
Metal			144						
Ferrous Metal	235	2,126	72			984	1,056		
Glass	413	520	192			241	433		
Plastics			51						
HDPE	169	168	17			78	95		
LDPE	464	679	17			314	331		
Food Waste	1,509	1,625		457	0	753		457	753
Yard Waste	1,753	650		919	1,185	301		919	1,486

Total waste disposed in 1998= 17,895 tonnes

Total waste recycled in 1998= 10,540 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF (%)	% OF M <sub>DIS</sub> to VLF (%)	% OF M <sub>DIS</sub> to FutLF (%)	% OF M <sub>DIS</sub> to BurInc (%)	% OF M <sub>DIS</sub> to FutInc (%)	Disposal CCLF 1998 (tonnes)	Disposal VLF 1998 (tonnes)	Disposal FutLF 1998 (tonnes)	Disposal BurInc 1998 (tonnes)	Disposal FutInc 1998 (tonnes)
Newsprint	2299	1,159	1,140	96.1	2.6	0.0	1.3	0.0	1,096	30	0	14	0
Office Paper	1017	313	704	96.1	2.6	0.0	1.3	0.0	677	18	0	9	0
Ferrous Metal	2361	1,056	1,305	96.1	2.6	0.0	1.3	0.0	1,254	34	0	16	0
Glass	932	433	500	96.1	2.6	0.0	1.3	0.0	481	13	0	6	0
HDPE	337	95	242	96.1	2.6	0.0	1.3	0.0	233	6	0	3	0
LDPE	1143	331	812	96.1	2.6	0.0	1.3	0.0	781	21	0	10	0
Food Waste	3134	1,209	1,925	96.1	2.6	0.0	1.3	0.0	1,851	50	0	24	0
Yard Waste	2403	2,404	0	96.1	2.6	0.0	1.3	0.0	0	0	0	0	0
Remainder		3,540	11,268	96.1	2.6	0.0	1.3	0.0	10,833	292	0	142	0
TOTAL=									17,205	464	0	226	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

All waste through the CTS.

Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0114 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0054 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

Refer to the City of Coquitlam for recycling transportation issues.

# CITY OF PORT MOODY:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	719	156	17,712	41	9	23,134	939	204	1143
Mixed Paper	1,495	967	17,712			23,134			
Office Paper	209	135	17,712	12	8	23,134	273	177	450
Ferrous Metal	102	519	17,712	6	29	23,134	133	678	811
Glass	195	146	17,712	11	8	23,134	255	191	445
HDPE	78	47	17,712	4	3	23,134	102	61	163
Mixed Plastics	368	391	17,712			23,134			
LDPE	166	176	17,712	9	10	23,134	216	230	446
Food Waste	542	471	17,712	31	27	23,134	708	615	1323
Yard Waste	1,293	183	17,712	73	10	23,134	1689	239	1928

Total ICI waste generated in 1998= 7,045 tonnes

Total ICI waste recycled in 1998= 3,245 tonnes

ICI Recycling Rate= 46 %

# of backyard composters = 0

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	939	204	271			94	365		
Mixed Paper			512						
Office Paper	273	177	72			81	153		
Metal			99						
Ferrous Metal	133	678	50			312	362		
Glass	255	191	216			88	304		
Plastics			65						
HDPE	102	61	21			28	50		
LDPE	216	230	21			106	127		
Food Waste	708	615		0	0	283		0	283
Yard Waste	1,689	239		0	1,170	110		0	1,280

Total waste disposed in 1998= 5,670 tonnes

Total waste recycled in 1998= 5,722 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to Burlnc 1998 (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal CCLF 1998 (tonnes)	Disposal VLF 1998 (tonnes)	Disposal FutLF 1998 (tonnes)	Disposal Burlnc 1998 (tonnes)	Disposal FutInc 1998 (tonnes)
Newsprint	1143	365	778	96.1	2.6	0.0	1.3	0.0	748	20	0	10	0
Office Paper	450	153	297	96.1	2.6	0.0	1.3	0.0	286	8	0	4	0
Ferrous Metal	811	362	449	96.1	2.6	0.0	1.3	0.0	432	12	0	6	0
Glass	445	304	142	96.1	2.6	0.0	1.3	0.0	136	4	0	2	0
HDPE	163	50	114	96.1	2.6	0.0	1.3	0.0	109	3	0	1	0
LDPE	446	127	319	96.1	2.6	0.0	1.3	0.0	307	8	0	4	0
Food Waste	1323	283	1,040	96.1	2.6	0.0	1.3	0.0	1,000	27	0	13	0
Yard Waste	1928	1,280	648	96.1	2.6	0.0	1.3	0.0	623	17	0	8	0
Remainder		2,798	1,884	96.1	2.6	0.0	1.3	0.0	1,812	49	0	24	0
TOTAL=									5,451	147	0	71	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

All waste through the CTS.

Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0114 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0054 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

### 5 Diesel Fuel Consumption for Yard Trimmings Transport to Fraser-Richmond BioCycle:

Tonnes hauled per trip = 20 tonnes/trip

Distance per trip = 60 km

Diesel Fuel Consumption = 45.0 L/100 km

GHG emission = 0.004 tCO<sub>2</sub>e/tonne

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CITY OF RICHMOND:

Variables that can be changed by users are in bold.

**MASS OF WASTE GENERATION (M<sub>GEN</sub>):**

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	7,630	2,979	126,624	60	24	161,957	9759	3810	13569
Mixed Paper	8,992	16,491	126,624			161,957			
Office Paper	1,259	2,309	126,624	10	18	161,957	1610	2953	4563
Ferrous Metal	796	9,796	126,624	6	77	161,957	1018	12529	13548
Glass	2,173	2,635	126,624	17	21	161,957	2779	3370	6150
HDPE	500	1,000	126,624	4	8	161,957	640	1279	1919
Mixed Plastics	3,055	7,438	126,624			161,957			
LDPE	1,375	3,347	126,624	11	26	161,957	1758	4281	6039
Food Waste	4,503	8,955	126,624	36	71	161,957	5760	11454	17213
Yard Waste	4,789	3,304	126,624	38	26	161,957	6125	4226	10351

Total ICI waste generated in 1998= 94,416 tonnes

Total ICI waste recycled in 1998= 51,091 tonnes

ICI Recycling Rate= 54 %

# of backyard composters = 7,627

**MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):**

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	9,759	3,810	5,153			2,062	7,215		
Mixed Paper			3,681						
Office Paper	1,610	2,953	515			1,598	2,113		
Metal			419						
Ferrous Metal	1,018	12,529	210			6,780	6,990		
Glass	2,779	3,370	191			1,824	2,015		
Plastics			53						
HDPE	640	1,279	17			692	710		
LDPE	1,758	4,281	17			2,317	2,334		
Food Waste	5,760	11,454		633	0	6,198		633	6,198
Yard Waste	6,125	4,226		1,274	10,737	2,287		1,274	13,024

Total waste disposed in 1998= 64,364 tonnes

Total waste recycled in 1998= 73,640 tonnes

**MASS OF WASTE DISPOSED (M<sub>DIS</sub>):**

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to Burlnc 1998 (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal CCLF 1998 (tonnes)	Disposal VLF 1998 (tonnes)	Disposal FutLF 1998 (tonnes)	Disposal Burlnc 1998 (tonnes)	Disposal FutInc 1998 (tonnes)
Newsprint	13569	7,215	6,354	8.9	79.7	0.0	11.4	0.0	566	5,062	0	726	0
Office Paper	4563	2,113	2,450	8.9	79.7	0.0	11.4	0.0	218	1,952	0	280	0
Ferrous Metal	13548	6,990	6,558	8.9	79.7	0.0	11.4	0.0	585	5,224	0	749	0
Glass	6150	2,015	4,135	8.9	79.7	0.0	11.4	0.0	369	3,294	0	473	0
HDPE	1919	710	1,209	8.9	79.7	0.0	11.4	0.0	108	963	0	138	0
LDPE	6039	2,334	3,705	8.9	79.7	0.0	11.4	0.0	330	2,952	0	423	0
Food Waste	17213	6,831	10,382	8.9	79.7	0.0	11.4	0.0	925	8,270	0	1,186	0
Yard Waste	10351	14,297	0	8.9	79.7	0.0	11.4	0.0	0	0	0	0	0
Remainder		31,135	29,570	8.9	79.7	0.0	11.4	0.0	2,636	23,555	0	3,379	0
TOTAL=									5,737	51,272	0	7,355	0

**1 Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

**2 Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

**3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

**4 Emission Factor for Waste Disposal:**

Waste disposed at the VLF, FutLF or FutI is assumed to have been transferred from the VTS.

Waste disposed at the BI is assumed to have been directly delivered there (thus no emission below).

Waste disposed at the CCLF is assumed to have been transferred through the CTS.

Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0078 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0009 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0000 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0009 tCO<sub>2</sub>e/tonne

CITY OF SURREY:

Variables that can be changed by users are in bold.

**MASS OF WASTE GENERATION (M<sub>GEN</sub>):**

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	12,180	2,447	245,173	50	10	332,244	16506	3316	19822
Mixed Paper	16,974	12,559	245,173			332,244			
Office Paper	2,376	1,758	245,173	10	7	332,244	3220	2383	5603
Ferrous Metal	1,517	7,791	245,173	6	32	332,244	2056	10558	12614
Glass	3,368	2,054	245,173	14	8	332,244	4564	2783	7348
HDPE	930	887	245,173	4	4	332,244	1260	1202	2462
Mixed Plastics	5,871	5,245	245,173			332,244			
LDPE	2,642	2,360	245,173	11	10	332,244	3580	3198	6779
Food Waste	8,597	8,192	245,173	35	33	332,244	11650	11101	22751
Yard Waste	15,204	2,885	245,173	62	12	332,244	20604	3910	24513

Total ICI waste generated in 1998= 119,481 tonnes

Total ICI waste recycled in 1998= 56,790 tonnes

ICI Recycling Rate= 48 %

# of backyard composters = 6,600

**MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):**

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	16,506	3,316	7,497			1,576	9,073		
Mixed Paper			5,551						
Office Paper	3,220	2,383	777			1,133	1,910		
Metal			516						
Ferrous Metal	2,056	10,558	258			5,018	5,276		
Glass	4,564	2,783	1,605			1,323	2,928		
Plastics			561						
HDPE	1,260	1,202	185			571	756		
LDPE	3,580	3,198	185			1,520	1,705		
Food Waste	11,650	11,101		548	0	5,277		548	5,277
Yard Waste	20,604	3,910		1,102	3,194	1,858		1,102	5,052

Total waste disposed in 1998= 126,130 tonnes

Total waste recycled in 1998= 95,357 tonnes

**MASS OF WASTE DISPOSED (M<sub>DIS</sub>):**

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to Burlnc 1998 (%)	% OF M <sub>DIS</sub> to FutInc 1998 (%)	Disposal CCLF 1998 (tonnes)	Disposal VLF 1998 (tonnes)	Disposal FutLF 1998 (tonnes)	Disposal Burlnc 1998 (tonnes)	Disposal FutInc 1998 (tonnes)
Newsprint	19822	9,073	10,749	74.2	7.9	0.0	17.8	0.0	7,980	851	0	1,918	0
Office Paper	5603	1,910	3,693	74.2	7.9	0.0	17.8	0.0	2,742	292	0	659	0
Ferrous Metal	12614	5,276	7,337	74.2	7.9	0.0	17.8	0.0	5,447	581	0	1,309	0
Glass	7348	2,928	4,420	74.2	7.9	0.0	17.8	0.0	3,281	350	0	789	0
HDPE	2462	756	1,706	74.2	7.9	0.0	17.8	0.0	1,266	135	0	304	0
LDPE	6779	1,705	5,073	74.2	7.9	0.0	17.8	0.0	3,766	402	0	905	0
Food Waste	22751	5,824	16,927	74.2	7.9	0.0	17.8	0.0	12,567	1,340	0	3,021	0
Yard Waste	24513	6,154	18,359	74.2	7.9	0.0	17.8	0.0	13,630	1,453	0	3,276	0
Remainder		61,729	57,866	74.2	7.9	0.0	17.8	0.0	42,960	4,580	0	10,326	0
TOTAL=									93,639	9,983	0	22,507	0

**1 Diesel Fuel Consumption for Curbside Waste Collection:**

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

**2 Diesel Fuel Consumption for Curbside Recyclables Collection:**

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

**3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

**4 Emission Factor for Waste Disposal:**

Waste disposed at the CCLF, FutLF or FutI is assumed to have been transferred from the CTS.

Waste disposed at the BI is assumed to have been directly delivered there (thus no emission below).

Waste disposed at the VLF is assumed to have been directly delivered there (thus no emission below).

Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0000 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0000 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

**5 Diesel Fuel Consumption for Yard Trimmings Transport to Fraser-Richmond BioCycle:**

Tonnes hauled per trip = 20 tonnes/trip

Distance per trip = 60 km

Diesel Fuel Consumption = 45.0 L/100 km

GHG emission = 0.004 tCO<sub>2</sub>e/tonne

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CITY OF VANCOUVER:

Variables that can be changed by users are in bold.

**MASS OF WASTE GENERATION ( $M_{GEN}$ ):**

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	24,865	10,675	471,844	53	23	552,481	29114	12499	41614
Mixed Paper	32,303	62,529	471,844			552,481			
Office Paper	4,522	8,754	471,844	10	19	552,481	5295	10250	15545
Ferrous Metal	3,409	33,178	471,844	7	70	552,481	3992	38848	42840
Glass	7,421	10,542	471,844	16	22	552,481	8689	12344	21033
HDPE	1,746	4,365	471,844	4	9	552,481	2044	5111	7155
Mixed Plastics	10,639	23,503	471,844			552,481			
LDPE	4,788	10,576	471,844	10	22	552,481	5606	12384	17990
Food Waste	15,909	35,550	471,844	34	75	552,481	18628	41625	60253
Yard Waste	21,407	11,975	471,844	45	25	552,481	25065	14021	39087

Total ICI waste generated in 1998= 382,660 tonnes

Total ICI waste recycled in 1998= 154,785 tonnes

ICI Recycling Rate= 40 %

# of backyard composters = 23,838

**MASS OF WASTE RECYCLED ( $M_{REC}$ ) & COMPOSTED ( $M_{COM}$ ):**

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	29,114	12,499	10,122			5,056	15,178		
Mixed Paper			8,126						
Office Paper	5,295	10,250	1,138			4,146	5,284		
Metal			2,947						
Ferrous Metal	3,992	38,848	1,474			15,714	17,187		
Glass	8,689	12,344	523			4,993	5,516		
Plastics			134						
HDPE	2,044	5,111	44			2,067	2,112		
LDPE	5,608	12,384	44			5,009	5,053		
Food Waste	18,628	41,625		1,979	0	16,837		1,979	16,837
Yard Waste	25,065	14,021		3,981	22,440	5,672		3,981	28,112

Total waste disposed in 1998= 346,991 tonnes

Total waste recycled in 1998= 206,323 tonnes

**MASS OF WASTE DISPOSED ( $M_{DIS}$ ):**

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF $M_{DIS}$ to CCLF (%)	% OF $M_{DIS}$ to VLF (%)	% OF $M_{DIS}$ to FutLF (%)	% OF $M_{DIS}$ to BurInc (%)	% OF $M_{DIS}$ to FutInc (%)	Disposal 1998 CCLF (tonnes)	Disposal 1998 VLF (tonnes)	Disposal 1998 FutLF (tonnes)	Disposal 1998 BurInc (tonnes)	Disposal 1998 FutInc (tonnes)
Newsprint	41614	15,178	26,436	17.7	68.0	0.0	14.3	0.0	4,669	17,984	0	3,782	0
Office Paper	15545	5,284	10,262	17.7	68.0	0.0	14.3	0.0	1,813	6,981	0	1,468	0
Ferrous Metal	42840	17,187	25,652	17.7	68.0	0.0	14.3	0.0	4,531	17,451	0	3,670	0
Glass	21033	5,516	15,517	17.7	68.0	0.0	14.3	0.0	2,741	10,556	0	2,220	0
HDPE	7155	2,112	5,044	17.7	68.0	0.0	14.3	0.0	891	3,431	0	722	0
LDPE	17990	5,053	12,936	17.7	68.0	0.0	14.3	0.0	2,285	8,801	0	1,851	0
Food Waste	60253	18,816	41,437	17.7	68.0	0.0	14.3	0.0	7,319	28,190	0	5,928	0
Yard Waste	39087	32,093	6,994	17.7	68.0	0.0	14.3	0.0	1,235	4,758	0	1,001	0
Remainder		105,084	202,713	17.7	68.0	0.0	14.3	0.0	35,806	137,907	0	29,000	0
TOTAL=									61,290	236,061	0	49,641	0

**1 Diesel Fuel Consumption for Curbside Waste Collection:**

Diesel fuel consumption during collection (1998)= 316,000 L  
 Mass collected during this consumption (1998)= 76,000 tonnes  
 GHG emission from waste collection = 0.012 tCO<sub>2</sub>e/tonne

**2 Diesel Fuel Consumption for Curbside Recyclables Collection:**

Diesel fuel consumption during collection (1998)= 190,000 L  
 Mass collected during this consumption (1998)= 17,500 tonnes  
 GHG emission from waste collection = 0.031 tCO<sub>2</sub>e/tonne

