Review of LCAs on Organics Management Methods & Development of an Environmental Hierarchy

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I. EXECUTIVE SUMMARY

Alberta Ministry of the Environment (Alberta Environment) contracted with Sound Resource Management Group, Inc. (SRMG) to provide a literature review of life cycle assessments (LCAs) for managing organic waste, including leaf and yard waste (LYW), to assess the relative environmental impact of alternative end-of-life management options. The purpose of the review was to use the information to recommend a management hierarchy for environmentally preferable end-of-life (EOL) management methods. To this end the SRMG project team reviewed and summarized over 80 LCAs, approximately two-thirds of which were published in peer-reviewed journals, and practically all of which were completed within the past five years.

Given the reasonably large number of reviewed studies one might have expected these LCAs to provide definitive answers on the environmental preferability, or lack thereof, for all the EOL management methods for organics under consideration by Alberta Environment as options for managing organic wastes – composting, anaerobic digestion, gasification, combustion, incineration with energy recovery, mechanical biological treatment, incineration without energy recovery, and disposal in landfills, both with and without energy recovery from generated methane. Yet it turned out that the LCAs provided enough data and results to make conclusions regarding just four EOL management methods – aerobic composting, anaerobic digestion, mass burn waste-to-energy (WTE), and landfill gas-to-energy (LFGTE). Furthermore, the LCA results were not sufficient to make conclusions regarding at home and other small scale, on-site aerobic composting methods.

For the four indicated management methods, the environmental impacts information gleaned from the LCAs was sufficient to determine that aerobic composting and anaerobic digestion are both environmentally preferable to either WTE or LFGTE, and should be listed at the top of an organics management hierarchy for Alberta. This conclusion was buttressed by using SRMG's measuring environmental benefits calculator (MEBCalc^{TM}) to compare EOL options for leaf and yard wastes generated in Red Deer during the five year period 2006 – 2010. The calculator's results showed that aerobic composting is environmentally preferable to either WTE or LFGTE, not only in terms of climate impacts, but also for six other types of environmental impacts to human health and ecosystems – human health impacts from particulates, toxics and carcinogens, and ecosystem impacts from toxics, acidification, and eutrophication.

For WTE versus LFGTE, the results were mixed, just as they were in the data from the reviewed LCAs. LFGTE was preferable to WTE for managing Red Deer leaf and yard wastes on the basis of climate change, human carcinogens and ecosystems toxics. WTE was preferable to LFGTE in terms of particulates, human toxics and acidification. The two methods essentially tied for eutrophication impacts.

These mixed MEBCalc^{TM} results for LFGTE and WTE exemplify the fact that in the reviewed literature no single EOL management method consistently topped all other management options across all environmental impacts. Furthermore, review of LCAs indicated additional study is needed to determine more definitively how all organic and leaf and yard wastes management methods compare amongst themselves with regard to environmental impacts other than climate change.

Nevertheless, in support of a management hierarchy, and to resolve the conundrum caused by trade-offs between different environmental impacts, the project team used the MEBCalc^{TM} model to calculate an aggregate index. This index summarizes the results for the seven environmental impacts into a single monetary value based on conceptual estimated costs to human health and ecosystems from each of the seven impacts evaluated by the model. This index for Red Deer LYW indicates that aerobic composting reduces overall environmental impacts, whereas disposal of Red Deer LYW increases overall environmental impacts by substantial amounts.

Anaerobic digestion was not included in the MEBCalc^{TM} comparative evaluation due to unavailability of empirically reliable estimates of the amount of input organics that are converted to energy output versus remaining in the digestate for processing into a compost product similar to the compost product output from aerobic composting. Until this uncertainty is resolved the project team does not feel comfortable proposing a ranking that distinguishes between these two composting technologies. The magnitude of any trade-off between generation of energy versus production of compost is critical for choosing between these two EOL methods for differing types of organics diversion streams.

II. INTRODUCTION & PROJECT PURPOSE

Alberta Ministry of the Environment (Alberta Environment) contracted with Sound Resource Management Group, Inc. (SRMG) to "conduct a literature review of life cycle assessments (LCAs) for managing organic waste, including leaf and yard waste, to assess the relative environmental impact of alternative end-of-life management options…These management options should include waste-to-energy (e.g., anaerobic digestion, gasification, combustion, incineration with energy recovery…), mechanical biological treatment, incineration, and disposal in landfills."[1]

As defined for this project, organic waste is "the putrescible fraction of municipal solid waste from households and the ICI sector including food preparation waste, spoiled food and fruit, and leaf and yard waste. This project will not include organic waste such as abattoir waste and manures, biosolids, or processing plant residuals from agricultural, industrial, or commercial generators.

"Leaf and yard waste is defined as vegetative matter including materials such as tree and shrub trimmings, plant remains, grass clippings, leaves, trees and stumps."[2]

In addition to researching and compiling the list of recent LCAs, and producing a high-level review and summary of the studies and articles on the list, SRMG is also tasked with developing

[1] Alberta Environment, *Life Cycle Assessment of Leaf and Yard Waste: Literature Review*, RFP# ES-PPC-2010-04, p. 3.
[2] *Ibid*, p.4.

a relative ranking of end-of-life (EOL) management methods for leaf and yard waste, as well as an EOL methods ranking for organic waste. The project report should discuss rationales for these rankings and explain any differences between them.

The following report narrates the results of each major task in the project. Section III reports the project team's search methodology for discovering the list of LCAs that are potentially relevant for managing these two organics streams in Alberta. Section IV provides a brief narrative on LCA methods and limitations. Section V summarizes and discusses some of the information and data that the project team gleaned from reviewing LCAs on organics EOL management. That section also explicates the LCA review matrix that the project team developed to assist in summarizing the findings of the LCAs.

Section VI reports the findings from the LCAs, using tables of summary data produced from the LCA review matrix. This section also details the numerous caveats that need to be taken into consideration in deriving a management hierarchy from the information in the reviewed LCAs. Section VII discusses development of the relative rankings of EOL management methods for organic waste and for leaf and yard waste. Section VII also reports the results of the project team's attempt to verify management method rankings and results using SRMG's life cycle impact assessment model MEBCalc™ (Measuring Environmental Benefits Calculator).

Section VIII contains the bibliography of reviewed LCAs. Appendix A provides an abstract or summary for each reviewed LCA. Appendix B provides a brief description of the MEBCalc™ model and its procedures for computing a composite index of the diverse environmental benefits and costs associated with each organics EOL management method.

III. RESEARCH METHODS FOR FINDING LCAS ON ORGANICS AND LYW EOL MANAGEMENT METHODS

The project team developed the list of life cycle assessments (LCAs) on organics and leaf/yard waste end-of-life management methods through five methods:

1. Reviewing bibliographies that project team members have on hand as a result of the LCA research on waste management methods that they have conducted.

2. Contacting recognized professional experts.

3. Accessing research documents and models developed by governmental agencies.

4. Examining the tables of content and article abstracts for a number of peer-reviewed journals for the period 2005 to the present.

5. Searching the internet using search engines such as Google Scholar.

6. Searching the trade publications.

Accessed Project Team Bibliographies

Matthews, Morawski and Morris have either recently conducted or provided peer review of LCA studies on end-of life (EOL) management methods for organics and leaf/yard wastes. Matthews was the main researcher for a recently completed review and attempted harmonization of two main models developed by the U.S. Environmental Protection Agency and its contractors for calculating environmental impacts of materials end-of-life management methods – WARM (WAste Reduction Model) and MSW DST (Municipal Solid Waste Decision Support Tool). Matthews also served as a peer reviewer for a 2009 article in the journal *Environmental Science & Technology* (*ES&T*) published by U.S. EPA researchers on landfilling versus waste-to-energy (WTE) incineration.

Morawski conducted an LCA on organics management for the Region of Niagara, using Sound Resource Management Group's MEBCalc™ (Measuring Environmental Benefits Calculator). *BioCycle* magazine published an article by Morawski summarizing that study.

In 2010 Morris published an article in *ES&T* on landfilling versus WTE. Along with Dr. Jennifer Bagby, Morris published a 2008 article in the *International Journal of Life Cycle Assessment*. That article assessed the environmental benefits of using compost as a substitute for synthetic fertilizers and pesticides on home lawn and garden soils.

These undertakings by the project team all required up to date familiarity with the literature and methodologies for LCAs on organics and leaf/yard waste EOL management methods. As a result all three project team members had relevant LCAs to include in the list of life cycle studies to review.

Contacted Professional Experts

The project team leader Morris emailed experts in the field of organics management with the following request:

> I'm working with Scott Matthews from Carnegie Mellon University and Clarissa Morawski from Toronto on a short and small project for Alberta Environment in which we are to gather and review life cycle analyses/assessments on end-of life management options for organics and leaf/yard wastes. We are to do the review so as to yield a suggested management hierarchy for Alberta for managing these two organics streams. Here are their definitions of these two streams:
>
> "For this project, organic waste is defined as the putrescible fraction of municipal solid waste from households and the ICI sector including food preparation waste, spoiled food and fruit, and leaf and yard waste. This project will not include organic waste such as abattoir waste and manures, biosolids, or processing plant residuals from agricultural, industrial, or commercial generators."
>
> Leaf and yard waste is "defined as vegetative matter including materials such as tree and shrub trimmings, plant remains, grass clippings, leaves, trees and stumps."
>
> The management methods we are to consider are "waste-to-energy (e.g. anaerobic digestion, gasification, combustion, incineration with energy recovery…), mechanical biological treatment, incineration, composting, and disposal in landfills."

(Note: all quotes are from the RFP issued by Alberta Environment.)

If you know of recent life cycle analyses/assessments (LCAs) that you think we should review, could you send me the names of the studies and even the PDFs if you have them digitally?

This email request was sent to:

1. Dr. Morton Barlaz – Professor and Chair Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC

2. Dr. Sally Brown – Research Associate Professor: Soil Amendments, In situ Remediation, & Carbon Sequestration; School of Forest Resources, University of Washington, Seattle, WA

3. Dr. Enzo Favoino – Scuola Agraria del Parco di Monza, Monza, Italy; Chair International Solid Waste Association Working Group on Biological Treatment

4. Jan Allen, PE – Chief Technology Officer, Harvest Power Inc., Seattle, WA

5. Matthew Cotton – Board of Directors, U.S. Composting Council

6. John Reindl – prior to retirement, Recycling Manager, Dane County Department of Public Works, Madison WI; member Wisconsin Governor's Task Force on Waste Materials Recovery and Disposal

Each of these experts responded with suggested studies and either included digital copies of the articles and studies they recommended that the project team include on the literature review list, or provided links to recommended studies.

Project team member Morawski made a similar request for information from the following contacts:

1. Susan Antler -- Executive Director, Composting Council of Canada

2. Dennis Jackson -- Waste Reduction and Management Division, Environmental Stewardship Branch, Environment Canada

3. Christina Seidel -- Executive Director, Recycling Council of Alberta

4. Richard Boyd -- Policy Analyst, Climate Change Central

5. Randy Feed -- ICF International

6. Julia Bray -- Principal, Infoplexxus

Accessed Government Studies and Models

The project team accessed models and/or supporting reports from U.S. EPA and Environment Canada. The US EPA models are WARM and MSW-DST. Supporting reports for these EPA models cover organics, yard trimmings and food scraps, along with composting, landfilling and WTE combustion. The Environment Canada model is the Canadian version of EPA's WARM, as adapted and updated by ICF Consulting (Toronto) to better portray Canadian materials management methods.