**3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:**

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

**4 Emission Factor for Waste Disposal:**

Waste disposed at the VLF, FutLF or FutI is assumed to have been transferred from the VTS.  
 Waste disposed at the CCLF or BI is assumed to have been transferred from the NSTS.  
 Waste Disposed at the Cache Creek Landfill= 0.0231 tCO<sub>2</sub>e/tonne  
 Waste Disposed at the Vancouver Landfill= 0.0078 tCO<sub>2</sub>e/tonne  
 Waste Disposed at a Future Landfill= 0.0009 tCO<sub>2</sub>e/tonne  
 Waste Disposed at the Burnaby Incinerator= 0.0039 tCO<sub>2</sub>e/tonne  
 Waste Disposed at a Future Incinerator= 0.0009 tCO<sub>2</sub>e/tonne

**5 Diesel Fuel Consumption for Yard Trimmings Transport to Composting Facility at the Vancouver Landfill:**

assuming similar to general waste transport  
 Total diesel fuel consumption = 334,000 L  
 # of round trips in 1998= 12500 trips  
 Mass of waste transported (1998)= 287,931 tonnes  
 Average mass of waste transported = 23.0 tonnes/trip  
 Average fuel consumption per trip = 26.7 L/trip  
 GHG emission from waste transport = 0.0033 tCO<sub>2</sub>e/tonne



# DISTRICT OF WEST VANCOUVER:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	3,105	410	38,783	80	11	42,664	3416	451	3867
Mixed Paper	2,542	1,924	38,783			42,664			
Office Paper	356	269	38,783	9	7	42,664	391	296	688
Ferrous Metal	253	1,170	38,783	7	30	42,664	278	1287	1565
Glass	797	377	38,783	21	10	42,664	877	415	1291
HDPE	138	195	38,783	4	5	42,664	152	215	366
Mixed Plastics	855	693	38,783			42,664			
LDPE	385	312	38,783	10	8	42,664	423	343	766
Food Waste	1,263	1,728	38,783	33	45	42,664	1389	1901	3290
Yard Waste	1,353	565	38,783	35	15	42,664	1488	622	2110

Total ICI waste generated in 1998= 55,397 tonnes

Total ICI waste recycled in 1998= 21,797 tonnes

ICI Recycling Rate= 39 %

# of backyard composters = 2,975

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	3,416	451	2,470			177	2,647		
Mixed Paper			841						
Office Paper	391	296	118			117	234		
Metal			81						
Ferrous Metal	278	1,287	41			506	547		
Glass	877	415	89			163	252		
Plastics			24						
HDPE	152	215	8			84	92		
LDPE	423	343	8			135	143		
Food Waste	1,389	1,901		247	0	748		247	748
Yard Waste	1,488	622		497	2,465	245		497	2,710

Total waste disposed in 1998= 15,733 tonnes

Total waste recycled in 1998= 18,167 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation	Total Recycling	Waste Disposal	% OF M <sub>DIS</sub> to CCLF	% OF M <sub>DIS</sub> to VLF	% OF M <sub>DIS</sub> to FutLF	% OF M <sub>DIS</sub> to BurInc	% OF M <sub>DIS</sub> to FutInc	Disposal CCLF	Disposal VLF	Disposal FutLF	Disposal BurInc	Disposal FutInc
	1998	1998	1998	1998	1998	1998	1998	1998	1998	1998	1998	1998	1998
	(tonnes)	(tonnes)	(tonnes)	(%)	(%)	(%)	(%)	(%)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
Newsprint	3867	2,647	1,219	47.5	1.0	0.0	51.5	0.0	579	12	0	628	0
Office Paper	688	234	453	47.5	1.0	0.0	51.5	0.0	215	5	0	234	0
Ferrous Metal	1565	547	1,018	47.5	1.0	0.0	51.5	0.0	484	10	0	525	0
Glass	1291	252	1,039	47.5	1.0	0.0	51.5	0.0	494	10	0	535	0
HDPE	366	92	274	47.5	1.0	0.0	51.5	0.0	130	3	0	141	0
LDPE	766	143	623	47.5	1.0	0.0	51.5	0.0	296	6	0	321	0
Food Waste	3290	995	2,295	47.5	1.0	0.0	51.5	0.0	1,090	23	0	1,182	0
Yard Waste	2110	3,206	0	47.5	1.0	0.0	51.5	0.0	0	0	0	0	0
Remainder		10,050	8,810	47.5	1.0	0.0	51.5	0.0	4,184	88	0	4,537	0
TOTAL=									7,472	158	0	8,103	0

Calculation/Results are in bold:

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

All waste through the NSTS.

Waste Disposed at the Cache Creek Landfill= 0.0231 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0101 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0013 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0039 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0013 tCO<sub>2</sub>e/tonne

Refer to the City of North Vancouver for recycling transportation issues.

# CITY OF WHITE ROCK:

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	650	180	38,783	17	5	42,664	715	198	913
Mixed Paper	1,221	1,007	38,783			42,664			
Office Paper	171	141	38,783	4	4	42,664	188	155	343
Ferrous Metal	107	498	38,783	3	13	42,664	118	548	666
Glass	283	149	38,783	7	4	42,664	311	164	475
HDPE	60	63	38,783	2	2	42,664	66	69	135
Mixed Plastics	409	341	38,783			42,664			
LDPE	184	153	38,783	5	4	42,664	202	169	371
Food Waste	610	618	38,783	16	16	42,664	671	680	1351
Yard Waste	617	234	38,783	16	6	42,664	679	257	936

Total ICI waste generated in 1998= 10,094 tonnes

Total ICI waste recycled in 1998= 2,126 tonnes

ICI Recycling Rate= 21 %

# of backyard composters = 1,921

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	715	198	469			42	511		
Mixed Paper			724						
Office Paper	188	155	101			33	134		
Metal			16						
Ferrous Metal	118	548	8			115	123		
Glass	311	164	22			35	57		
Plastics			6						
HDPE	66	69	2			15	17		
LDPE	202	169	2			36	38		
Food Waste	671	680		159	0	143		159	143
Yard Waste	679	257		321	0	54		321	54

Total waste disposed in 1998= 8,964 tonnes

Total waste recycled in 1998= 3,937 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF (%)	% OF M <sub>DIS</sub> to VLF (%)	% OF M <sub>DIS</sub> to FuLIF (%)	% OF M <sub>DIS</sub> to Burlnc (%)	% OF M <sub>DIS</sub> to FutInc (%)	Disposal 1998 CCLF (tonnes)	Disposal 1998 VLF (tonnes)	Disposal 1998 FuLIF (tonnes)	Disposal 1998 Burlnc (tonnes)	Disposal 1998 FutInc (tonnes)
Newsprint	913	511	402	3.1	96.9	0.0	0.0	0.0	12	390	0	0	0
Office Paper	343	134	209	3.1	96.9	0.0	0.0	0.0	6	203	0	0	0
Ferrous Metal	666	123	542	3.1	96.9	0.0	0.0	0.0	17	525	0	0	0
Glass	475	57	419	3.1	96.9	0.0	0.0	0.0	13	406	0	0	0
HDPE	135	17	119	3.1	96.9	0.0	0.0	0.0	4	115	0	0	0
LDPE	371	38	334	3.1	96.9	0.0	0.0	0.0	10	323	0	0	0
Food Waste	1351	303	1,048	3.1	96.9	0.0	0.0	0.0	32	1,016	0	0	0
Yard Waste	936	375	561	3.1	96.9	0.0	0.0	0.0	17	544	0	0	0
Remainder		2,381	5,330	3.1	96.9	0.0	0.0	0.0	164	5,164	0	2	0
TOTAL=									276	8,684	0	4	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection = 0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection = 0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection = 0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

Waste disposed at the VLF is directly delivered there (thus no emission factor below).

Waste disposed at the CCLF, BI, FuLIF, Futl is transferred through the CTS.

Waste Disposed at the Cache Creek Landfill= 0.0226 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill= 0.0000 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill= 0.0025 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator= 0.0054 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator= 0.0025 tCO<sub>2</sub>e/tonne

# ELECTORAL A (U.B.C. & U.E.L.):

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	172		4,534	38	23	6,144	233	139	372
Mixed Paper	330		4,534			6,144			
Office Paper	46		4,534	10	19	6,144	63	114	177
Ferrous Metal	24		4,534	5	70	6,144	33	432	465
Glass	57		4,534	13	22	6,144	77	137	215
HDPE	14		4,534	3	9	6,144	19	57	76
Mixed Plastics	113		4,534			6,144			
LDPE	51		4,534	11	22	6,144	69	138	207
Food Waste	172		4,534	38	75	6,144	233	463	696
Yard Waste	146		4,534	32	25	6,144	198	156	354

Total ICI waste generated in 1998=

tonnes

Total ICI waste recycled in 1998=

tonnes

ICI Recycling Rate=

40 %

# of backyard composters =

0

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	233	139	144			56	200		
Mixed Paper			985						
Office Paper	63	114	138			46	184		
Metal			222						
Ferrous Metal	33	432	111			175	286		
Glass	77	137	52			56	108		
Plastics			12						
HDPE	19	57	4			23	27		
LDPE	69	138	4			56	60		
Food Waste	233	463		0	0	187		0	187
Yard Waste	198	156		0	200	63		0	263

Total waste disposed in 1998=

3,349 tonnes

Total waste recycled in 1998=

2,205 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation 1998 (tonnes)	Total Recycling 1998 (tonnes)	Waste Disposal 1998 (tonnes)	% OF M <sub>DIS</sub> to CCLF 1998 (%)	% OF M <sub>DIS</sub> to VLF 1998 (%)	% OF M <sub>DIS</sub> to FutLF 1998 (%)	% OF M <sub>DIS</sub> to Burlnc 1998 (%)	% OF M <sub>DIS</sub> to Futlnc 1998 (%)	Disposal 1998 CCLF (tonnes)	Disposal 1998 VLF (tonnes)	Disposal 1998 FutLF (tonnes)	Disposal 1998 Burlnc (tonnes)	Disposal 1998 Futlnc (tonnes)
Newsprint	372	200	172	0.0	100.0	0.0	0.0	0.0	0	172	0	0	0
Office Paper	177	184	0	0.0	100.0	0.0	0.0	0.0	0	0	0	0	0
Ferrous Metal	465	286	179	0.0	100.0	0.0	0.0	0.0	0	179	0	0	0
Glass	215	108	107	0.0	100.0	0.0	0.0	0.0	0	107	0	0	0
HDPE	76	27	49	0.0	100.0	0.0	0.0	0.0	0	49	0	0	0
LDPE	207	60	147	0.0	100.0	0.0	0.0	0.0	0	147	0	0	0
Food Waste	696	187	509	0.0	100.0	0.0	0.0	0.0	0	509	0	0	0
Yard Waste	354	263	91	0.0	100.0	0.0	0.0	0.0	0	91	0	0	0
Remainder		891	2,096	0.0	100.0	0.0	0.0	0.0	0	2,096	0	0	0
TOTAL=										0	3,349	0	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection =

0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection =

0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection =

0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

All waste through the VTS.

Waste Disposed at the Cache Creek Landfill=

0.0227 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill=

0.0078 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill=

0.0009 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator=

0.0023 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator=

0.0009 tCO<sub>2</sub>e/tonne

### 5 Diesel Fuel Consumption for Yard Trimmings Transport to Composting Facility at the Vancouver Landfill:

assuming similar to general waste transport

Total diesel fuel consumption =

334,000 L

# of round trips in 1998=

12500 trips

Mass of waste transported (1998)=

287,931 tonnes

Average mass of waste transported =

23.0 tonnes/trip

Average fuel consumption per trip =

26.7 L/trip

GHG emission from waste transport =

0.0033 tCO<sub>2</sub>e/tonne

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# ELECTORAL C (BOWEN ISLAND & HOWE SOUND):

Variables that can be changed by users are in bold.

## MASS OF WASTE GENERATION (M<sub>GEN</sub>):

Waste Material	Residential Generation 1991 (tonnes)	ICI Generation 1991 (tonnes)	Population of Municipality 1991	Residential Generation per capita (kg/cap*yr)	ICI Generation per capita (kg/cap*yr)	Population of Municipality 1998	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Total Generation 1998 (tonnes)
Newsprint	155		2,459	63		3,332	210		210
Mixed Paper	256		2,459	104		3,332	347		347
Office Paper	36		2,459	15		3,332	49		49
Ferrous Metal	32		2,459	13		3,332	43		43
Glass	71		2,459	29		3,332	96		96
HDPE	14		2,459	6		3,332	19		19
Mixed Plastics	97		2,459			3,332			
LDPE	44		2,459	18		3,332	59		59
Food Waste	143		2,459	58		3,332	194		194
Yard Waste	115		2,459	47		3,332	156		156

Total ICI waste generated in 1998=

tonnes

Total ICI waste recycled in 1998=

tonnes

ICI Recycling Rate=

#DIV/0! %

# of backyard composters =

0

## MASS OF WASTE RECYCLED (M<sub>REC</sub>) & COMPOSTED (M<sub>COM</sub>):

Waste Material	Residential Generation 1998 (tonnes)	ICI Generation 1998 (tonnes)	Residential Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)	ICI Recycling 1998 (tonnes)	Total Recycling 1998 (tonnes)	Backyard Composting 1998 (tonnes)	Centralized Composting 1998 (tonnes)
Newsprint	210	0	46				46		
Mixed Paper	347	0	35						
Office Paper	49	0	5				5		
Metal			9						
Ferrous Metal	43	0	5				5		
Glass	96	0	43				43		
Plastics			2						
HDPE	19	0	1				1		
LDPE	59	0	1				1		
Food Waste	194	0		0	0			0	0
Yard Waste	156	0		0	8			0	8

Total waste disposed in 1998=

1,289 tonnes

Total waste recycled in 1998=

205 tonnes

## MASS OF WASTE DISPOSED (M<sub>DIS</sub>):

Waste Material	Total Generation	Total Recycling	Waste Disposal	% OF M <sub>DIS</sub> to CCLF	% OF M <sub>DIS</sub> to VLF	% OF M <sub>DIS</sub> to FutLF	% OF M <sub>DIS</sub> to Burlnc	% OF M <sub>DIS</sub> to FutInc	Disposal CCLF	Disposal VLF	Disposal FutLF	Disposal Burlnc	Disposal FutInc
	1998 (tonnes)	1998 (tonnes)	1998 (tonnes)	1998 (%)	1998 (%)	1998 (%)	1998 (%)	1998 (%)	1998 (tonnes)	1998 (tonnes)	1998 (tonnes)	1998 (tonnes)	1998 (tonnes)
Newsprint	210	46	164	47.5	1.0	0.0	51.5	0.0	78	2	0	84	0
Office Paper	49	5	44	47.5	1.0	0.0	51.5	0.0	21	0	0	22	0
Ferrous Metal	43	5	39	47.5	1.0	0.0	51.5	0.0	18	0	0	20	0
Glass	96	43	53	47.5	1.0	0.0	51.5	0.0	25	1	0	27	0
HDPE	19	1	18	47.5	1.0	0.0	51.5	0.0	9	0	0	9	0
LDPE	59	1	58	47.5	1.0	0.0	51.5	0.0	28	1	0	30	0
Food Waste	194	0	194	47.5	1.0	0.0	51.5	0.0	92	2	0	100	0
Yard Waste	156	8	148	47.5	1.0	0.0	51.5	0.0	70	1	0	76	0
Remainder		97	571	47.5	1.0	0.0	51.5	0.0	271	6	0	294	0
TOTAL=									612	13	0	664	0

### 1 Diesel Fuel Consumption for Curbside Waste Collection:

Average GHG emission from waste collection =

0.014 tCO<sub>2</sub>e/tonne

### 2 Diesel Fuel Consumption for Curbside Recyclables Collection:

Average GHG emission from waste collection =

0.043 tCO<sub>2</sub>e/tonne

### 3 Diesel Fuel Consumption for Curbside Yard Trimmings Collection:

Average GHG emission from waste collection =

0.027 tCO<sub>2</sub>e/tonne

### 4 Emission Factor for Waste Disposal:

All waste through the NTS:

Waste Disposed at the Cache Creek Landfill=

0.0231 tCO<sub>2</sub>e/tonne

Waste Disposed at the Vancouver Landfill=

0.0101 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Landfill=

0.0013 tCO<sub>2</sub>e/tonne

Waste Disposed at the Burnaby Incinerator=

0.0039 tCO<sub>2</sub>e/tonne

Waste Disposed at a Future Incinerator=

0.0013 tCO<sub>2</sub>e/tonne

Refer to the City of North Vancouver for recycling transportation issues.

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# NEWSPRINT MANAGEMENT:

Variables that can be changed by users are in bold.