The project team also accessed other governmental agency reports that included coverage of organics and leaf/yard waste EOL management methods' environmental impacts. These reports were prepared for or by the United Nations Environment Programme, Alberta Environment Climate Change Policy Unit, California Integrated Waste Management Board, Niagara Region of Ontario, Metro (Portland, OR), and Seattle Public Utilities (Seattle, WA).

Reviewed Peer-Reviewed Journal Tables of Content and Abstracts for 2005 to Present

As a fourth method for gathering LCAs on organics and leaf/yard waste EOL management, the project team reviewed the tables of contents and appropriate abstracts for all editions of a number of peer-reviewed journals published between January 2005 and the latest edition available for 2010 or 2011. The journals examined included *Environmental Science & Technology, International Journal of Life Cycle Assessment, Journal of Cleaner Production, Journal of Industrial Ecology, Resource Conservation and Recycling, Waste Management,* and *Waste Management & Research.* The project team conducted this perusal of tables of contents to assure capture of all relevant LCAs that may have appeared in these most popular and distinguished journals during recent years. Perusal of journal editions published prior to 2005 was not conducted because the rapid change and development of EOL methods and practices for organics and leaf/yard wastes over the past five years likely rendered earlier LCAs outdated or superfluous.

Acquired Relevant LCAs via Use of Internet Search Engines

The project team used Internet searches as a fifth method for discovering relevant LCAs. This method provided references for articles in peer-reviewed journals for which the project team could not conduct tables of contents review due to time and budgetary constraints.

In conducting these Internet searches, the following sites were used: Google Scholar (http://scholar.google.com), ISI Web of Knowledge (http://apps.isiknowledge.com/), and websites of journals listed above. A benefit of using the Internet-based engines is they can show the ancestor and descendant papers that build the literature base for identified research. For example, papers found in a literature search can additionally show the papers which cite it, and which papers are cited. Those external papers can then be checked as potential sources.

Reviewed Articles Published in Trade Magazines

Perusal of trade publications was the sixth method used by the project team to acquire LCAs on EOL management methods for organics and leaf/yard wastes. Trade publications reviewed included *BioCycle, Resource Recycling,* and *Solid Waste & Recycling*.

IV. BRIEF NARRATIVE ON LIFE CYCLE ASSESSMENT OF ORGANIC WASTE MANAGEMENT METHODS

Life cycle assessment (LCA) is a methodology that attempts to enumerate and codify potential environmental impacts that may result from an activity or process. For this review of LCAs the activity of interest is the management of organic waste generated by households, commercial businesses, government agencies and institutions in Alberta.

Examples of environmental impacts that may be covered by an LCA, and that may result from a particular organic waste management method, include:

- Climate change
- Human respiratory health decrement from particulates
- Human health decrement from toxics
- Human health decrement from carcinogens
- Acidification
- Eutrophication
- Ecosystem toxicity
- Ozone depletion
- Smog formation
- Habitat alteration
- Biodiversity decrease
- Resource depletion
- Water consumption
- Land use and/or land use change

A number of these environmental and public health impacts result from release of pollutants to air, water and/or land. By grouping pollution impacts into a handful of categories, life cycle assessment is able to reduce the complexity of following trends for hundreds of pollutants. This simplifies life for policy makers. However, the trade-off is that aggregation of impacts from hundreds of pollutants into a few broad categories of environmental and health impacts involves using complex pollutant aggregation and weighting methods. As with all scientific endeavors these aggregation methods are continually undergoing refinement and updating.

For example, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs) are some of the pollutants that cause climate change when they are released to the atmosphere. In its periodic climate change assessment reports the United Nations Intergovernmental Panel on Climate Change (IPCC) has presented aggregation weights called global warming potentials (GWPs) for expressing releases of climate changing pollutants as equivalent releases of carbon dioxide – i.e., carbon dioxide equivalents (CO_2e).

Each successive IPCC climate assessment report updates these GWPs. For example, IPCC's estimates of GWPs over a 100-year time horizon for CH_4, N_2O, and CFC-11 were 25, 298, and 4,750, respectively, in its 4th assessment report, compared with 21, 310 and 3,800 in the 2nd assessment report.[3] Such changes in aggregation and indexing weights need to be kept in mind when comparing results from LCAs conducted at different points in time by different researchers.

In addition to noting which impacts are included and which excluded, and which aggregation methods are used for the included impacts, another critical aspect of an LCA is the system boundary used for the analysis. For example, an LCA on organic waste might consider environmental impacts only from pollutants released at the organic waste management facility, be that facility an aerobic composter, an anaerobic digester, a landfill, or a mass burn waste-to-energy (WTE) operation. Another LCA might include the impacts of collection and hauling organic waste to the management facility, as well as follow-on impacts such as those caused by disposal of combustion ash. Furthermore, an LCA may choose to include environmental benefits (sometimes referred to as "offsets") that result from, say, displacing synthetic fertilizers with compost or displacing electricity generated from coal- or natural gas-fired power generation facilities with electricity produced from anaerobic digestion, landfill gas-to-energy or mass burn WTE. Clearly, including or excluding various components of the organic waste management system and the benefits of products or services produced by that system can materially affect the estimated life cycle impacts and resultant rankings of one management method compared with another.

In order to provide a broad perspective on the environmental impacts of EOL management methods for organics and leaf/yard wastes, and also to develop a robust ranking of management methods, the project team categorized LCAs according to whether their coverage of the organics waste management life cycle was comprehensive or limited in some ways. This categorization was used to develop subsamples for comparing average study results, as discussed in Section VI. The team also made sure to record results for all LCA impact categories covered in each study, and in addition to record results for individual pollutants such as ammonia when reported by a particular study.