Carbon Available for Anaerobic Decomposition\* 0.0795 kg C/dry kg  
 Carbon storage factor for newsprint (dry)\* 0.41 kg C/dry kg  
 Moisture content of newsprint\* 6 %  
 Nitrogen content of newsprint (dry mass basis)\* 0 %N  
 Net energy content of wet newsprint\* 18.4 GJ/tonne

## 1 Methane & Energy Implications of the Cache Creek Landfill

Carbon available for anaerobic decomposition\* 0.075 tC/wet tonne  
 Methane generation potential, L<sub>0</sub>\* 0.050 tCH<sub>4</sub>/wet tonne  
 Best-guess first order decay rate constant, k\* 0.04 year<sup>-1</sup>  
 Low estimate first order decay rate constant, k\* 0.02 year<sup>-1</sup>  
 High estimate first order decay rate constant, k\* 0.06 year<sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00199	10	43	0	0.0215	0.0000	0.00100	15	43	0	0.0101	0.0000	0.00299	5	43	0	0.0340	0.0000
2000	0.00191	10	50	0	0.0181	0.0000	0.00098	15	50	0	0.0087	0.0000	0.00282	5	50	0	0.0281	0.0000
2001	0.00184	10	50	10	0.0139	0.0005	0.00098	15	50	10	0.0066	0.0003	0.00265	5	50	0	0.0264	0.0000
2002	0.00177	10	50	15	0.0117	0.0007	0.00094	15	55	15	0.0050	0.0004	0.00250	5	50	0	0.0249	0.0000
2003	0.00170	10	45	20	0.0112	0.0009	0.00092	15	55	20	0.0041	0.0005	0.00235	5	50	0	0.0235	0.0000
2004	0.00163	10	40	25	0.0108	0.0011	0.00090	15	50	25	0.0040	0.0006	0.00221	5	55	0	0.0199	0.0000
2005	0.00157	10	35	35	0.0089	0.0015	0.00088	15	40	35	0.0039	0.0009	0.00209	5	55	0	0.0187	0.0000
2006	0.00151	10	30	40	0.0085	0.0017	0.00087	15	35	40	0.0039	0.0010	0.00196	5	55	5	0.0157	0.0003
2007	0.00145	10	25	50	0.0068	0.0020	0.00085	15	25	50	0.0038	0.0012	0.00185	5	55	5	0.0148	0.0003
2008	0.00138	10	25	50	0.0066	0.0019	0.00083	15	30	50	0.0030	0.0011	0.00174	5	50	10	0.0139	0.0005
2009	0.00134	10	20	55	0.0063	0.0020	0.00082	15	25	55	0.0029	0.0012	0.00164	5	50	10	0.0131	0.0005
2010	0.00128	10	20	55	0.0061	0.0019	0.00080	15	25	55	0.0029	0.0012	0.00154	5	50	10	0.0123	0.0004
2011	0.00123	10	15	60	0.0058	0.0020	0.00078	15	20	60	0.0028	0.0013	0.00145	5	45	15	0.0116	0.0006
2012	0.00118	10	15	60	0.0056	0.0020	0.00077	15	20	60	0.0027	0.0013	0.00137	5	45	15	0.0109	0.0006
2013	0.00114	10	10	65	0.0054	0.0020	0.00075	15	15	65	0.0027	0.0013	0.00129	5	45	15	0.0103	0.0005
2014	0.00109	10	10	65	0.0052	0.0020	0.00074	15	15	65	0.0026	0.0013	0.00122	5	40	20	0.0097	0.0007
2015	0.00105	10	5	70	0.0050	0.0020	0.00072	15	10	70	0.0026	0.0014	0.00114	5	40	20	0.0091	0.0006
2016	0.00101	10	5	70	0.0048	0.0019	0.00071	15	10	70	0.0025	0.0014	0.00108	5	35	25	0.0086	0.0007
2017	0.00097	10	0	75	0.0046	0.0020	0.00070	15	0	85	0.0019	0.0016	0.00102	5	35	25	0.0081	0.0007
2018	0.00093	10	0	75	0.0044	0.0019	0.00068	15	0	85	0.0018	0.0016	0.00096	5	35	25	0.0076	0.0007
TOTAL *	0.02799				0.171	0.039	0.017				0.078	0.020	0.036				0.321	0.007

Best-Guess of Atmospheric Methane Emissions\* 0.171 tCO<sub>2</sub>e/tonne  
 Best-Guess of Benefit of Energy Utilization\* -0.030 tCO<sub>2</sub>e/tonne  
 Low Estimate of Atmospheric Methane Emissions\* 0.078 tCO<sub>2</sub>e/tonne  
 Low Estimate of Benefit of Energy Utilization\* -0.020 tCO<sub>2</sub>e/tonne  
 High Estimate of Atmospheric Methane Emissions\* 0.321 tCO<sub>2</sub>e/tonne  
 High Estimate of Benefit of Energy Utilization\* -0.007 tCO<sub>2</sub>e/tonne

## 2 Long-Term Carbon Sequestration in the Cache Creek Landfill:

From research by Barlaz:  
 Long term carbon sequestration from newsprint\* -1.41 tCO<sub>2</sub>e/tonne

## 3 Immediate & Future N<sub>2</sub>O Emissions from the Cache Creek Landfill:

The potential of this emission is ignored.  
 Estimate of the N<sub>2</sub>O Emissions\* 0 tCO<sub>2</sub>e/tonne

## 4 Methane & Energy Implications of the Vancouver Landfill

Carbon available for anaerobic decomposition\* 0.075 tC/wet tonne  
 Methane generation potential, L<sub>0</sub>\* 0.050 tCH<sub>4</sub>/wet tonne  
 Best-guess first order decay rate constant, k\* 0.05 year<sup>-1</sup>  
 Low estimate first order decay rate constant, k\* 0.025 year<sup>-1</sup>  
 High estimate first order decay rate constant, k\* 0.075 year<sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00249	10	22	0	0.0367	0.0000	0.00125	15	22	0	0.0173	0.0000	0.00374	5	22	0	0.0581	0.0000
2000	0.00237	10	30	0	0.0313	0.0000	0.00121	15	35	0	0.0141	0.0000	0.00347	5	30	0	0.0484	0.0000
2001	0.00225	10	35	10	0.0234	0.0006	0.00118	15	40	10	0.0106	0.0003	0.00322	5	35	0	0.0417	0.0000
2002	0.00214	10	40	15	0.0182	0.0008	0.00116	15	45	15	0.0083	0.0005	0.00298	5	40	0	0.0357	0.0000
2003	0.00204	10	45	20	0.0135	0.0011	0.00113	15	55	20	0.0050	0.0006	0.00277	5	50	0	0.0276	0.0000
2004	0.00194	10	40	25	0.0128	0.0013	0.00110	15	50	25	0.0049	0.0008	0.00257	5	55	0	0.0231	0.0000
2005	0.00185	10	30	40	0.0105	0.0020	0.00107	15	40	35	0.0048	0.0010	0.00238	5	55	0	0.0214	0.0000
2006	0.00176	10	30	40	0.0100	0.0019	0.00105	15	35	40	0.0047	0.0012	0.00221	5	55	5	0.0176	0.0003
2007	0.00167	10	25	50	0.0079	0.0023	0.00102	15	25	50	0.0046	0.0014	0.00205	5	55	5	0.0164	0.0003
2008	0.00159	10	25	50	0.0075	0.0022	0.00099	15	30	50	0.0036	0.0014	0.00190	5	50	10	0.0152	0.0005
2009	0.00151	10	20	55	0.0071	0.0023	0.00097	15	25	55	0.0035	0.0015	0.00176	5	50	10	0.0141	0.0005
2010	0.00144	10	20	55	0.0068	0.0022	0.00095	15	25	55	0.0034	0.0014	0.00164	5	50	10	0.0131	0.0005
2011	0.00137	10	15	60	0.0065	0.0023	0.00092	15	20	60	0.0033	0.0015	0.00152	5	45	15	0.0121	0.0006
2012	0.00130	10	15	60	0.0061	0.0021	0.00090	15	20	60	0.0032	0.0015	0.00141	5	45	15	0.0112	0.0006
2013	0.00124	10	10	65	0.0058	0.0022	0.00088	15	15	65	0.0031	0.0016	0.00131	5	45	15	0.0104	0.0005
2014	0.00118	10	10	65	0.0056	0.0021	0.00086	15	15	65	0.0031	0.0016	0.00121	5	40	20	0.0097	0.0007
2015	0.00112	10	5	70	0.0053	0.0022	0.00083	15	10	70	0.0030	0.0016	0.00113	5	40	20	0.0090	0.0006
2016	0.00106	10	5	70	0.0050	0.0020	0.00081	15	10	70	0.0029	0.0016	0.00104	5	35	25	0.0083	0.0007
2017	0.00101	10	0	75	0.0048	0.0021	0.00079	15	0	85	0.0021	0.0019	0.00097	5	35	25	0.0077	0.0007
2018	0.00096	10	0	75	0.0046	0.0020	0.00077	15	0	85	0.0021	0.0018	0.00090	5	35	25	0.0072	0.0006
TOTAL *	0.032				0.229	0.034	0.020				0.107	0.023	0.040				0.408	0.007

Best-Guess of Atmospheric Methane Emissions\* 0.229 tCO<sub>2</sub>e/tonne  
 Best-Guess of Benefit of Energy Utilization\* -0.034 tCO<sub>2</sub>e/tonne  
 Low Estimate of Atmospheric Methane Emissions\* 0.107 tCO<sub>2</sub>e/tonne  
 Low Estimate of Benefit of Energy Utilization\* -0.023 tCO<sub>2</sub>e/tonne  
 High Estimate of Atmospheric Methane Emissions\* 0.408 tCO<sub>2</sub>e/tonne  
 High Estimate of Benefit of Energy Utilization\* -0.007 tCO<sub>2</sub>e/tonne

## 5 Long-Term Carbon Sequestration in the Vancouver Landfill:

From research by Barlaz:  
 Long term carbon sequestration from newsprint\* -1.41 tCO<sub>2</sub>e/tonne

6 Immediate & Future N<sub>2</sub>O Emissions from the Vancouver Landfill:

The potential of this emission is ignored.

Estimate of the N<sub>2</sub>O Emissions = 0 tCO<sub>2</sub>e/tonne

7 Methane & Energy Implications at a Future Landfill

Carbon available for anaerobic decomposition = 0.075 tC/wet tonne  
Methane generation potential, L<sub>0</sub> = 0.050 tCH<sub>4</sub>/wet tonne  
Best-guess first order decay rate constant, k = 0.04 year<sup>-1</sup>  
Low estimate first order decay rate constant, k = 0.02 year<sup>-1</sup>  
High estimate first order decay rate constant, k = 0.06 year<sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00199	10	43	0	0.0215	0.0000	0.00199	15	43	0	0.0203	0.0000	0.00199	5	43	0	0.0227	0.0000
2000	0.00191	10	50	0	0.0181	0.0000	0.00191	15	50	0	0.0171	0.0000	0.00191	5	50	0	0.0191	0.0000
2001	0.00184	10	50	10	0.0139	0.0005	0.00184	15	50	10	0.0131	0.0005	0.00184	5	50	0	0.0183	0.0000
2002	0.00177	10	50	15	0.0117	0.0007	0.00177	15	55	15	0.0095	0.0007	0.00177	5	50	0	0.0176	0.0000
2003	0.00170	10	45	20	0.0112	0.0009	0.00170	15	55	20	0.0076	0.0009	0.00170	5	50	0	0.0169	0.0000
2004	0.00163	10	40	25	0.0108	0.0011	0.00163	15	50	25	0.0073	0.0011	0.00163	5	55	0	0.0146	0.0000
2005	0.00157	10	35	35	0.0089	0.0015	0.00157	15	40	35	0.0070	0.0015	0.00157	5	55	0	0.0141	0.0000
2006	0.00151	10	30	40	0.0085	0.0017	0.00151	15	35	40	0.0067	0.0017	0.00151	5	55	5	0.0120	0.0002
2007	0.00145	10	25	50	0.0068	0.0020	0.00145	15	25	50	0.0065	0.0020	0.00145	5	55	5	0.0115	0.0002
2008	0.00139	10	25	50	0.0066	0.0019	0.00139	15	30	50	0.0050	0.0019	0.00139	5	50	10	0.0111	0.0004
2009	0.00134	10	20	55	0.0063	0.0020	0.00134	15	25	55	0.0048	0.0020	0.00134	5	50	10	0.0107	0.0004
2010	0.00128	10	20	55	0.0061	0.0019	0.00128	15	25	55	0.0046	0.0019	0.00128	5	50	10	0.0102	0.0004
2011	0.00123	10	15	60	0.0058	0.0020	0.00123	15	20	60	0.0044	0.0020	0.00123	5	45	15	0.0098	0.0005
2012	0.00118	10	15	60	0.0056	0.0020	0.00118	15	20	60	0.0042	0.0020	0.00118	5	45	15	0.0095	0.0005
2013	0.00114	10	10	65	0.0054	0.0020	0.00114	15	15	65	0.0041	0.0020	0.00114	5	45	15	0.0091	0.0005
2014	0.00109	10	10	65	0.0052	0.0020	0.00109	15	15	65	0.0039	0.0020	0.00109	5	40	20	0.0087	0.0006
2015	0.00105	10	5	70	0.0050	0.0020	0.00105	15	10	70	0.0038	0.0020	0.00105	5	40	20	0.0084	0.0006
2016	0.00101	10	5	70	0.0048	0.0019	0.00101	15	10	70	0.0036	0.0019	0.00101	5	35	25	0.0081	0.0007
2017	0.00097	10	0	75	0.0046	0.0020	0.00097	15	0	85	0.0026	0.0023	0.00097	5	35	25	0.0077	0.0007
2018	0.00093	10	0	75	0.0044	0.0019	0.00093	15	0	85	0.0025	0.0022	0.00093	5	35	25	0.0074	0.0006
TOTAL =	0.028				0.171	0.030	0.028				0.138	0.031	0.028				0.248	0.006

Best-Guess of Atmospheric Methane Emissions = 0.171 tCO<sub>2</sub>e/tonne  
Best-Guess of Benefit of Energy Utilization = -0.030 tCO<sub>2</sub>e/tonne  
Low Estimate of Atmospheric Methane Emissions = 0.138 tCO<sub>2</sub>e/tonne  
Low Estimate of Benefit of Energy Utilization = -0.031 tCO<sub>2</sub>e/tonne  
High Estimate of Atmospheric Methane Emissions = 0.248 tCO<sub>2</sub>e/tonne  
High Estimate of Benefit of Energy Utilization = -0.006 tCO<sub>2</sub>e/tonne

8 Long-Term Carbon Sequestration at a Future Landfill:

From research by Baritz:

Long term carbon sequestration from newsprint = -1.41 tCO<sub>2</sub>e/tonne

9 Immediate & Future N<sub>2</sub>O Emissions at a Future Landfill:

The potential of this emission is ignored.

Estimate of the N<sub>2</sub>O Emissions = 0 tCO<sub>2</sub>e/tonne

10 Energy Generation from Waste Incineration at the Burnaby Incinerator:

Net energy content of wet newsprint = 18.4 GJ/tonne

Utilized steam energy by Crown = 7.21 GJ/tonne

Turbogenerator electricity produced = 0.00 GJ/tonne

Emission prevention by steam utilization at Crown = 0.448 tCO<sub>2</sub>e/tonne

Emission prevention by offsetting BC Hydro (Burrard Thermal) = 0.000 tCO<sub>2</sub>e/tonne

Total GHG emission prevented by energy production = -0.45 tCO<sub>2</sub>e/tonne

11 GHG Emissions from Waste Incineration at the Burnaby Incinerator:

Best-guess estimate of total GHG emissions from waste incineration = 0.027 tCO<sub>2</sub>e/tonne

Low estimate of total GHG emissions from waste incineration = 0.016 tCO<sub>2</sub>e/tonne

High estimate of total GHG emissions from waste incineration = 0.037 tCO<sub>2</sub>e/tonne

12 Energy Generation from Waste Incineration at a Future Incinerator:

Net energy content of wet newsprint = 18.4 GJ/tonne

Utilized steam energy by Crown = 7.21 GJ/tonne

Turbogenerator electricity produced = 0.00 GJ/tonne

Emission prevention by steam utilization at Crown = 0.448 tCO<sub>2</sub>e/tonne

Emission prevention by offsetting BC Hydro (Burrard Thermal) = 0.000 tCO<sub>2</sub>e/tonne

Total GHG emission prevented by energy production = -0.448 tCO<sub>2</sub>e/tonne

13 GHG Emissions from Waste Incineration at a Future Incinerator:

Best-guess estimate of total GHG emissions from waste incineration = 0.027 tCO<sub>2</sub>e/tonne

Low estimate of total GHG emissions from waste incineration = 0.016 tCO<sub>2</sub>e/tonne

High estimate of total GHG emissions from waste incineration = 0.037 tCO<sub>2</sub>e/tonne

14 GHG Emissions of Recycled Newsprint Utilization:

GHG benefit of recycled versus virgin manufacturing = 0 tCO<sub>2</sub>e/tonne

15 Effect of Recycling Newsprint on Forest Carbon Storage:

GHG implications of recycled newsprint on Forestry = 0 tCO<sub>2</sub>e/tonne

# OFFICE PAPER MANAGEMENT:

Variables that can be changed by users are in bold.