LCA Limitations & Can, Can't Do's

Aggregation methodologies used for LCA impact categories to portray impacts from pollutants are based on assessing environmental impacts of pollutants at what is termed "mid-points" in the causal chain flowing from pollutant release to endpoint effect. For example, in the case of ozone depletion the characterization of the impact of each pollutant could take place at the specific effect level. That is, a particular pollutant causes decreases in the ozone layer which leads to increased skin cancer, cataracts, crop damage and/or other specific health and environmental effects. In this case the LCA, which in the context of evaluating impacts of pollutant emissions is also referred to as a life cycle impact assessment (LCIA), would need to estimate the specific increase in skin cancer, cataracts, crop damage and all other effects caused by the particular pollutant. Or the characterization could be based simply on the midpoint effect – i.e., the potential for the release of that pollutant to cause ozone depletion.

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[3] United Nations Intergovernmental Panel on Climate Change, *IPCC Fourth Assessment Report: Climate Change 2007 (AR4), Working Group 1 Report – The Physical Science Basis*, Table 2.14.

The midpoint characterization for pollutant impacts has several important advantages for an LCIA. "Analysis at a midpoint minimizes the amount of forecasting and effect modeling incorporated into the LCIA, thereby reducing the complexity of the modeling and often simplifying communication. Another factor supporting the use of midpoint modeling is the incompleteness of model coverage for endpoint estimation. For example, …models and data may exist to allow a prediction of potential endpoint effects such as skin cancer and cataracts, but the inclusion of effects such as crop damage, immune-system suppression, damage to materials, and marine-life damage is less well supported."[4]

A cautionary note is that the simplifications provided by averaging, aggregation of pollutants, and midpoint effects modeling come at a cost in terms of what can be said about potential specific effects at a particular time and place from a particular activity. This is why an LCA or LCIA should not be confused with an environmental impact assessment (EIA) or environmental impact statement (EIS) for any given specific organic waste EOL management method that might be proposed for use at a particular locale. Furthermore, as will hopefully become apparent in the discussion in Section VII on ranking the EOL management methods, aggregation and midpoint effects modeling introduce uncertainties into an LCA-based comparison of management methods that make it difficult to rank one method better than another without noting a number of qualifiers on that ranking.

Another cautionary note comes from the observation that measuring environmental impacts via an LCA provides information on potential environmental benefits and costs, but does not directly illuminate economic or social benefits and costs, or the trade-offs that one may have to make between these three types of costs and benefits. In this sense the discussion of findings from reviewing numerous LCAs and the development of suggested rankings reported below should be taken as one piece, albeit a very important piece, of the puzzle of deciding what organic waste management method is likely to be best for a particular community in Alberta.

Finally, it should also be noted that the characterizations of pollutant releases and product/energy offsets for an EOL management method discussed in an LCA will often be based on management method modeling, on actual measurements at only one or at best a few actual facilities, or on estimated industry average performance levels. This aspect of typical LCA practice also explains some of the wide differences in results from one LCA to the next. The differing LCA results from different studies may, thus, in part be due to incorporating data from facilities using best practices versus data for the average facility. This can be especially troublesome when one EOL management method's characterization represents best state of the art practices, while a competing method's characterization is based on industry averages or on outdated modeling assumptions.

[4] Bare, J.C.; Norris, G.A.; Pennington, D.W.; McKone, T. TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. *Journal of Industrial Ecology* **2003**, 6(3-4), 49-78.

V. Development of a Review Matrix for Summarizing Information & Data in Reviewed LCAs

Alberta Environment's RFP for this project directed the project team to collect the following information on each study:

1. Title and author,
2. Overview of goal and scope of work, and,
3. Main conclusions.

The RFP also suggested that the literature review include for each LCA study:

1. Brief summary of content and findings, data sources, system boundaries, LCA approach and methodology,
2. Life cycle impacts with relevant indicators,
3. Evidence on feasibility, reliability and scale of each technology,
4. Typical feedstock,
5. Type of peer review,
6. Consideration of cumulative effects, and,
7. Gaps in the LCA study.

To this end the project team developed an Excel-based spreadsheet matrix with columns that collected the following information and data from each LCA study:

1. Author (s),
2. Article or report title,
3. Name of journal, trade magazine or agency publishing the study,
4. Type of review (e.g., formal peer review),
5. Year (s) study conducted,
6. Geographic site (if any) of the study,
7. Description of important characteristics for specific facilities studied, or for generic EOL methods included in the LCA -- EOL organic waste management methods discussed in the LCAs included aerobic composting (AC), anaerobic digestion (AD), home or localized aerobic composting, mechanical biological treatment (MBT), gasification, plasma arc gasification, biomass-to-energy, mass burn WTE, landfill gas-to-energy (LFGTE), mass burn without energy recovery, landfill gas capture and flaring, and landfill gas venting -- i.e., no landfill gas capture.,
8. Estimates of the potential impact of each management method on climate change, human health (respiratory, toxic, carcinogenic), ecosystem toxicity, acidification, eutrophication, habitat, biodiversity, ground level smog, ozone depletion, water use, resource use, and energy use,
9. Results for any composite indexes or valuations for groups of environmental and health impacts,
10. Estimates for emissions/outputs of odors, VOCs, methane, biofuels, compost, and energy,

11. Estimates of offsets and substitution rates for electricity, heat, fertilizers, and carbon sequestration,
12. Sensitive variables and assumptions that tended to drive the particular LCA's results,
13. Need for additional research,
14. Organic waste input - product output (e.g., compost or energy) relationships and/or mass balances,
15. Compost quality characteristics,
16. Collection and hauling characteristics, and,
17. General commentary on any additional important aspects of a particular LCA.

One of the salient characteristics of the 82 reviewed studies is that two-thirds are published as journal articles which required formal peer review. Peer review for journal publication typically means that two to four experts in the study's subject matter read and submit comments to a journal editor regarding whether the study merits publication. If the study does merit publication, the reviewers also suggest what minor and/or major revisions are necessary prior to final acceptance for publication. To further ensure the integrity of this peer review process, reviewers remain anonymous to the study's author(s). In some cases, authors' identities also are anonymous to the reviewers.

Most of the studies that did not undergo formal peer review for journal publication did at least likely face scrutiny by the study funders. In most cases the funder was a governmental agency. This suggests that study managers and perhaps other agency readers of study drafts found the study scientifically sound enough to warrant publication under their agency's name.

Another important finding is that those articles and reports that provided actual LCA data and results often were based on EOL organic waste management facilities and methods that had passed the hurdle of becoming operational on an ongoing commercially reliable scale. Also, several of the management methods listed in Alberta Environment's RFP as possible technologies for managing organic waste in Alberta were not discussed in any of the reviewed LCAs. Specifically, the project team did not find any peer-reviewed LCAs that covered gasification, plasma arc gasification, or household or other very small scale anaerobic digestion for organic wastes. Similarly, biomass to energy conversion technologies targeting only source separated organic or leaf & yard wastes remain unavailable at commercial scale, other than anaerobic digestion.

Furthermore, due to research on measurement metrics for biodiversity and habitat still being in the developmental stage, the project team did not discover any LCAs that covered these two impacts of organic waste management methods. Also, very few of the reviewed LCAs reported a composite index or valuation to represent overall environmental benefits or costs of EOL organic waste management methods. In fact, surprisingly few of the LCAs covered multiple environmental impacts, with most tending to focus mainly on climate change.

VI. Discussion of Findings and Summary Tables from the Review Matrix

Table VI.1, Comparison of Climate Change Impacts of Organic Waste Management Methods, displays descriptive statistics for the climate change impacts reported in the reviewed LCAs. The first thing to note in the table is that even though climate change is the environmental impact investigated most frequently in the studies reviewed, many LCAs addressed climate effects for only a few of the available management methods for organic waste. For example, thirty of the eighty-two reviewed LCAs contain climate results on aerobic composting, but only five reported climate impacts for anaerobic digestion. Hence, the reader is reminded to recognize that the averages and ranges shown in the table for many of the management methods are very uncertain, in the sense that the variance about the mean is quite large. This is because there were so few LCAs that covered some of the EOL management methods, as well as because of the relatively small number of studies reporting quantified LCA results.

For example, the LCAs cover climate impacts for just nine landfills that capture landfill methane and use the gas to generate energy (shown as LFGTE, i.e., landfill gas-to-energy, in the table). For this small sample the estimate of the average impact is a release of 0.16 metric tons of carbon dioxide equivalents ($MTCO_2E$) per metric ton of organic waste landfilled. The estimated standard deviation is 0.41 $MTCO_2E$. This indicates that the true average emission for the population of all such landfills has a 95% chance of falling in the interval between -0.15 and +0.47 $MTCO_2E$. These 95% confidence intervals are an indication of the degree of uncertainty as to what the true average is when the sample size is so small. In other words, based on the data in reviewed LCAs it is not possible to conclude with any degree of confidence whether LFGTE increases or decreases climate change.

A second important conclusion from the data shown in Table VI.1 is that data outliers and differences in LCA study assumptions can substantially alter the estimates of average impact for a particular management method. For example, excluding outliers, LFGTE on average decreases climate impacts by 0.01 $MTCO_2E$ and true average GHG emissions for LFGTE have a 95% chance of being between -0.20 and +0.17 $MTCO_2E$. The differences in length and location between the two confidence intervals for LFGTE indicate the substantial effect of extreme values in the small sample of estimates for the climate impact of landfilling organics.

An example of the effect of study assumptions regarding boundary conditions is provided by the descriptive statistics for aerobic composting. Across all thirty LCAs that provided estimates of climate impact for this EOL technology, the estimated mean climate impact is -0.07 $MTCO_2E$ per metric ton of organic waste composted – that is, on average this EOL method results in a reduction in emissions of climate changing pollutants. For the subsample of eleven LCAs that included the benefits from compost use on carbon sequestration in soils and/or from substitution of compost for synthetic fertilizers, however, the estimated average climate impact is -0.21 $MTCO_2E$. This is close to the estimated mean for anaerobic digestion of -0.25 $MTCO_2E$.

To explore the difference between aerobic composting and anaerobic digestion further, note that the 95% confidence interval for the aerobic composting subsample is -0.40 to -0.01 $MTCO_2E$. The confidence interval for anaerobic digestion is -0.59 to +0.10 $MTCO_2E$.

Table VI.1
Comparison of Climate Change Impacts of Organic Waste Management Methods

Management Method	Descriptive Statistics for Potential Climate Change Impacts				
	sample size	minimum	maximum	median	mean
		(metric tons of carbon dioxide equivalents/metric ton organic waste)			
Anaerobic Digestion	5	-0.74	-0.06	-0.14	-0.25
Aerobic Composting	30	-0.76	0.22	0.04	-0.07
- subset 1*	11	-0.76	0.06	-0.20	-0.21
- subset 2**	9	-0.26	0.06	-0.04	-0.09
Mass Burn WTE	9	-0.24	0.63	-0.02	0.02
- subset 1***	8	-0.24	0.02	-0.03	-0.06
Home Aerobic Composting	8	-0.69	0.29	0.14	0.05
LFGTE	9	-0.31	1.00	0.11	0.16
- subset 1****	7	-0.31	0.24	-0.10	-0.01
LF flaring	2	-0.06	-0.05	-0.06	-0.06
Mass Burn Incineration	1	0.07	0.07	0.07	0.07

* Aerobic composting subset 1 excludes studies that did not include carbon sequestration in soils and also did not include substitution of compost for synthetic fertilizer.
** Aerobic composting subset 2 is subset 1 without low outliers.
*** Mass burn WTE subset 1 excludes high outlier.
**** Landfill gas-to-energy (LFGTE) subset 1 excludes high outliers.