Carbon Available for Anaerobic Decomposition	0.371 kg C/dry kg
Carbon storage factor for office paper (dry) <sup>a</sup>	0.03 kg C/dry kg
Moisture content of office paper <sup>a</sup>	6 %
Nitrogen content of office paper (dry mass basis) <sup>a</sup>	0 %N
Net energy content of office paper <sup>a</sup>	15.7 GJ/tonne

## 1 Methane & Energy Implications of the Cache Creek Landfill

Carbon available for anaerobic decomposition	0.348 tC/wet tonne
Methane generation potential, L <sub>0</sub>	0.232 tCH <sub>4</sub> /wet tonne
Best-guess first order decay rate constant, k <sub>1</sub>	0.04 year <sup>-1</sup>
Low estimate first order decay rate constant, k <sub>1</sub>	0.02 year <sup>-1</sup>
High estimate first order decay rate constant, k <sub>1</sub>	0.06 year <sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00929	10	43	0	0.1001	0.0000	0.00465	15	43	0	0.0473	0.0000	0.01394	5	43	0	0.1585	0.0000
2000	0.00383	10	50	0	0.0844	0.0000	0.00455	15	50	0	0.0406	0.0000	0.01313	5	50	0	0.1309	0.0000
2001	0.00358	10	50	10	0.0648	0.0024	0.00446	15	50	10	0.0319	0.0012	0.01236	5	50	0	0.1233	0.0000
2002	0.00324	10	50	15	0.0545	0.0034	0.00436	15	55	15	0.0234	0.0018	0.01164	5	50	0	0.1161	0.0000
2003	0.00792	10	45	20	0.0524	0.0044	0.00429	15	55	20	0.0191	0.0024	0.01096	5	50	0	0.1094	0.0000
2004	0.00781	10	40	25	0.0503	0.0052	0.00420	15	50	25	0.0188	0.0029	0.01033	5	55	0	0.0927	0.0000
2005	0.00731	10	35	35	0.0414	0.0070	0.00412	15	40	35	0.0184	0.0040	0.00972	5	55	0	0.0873	0.0000
2006	0.00702	10	30	40	0.0398	0.0077	0.00404	15	35	40	0.0180	0.0044	0.00916	5	55	5	0.0731	0.0013
2007	0.00675	10	25	50	0.0319	0.0093	0.00396	15	25	50	0.0177	0.0054	0.00862	5	55	5	0.0688	0.0012
2008	0.00648	10	25	50	0.0306	0.0099	0.00388	15	30	50	0.0139	0.0053	0.00812	5	50	10	0.0648	0.0022
2009	0.00623	10	20	55	0.0294	0.0094	0.00380	15	25	55	0.0136	0.0058	0.00785	5	50	10	0.0610	0.0021
2010	0.00598	10	20	55	0.0283	0.0091	0.00373	15	25	55	0.0133	0.0056	0.00720	5	50	10	0.0575	0.0020
2011	0.00575	10	15	60	0.0272	0.0095	0.00365	15	20	60	0.0130	0.0060	0.00678	5	45	15	0.0541	0.0028
2012	0.00552	10	15	60	0.0261	0.0095	0.00358	15	20	60	0.0128	0.0059	0.00639	5	45	15	0.0510	0.0026
2013	0.00531	10	10	65	0.0251	0.0091	0.00351	15	15	65	0.0125	0.0063	0.00602	5	45	15	0.0480	0.0025
2014	0.00510	10	10	65	0.0241	0.0091	0.00344	15	15	65	0.0123	0.0062	0.00567	5	40	20	0.0452	0.0031
2015	0.00490	10	5	70	0.0232	0.0094	0.00337	15	10	70	0.0120	0.0065	0.00534	5	40	20	0.0426	0.0029
2016	0.00471	10	5	70	0.0222	0.0091	0.00331	15	10	70	0.0118	0.0064	0.00503	5	35	25	0.0401	0.0035
2017	0.00452	10	0	75	0.0214	0.0093	0.00324	15	0	85	0.0087	0.0076	0.00473	5	35	25	0.0378	0.0033
2018	0.00435	10	0	75	0.0205	0.0090	0.00318	15	0	85	0.0085	0.0074	0.00446	5	35	25	0.0356	0.0031
TOTAL =	0.130	-	-	-	0.798	0.141	0.077	-	-	-	0.368	0.091	0.167	-	-	-	1.498	0.033

Best-Guess of Atmospheric Methane Emissions	0.798 tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization	-0.141 tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions	0.368 tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization	-0.091 tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions	1.498 tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization	-0.033 tCO <sub>2</sub> e/tonne

## 2 Long-Term Carbon Sequestration in the Cache Creek Landfill:

From research by Barlaz:	
Long term carbon sequestration from newspaper	-0.10 tCO <sub>2</sub> e/tonne

## 3 Immediate & Future N<sub>2</sub>O Emissions from the Cache Creek Landfill:

The potential of this emission is ignored.	
Estimate of the N <sub>2</sub> O Emissions	0 tCO <sub>2</sub> e/tonne

## 4 Methane & Energy Implications of the Vancouver Landfill

Carbon available for anaerobic decomposition	0.348 tC/wet tonne
Methane generation potential, L <sub>0</sub>	0.232 tCH <sub>4</sub> /wet tonne
Best-guess first order decay rate constant, k <sub>1</sub>	0.05 year <sup>-1</sup>
Low estimate first order decay rate constant, k <sub>1</sub>	0.025 year <sup>-1</sup>
High estimate first order decay rate constant, k <sub>1</sub>	0.075 year <sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.01162	10	22	0	0.1712	0.0000	0.00581	15	22	0	0.0809	0.0000	0.01742	5	22	0	0.2711	0.0000
2000	0.01105	10	30	0	0.1462	0.0000	0.00566	15	35	0	0.0657	0.0000	0.01616	5	30	0	0.2257	0.0000
2001	0.01051	10	35	10	0.1093	0.0029	0.00552	15	40	10	0.0493	0.0015	0.01500	5	35	0	0.1945	0.0000
2002	0.01000	10	40	15	0.0850	0.0041	0.00539	15	45	15	0.0385	0.0022	0.01391	5	40	0	0.1665	0.0000
2003	0.00951	10	45	20	0.0629	0.0052	0.00525	15	55	20	0.0235	0.0029	0.01291	5	50	0	0.1287	0.0000
2004	0.00905	10	40	25	0.0598	0.0062	0.00513	15	50	25	0.0229	0.0035	0.01197	5	55	0	0.1075	0.0000
2005	0.00860	10	30	40	0.0488	0.0095	0.00500	15	40	35	0.0223	0.0048	0.01111	5	55	0	0.0997	0.0000
2006	0.00819	10	30	40	0.0464	0.0090	0.00488	15	35	40	0.0218	0.0054	0.01031	5	55	5	0.0822	0.0014
2007	0.00779	10	25	50	0.0368	0.0107	0.00475	15	25	50	0.0212	0.0065	0.00956	5	55	5	0.0763	0.0013
2008	0.00741	10	25	50	0.0350	0.0102	0.00464	15	30	50	0.0166	0.0064	0.00887	5	50	10	0.0708	0.0024
2009	0.00705	10	20	55	0.0333	0.0107	0.00452	15	25	55	0.0161	0.0068	0.00823	5	50	10	0.0657	0.0023
2010	0.00670	10	20	55	0.0317	0.0101	0.00441	15	25	55	0.0157	0.0067	0.00784	5	50	10	0.0609	0.0021
2011	0.00637	10	15	60	0.0301	0.0105	0.00430	15	20	60	0.0154	0.0071	0.00708	5	45	15	0.0565	0.0029
2012	0.00606	10	15	60	0.0287	0.0100	0.00420	15	20	60	0.0150	0.0069	0.00657	5	45	15	0.0524	0.0027
2013	0.00577	10	10	65	0.0273	0.0103	0.00409	15	15	65	0.0146	0.0073	0.00610	5	45	15	0.0487	0.0025
2014	0.00549	10	10	65	0.0259	0.0098	0.00399	15	15	65	0.0142	0.0071	0.00566	5	40	20	0.0451	0.0031
2015	0.00522	10	5	70	0.0247	0.0100	0.00389	15	10	70	0.0139	0.0075	0.00525	5	40	20	0.0419	0.0029
2016	0.00496	10	5	70	0.0235	0.0096	0.00380	15	10	70	0.0136	0.0073	0.00487	5	35	25	0.0389	0.0033
2017	0.00472	10	0	75	0.0223	0.0097	0.00370	15	0	85	0.0099	0.0087	0.00452	5	35	25	0.0360	0.0031
2018	0.00449	10	0	75	0.0212	0.0093	0.00361	15	0	85	0.0097	0.0084	0.00419	5	35	25	0.0334	0.0029
TOTAL =	0.151	-	-	-	1.070	0.158	0.093	-	-	-	0.501	0.107	0.187	-	-	-	1.903	0.033

Best-Guess of Atmospheric Methane Emissions	1.070 tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization	-0.158 tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions	0.501 tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization	-0.107 tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions	1.903 tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization	-0.033 tCO <sub>2</sub> e/tonne

## 5 Long-Term Carbon Sequestration in the Vancouver Landfill:

From research by Barlaz:	
Long term carbon sequestration from office papers	-0.10 tCO <sub>2</sub> e/tonne

6 Immediate & Future N<sub>2</sub>O Emissions from the Vancouver Landfill:

The potential of this emission is ignored.

Estimate of the N<sub>2</sub>O Emissions = 0 tCO<sub>2</sub>e/tonne

7 Methane & Energy Implications at a Future Landfill

Carbon available for anaerobic decomposition = 0.348 tCO<sub>2</sub>e/tonne  
 Methane generation potential, L<sub>0</sub> = 0.232 tCH<sub>4</sub>/wet tonne  
 Best-guess first order decay rate constant, k = 0.04 year<sup>-1</sup>  
 Low estimate first order decay rate constant, k = 0.02 year<sup>-1</sup>  
 High estimate first order decay rate constant, k = 0.06 year<sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
	(tCH <sub>4</sub> /yr)	(%)	(%)	(%)	(tCO <sub>2</sub> e/yr)	(tCO <sub>2</sub> e/yr)	(tCH <sub>4</sub> /yr)	(%)	(%)	(%)	(tCO <sub>2</sub> e/yr)	(tCO <sub>2</sub> e/yr)	(tCH <sub>4</sub> /yr)	(%)	(%)	(%)	(tCO <sub>2</sub> e/yr)	(tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00929	10	43	0	0.1001	0.0000	0.00465	15	43	0	0.0473	0.0000	0.01394	5	43	0	0.1585	0.0000
2000	0.00893	10	50	0	0.0844	0.0000	0.00455	15	50	0	0.0406	0.0000	0.01313	5	50	0	0.1309	0.0000
2001	0.00858	10	50	10	0.0648	0.0024	0.00446	15	50	10	0.0319	0.0012	0.01236	5	50	0	0.1233	0.0000
2002	0.00824	10	50	15	0.0545	0.0034	0.00438	15	55	15	0.0234	0.0018	0.01164	5	50	0	0.1181	0.0000
2003	0.00792	10	45	20	0.0524	0.0044	0.00429	15	55	20	0.0191	0.0024	0.01096	5	50	0	0.1094	0.0000
2004	0.00761	10	40	25	0.0503	0.0052	0.00420	15	50	25	0.0188	0.0029	0.01033	5	55	0	0.0927	0.0000
2005	0.00731	10	35	35	0.0414	0.0070	0.00412	15	40	35	0.0184	0.0040	0.00972	5	55	0	0.0873	0.0000
2006	0.00702	10	30	40	0.0398	0.0077	0.00404	15	35	40	0.0180	0.0044	0.00916	5	55	5	0.0731	0.0013
2007	0.00675	10	25	50	0.0319	0.0093	0.00396	15	25	50	0.0177	0.0054	0.00862	5	55	5	0.0688	0.0012
2008	0.00648	10	25	50	0.0268	0.0089	0.00388	15	30	50	0.0139	0.0053	0.00812	5	50	10	0.0648	0.0022
2009	0.00623	10	20	55	0.0204	0.0094	0.00380	15	25	55	0.0136	0.0058	0.00765	5	50	10	0.0610	0.0021
2010	0.00598	10	20	55	0.0283	0.0091	0.00373	15	25	55	0.0123	0.0056	0.00730	5	50	10	0.0575	0.0020
2011	0.00575	10	15	60	0.0272	0.0095	0.00365	15	20	60	0.0130	0.0060	0.00678	5	45	15	0.0541	0.0028
2012	0.00552	10	15	60	0.0261	0.0091	0.00358	15	20	60	0.0128	0.0059	0.00639	5	45	15	0.0510	0.0028
2013	0.00531	10	10	65	0.0251	0.0095	0.00351	15	15	65	0.0125	0.0063	0.00602	5	45	15	0.0480	0.0025
2014	0.00510	10	10	65	0.0241	0.0091	0.00344	15	15	65	0.0123	0.0062	0.00567	5	40	20	0.0452	0.0031
2015	0.00490	10	5	70	0.0232	0.0094	0.00337	15	10	70	0.0120	0.0065	0.00534	5	40	20	0.0426	0.0029
2016	0.00471	10	5	70	0.0222	0.0091	0.00331	15	10	70	0.0118	0.0064	0.00503	5	35	25	0.0401	0.0035
2017	0.00452	10	0	75	0.0214	0.0092	0.00324	15	0	85	0.0087	0.0076	0.00473	5	35	25	0.0378	0.0033
2018	0.00435	10	0	75	0.0205	0.0090	0.00318	15	0	85	0.0085	0.0074	0.00446	5	35	25	0.0356	0.0031
TOTAL =	0.138				0.798	0.141	0.077				0.358	0.091	0.167				1.498	0.033

Best-Guess of Atmospheric Methane Emissions = 0.798 tCO<sub>2</sub>e/tonne  
 Best-Guess of Benefit of Energy Utilization = -0.141 tCO<sub>2</sub>e/tonne  
 Low Estimate of Atmospheric Methane Emissions = 0.368 tCO<sub>2</sub>e/tonne  
 Low Estimate of Benefit of Energy Utilization = -0.091 tCO<sub>2</sub>e/tonne  
 High Estimate of Atmospheric Methane Emissions = 1.498 tCO<sub>2</sub>e/tonne  
 High Estimate of Benefit of Energy Utilization = -0.033 tCO<sub>2</sub>e/tonne

8 Long-Term Carbon Sequestration at a Future Landfill:

From research by Berlitz:

Long term carbon sequestration from office papers = -0.10 tCO<sub>2</sub>e/tonne

9 Immediate & Future N<sub>2</sub>O Emissions at a Future Landfill:

The potential of this emission is ignored.

Estimate of the N<sub>2</sub>O Emissions = 0 tCO<sub>2</sub>e/tonne

10 Energy Generation from Waste Incineration at the Burnaby Incinerator:

Net energy content of wet newspaper = 15.7 GJ/tonne  
 Utilized steam energy by Crown = 6.15 GJ/tonne  
 Turbogenerator electricity produced = 0.00 GJ/tonne  
 Emission prevention by steam utilization at Crown = 0.382 tCO<sub>2</sub>e/tonne  
 Emission prevention by offsetting BC Hydro (Burnard Thermal) = 0.000 tCO<sub>2</sub>e/tonne  
 Total GHG emission prevented by energy production = -0.38 tCO<sub>2</sub>e/tonne

11 GHG Emissions from Waste Incineration at the Burnaby Incinerator:

Best-guess estimate of total GHG emissions from waste incineration = 0.027 tCO<sub>2</sub>e/tonne  
 Low estimate of total GHG emissions from waste incineration = 0.016 tCO<sub>2</sub>e/tonne  
 High estimate of total GHG emissions from waste incineration = 0.037 tCO<sub>2</sub>e/tonne

12 Energy Generation from Waste Incineration at a Future Incinerator:

Net energy content of wet newspaper = 15.7 GJ/tonne  
 Utilized steam energy by Crown = 6.15 GJ/tonne  
 Turbogenerator electricity produced = 0.00 GJ/tonne  
 Emission prevention by steam utilization at Crown = 0.382 tCO<sub>2</sub>e/tonne  
 Emission prevention by offsetting BC Hydro (Burnard Thermal) = 0.000 tCO<sub>2</sub>e/tonne  
 Total GHG emission prevented by energy production = -0.38 tCO<sub>2</sub>e/tonne

13 GHG Emissions from Waste Incineration at a Future Incinerator:

Best-guess estimate of total GHG emissions from waste incineration = 0.027 tCO<sub>2</sub>e/tonne  
 Low estimate of total GHG emissions from waste incineration = 0.016 tCO<sub>2</sub>e/tonne  
 High estimate of total GHG emissions from waste incineration = 0.037 tCO<sub>2</sub>e/tonne

14 GHG Emissions of Recycled Office Paper Utilization:

GHG benefit of recycled versus virgin manufacturing = 0 tCO<sub>2</sub>e/tonne

15 Effect of Recycling Office Paper on Forest Carbon Storage:

GHG implications of recycled office paper on Forestry = 0 tCO<sub>2</sub>e/tonne



## FERROUS METAL MANAGEMENT:

Variables that can be changed by users are in bold.

- 1 Recycling of Metal:  
GHG benefit of recycled versus virgin manufacturing=  
(includes transportation emissions) -2.35 tCO<sub>2</sub>e/tonne
  
- 2 Recovery of Metal at the Burnaby Incinerator:  
Capture efficiency to recover ferrous metal= 50 %  
GHG benefit of the metal for recycling= -1.18 tCO<sub>2</sub>e/tonne
  
- 3 Recovery of Metal at a Future Incinerator:  
Capture efficiency to recover ferrous metal= 50 %  
GHG benefit of the metal for recycling= -1.18 tCO<sub>2</sub>e/tonne

## GLASS MANAGEMENT:

Variables that can be changed by users are in bold.

### 1 Recycling of Glass:

**GHG benefit of recycled versus virgin manufacturing=**  
**(includes transportation emissions)**

**-0.37 tCO<sub>2</sub>e/tonne**

## HIGH-DENSITY POLYETHYLENE MANAGEMENT:

Variables that can be changed by users are in bold.