Furthermore, as suggested by the fact that the 95% confidence interval for aerobic composting is nested inside the 95% confidence interval for anaerobic digestion, estimated mean climate impacts for aerobic composting and anaerobic digestion are not significantly different at the 5% significance level, regardless of whether the statistical t-test for significant differences is based on the whole sample or just subsample 1 for aerobic composting. This indicates that the LCA studies do not provide enough information to determine which of these two EOL management methods is better for the climate.

Similarly, a t-test shows that the reviewed LCAs do not provide enough evidence to conclude that mass burn WTE and LFGTE have significantly different impacts on climate at a 5% significance level.

On the other hand, both aerobic composting and anaerobic digestion have a significantly lower climate impact than WTE, at the 5% significance level versus the whole WTE sample and at the 10% significance level versus the WTE subsample without the high climate impact outlier. The same conclusions hold for aerobic composting and anaerobic digestion versus LFGTE and the LFGTE subsample.

The home aerobic composting results shown in Table VI.1 indicate that home composting has a significantly higher climate impact than either aerobic composting or anaerobic digestion. However, this result may be due to the lack of consideration in those LCAs that covered home composting of the climate benefits from the use of the compost produced via the home composting technologies.

Finally, the number of studies covering landfills that flare collected landfill gas rather than using it to generate electricity are too few to make statistically reliable conclusions on that technology's climate impact. The same applies to mass burn combustion without energy recovery.

Table VI.2, Ranking of Organic Waste Management Methods for Non-Climate LCIA Categories, shows results from the reviewed LCA studies for environmental impacts other than climate change. For each LCA that reported comparative LCIA results for an impact other than climate change, the study team assigned a 1, signifying "best", to the EOL management method with the lowest impact, a 2 to the method with the second lowest impact, and so on for all management methods covered by the LCIA. Table VI.2 shows the average for these rankings; the number in parentheses indicates the number of LCIAs that provided an estimate of that impact for that EOL management method. The project team used this approach to report the non-climate impacts, both because the number of studies that covered any particular impact is very small, and because for a given impact different studies sometimes used different impact indicators.

The average rankings for the eight non-climate human health and environmental impacts in Table VI.2 display substantial inconsistency across these impact categories in ranking for each EOL management method. Also, for any given impact category there are important management methods for which there are two or fewer LCAs that provide results.

The relative rankings for the four management methods – aerobic composting, anaerobic digestion, LFGTE and mass burn WTE – do tend to follow the definitive results for climate change. That is, aerobic composting and anaerobic digestion are environmentally indistinguishable, but tend to be better than LFGTE and mass burn WTE, which themselves are also indistinguishable. However, without an indexing or valuation methodology to aggregate the average rankings that vary so widely across impact categories, it is not possible to be very certain even about the higher ranking for aerobic composting and anaerobic digestion, on the one hand, and the lower ranking for LFGTE and mass burn WTE, on the other.

Table VI.2
Ranking of Organic Waste Management Methods for Non-Climate LCIA Categories

Management Method	Average Ranking*							
	Human Respiratory	Human Toxicity	Human Carcinogencitiy	Ecotoxicity	Acidification	Eutrophication	Ground Level Smog	Ozone Depletion
Anaerobic Digestion	1.0 (2)	2.2 (5)	1.5 (2)	1.3 (3)	1.0 (2)	3.0 (1)	1.0 (2)	NR
Aerobic Composting	2.0 (5)	1.3 (7)	1.2 (5)	1.3 (6)	1.8 (6)	1.6 (5)	2.0 (2)	2.0 (1)
Mass Burn WTE	2.7 (3)	2.0 (7)	2.4 (5)	2.3 (6)	2.2 (6)	2.3 (4)	1.7 (3)	NR
Home Aerobic Composting	NR	1.0 (1)	NR	1.0 (1)	1.5 (2)	1.5 (2)	1.0 (1)	1.0 (1)
LFGTE	2.0 (4)	2.3 (4)	1.8 (5)	2.0 (5)	1.8 (5)	2.0 (3)	1.5 (2)	NR
LF Flare	3.5 (2)	2.5 (4)	2.5 (2)	3.5 (2)	3.5 (2)	3.5 (2)	NR	NR
Mass Burn Incineration	NR	NRA	NR	3.0 (1)	3.0 (1)	2.0 (1)	3.0 (1)	NR
in-Sink Food Waste Disposer	NR	3.0 (1)	NR	3.0 (1)	2.0 (1)	3.0 (1)	NR	NR

* A higher ranking (e.g., 1.0 is the highest) means lower potential impact; number in parentheses is the number of studies that ranked that management method for the indicated environmental impact.
NR = not ranked, because none of the reviewed LCAs provided quantitative rankings on the management method For the indicated environmental impact category.

Furthermore, even though home aerobic composting ranks better than any of the other technologies, that is the result of just two studies, one of which only compared home aerobic composting against centralized aerobic compositing. The other only compared these two aerobic composting technologies and the in-sink food waste disposer management method.

Thus, the conclusion would seem to be that additional study is required to definitely determine how these organic waste management methods compare amongst themselves with regard to environmental impacts other than climate change.

Finally, Table VI.3, Ranking of Organic Waste Management Methods for Other Environmental Indicators, provides average rankings of the management methods in terms of water use, energy use, a composite index (based in one study on conceptual costs for environmental impacts as implemented in MEBCalc™ and in another study on a qualitative ranking developed from peer-reviewed studies on post-consumer materials management methods), emissions of volatile organic compounds (VOCs), and emissions of ammonia.

Water use data is available from only two studies and for only the two aerobic composting and the one food waste disposer methods. The rankings shown in the table conform to casual observation – i.e., home composters typically require little if any addition of water, commercial scale composting often requires addition of water to maintain optimal biological conditions for converting organics into marketable compost, and in-sink food waste disposers require running tap water to facilitate grinding and flushing.

Table VI.3
Ranking of Organic Waste Management Methods for Other Environmental Indicators

Management Method	Average Ranking*				
	Water Use	Energy Use	Composite Index	VOCs	Ammonia
Anaerobic Digestion	NR	1.0 (1)	NR	NR	NR
Aerobic Composting	2.0 (2)	2.2 (5)	1.0 (2)	2.0 (1)	1.0 (1)
Mass Burn WTE	NR	1.0 (1)	2.0 (2)	1.0 (1)	2.0 (1)
Home Aerobic Composting	1.0 (2)	1.3 (3)	NR	NR	NR
LFGTE	NR	2.0 (1)	3.0 (2)	NR	NR
LF Flare	NR	NR	4.0 (1)	NR	NR
Mass Burn Incineration	NR	NR	NR	NR	NR
in-Sink Food Waste Disposer	3.0 (1)	2.0 (1)	NR	NR	NR

* Higher ranking (e.g., 1.0 in the highest) means lower potential impact; number in parentheses is the number of studies that ranked that management method for the indicated impact indicator.
NR = not ranked, because none of the reviewed LCAs provided quantitative rankings on the management method for the indicated environmental impact category.

System wide energy use (e.g., cumulative energy demand) is often analyzed in LCAs, but even for this parameter there were data in only five studies. Here again the rankings conform to casual observation. The energy generation focused technologies – anaerobic digestion and mass burn WTE – provide high energy outputs to offset the energy uses in these two systems for managing organic waste. Home aerobic composting uses very little energy input, other than human labor which is not taken into account in the LCAs reporting energy use. LFGTE provides an energy output to offset some of the energy input for collection, hauling and landfill operations.

The in-sink food waste disposer does not require collection vehicles and can produce some energy from anaerobic digestion of wastewater biosolids to offset energy requirements for pumping and wastewater treatment facility operations. On the other hand, centralized aerobic composting typically does not provide an energy benefit, other than the offset of energy for fertilizer production, to counterbalance energy needed for collection, hauling and composting facility operations. Thus, this EOL management method ranks last in terms of energy use – i.e., it has the highest net energy use. However, the reader should note that its average ranking is only 10% below the average rankings for LFGTE and in-sink food waste disposers.

A composite environmental index or valuation is reported in only two of the reviewed LCAs. Although the rankings shown in Table VI.3 do tend to confirm the results shown in Tables VI.1 and VI.2, two studies is not sufficient to make this conclusion very firm.

Lastly, one study did provide estimated emissions of VOCs and ammonia for centralized composting and mass burn WTE. Interestingly, these two technologies traded first place in the rankings for minimizing emissions of these two pollutants. This is another illustration of the need to have a way to aggregate performance across numerous pollutant releases and environmental impacts in order to produce a single-dimensional ranking of the available methods for managing the end-of-life for organic wastes. It also illustrates the finding in this review that there was no obvious and consistent winner across all the environmental impacts investigated in the reviewed LCAs.

Sensitivity of LCA Results for EOL Management Methods

As indicated by the preceding discussion, there are wide variations in LCIA results for each organic waste management method. This subsection discusses some of the factors which cause substantial sensitivity in results for each method for which there are adequate LCIA findings to discuss.

Aerobic Composting

The environmental impacts of aerobic composting are very sensitive to compost facility management practices for maintaining aerobic conditions. Variations from aerobic conditions can result in releases of methane and/or nitrous oxide, both of which are potent greenhouse gases.

Results for an aerobic composting LCA are also very dependent on offsets. For example, when peat is the product which compost replaces, the carbon offset is much larger than for replacing synthetic fertilizer. In addition, there is substantial ongoing research on the enhancement of carbon storage/sequestration in soils to which compost has been applied. Review of some of this research for this project suggests that the enhancement of soil carbon storage from compost utilization may have been underestimated in earlier studies, as well as completely ignored at times.

Anaerobic Digestion

LCA data for anaerobic digestion are sensitive to the amount of methane which is produced for use as an energy offset. This can depend on both the actual composition of the organic waste inputs and the specific digestion technology. The magnitude of the benefit from energy offsets also depends on the energy fuel displaced. For example, if the displaced fuel is coal the climate benefit is much larger than if the displaced fuel is natural gas. If the displaced energy is one that is close to carbon neutral such as solar thin film photovoltaics, then the energy offset will be small no matter how much methane is generated during the digestion process. The project team notes that the LCA standard does not specify a method of choosing the marginal energy type, which leads to different assumptions across studies.

Finally, because anaerobic digestion specifically attempts to maximize methane production, any system deficiencies with respect to best practices may result in fugitive emission releases that will substantially degrade this technology's environmental performance.

Home or Small Scale Aerobic Composting

Home and small scale aerobic composting's environmental performance will be subject to the same deviations as centralized aerobic composting with respect to failure to achieve best management practices. In this case the propensity for inadequate maintenance of aerobic conditions may be much higher than for professionally managed centralized aerobic composting, with a resulting higher probability of release of methane and nitrous oxide to the atmosphere.

At the same time, home and small scale composting avoids the environmental impacts of organics collection and hauling systems. Whether this cost for other management methods is included in the LCA or not has an impact on the relative performance of home and small scale composting methods. However, the impact of collection and hauling relative to facility operations and offsets is typically small for most environmental impacts.