Moisture content of HDPE=	6 %
Fossil carbon content of HDPE (dry mass basis)=	85 %
Nitrogen content of HDPE (dry mass basis)=	0 %N
Net energy content of HDPE=	43.3 GJ/tonne

### 1 Energy Generation from Waste Incineration at the Burnaby Incinerator:

Net energy content of HDPE=	43.3 GJ/tonne
Utilized steam energy by Crown=	16.97 GJ/tonne
Turbogenerator electricity produced=	0.00 GJ/tonne
Emission prevention by steam utilization at Crown=	1.054 tCO <sub>2</sub> e/tonne
Emission prevention by offsetting BC Hydro (Burrard Thermal)=	0.000 tCO <sub>2</sub> e/tonne
Total GHG emission prevented by energy production=	-1.05 tCO <sub>2</sub> e/tonne

### 2 GHG Emissions from Waste Incineration at the Burnaby Incinerator:

CO <sub>2</sub> emission from fossil-carbon in polyethylene=	3.117 tCO <sub>2</sub> e/tonne
Best-guess estimate of total GHG emissions from waste incineration=	3.143 tCO <sub>2</sub> e/tonne
Low estimate of total GHG emissions from waste incineration=	3.133 tCO <sub>2</sub> e/tonne
High estimate of total GHG emissions from waste incineration=	3.154 tCO <sub>2</sub> e/tonne

### 3 Energy Generation from Waste Incineration at a Future Incinerator:

Net energy content of HDPE=	43.3 GJ/tonne
Utilized steam energy by Crown=	16.97 GJ/tonne
Turbogenerator electricity produced=	0.00 GJ/tonne
Emission prevention by steam utilization at Crown=	1.054 tCO <sub>2</sub> e/tonne
Emission prevention by offsetting BC Hydro (Burrard Thermal)=	0.000 tCO <sub>2</sub> e/tonne
Total GHG emission prevented by energy production=	-1.05 tCO <sub>2</sub> e/tonne

### 4 GHG Emissions from Waste Incineration at a Future Incinerator:

CO <sub>2</sub> emission from fossil-carbon in polyethylene=	3.12 tCO <sub>2</sub> e/tonne
Estimate of total GHG emissions from waste incineration=	3.14 tCO <sub>2</sub> e/tonne

### 5 GHG Emissions of Recycled HDPE Utilization:

GHG benefit of recycled versus virgin manufacturing= (includes transportation emissions)	-1.70 tCO <sub>2</sub> e/tonne
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## LOW-DENSITY POLYETHYLENE MANAGEMENT:

Variables that can be changed by users are in bold.

Moisture content of LDPE=	6 %
Fossil carbon content of LDPE (dry mass basis)=	85 %
Nitrogen content of LDPE (dry mass basis)=	0 %N
Net energy content of LDPE=	43.3 GJ/tonne

### 1 Energy Generation from Waste Incineration at the Burnaby Incinerator:

Net energy content of LDPE=	43.3 GJ/tonne
Utilized steam energy by Crown=	16.97 GJ/tonne
Turbogenerator electricity produced=	0.00 GJ/tonne
Emission prevention by steam utilization at Crown=	1.054 tCO <sub>2</sub> e/tonne
Emission prevention by offsetting BC Hydro (Burrard Thermal)=	0.000 tCO <sub>2</sub> e/tonne
Total GHG emission prevented by energy production=	-1.05 tCO <sub>2</sub> e/tonne

### 2 GHG Emissions from Waste Incineration at the Burnaby Incinerator:

CO <sub>2</sub> emission from fossil-carbon in polyethylene=	3.117 tCO <sub>2</sub> e/tonne
Best-guess estimate of total GHG emissions from waste incineration=	3.143 tCO <sub>2</sub> e/tonne
Low estimate of total GHG emissions from waste incineration=	3.133 tCO <sub>2</sub> e/tonne
High estimate of total GHG emissions from waste incineration=	3.154 tCO <sub>2</sub> e/tonne

### 3 Energy Generation from Waste Incineration at a Future Incinerator:

Net energy content of LDPE=	43.3 GJ/tonne
Utilized steam energy by Crown=	16.97 GJ/tonne
Turbogenerator electricity produced=	0.00 GJ/tonne
Emission prevention by steam utilization at Crown=	1.054 tCO <sub>2</sub> e/tonne
Emission prevention by offsetting BC Hydro (Burrard Thermal)=	0.000 tCO <sub>2</sub> e/tonne
Total GHG emission prevented by energy production=	-1.05 tCO <sub>2</sub> e/tonne

### 4 GHG Emissions from Waste Incineration at a Future Incinerator:

CO <sub>2</sub> emission from fossil-carbon in polyethylene=	3.12 tCO <sub>2</sub> e/tonne
Estimate of total GHG emissions from waste incineration=	3.14 tCO <sub>2</sub> e/tonne

### 5 GHG Emissions of Recycled LDPE Utilization:

GHG benefit of recycled versus virgin manufacturing= (includes transportation emissions)	-2.25 tCO <sub>2</sub> e/tonne
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# FOOD WASTE MANAGEMENT:

Variables that can be changed by users are in bold.

Carbon available for anaerobic decomposition=	0.322 kg C/dry kg
Carbon storage factor for food waste (dry)=	0.08 kg C/dry kg
Moisture content of food waste=	70 %
Carbon content of food waste (dry)=	48 %
Nitrogen content of dry food waste=	2.6 %N
Best-Guess Estimate of the net energy content of wet food waste=	4.0 GJ/tonne
Low Estimate of the net energy content of wet food waste=	2.4 GJ/tonne
High Estimate of the net energy content of wet food waste=	5.5 GJ/tonne
Carbon storage factor (wet)=	0.024 tC/wet tonne

## 1 Methane & Energy Implications of the Cache Creek Landfill

Carbon available for anaerobic decomposition=	0.120 tC/wet tonne
Methane generation potential, L <sub>0</sub> =	0.080 tCH <sub>4</sub> /wet tonne
Best-guess first order decay rate constant, k=	0.070 year <sup>-1</sup>
Low estimate first order decay rate constant, k=	0.035 year <sup>-1</sup>
High estimate first order decay rate constant, k=	0.105 year <sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00500	10	43	0	0.0603	0.0000	0.00280	15	43	0	0.0285	0.0000	0.00840	5	43	0	0.0955	0.0000
2000	0.00522	10	50	0	0.0493	0.0000	0.00270	15	50	0	0.0241	0.0000	0.00756	5	50	0	0.0754	0.0000
2001	0.00487	10	50	10	0.0368	0.0013	0.00261	15	50	10	0.0186	0.0007	0.00681	5	50	0	0.0679	0.0000
2002	0.00454	10	50	15	0.0300	0.0019	0.00252	15	55	15	0.0135	0.0010	0.00613	5	50	0	0.0611	0.0000
2003	0.00423	10	45	20	0.0280	0.0023	0.00243	15	55	20	0.0109	0.0013	0.00552	5	50	0	0.0551	0.0000
2004	0.00395	10	40	25	0.0261	0.0027	0.00235	15	50	25	0.0105	0.0016	0.00497	5	55	0	0.0446	0.0000
2005	0.00368	10	35	35	0.0209	0.0035	0.00227	15	40	35	0.0101	0.0022	0.00447	5	55	0	0.0402	0.0000
2006	0.00343	10	30	40	0.0195	0.0038	0.00219	15	35	40	0.0098	0.0024	0.00403	5	55	5	0.0321	0.0006
2007	0.00320	10	25	50	0.0151	0.0044	0.00212	15	25	50	0.0094	0.0029	0.00363	5	55	5	0.0289	0.0005
2008	0.00298	10	25	50	0.0141	0.0041	0.00204	15	30	50	0.0073	0.0028	0.00326	5	50	10	0.0261	0.0009
2009	0.00278	10	20	55	0.0131	0.0042	0.00197	15	25	55	0.0070	0.0030	0.00294	5	50	10	0.0235	0.0008
2010	0.00259	10	20	55	0.0123	0.0039	0.00191	15	25	55	0.0068	0.0029	0.00265	5	50	10	0.0211	0.0007
2011	0.00242	10	15	60	0.0114	0.0040	0.00184	15	20	60	0.0066	0.0030	0.00238	5	45	15	0.0190	0.0010
2012	0.00225	10	15	60	0.0107	0.0037	0.00178	15	20	60	0.0063	0.0029	0.00215	5	45	15	0.0171	0.0009
2013	0.00210	10	10	65	0.0099	0.0038	0.00172	15	15	65	0.0061	0.0031	0.00193	5	45	15	0.0154	0.0008
2014	0.00196	10	10	65	0.0093	0.0035	0.00166	15	15	65	0.0059	0.0030	0.00174	5	40	20	0.0139	0.0010
2015	0.00183	10	5	70	0.0086	0.0035	0.00160	15	10	70	0.0057	0.0031	0.00157	5	40	20	0.0125	0.0009
2016	0.00170	10	5	70	0.0080	0.0033	0.00154	15	10	70	0.0055	0.0030	0.00141	5	35	25	0.0112	0.0010
2017	0.00159	10	0	75	0.0075	0.0033	0.00149	15	0	85	0.0040	0.0035	0.00127	5	35	25	0.0101	0.0009
2018	0.00148	10	0	75	0.0070	0.0031	0.00144	15	0	85	0.0039	0.0034	0.00114	5	35	25	0.0091	0.0008
TOTAL =	0.062				0.398	0.060	0.041				0.201	0.046	0.074				0.680	0.011

Best-Guess of Atmospheric Methane Emissions=	0.398 tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.060 tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.201 tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.046 tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.680 tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.011 tCO <sub>2</sub> e/tonne

## 2 Long-Term Carbon Sequestration in the Cache Creek Landfill:

From research by Barlaz:	
Long term carbon sequestration from food waste=	-0.088 tCO <sub>2</sub> e/tonne

## 3 Immediate & Future N<sub>2</sub>O Emissions from the Cache Creek Landfill:

Best-Guess Estimate of the N <sub>2</sub> O from vented nitrogen=	1.0 %N <sub>2</sub> O/vented NH <sub>3</sub> or NO <sub>x</sub>
Low Estimate of the N <sub>2</sub> O from vented nitrogen=	0.2 %N <sub>2</sub> O/vented NH <sub>3</sub> or NO <sub>x</sub>
High Estimate of the N <sub>2</sub> O from vented nitrogen=	2.0 %N <sub>2</sub> O/vented NH <sub>3</sub> or NO <sub>x</sub>
Nitrogen content of wet food waste=	0.78 %N
Best-Guess Estimate of the N <sub>2</sub> O Emission=	0.038 tCO <sub>2</sub> e/tonne
Low Estimate of the N <sub>2</sub> O Emission=	0.008 tCO <sub>2</sub> e/tonne
High Estimate of the N <sub>2</sub> O Emission=	0.076 tCO <sub>2</sub> e/tonne

## 4 Methane & Energy Implications of the Vancouver Landfill

Carbon available for anaerobic decomposition=	0.120 tC/wet tonne
Methane generation potential, L <sub>0</sub> =	0.080 tCH <sub>4</sub> /wet tonne
Best-guess first order decay rate constant, k=	0.08 year <sup>-1</sup>
Low estimate first order decay rate constant, k=	0.04 year <sup>-1</sup>
High estimate first order decay rate constant, k=	0.12 year <sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00640	10	22	0	0.0943	0.0000	0.00320	15	22	0	0.0446	0.0000	0.00960	5	22	0	0.1494	0.0000
2000	0.00591	10	30	0	0.0782	0.0000	0.00307	15	35	0	0.0357	0.0000	0.00851	5	30	0	0.1189	0.0000
2001	0.00545	10	35	10	0.0567	0.0015	0.00295	15	40	10	0.0264	0.0008	0.00755	5	35	0	0.0979	0.0000
2002	0.00503	10	40	15	0.0428	0.0021	0.00284	15	45	15	0.0203	0.0012	0.00670	5	40	0	0.0802	0.0000
2003	0.00465	10	45	20	0.0307	0.0026	0.00273	15	55	20	0.0122	0.0015	0.00594	5	50	0	0.0593	0.0000
2004	0.00429	10	40	25	0.0284	0.0029	0.00262	15	50	25	0.0117	0.0018	0.00527	5	55	0	0.0473	0.0000
2005	0.00396	10	30	40	0.0225	0.0044	0.00252	15	40	35	0.0112	0.0024	0.00467	5	55	0	0.0420	0.0000
2006	0.00366	10	30	40	0.0207	0.0040	0.00242	15	35	40	0.0108	0.0027	0.00414	5	55	5	0.0331	0.0006
2007	0.00337	10	25	50	0.0159	0.0046	0.00232	15	25	50	0.0104	0.0032	0.00368	5	55	5	0.0293	0.0005
2008	0.00312	10	25	50	0.0147	0.0043	0.00223	15	30	50	0.0080	0.0031	0.00326	5	50	10	0.0260	0.0009
2009	0.00288	10	20	55	0.0136	0.0043	0.00215	15	25	55	0.0077	0.0032	0.00289	5	50	10	0.0231	0.0008
2010	0.00265	10	20	55	0.0125	0.0040	0.00206	15	25	55	0.0074	0.0031	0.00256	5	50	10	0.0205	0.0007
2011	0.00245	10	15	60	0.0116	0.0040	0.00198	15	20	60	0.0071	0.0033	0.00227	5	45	15	0.0182	0.0009
2012	0.00226	10	15	60	0.0107	0.0037	0.00190	15	20	60	0.0068	0.0031	0.00202	5	45	15	0.0161	0.0008
2013	0.00209	10	10	65	0.0099	0.0037	0.00183	15	15	65	0.0065	0.0033	0.00179	5	45	15	0.0143	0.0007
2014	0.00193	10	10	65	0.0091	0.0034	0.00176	15	15	65	0.0063	0.0031	0.00159	5	40	20	0.0127	0.0009
2015	0.00178	10	5	70	0.0084	0.0034	0.00169	15	10	70	0.0060	0.0032	0.00141	5	40	20	0.0112	0.0008
2016	0.00164	10	5	70	0.0078	0.0032	0.00162	15	10	70	0.0058	0.0031	0.00125	5	35	25	0.0100	0.0009
2017	0.00152	10	0	75	0.0072	0.0031	0.00156	15	0	85	0.0042	0.0036	0.00111	5	35	25	0.0088	0.0008

2018	0.00140	10	0	75	0.0066	0.0029	0.00150	15	0	85	0.0040	0.0035	0.00098	5	35	25	0.0078	0.0007
TOTAL =	0.066				0.502	0.062	0.045				0.253	0.049	0.077				0.826	0.010

Best-Guess of Atmospheric Methane Emissions=	0.502	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.062	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.253	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.049	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.826	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.010	tCO <sub>2</sub> e/tonne

#### 5 Long-Term Carbon Sequestration in the Vancouver Landfill:

From research by Barlaz:

Long term carbon sequestration from food waste=	-0.088	tCO <sub>2</sub> e/tonne
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#### 6 Immediate & Future N<sub>2</sub>O Emissions from the Vancouver Landfill:

Best-Guess Estimate of the N <sub>2</sub> O from wastewater nitrogen=	1.0	%N <sub>2</sub> O/influent-N
Low Estimate of the N <sub>2</sub> O from wastewater nitrogen=	0.2	%N <sub>2</sub> O/influent-N
High Estimate of the N <sub>2</sub> O from wastewater nitrogen=	2.0	%N <sub>2</sub> O/influent-N
Nitrogen content of wet food waste=	0.78	%N
Best-Guess Estimate of the N <sub>2</sub> O Emission=	0.038	tCO <sub>2</sub> e/tonne
Low Estimate of the N <sub>2</sub> O Emission=	0.008	tCO <sub>2</sub> e/tonne
High Estimate of the N <sub>2</sub> O Emission=	0.076	tCO <sub>2</sub> e/tonne

#### 7 Methane & Energy Implications at a Future Landfill

Carbon available for anaerobic decomposition=	0.120	tC/wet tonne
Methane generation potential, L <sub>0</sub> =	0.080	tCH <sub>4</sub> /wet tonne
Best-guess first order decay rate constant, k=	0.07	year <sup>-1</sup>
Low estimate first order decay rate constant, k=	0.035	year <sup>-1</sup>
High estimate first order decay rate constant, k=	0.105	year <sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Oxidation by Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00560	10	43	0	0.0503	0.0000	0.00280	15	43	0	0.0285	0.0000	0.00840	5	43	0	0.0955	0.0000
2000	0.00522	10	50	0	0.0493	0.0000	0.00270	15	50	0	0.0241	0.0000	0.00756	5	50	0	0.0754	0.0000
2001	0.00487	10	50	10	0.0368	0.0013	0.00261	15	50	10	0.0186	0.0007	0.00681	5	50	0	0.0679	0.0000
2002	0.00454	10	50	15	0.0300	0.0019	0.00252	15	55	15	0.0135	0.0010	0.00613	5	50	0	0.0611	0.0000
2003	0.00423	10	45	20	0.0280	0.0023	0.00243	15	55	20	0.0109	0.0013	0.00552	5	50	0	0.0551	0.0000
2004	0.00395	10	40	25	0.0261	0.0027	0.00235	15	50	25	0.0105	0.0016	0.00497	5	55	0	0.0446	0.0000
2005	0.00368	10	35	35	0.0209	0.0035	0.00227	15	40	35	0.0101	0.0022	0.00447	5	55	0	0.0402	0.0000
2006	0.00343	10	30	40	0.0195	0.0038	0.00219	15	35	40	0.0098	0.0024	0.00403	5	55	5	0.0321	0.0006
2007	0.00320	10	25	50	0.0151	0.0044	0.00212	15	25	50	0.0094	0.0029	0.00363	5	55	5	0.0289	0.0005
2008	0.00298	10	25	50	0.0141	0.0041	0.00204	15	30	50	0.0073	0.0028	0.00326	5	50	10	0.0261	0.0009
2009	0.00278	10	20	55	0.0131	0.0042	0.00197	15	25	55	0.0070	0.0030	0.00294	5	50	10	0.0235	0.0008
2010	0.00259	10	20	55	0.0123	0.0039	0.00191	15	25	55	0.0068	0.0029	0.00265	5	50	10	0.0211	0.0007
2011	0.00242	10	15	60	0.0114	0.0040	0.00184	15	20	60	0.0066	0.0030	0.00238	5	45	15	0.0190	0.0010
2012	0.00225	10	15	60	0.0107	0.0037	0.00178	15	20	60	0.0063	0.0029	0.00215	5	45	15	0.0171	0.0009
2013	0.00210	10	10	65	0.0099	0.0038	0.00172	15	15	65	0.0061	0.0031	0.00193	5	45	15	0.0154	0.0008
2014	0.00196	10	10	65	0.0093	0.0035	0.00166	15	15	65	0.0059	0.0030	0.00174	5	40	20	0.0139	0.0010
2015	0.00183	10	5	70	0.0086	0.0035	0.00160	15	10	70	0.0057	0.0031	0.00157	5	40	20	0.0125	0.0009
2016	0.00170	10	5	70	0.0080	0.0033	0.00154	15	10	70	0.0055	0.0030	0.00141	5	35	25	0.0112	0.0010
2017	0.00159	10	0	75	0.0075	0.0033	0.00149	15	0	85	0.0040	0.0035	0.00127	5	35	25	0.0101	0.0009
2018	0.00148	10	0	75	0.0070	0.0031	0.00144	15	0	85	0.0039	0.0034	0.00114	5	35	25	0.0091	0.0008
TOTAL =	0.062				0.398	0.060	0.041				0.201	0.046	0.074				0.680	0.011

Best-Guess of Atmospheric Methane Emissions=	0.398	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.060	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.201	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.046	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.680	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.011	tCO <sub>2</sub> e/tonne

#### 8 Long-Term Carbon Sequestration at a Future Landfill:

From research by Barlaz:

Long term carbon sequestration from food waste=	-0.088	tCO <sub>2</sub> e/tonne
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#### 9 Immediate & Future N<sub>2</sub>O Emissions at a Future Landfill:

Best-Guess Estimate of the N <sub>2</sub> O from vented nitrogen=	1.0	%N <sub>2</sub> O/vented NH <sub>3</sub> or NO <sub>x</sub>
Low Estimate of the N <sub>2</sub> O from vented nitrogen=	0.2	%N <sub>2</sub> O/vented NH <sub>3</sub> or NO <sub>x</sub>
High Estimate of the N <sub>2</sub> O from vented nitrogen=	2.0	%N <sub>2</sub> O/vented NH <sub>3</sub> or NO <sub>x</sub>
Nitrogen content of wet food waste=	0.78	%N
Best-Guess Estimate of the N <sub>2</sub> O Emission=	0.038	tCO <sub>2</sub> e/tonne
Low Estimate of the N <sub>2</sub> O Emission=	0.008	tCO <sub>2</sub> e/tonne
High Estimate of the N <sub>2</sub> O Emission=	0.076	tCO <sub>2</sub> e/tonne

#### 10 Energy Generation from Waste Incineration at the Burnaby Incinerator:

Best-Guess Estimate of the net energy content of wet food waste=	4.0	GJ/tonne
Low Estimate of the net energy content of wet food waste=	2.4	GJ/tonne
High Estimate of the net energy content of wet food waste=	5.5	GJ/tonne
Best-guess estimate of utilized steam energy by Crown=	1.57	GJ/tonne
Low estimate utilized steam energy by Crown =	0.94	GJ/tonne
High estimate utilized steam energy by Crown =	2.16	GJ/tonne
Best-guess estimate of turbogenerator electricity produced=	0.00	GJ/tonne
Low estimate of turbogenerator electricity produced=	0.00	GJ/tonne
High estimate of turbogenerator electricity produced=	0.00	GJ/tonne
Best-Guess of emission prevention by steam utilization at Crown=	0.097	tCO <sub>2</sub> e/tonne
Low Estimate of emission prevention by steam utilization at Crown=	0.058	tCO <sub>2</sub> e/tonne
High Estimate of emission prevention by steam utilization at Crown=	0.134	tCO <sub>2</sub> e/tonne
Best-Guess of emission prevention by offsetting BC Hydro=	0.000	tCO <sub>2</sub> e/tonne
Low Estimate of emission prevention by offsetting BC Hydro=	0.000	tCO <sub>2</sub> e/tonne

High Estimate of emission prevention by offsetting BC Hydro=	0.000 tCO <sub>2</sub> e/tonne
Best-Guess Total GHG emission prevented by energy production=	-0.097 tCO <sub>2</sub> e/tonne
Low Estimate Total GHG emission prevented by energy production=	-0.058 tCO <sub>2</sub> e/tonne
High Estimate Total GHG emission prevented by energy production=	-0.134 tCO <sub>2</sub> e/tonne
<b>11 GHG Emissions from Waste Incineration at the Burnaby Incinerator:</b>	
Nitrogen content of wet food waste=	0.78 %N
Best-guess estimate immediate N <sub>2</sub> O emission from waste-N=	0.065 tCO <sub>2</sub> e/tonne
Low estimate immediate N <sub>2</sub> O emission from waste-N=	0.011 tCO <sub>2</sub> e/tonne
High estimate immediate N <sub>2</sub> O emission from waste-N=	0.118 tCO <sub>2</sub> e/tonne
Best-guess estimate of total GHG emissions from waste incineration=	0.091 tCO <sub>2</sub> e/tonne
Low estimate of total GHG emissions from waste incineration=	0.028 tCO <sub>2</sub> e/tonne
High estimate of total GHG emissions from waste incineration=	0.155 tCO <sub>2</sub> e/tonne
<b>12 Energy Generation from Waste Incineration at a Future Incinerator:</b>	
Best-Guess Estimate of the net energy content of wet food waste=	4.0 GJ/tonne
Low Estimate of the net energy content of wet food waste=	2.4 GJ/tonne
High Estimate of the net energy content of wet food waste=	5.5 GJ/tonne
Best-guess estimate of utilized steam energy by Crown=	1.57 GJ/tonne
Low estimate utilized steam energy by Crown =	0.94 GJ/tonne
High estimate utilized steam energy by Crown =	2.16 GJ/tonne
Best-guess estimate of turbogenerator electricity produced=	0.00 GJ/tonne
Low estimate of turbogenerator electricity produced=	0.00 GJ/tonne
High estimate of turbogenerator electricity produced=	0.00 GJ/tonne
Best-Guess of emission prevention by steam utilization at Crown=	0.097 tCO <sub>2</sub> e/tonne
Low Estimate of emission prevention by steam utilization at Crown=	0.058 tCO <sub>2</sub> e/tonne
High Estimate of emission prevention by steam utilization at Crown=	0.134 tCO <sub>2</sub> e/tonne
Best-Guess of emission prevention by offsetting BC Hydro=	0.000 tCO <sub>2</sub> e/tonne
Low Estimate of emission prevention by offsetting BC Hydro=	0.000 tCO <sub>2</sub> e/tonne
High Estimate of emission prevention by offsetting BC Hydro=	0.000 tCO <sub>2</sub> e/tonne
Best-Guess Total GHG emission prevented by energy production=	-0.097 tCO <sub>2</sub> e/tonne
Low Estimate Total GHG emission prevented by energy production=	-0.058 tCO <sub>2</sub> e/tonne
High Estimate Total GHG emission prevented by energy production=	-0.134 tCO <sub>2</sub> e/tonne
<b>13 GHG Emissions from Waste Incineration at a Future Incinerator:</b>	
Nitrogen content of wet food waste=	0.78 %N
Best-guess estimate immediate N <sub>2</sub> O emission from waste-N=	0.065 tCO <sub>2</sub> e/tonne
Low estimate immediate N <sub>2</sub> O emission from waste-N=	0.011 tCO <sub>2</sub> e/tonne
High estimate immediate N <sub>2</sub> O emission from waste-N=	0.118 tCO <sub>2</sub> e/tonne
Best-guess estimate of total GHG emissions from waste incineration=	0.091 tCO <sub>2</sub> e/tonne
Low estimate of total GHG emissions from waste incineration=	0.028 tCO <sub>2</sub> e/tonne
High estimate of total GHG emissions from waste incineration=	0.155 tCO <sub>2</sub> e/tonne
<b>14 Greenhouse Gas Emissions from Backyard Composting</b>	
Nitrogen content of wet food waste=	0.78 %N
Best-guess estimate of the immediate N <sub>2</sub> O emission factor=	0.8 % of Initial-N
Low estimate of the immediate N <sub>2</sub> O emission factor=	0.2 % of Initial-N
High estimate of the immediate N <sub>2</sub> O emission factor=	2 % of Initial-N
Best-guess estimate of the immediate N <sub>2</sub> O emission =	0.030 tCO <sub>2</sub> e/tonne
Low estimate of the immediate N <sub>2</sub> O emission =	0.008 tCO <sub>2</sub> e/tonne
High estimate of the immediate N <sub>2</sub> O emission =	0.076 tCO <sub>2</sub> e/tonne
Nitrogen content of wet food waste=	0.78 %N
Best-guess estimate of the fraction to future N <sub>2</sub> O emissions=	70 % of Initial-N
Low estimate of the fraction undergoing future N <sub>2</sub> O emissions=	50 % of Initial-N
High estimate of the fraction undergoing future N <sub>2</sub> O emissions=	90 % of Initial-N
Best-guess estimate mass of nitrogen available for future N <sub>2</sub> O=	0.0055 tonne Future N/tonne food waste
Low estimate mass of nitrogen available for future N <sub>2</sub> O=	0.0039 tonne Future N/tonne food waste
High estimate mass of nitrogen available for future N <sub>2</sub> O=	0.0070 tonne Future N/tonne food waste
Best-guess estimate of the future N <sub>2</sub> O emission factor=	1.0 % of Initial-N
Low estimate of the future N <sub>2</sub> O emission factor=	0.2 % of Initial-N
High estimate of the future N <sub>2</sub> O emission factor=	2 % of Initial-N
Best-guess estimate of the future N <sub>2</sub> O emission =	0.027 tCO <sub>2</sub> e/tonne
Low estimate of the future N <sub>2</sub> O emission =	0.004 tCO <sub>2</sub> e/tonne
High estimate of the future N <sub>2</sub> O emission =	0.068 tCO <sub>2</sub> e/tonne
Best-guess estimate Total GHG emissions from backyard composting=	0.057 tCO <sub>2</sub> e/tonne
Low estimate Total GHG emissions from backyard composting=	0.011 tCO <sub>2</sub> e/tonne
High estimate Total GHG emissions from backyard composting=	0.144 tCO <sub>2</sub> e/tonne
<b>15 Greenhouse Gas Emissions from Centralized Composting</b>	
Best-guess estimate of the methane emission factor=	0.5 % of initial carbon
Low estimate of the methane emission factor=	0.1 % of initial carbon
High estimate of the methane emission factor=	1.0 % of initial carbon
Best-guess estimate of the CH <sub>4</sub> emission from centralized composting=	0.020 tCO <sub>2</sub> e/tonne
Low estimate of the CH <sub>4</sub> emission from centralized composting=	0.004 tCO <sub>2</sub> e/tonne
High estimate of the CH <sub>4</sub> emission from centralized composting=	0.040 tCO <sub>2</sub> e/tonne
Best-guess estimate Total GHG emissions from centralized composting=	0.077 tCO <sub>2</sub> e/tonne
Low estimate Total GHG emissions from centralized composting=	0.015 tCO <sub>2</sub> e/tonne
High estimate Total GHG emissions from centralized composting=	0.185 tCO <sub>2</sub> e/tonne
<b>16 Long-Term Carbon Sequestration of Compost</b>	
Carbon sequestration of composted food waste =	0 tCO <sub>2</sub> e/tonne
GHG benefit from composting food waste via sequestration=	0 tCO <sub>2</sub> e/tonne

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## YARD WASTE MANAGEMENT:

Variables that can be changed by users are in bold.

Mass Fraction of Grass in Yard Waste=	50 %
Mass Fraction of Leaves in Yard Waste=	25 %
Mass Fraction of Branches in Yard Waste=	25 %
Carbon available for anaerobic decomposition in Grass=	0.155 kg C/dry kg
Carbon available for anaerobic decomposition in Leaves=	0.060 kg C/dry kg
Carbon available for anaerobic decomposition in Branches=	0.032 kg C/dry kg
Carbon storage factor for grass (dry)=	0.29 kg C/dry kg
Carbon storage factor for leaves (dry)=	0.43 kg C/dry kg
Carbon storage factor for branches (dry)=	0.41 kg C/dry kg
Moisture content of grass=	60 %
Moisture content of leaves=	20 %
Moisture content of branches=	40 %
Nitrogen content of yard waste (dry basis)=	3.4 %N
Nitrogen content of yard waste (wet basis)=	1.9 %N
Assumed anthropogenic fraction of the nitrogen content=	50 %
Anthropogenic nitrogen content of yard waste (wet basis)=	0.94 %
Net energy content of wet yard waste=	5.7 GJ/tonne
Mass Averaged Carbon storage factor for yard waste (wet)=	0.206 kg C/wet kg
Mass Averaged Carbon for decomposition in yard waste (wet)=	0.055 kg C/wet kg
Mass Averaged Moisture content of yard waste=	45 %
Mass Averaged Carbon Content of yard waste (dry)=	47.1 %

### 1 Methane & Energy Implications of the Cache Creek Landfill

Carbon available for anaerobic decomposition=	0.055 tC/wet tonne yard waste
Methane generation potential, $L_0$ =	0.037 tCH <sub>4</sub> /wet tonne
Best-guess first order decay rate constant, $k$ =	0.070 year <sup>-1</sup>
Low estimate first order decay rate constant, $k$ =	0.035 year <sup>-1</sup>
High estimate first order decay rate constant, $k$ =	0.105 year <sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00258	10	43	0	0.0278	0.0000	0.00129	15	43	0	0.0131	0.0000	0.00387	5	43	0	0.0440	0.0000
2000	0.00241	10	50	0	0.0227	0.0000	0.00125	15	50	0	0.0111	0.0000	0.00349	5	50	0	0.0348	0.0000
2001	0.00224	10	50	10	0.0170	0.0006	0.00120	15	50	10	0.0086	0.0003	0.00314	5	50	0	0.0313	0.0000
2002	0.00209	10	50	15	0.0138	0.0009	0.00116	15	55	15	0.0062	0.0005	0.00283	5	50	0	0.0282	0.0000
2003	0.00195	10	45	20	0.0129	0.0011	0.00112	15	55	20	0.0050	0.0006	0.00254	5	50	0	0.0254	0.0000
2004	0.00182	10	40	25	0.0120	0.0013	0.00108	15	50	25	0.0048	0.0007	0.00229	5	55	0	0.0206	0.0000
2005	0.00170	10	35	35	0.0096	0.0016	0.00105	15	40	35	0.0047	0.0010	0.00206	5	55	0	0.0185	0.0000
2006	0.00158	10	30	40	0.0090	0.0017	0.00101	15	35	40	0.0045	0.0011	0.00186	5	55	5	0.0148	0.0003
2007	0.00147	10	25	50	0.0070	0.0020	0.00098	15	25	50	0.0044	0.0013	0.00167	5	55	5	0.0133	0.0002
2008	0.00137	10	25	50	0.0065	0.0019	0.00094	15	30	50	0.0034	0.0013	0.00150	5	50	10	0.0120	0.0004
2009	0.00128	10	20	55	0.0061	0.0019	0.00091	15	25	55	0.0032	0.0014	0.00135	5	50	10	0.0108	0.0004
2010	0.00119	10	20	55	0.0056	0.0018	0.00088	15	25	55	0.0031	0.0013	0.00122	5	50	10	0.0097	0.0003
2011	0.00111	10	15	60	0.0053	0.0018	0.00085	15	20	60	0.0030	0.0014	0.00110	5	45	15	0.0088	0.0005
2012	0.00104	10	15	60	0.0049	0.0017	0.00082	15	20	60	0.0029	0.0014	0.00099	5	45	15	0.0079	0.0004
2013	0.00097	10	10	65	0.0046	0.0017	0.00079	15	15	65	0.0028	0.0014	0.00089	5	45	15	0.0071	0.0004
2014	0.00090	10	10	65	0.0043	0.0016	0.00076	15	15	65	0.0027	0.0014	0.00080	5	40	20	0.0064	0.0004
2015	0.00084	10	5	70	0.0040	0.0016	0.00074	15	10	70	0.0026	0.0014	0.00072	5	40	20	0.0058	0.0004
2016	0.00079	10	5	70	0.0037	0.0015	0.00071	15	10	70	0.0025	0.0014	0.00065	5	35	25	0.0052	0.0004
2017	0.00073	10	0	75	0.0035	0.0015	0.00069	15	0	85	0.0018	0.0016	0.00058	5	35	25	0.0047	0.0004
2018	0.00068	10	0	75	0.0032	0.0014	0.00066	15	0	85	0.0018	0.0016	0.00053	5	35	25	0.0042	0.0004
TOTAL =	0.029				0.183	0.028	0.019				0.092	0.021	0.034				0.313	0.005

Best-Guess of Atmospheric Methane Emissions=	0.183 tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.028 tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.092 tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.021 tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.313 tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.005 tCO <sub>2</sub> e/tonne

### 2 Long-Term Carbon Sequestration in the Cache Creek Landfill:

From research by Barlaz:	
Long term carbon sequestration from yard waste=	-0.75 tCO <sub>2</sub> e/tonne

### 3 Immediate & Future N<sub>2</sub>O Emissions from the Cache Creek Landfill:

Best-Guess Estimate of the N <sub>2</sub> O from vented nitrogen=	1.0 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
Low Estimate of the N <sub>2</sub> O from vented nitrogen=	0.2 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
High Estimate of the N <sub>2</sub> O from vented nitrogen=	2.0 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
Decomposition of the yard waste=	34 %
Nitrogen content of wet yard waste=	1.9 %N
Best-Guess Estimate of the N <sub>2</sub> O Emission=	0.031 tCO <sub>2</sub> e/tonne
Low Estimate of the N <sub>2</sub> O Emission=	0.006 tCO <sub>2</sub> e/tonne
High Estimate of the N <sub>2</sub> O Emission=	0.062 tCO <sub>2</sub> e/tonne

### 4 Methane & Energy Implications of the Vancouver Landfill

Carbon available for anaerobic decomposition=	0.055 tC/tonne food waste
Methane generation potential, $L_0$ =	0.037 tCH <sub>4</sub> /wet tonne
Best-guess first order decay rate constant, $k$ =	0.08 year <sup>-1</sup>
Low estimate first order decay rate constant, $k$ =	0.04 year <sup>-1</sup>
High estimate first order decay rate constant, $k$ =	0.12 year <sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00295	10	22	0	0.0435	0.0000	0.00147	15	22	0	0.0205	0.0000	0.00442	5	22	0	0.0688	0.0000
2000	0.00272	10	30	0	0.0360	0.0000	0.00142	15	35	0	0.0164	0.0000	0.00392	5	30	0	0.0548	0.0000
2001	0.00251	10	35	10	0.0261	0.0007	0.00136	15	40	10	0.0121	0.0004	0.00348	5	35	0	0.0451	0.0000
2002	0.00232	10	40	15	0.0197	0.0010	0.00131	15	45	15	0.0093	0.0005	0.00309	5	40	0	0.0369	0.0000
2003	0.00214	10	45	20	0.0142	0.0012	0.00126	15	55	20	0.0056	0.0007	0.00274	5	50	0	0.0273	0.0000
2004	0.00198	10	40	25	0.0131	0.0014	0.00121	15	50	25	0.0054	0.0008	0.00243	5	55	0	0.0218	0.0000
2005	0.00182	10	30	40	0.0103	0.0020	0.00116	15	40	35	0.0052	0.0011	0.00215	5	55	0	0.0193	0.0000



2006	0.00168	10	30	40	0.0096	0.0019	0.00111	15	35	40	0.0050	0.0012	0.00191	5	55	5	0.0152	0.0003
2007	0.00156	10	25	50	0.0073	0.0021	0.00107	15	25	50	0.0048	0.0015	0.00169	5	55	5	0.0135	0.0002
2008	0.00144	10	25	50	0.0068	0.0020	0.00103	15	30	50	0.0037	0.0014	0.00150	5	50	10	0.0120	0.0004
2009	0.00133	10	20	55	0.0063	0.0020	0.00099	15	25	55	0.0035	0.0015	0.00133	5	50	10	0.0106	0.0004
2010	0.00122	10	20	55	0.0058	0.0019	0.00095	15	25	55	0.0034	0.0014	0.00118	5	50	10	0.0094	0.0003
2011	0.00113	10	15	60	0.0053	0.0019	0.00091	15	20	60	0.0033	0.0015	0.00105	5	45	15	0.0084	0.0004
2012	0.00104	10	15	60	0.0049	0.0017	0.00088	15	20	60	0.0031	0.0014	0.00093	5	45	15	0.0074	0.0004
2013	0.00096	10	10	65	0.0045	0.0017	0.00084	15	15	65	0.0030	0.0015	0.00082	5	45	15	0.0066	0.0003
2014	0.00089	10	10	65	0.0042	0.0016	0.00081	15	15	65	0.0029	0.0014	0.00073	5	40	20	0.0058	0.0004
2015	0.00082	10	5	70	0.0039	0.0016	0.00078	15	10	70	0.0028	0.0015	0.00065	5	40	20	0.0052	0.0004
2016	0.00076	10	5	70	0.0036	0.0015	0.00075	15	10	70	0.0027	0.0014	0.00058	5	35	25	0.0046	0.0004
2017	0.00070	10	0	75	0.0033	0.0014	0.00072	15	0	85	0.0019	0.0017	0.00051	5	35	25	0.0041	0.0004
2018	0.00065	10	0	75	0.0030	0.0013	0.00069	15	0	85	0.0018	0.0016	0.00045	5	35	25	0.0036	0.0003
TOTAL =	0.031				0.231	0.029	0.021				0.116	0.023	0.036				0.381	0.005

Best-Guess of Atmospheric Methane Emissions=	0.231	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.029	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.116	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.023	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.381	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.005	tCO <sub>2</sub> e/tonne

##### 5 Long-Term Carbon Sequestration in the Vancouver Landfill:

From research by Barlaz:	
Long term carbon sequestration from yard waste=	-0.75 tCO <sub>2</sub> e/tonne

##### 6 Immediate & Future N<sub>2</sub>O Emissions from the Vancouver Landfill:

Best-Guess Estimate of the N <sub>2</sub> O from wastewater nitrogen=	1.0 %N <sub>2</sub> O/influent-N
Low Estimate of the N <sub>2</sub> O from wastewater nitrogen=	0.2 %N <sub>2</sub> O/influent-N
High Estimate of the N <sub>2</sub> O from wastewater nitrogen=	2.0 %N <sub>2</sub> O/influent-N
Decomposition of the yard waste=	34 %
Nitrogen content of wet yard waste=	1.9 %N
Best-Guess Estimate of the N <sub>2</sub> O Emission=	0.031 tCO <sub>2</sub> e/tonne
Low Estimate of the N <sub>2</sub> O Emission=	0.006 tCO <sub>2</sub> e/tonne
High Estimate of the N <sub>2</sub> O Emission=	0.062 tCO <sub>2</sub> e/tonne

##### 7 Methane & Energy Implications at a Future Landfill

Carbon available for anaerobic decomposition=	0.055 tCH <sub>4</sub> /wet tonne yard waste
Methane generation potential, L <sub>0</sub> =	0.037 tCH <sub>4</sub> /wet tonne
Best-guess first order decay rate constant, k=	0.070 year <sup>-1</sup>
Low estimate first order decay rate constant, k=	0.035 year <sup>-1</sup>
High estimate first order decay rate constant, k=	0.105 year <sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00258	10	43	0	0.0278	0.0000	0.00129	15	43	0	0.0131	0.0000	0.00387	5	43	0	0.0440	0.0000
2000	0.00241	10	50	0	0.0227	0.0000	0.00125	15	50	0	0.0111	0.0000	0.00349	5	50	0	0.0348	0.0000
2001	0.00224	10	50	10	0.0170	0.0006	0.00120	15	50	10	0.0086	0.0003	0.00314	5	50	0	0.0313	0.0000
2002	0.00209	10	50	15	0.0138	0.0009	0.00116	15	55	15	0.0062	0.0005	0.00283	5	50	0	0.0282	0.0000
2003	0.00195	10	45	20	0.0129	0.0011	0.00112	15	55	20	0.0050	0.0006	0.00254	5	50	0	0.0254	0.0000
2004	0.00182	10	40	25	0.0120	0.0013	0.00108	15	50	25	0.0048	0.0007	0.00229	5	55	0	0.0206	0.0000
2005	0.00170	10	35	35	0.0096	0.0016	0.00105	15	40	35	0.0047	0.0010	0.00206	5	55	0	0.0185	0.0000
2006	0.00158	10	30	40	0.0090	0.0017	0.00101	15	35	40	0.0045	0.0011	0.00186	5	55	5	0.0148	0.0003
2007	0.00147	10	25	50	0.0070	0.0020	0.00098	15	25	50	0.0044	0.0013	0.00167	5	55	5	0.0133	0.0002
2008	0.00137	10	25	50	0.0065	0.0019	0.00094	15	30	50	0.0034	0.0013	0.00150	5	50	10	0.0120	0.0004
2009	0.00128	10	20	55	0.0061	0.0019	0.00091	15	25	55	0.0032	0.0014	0.00135	5	50	10	0.0108	0.0004
2010	0.00119	10	20	55	0.0056	0.0018	0.00088	15	25	55	0.0031	0.0013	0.00122	5	50	10	0.0097	0.0003
2011	0.00111	10	15	60	0.0053	0.0018	0.00085	15	20	60	0.0030	0.0014	0.00110	5	45	15	0.0088	0.0005
2012	0.00104	10	15	60	0.0049	0.0017	0.00082	15	20	60	0.0029	0.0014	0.00099	5	45	15	0.0079	0.0004
2013	0.00097	10	10	65	0.0046	0.0017	0.00079	15	15	65	0.0028	0.0014	0.00089	5	45	15	0.0071	0.0004
2014	0.00090	10	10	65	0.0043	0.0016	0.00076	15	15	65	0.0027	0.0014	0.00080	5	40	20	0.0064	0.0004
2015	0.00084	10	5	70	0.0040	0.0016	0.00074	15	10	70	0.0026	0.0014	0.00072	5	40	20	0.0058	0.0004
2016	0.00079	10	5	70	0.0037	0.0015	0.00071	15	10	70	0.0025	0.0014	0.00065	5	35	25	0.0052	0.0004
2017	0.00073	10	0	75	0.0035	0.0015	0.00069	15	0	85	0.0018	0.0016	0.00058	5	35	25	0.0047	0.0004
2018	0.00068	10	0	75	0.0032	0.0014	0.00066	15	0	85	0.0018	0.0016	0.00053	5	35	25	0.0042	0.0004
TOTAL =	0.029				0.183	0.028	0.019				0.092	0.021	0.034				0.313	0.005

Best-Guess of Atmospheric Methane Emissions=	0.183	tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization=	-0.028	tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions=	0.092	tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization=	-0.021	tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions=	0.313	tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization=	-0.005	tCO <sub>2</sub> e/tonne

##### 8 Long-Term Carbon Sequestration at a Future Landfill:

From research by Barlaz:	
Long term carbon sequestration from yard waste=	-0.75 tCO <sub>2</sub> e/tonne

##### 9 Immediate & Future N<sub>2</sub>O Emissions at a Future Landfill:

Best-Guess Estimate of the N <sub>2</sub> O from vented nitrogen=	1.0 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
Low Estimate of the N <sub>2</sub> O from vented nitrogen=	0.2 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
High Estimate of the N <sub>2</sub> O from vented nitrogen=	2.0 %N <sub>2</sub> O/emitted NH <sub>3</sub> or NO <sub>x</sub>
Decomposition of the yard waste=	34 %
Nitrogen content of wet yard waste=	1.9 %N
Best-Guess Estimate of the N <sub>2</sub> O Emission=	0.031 tCO <sub>2</sub> e/tonne
Low Estimate of the N <sub>2</sub> O Emission=	0.006 tCO <sub>2</sub> e/tonne
High Estimate of the N <sub>2</sub> O Emission=	0.062 tCO <sub>2</sub> e/tonne

##### 10 Energy Generation from Waste Incineration at the Burnaby Incinerator:

Net energy content of wet yard waste=	5.7 GJ/tonne
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Utilized steam energy by Crown=	2.23 GJ/tonne
Turbogenerator electricity produced=	0.00 GJ/tonne
Emission prevention by steam utilization at Crown=	0.139 tCO <sub>2</sub> e/tonne
Emission prevention by offsetting BC Hydro (Burrard Thermal)=	0.000 tCO <sub>2</sub> e/tonne
Total GHG emission prevented by energy production=	-0.139 tCO <sub>2</sub> e/tonne

#### 11 GHG Emissions from Waste Incineration at the Burnaby Incinerator:

Nitrogen content of wet yard waste=	1.9 %N
Best-guess estimate immediate N <sub>2</sub> O emission from waste-N=	0.155 tCO <sub>2</sub> e/tonne
Low estimate immediate N <sub>2</sub> O emission from waste-N=	0.027 tCO <sub>2</sub> e/tonne
High estimate immediate N <sub>2</sub> O emission from waste-N=	0.282 tCO <sub>2</sub> e/tonne
Best-guess estimate of total GHG emissions from waste incineration	0.181 tCO <sub>2</sub> e/tonne
Low estimate of total GHG emissions from waste incineration=	0.044 tCO <sub>2</sub> e/tonne
High estimate of total GHG emissions from waste incineration=	0.320 tCO <sub>2</sub> e/tonne

#### 12 Energy Generation from Waste Incineration at a Future Incinerator:

Net energy content of wet yard waste=	5.7 GJ/tonne
Utilized steam energy by Crown=	2.23 GJ/tonne
Turbogenerator electricity produced=	0.00 GJ/tonne
Emission prevention by steam utilization at Crown=	0.139 tCO <sub>2</sub> e/tonne
Emission prevention by offsetting BC Hydro (Burrard Thermal)=	0.000 tCO <sub>2</sub> e/tonne
Total GHG emission prevented by energy production=	-0.139 tCO <sub>2</sub> e/tonne

#### 13 GHG Emissions from Waste Incineration at a Future Incinerator:

Nitrogen content of wet yard waste=	1.9 %N
Best-guess estimate immediate N <sub>2</sub> O emission from waste-N=	0.155 tCO <sub>2</sub> e/tonne
Low estimate immediate N <sub>2</sub> O emission from waste-N=	0.027 tCO <sub>2</sub> e/tonne
High estimate immediate N <sub>2</sub> O emission from waste-N=	0.282 tCO <sub>2</sub> e/tonne
Best-guess estimate of total GHG emissions from waste incineration	0.181 tCO <sub>2</sub> e/tonne
Low estimate of total GHG emissions from waste incineration=	0.044 tCO <sub>2</sub> e/tonne
High estimate of total GHG emissions from waste incineration=	0.320 tCO <sub>2</sub> e/tonne

#### 14 Greenhouse Gas Emissions from Backyard Composting

Anthropogenic Nitrogen content of wet yard waste=	0.94 %N
Best-guess estimate of the immediate N <sub>2</sub> O emission factor=	0.8 % of initial-N
Low estimate of the immediate N <sub>2</sub> O emission factor=	0.2 % of initial-N
High estimate of the immediate N <sub>2</sub> O emission factor=	2 % of initial-N
Best-guess estimate of the immediate N <sub>2</sub> O emission =	0.036 tCO <sub>2</sub> e/tonne
Low estimate of the immediate N <sub>2</sub> O emission =	0.009 tCO <sub>2</sub> e/tonne
High estimate of the immediate N <sub>2</sub> O emission =	0.091 tCO <sub>2</sub> e/tonne
Nitrogen content of wet yard waste=	0.94 %N
Best-guess estimate of the fraction to future N <sub>2</sub> O emissions=	79 % of initial-N
Low estimate of the fraction undergoing future N <sub>2</sub> O emissions=	59 % of initial-N
High estimate of the fraction undergoing future N <sub>2</sub> O emissions=	99 % of initial-N
Best-guess estimate mass of nitrogen available for future N <sub>2</sub> O=	0.0065 tonne Future N/tonne yard waste
Low estimate mass of nitrogen available for future N <sub>2</sub> O=	0.0047 tonne Future N/tonne yard waste
High estimate mass of nitrogen available for future N <sub>2</sub> O=	0.0084 tonne Future N/tonne yard waste
Best-guess estimate of the future N <sub>2</sub> O emission factor=	1.0 % of initial-N
Low estimate of the future N <sub>2</sub> O emission factor=	0.2 % of initial-N
High estimate of the future N <sub>2</sub> O emission factor=	2 % of initial-N
Best-guess estimate of the future N <sub>2</sub> O emission =	0.032 tCO <sub>2</sub> e/tonne
Low estimate of the future N <sub>2</sub> O emission =	0.005 tCO <sub>2</sub> e/tonne
High estimate of the future N <sub>2</sub> O emission =	0.082 tCO <sub>2</sub> e/tonne
Best-guess Estimate Total emissions from backyard composting=	0.068 tCO <sub>2</sub> e/tonne
Low Estimate Total emissions from backyard composting=	0.014 tCO <sub>2</sub> e/tonne
High Estimate Total emissions from backyard composting=	0.173 tCO <sub>2</sub> e/tonne

#### 15 Greenhouse Gas Emissions from Centralized Composting

Best-guess estimate of the methane emission factor=	0.5 % of initial carbon
Low estimate of the methane emission factor=	0.1 % of initial carbon
High estimate of the methane emission factor=	1.0 % of initial carbon
Best-guess estimate of the CH <sub>4</sub> emission from centralized composting=	0.036 tCO <sub>2</sub> e/tonne
Low estimate of the CH <sub>4</sub> emission from centralized composting=	0.007 tCO <sub>2</sub> e/tonne
High estimate of the CH <sub>4</sub> emission from centralized composting=	0.073 tCO <sub>2</sub> e/tonne
Best-guess estimate N <sub>2</sub> O emissions from composting=	0.068 tCO <sub>2</sub> e/tonne
Low estimate N <sub>2</sub> O emissions from composting=	0.014 tCO <sub>2</sub> e/tonne
High estimate N <sub>2</sub> O emissions from composting=	0.173 tCO <sub>2</sub> e/tonne
Best-guess estimate Total GHG emissions from centralized compost	0.105 tCO <sub>2</sub> e/tonne
Low estimate Total GHG emissions from centralized composting=	0.021 tCO <sub>2</sub> e/tonne
High estimate Total GHG emissions from centralized composting=	0.246 tCO <sub>2</sub> e/tonne

#### 16 Long-Term Carbon Sequestration of Compost

Best-Guess of Carbon Seq. of Centralized Composted Yard Waste =	-0.10 tCO <sub>2</sub> e/tonne
Low Estimate of Carbon Seq. of Centralized Composted Yard Waste =	-0.004 tCO <sub>2</sub> e/tonne
High Estimate of Carbon Seq. of Centralized Composted Yard Waste =	-0.20 tCO <sub>2</sub> e/tonne
Estimate of Carbon Seq. of Backyard Composted Yard Waste =	0 tCO <sub>2</sub> e/tonne

# REMAINDER WASTE MANAGEMENT:

Variables that can be changed by users are in bold.

Biodegradable fraction of Remainder	70 %
Moisture content of biodegradable organic-C in Remainder	30 %
Carbon content of biodegradable C in Remainder (dry)	50 %
Carbon storage factor for Remainder (wet)	0.09 kg C/wet kg
Nitrogen content of Remainder	0 %N
Estimate of the net energy content of Remainder	11.6 GJ/tonne
Fossil Carbon Content of Remainder	0.060 tC/tonne Remainder

## 1 Methane & Energy Implications of the Cache Creek Landfill

Carbon storage factor for Remainder (wet)	0.090 tC/tonne
Carbon available for anaerobic decomposition	0.155 tC/tonne
Methane generation potential, $L_0$	0.103 tCH <sub>4</sub> /tonne
Best-guess first order decay rate constant, $k$	0.04 year <sup>-1</sup>
Low estimate first order decay rate constant, $k$	0.02 year <sup>-1</sup>
High estimate first order decay rate constant, $k$	0.06 year <sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00413	10	43	0	0.0445	0.0000	0.00207	15	43	0	0.0210	0.0000	0.00620	5	43	0	0.0705	0.0000
2000	0.00389	10	50	0	0.0368	0.0000	0.00203	15	50	0	0.0181	0.0000	0.00584	5	50	0	0.0582	0.0000
2001	0.00367	10	50	10	0.0277	0.0010	0.00199	15	50	10	0.0142	0.0005	0.00550	5	50	0	0.0549	0.0000
2002	0.00345	10	50	15	0.0228	0.0014	0.00195	15	55	15	0.0104	0.0008	0.00518	5	50	0	0.0517	0.0000
2003	0.00325	10	45	20	0.0215	0.0018	0.00191	15	55	20	0.0085	0.0010	0.00488	5	50	0	0.0486	0.0000
2004	0.00306	10	40	25	0.0203	0.0021	0.00187	15	50	25	0.0063	0.0013	0.00459	5	55	0	0.0412	0.0000
2005	0.00288	10	35	35	0.0164	0.0028	0.00163	15	40	35	0.0042	0.0018	0.00433	5	55	0	0.0388	0.0000
2006	0.00272	10	30	40	0.0154	0.0030	0.00160	15	35	40	0.0040	0.0020	0.00407	5	55	5	0.0325	0.0006
2007	0.00256	10	25	50	0.0121	0.0035	0.00176	15	25	50	0.0079	0.0024	0.00384	5	55	5	0.0306	0.0005
2008	0.00241	10	25	50	0.0114	0.0033	0.00173	15	30	50	0.0062	0.0024	0.00361	5	50	10	0.0288	0.0010
2009	0.00227	10	20	55	0.0107	0.0034	0.00169	15	25	55	0.0060	0.0026	0.00340	5	50	10	0.0272	0.0009
2010	0.00214	10	20	55	0.0101	0.0032	0.00166	15	25	55	0.0059	0.0025	0.00320	5	50	10	0.0256	0.0009
2011	0.00201	10	15	60	0.0095	0.0033	0.00163	15	20	60	0.0058	0.0027	0.00302	5	45	15	0.0241	0.0012
2012	0.00189	10	15	60	0.0090	0.0031	0.00159	15	20	60	0.0057	0.0026	0.00284	5	45	15	0.0227	0.0012
2013	0.00178	10	10	65	0.0084	0.0032	0.00156	15	15	65	0.0056	0.0028	0.00268	5	45	15	0.0214	0.0011
2014	0.00168	10	10	65	0.0079	0.0030	0.00153	15	15	65	0.0055	0.0027	0.00252	5	40	20	0.0201	0.0014
2015	0.00158	10	5	70	0.0075	0.0030	0.00150	15	10	70	0.0054	0.0029	0.00237	5	40	20	0.0189	0.0013
2016	0.00149	10	5	70	0.0070	0.0029	0.00147	15	10	70	0.0053	0.0028	0.00224	5	35	25	0.0178	0.0015
2017	0.00140	10	0	75	0.0066	0.0029	0.00144	15	0	85	0.0039	0.0034	0.00211	5	35	25	0.0168	0.0014
2018	0.00132	10	0	75	0.0062	0.0027	0.00141	15	0	85	0.0038	0.0033	0.00198	5	35	25	0.0158	0.0014
TOTAL =	0.050				0.312	0.050	0.034				0.164	0.041	0.074				0.586	0.014

Best-Guess of Atmospheric Methane Emissions	0.312 tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization	-0.050 tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions	0.164 tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization	-0.041 tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions	0.686 tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization	-0.014 tCO <sub>2</sub> e/tonne

## 2 Long-Term Carbon Sequestration in the Cache Creek Landfill:

From research by Barlaz:	
Long term carbon sequestration from Remainder	-0.33 tCO <sub>2</sub> e/tonne

## 3 Immediate & Future N<sub>2</sub>O Emissions from the Cache Creek Landfill:

The potential of this emission is ignored.	
Estimate of the N <sub>2</sub> O Emissions	0 tCO <sub>2</sub> e/tonne

## 4 Methane & Energy Implications of the Vancouver Landfill

Carbon storage factor for Remainder (wet)	0.090 tC/tonne
Carbon available for anaerobic decomposition	0.155 tC/tonne
Methane generation potential, $L_0$	0.103 tCH <sub>4</sub> /tonne
Best-guess first order decay rate constant, $k$	0.05 year <sup>-1</sup>
Low estimate first order decay rate constant, $k$	0.025 year <sup>-1</sup>
High estimate first order decay rate constant, $k$	0.075 year <sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00517	10	22	0	0.0762	0.0000	0.00258	15	22	0	0.0380	0.0000	0.00775	5	22	0	0.1206	0.0000
2000	0.00491	10	30	0	0.0650	0.0000	0.00252	15	35	0	0.0292	0.0000	0.00719	5	30	0	0.1004	0.0000
2001	0.00467	10	35	10	0.0486	0.0013	0.00246	15	40	10	0.0219	0.0007	0.00667	5	35	0	0.0865	0.0000
2002	0.00445	10	40	15	0.0378	0.0018	0.00240	15	45	15	0.0171	0.0010	0.00619	5	40	0	0.0741	0.0000
2003	0.00423	10	45	20	0.0280	0.0023	0.00234	15	55	20	0.0104	0.0013	0.00574	5	50	0	0.0573	0.0000
2004	0.00402	10	40	25	0.0266	0.0028	0.00228	15	50	25	0.0102	0.0016	0.00533	5	55	0	0.0478	0.0000
2005	0.00383	10	30	40	0.0217	0.0042	0.00222	15	40	35	0.0099	0.0021	0.00494	5	55	0	0.0444	0.0000
2006	0.00364	10	30	40	0.0206	0.0040	0.00217	15	35	40	0.0097	0.0024	0.00458	5	55	5	0.0366	0.0006
2007	0.00346	10	25	50	0.0164	0.0048	0.00212	15	25	50	0.0094	0.0029	0.00425	5	55	5	0.0339	0.0006
2008	0.00329	10	25	50	0.0156	0.0045	0.00206	15	30	50	0.0074	0.0028	0.00395	5	50	10	0.0315	0.0011
2009	0.00313	10	20	55	0.0148	0.0047	0.00201	15	25	55	0.0072	0.0030	0.00366	5	50	10	0.0292	0.0010
2010	0.00298	10	20	55	0.0141	0.0045	0.00196	15	25	55	0.0070	0.0030	0.00340	5	50	10	0.0271	0.0009
2011	0.00284	10	15	60	0.0134	0.0047	0.00191	15	20	60	0.0068	0.0032	0.00315	5	45	15	0.0251	0.0013
2012	0.00270	10	15	60	0.0127	0.0045	0.00187	15	20	60	0.0067	0.0031	0.00292	5	45	15	0.0233	0.0012
2013	0.00257	10	10	65	0.0121	0.0046	0.00182	15	15	65	0.0065	0.0033	0.00271	5	45	15	0.0216	0.0011
2014	0.00244	10	10	65	0.0115	0.0044	0.00178	15	15	65	0.0063	0.0032	0.00252	5	40	20	0.0201	0.0014
2015	0.00232	10	5	70	0.0110	0.0045	0.00173	15	10	70	0.0062	0.0033	0.00233	5	40	20	0.0186	0.0013
2016	0.00221	10	5	70	0.0104	0.0043	0.00169	15	10	70	0.0060	0.0033	0.00217	5	35	25	0.0173	0.0015
2017	0.00210	10	0	75	0.0099	0.0043	0.00165	15	0	85	0.0044	0.0039	0.00201	5	35	25	0.0160	0.0014
2018	0.00200	10	0	75	0.0094	0.0041	0.00161	15	0	85	0.0043	0.0038	0.00186	5	35	25	0.0149	0.0013
TOTAL =	0.067				0.476	0.070	0.041				0.223	0.048	0.083				0.846	0.015

Best-Guess of Atmospheric Methane Emissions	0.476 tCO <sub>2</sub> e/tonne
Best-Guess of Benefit of Energy Utilization	-0.070 tCO <sub>2</sub> e/tonne
Low Estimate of Atmospheric Methane Emissions	0.223 tCO <sub>2</sub> e/tonne
Low Estimate of Benefit of Energy Utilization	-0.048 tCO <sub>2</sub> e/tonne
High Estimate of Atmospheric Methane Emissions	0.846 tCO <sub>2</sub> e/tonne
High Estimate of Benefit of Energy Utilization	-0.015 tCO <sub>2</sub> e/tonne

## 5 Long-Term Carbon Sequestration in the Vancouver Landfill:

From research by Barlaz:

Long term carbon sequestration from newsprint= -0.33 tCO<sub>2</sub>e/tonne

6 Immediate & Future N<sub>2</sub>O Emissions from the Vancouver Landfill:

The potential of this emission is ignored.

Estimate of the N<sub>2</sub>O Emissions= 0 tCO<sub>2</sub>e/tonne

7 Methane & Energy Implications at a Future Landfill

Carbon storage factor for Remainder (wet)= 0.090 tC/tonne  
Carbon available for anaerobic decomposition= 0.155 tC/tonne  
Methane generation potential, L<sub>0</sub>= 0.103 tCH<sub>4</sub>/tonne  
Best-guess first order decay rate constant, k= 0.04 year<sup>-1</sup>  
Low estimate first order decay rate constant, k= 0.02 year<sup>-1</sup>  
High estimate first order decay rate constant, k= 0.06 year<sup>-1</sup>

YEAR	BEST-GUESS:						LOW-ESTIMATE:						HIGH-ESTIMATE:					
	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)	Methane Generation (tCH <sub>4</sub> /yr)	Cover Material (%)	Percentage of LFG Flared (%)	Percentage of LFG for Energy (%)	Atmospheric Methane Emissions (tCO <sub>2</sub> e/yr)	GHG Benefit of Energy Utilization (tCO <sub>2</sub> e/yr)
1996	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.00413	10	43	0	0.0445	0.0000	0.00207	15	43	0	0.0210	0.0000	0.00620	5	43	0	0.0705	0.0000
2000	0.00397	10	50	0	0.0375	0.0000	0.00203	15	50	0	0.0181	0.0000	0.00584	5	50	0	0.0582	0.0000
2001	0.00382	10	50	10	0.0288	0.0010	0.00199	15	50	10	0.0142	0.0005	0.00550	5	50	0	0.0549	0.0000
2002	0.00367	10	50	15	0.0243	0.0015	0.00185	15	55	15	0.0104	0.0008	0.00518	5	50	0	0.0517	0.0000
2003	0.00352	10	45	20	0.0223	0.0019	0.00191	15	55	20	0.0085	0.0010	0.00485	5	50	0	0.0486	0.0000
2004	0.00338	10	40	25	0.0224	0.0023	0.00187	15	50	25	0.0083	0.0013	0.00459	5	55	0	0.0412	0.0000
2005	0.00325	10	35	35	0.0184	0.0031	0.00183	15	40	35	0.0082	0.0018	0.00433	5	55	0	0.0388	0.0000
2006	0.00312	10	30	40	0.0177	0.0034	0.00180	15	35	40	0.0080	0.0020	0.00407	5	55	5	0.0325	0.0006
2007	0.00300	10	25	50	0.0142	0.0041	0.00176	15	25	50	0.0079	0.0024	0.00384	5	55	5	0.0306	0.0005
2008	0.00288	10	25	50	0.0136	0.0040	0.00173	15	30	50	0.0062	0.0024	0.00361	5	50	10	0.0288	0.0010
2009	0.00277	10	20	55	0.0131	0.0042	0.00169	15	25	55	0.0060	0.0026	0.00340	5	50	10	0.0272	0.0009
2010	0.00266	10	20	55	0.0126	0.0040	0.00166	15	25	55	0.0059	0.0025	0.00320	5	50	10	0.0256	0.0009
2011	0.00256	10	15	60	0.0121	0.0042	0.00163	15	20	60	0.0058	0.0027	0.00302	5	45	15	0.0241	0.0012
2012	0.00248	10	15	60	0.0118	0.0041	0.00159	15	20	60	0.0057	0.0026	0.00284	5	45	15	0.0227	0.0012
2013	0.00238	10	10	65	0.0112	0.0042	0.00156	15	15	65	0.0056	0.0028	0.00268	5	45	15	0.0214	0.0011
2014	0.00227	10	10	65	0.0107	0.0041	0.00153	15	15	65	0.0055	0.0027	0.00252	5	40	20	0.0201	0.0014
2015	0.00216	10	5	70	0.0103	0.0042	0.00150	15	10	70	0.0054	0.0029	0.00237	5	40	20	0.0189	0.0013
2016	0.00209	10	5	70	0.0099	0.0040	0.00147	15	10	70	0.0053	0.0028	0.00224	5	35	25	0.0178	0.0015
2017	0.00201	10	0	75	0.0095	0.0041	0.00144	15	0	85	0.0039	0.0034	0.00211	5	35	25	0.0168	0.0014
2018	0.00193	10	0	75	0.0091	0.0040	0.00141	15	0	85	0.0038	0.0033	0.00188	5	35	25	0.0158	0.0014
TOTAL =	0.058				0.355	0.063	0.034				0.164	0.041	0.074				0.666	0.014

Best-Guess of Atmospheric Methane Emissions= 0.355 tCO<sub>2</sub>e/tonne  
Best-Guess of Benefit of Energy Utilization= -0.063 tCO<sub>2</sub>e/tonne  
Low Estimate of Atmospheric Methane Emissions= 0.164 tCO<sub>2</sub>e/tonne  
Low Estimate of Benefit of Energy Utilization= -0.041 tCO<sub>2</sub>e/tonne  
High Estimate of Atmospheric Methane Emissions= 0.666 tCO<sub>2</sub>e/tonne  
High Estimate of Benefit of Energy Utilization= -0.014 tCO<sub>2</sub>e/tonne

8 Long-Term Carbon Sequestration at a Future Landfill:

From research by Barlaz:

Long term carbon sequestration from Remainder= -0.33 tCO<sub>2</sub>e/tonne

9 Immediate & Future N<sub>2</sub>O Emissions at a Future Landfill:

The potential of this emission is ignored.

Estimate of the N<sub>2</sub>O Emissions= 0 tCO<sub>2</sub>e/tonne

10 Energy Generation from Waste Incineration at the Burnaby Incinerator:

Net energy content of Remainder= 11.6 GJ/tonne  
Utilized steam energy by Crown= 4.55 GJ/tonne  
Turbogenerator electricity produced= 0.00 GJ/tonne  
Emission prevention by steam utilization at Crown= 0.282 tCO<sub>2</sub>e/tonne  
Emission prevention by offsetting BC Hydro (Burnard Thermal)= 0.000 tCO<sub>2</sub>e/tonne  
Total GHG emission prevented by energy production= -0.282 tCO<sub>2</sub>e/tonne

11 GHG Emissions from Waste Incineration at the Burnaby Incinerator:

CO<sub>2</sub> emission from fossil-carbon in Remainder= 0.220 tCO<sub>2</sub>e/tonne  
Best-guess estimate of total GHG emissions from waste incineration= 0.247 tCO<sub>2</sub>e/tonne  
Low estimate of total GHG emissions from waste incineration= 0.236 tCO<sub>2</sub>e/tonne  
High estimate of total GHG emissions from waste incineration= 0.257 tCO<sub>2</sub>e/tonne

12 Energy Generation from Waste Incineration at a Future Incinerator:

Net energy content of Remainder= 11.6 GJ/tonne  
Utilized steam energy by Crown= 4.55 GJ/tonne  
Turbogenerator electricity produced= 0.00 GJ/tonne  
Emission prevention by steam utilization at Crown= 0.282 tCO<sub>2</sub>e/tonne  
Emission prevention by offsetting BC Hydro (Burnard Thermal)= 0.000 tCO<sub>2</sub>e/tonne  
Total GHG emission prevented by energy production= -0.282 tCO<sub>2</sub>e/tonne

13 GHG Emissions from Waste Incineration at a Future Incinerator:

CO<sub>2</sub> emission from fossil-carbon in Remainder= 0.220 tCO<sub>2</sub>e/tonne  
Best-guess estimate of total GHG emissions from waste incineration= 0.247 tCO<sub>2</sub>e/tonne  
Low estimate of total GHG emissions from waste incineration= 0.236 tCO<sub>2</sub>e/tonne  
High estimate of total GHG emissions from waste incineration= 0.257 tCO<sub>2</sub>e/tonne

14 GHG Emissions of Recycled Remainder Utilization:

GHG benefit of recycled versus virgin manufacturing= 0.0 tCO<sub>2</sub>e/tonne  
(includes transportation emissions)

15 Effect of Recycling Remainder on Forest Carbon Storage:

GHG implications of recycled office paper on Forestry= 0 tCO<sub>2</sub>e/tonne

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