Mass Burn WTE

Mass burn WTE is very sensitive to the type of energy displaced by the energy produced from combusting organic wastes. For this sensitivity the same considerations apply that were mentioned for anaerobic digestion.

This technology is also very sensitive to the composition of the organic wastes. If the waste stream is virtually all food wastes, especially if it tends to be mostly high moisture content vegetables and fruits, then net energy production will be quite small if not close to zero. At the other end of the composition spectrum is an organic waste stream composed of mostly clean, dry wood. In that case net energy production can be equivalent to the net from typical MSW.

Finally, the environmental costs and benefits of this technology are sensitive to whether the facility produces and markets electricity, heat or combined heat and power (CHP), with the latter likely providing the greatest amount of energy offsets.

LFGTE

The relative climate impact of this EOL management method is most affected by the landfill gas capture rate, the fugitive methane oxidation rate within the landfill and landfill cover, and the carbon storage rate versus the methane generation rate for the organic waste. The latter depends on the organic waste stream's composition. Due to its high lignin content, which inhibits methanogens, over 80% of the carbon in wood waste remains non-degraded and stored for the long term under the anaerobic conditions of an MSW landfill. On the other hand, only between 15% and 20% of the carbon in food waste remains non-degraded and stored. Branches, leaves and grass clippings fall between these two extremes.[5]

The result is that a landfill receiving an organic waste stream that is mostly composed of food scraps needs to have a much higher landfill gas capture rate to be environmentally competitive with mass burn WTE than does a landfill receiving mostly wood waste organics. A high fugitive methane oxidation rate can compensate somewhat for a lower landfill gas capture rate in the environmental performance competition between LFGTE and WTE.

The environmental performance of both LFGTE and mass burn WTE is also sensitive to the combustion control practices and air pollution emissions control equipment employed to prevent release of particulates, heavy metals, toxics, and additional hazardous products of incomplete combustion and inadequate emissions safeguards.

Some Suggestions for Additional Research

Based on review of more than eighty LCAs on organic waste management methods the greatest needs for additional research and analysis seem to be of two kinds:

1. The need for an LCA using a system boundary that includes handling of organic waste across the whole life cycle, from generation to final disposition, and encompassing the environmental benefits of products and energy produced from processing the organic material, ***across all important management methods*** and all environmental impacts for which adequate and comparable data exist.
2. The need for a systematic sensitivity analysis for each management method that can be used to inform an environmental hierarchy with information as to the conditions under which the rankings in the hierarchy should be changed – in other words, a sort of conditional hierarchy that may remain fixed for most situations but that is informed with caveats that indicate when the usual hierarchy does not apply.

VII. Environmental Hierarchy for Organics & LYW EOL Management Methods

Based on the discussion in Section VI the project team is comfortable proposing an EOL management hierarchy for both organics and leaf & yard wastes (LYW) with aerobic composting and anaerobic digestion as preferred methods and the disposal methods landfill and WTE incineration as less preferred.

To further verify the preference for aerobic composting over the two disposal methods, as well as to provide a ranking between landfill and WTE, the project team applied Sound Resource Management Group's Measuring Environmental Benefits Calculator (MEBCalc™) to data on Red Deer leaf and yard waste diversion during the five year period 2006 - 2010 to determine potential impacts for climate change and six non-climate categories of public health and

[5] Morris, J. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. *Environmental Science & Technology* **2010**, 44(20), 7944-7949, supporting information tables.

ecosystem environmental outcomes for the three EOL methods.[6] The Red Deer LYW stream during this five year period was composed of leaves, branches, yard waste and grass, of which at least 17% was branches.

Anaerobic digestion was not included in this evaluation due to unavailability of empirically reliable estimates of the amount of input leaf and yard wastes that are converted to energy output versus remaining in the digestate for processing into a compost product similar to the compost product output from aerobic composting. Until this uncertainty is resolved the project team does not feel comfortable proposing a ranking for these two composting technologies. The magnitude of any trade-off between generation of energy versus production of compost is critical for choosing between these two EOL methods for differing types of organics diversion streams.

Table VII.1, MEBCalc™ Evaluation of Three EOL Methods for LYW, shows the results from applying the calculator to Red Deer LYW. The climate impact for aerobic composting is the only impact category and EOL management method which shows an environmental improvement as a result of EOL management for LYW. This result is due to the soil carbon enhancements from using compost as a soil amendment.

In addition, the table indicates that aerobic composting has substantially lower impacts for the six non-climate health and ecosystem categories than do either landfilling or WTE combustion of LYW. For all seven impacts these disposal methods incur an environmental deficit due to the impacts from production of fertilizer that is necessary to offset the soil nutrients that are lost when LFW is sent to landfill or WTE rather than being composted and returned to the soil.

Comparing impacts for landfill versus WTE management of LYW, each method shows lower impact for three categories. The two methods essentially tie for eutrophication impacts.

To resolve this standoff between LFGTE and WTE, MEBCalc™ allows the user to estimate conceptual costs for the seven environmental impacts in order to calculate a composite overall valuation for the net environmental cost or benefit from using each of the three EOL management methods.[7] Table VII.1 is based on the MEBCalc™ model's default conceptual costs, which are also listed in the table. As shown in Table VII.1, this composite valuation reveals that aerobic composting has a benefit of $3 per tonne diverted from disposal to aerobic composting, compared with $67 and $71 environmental costs for each tonne sent to landfill or WTE, respectively.

[6] A brief description and discussion of MEBCalc™ is provided in Appendix B.
[7] Appendix B provides a discussion of the default conceptual costs for each of the seven environmental impacts, including the main references used to develop the defaults.

Table VII.1
MEBCalc™ Evaluation of Three EOL Methods for LYW

EOL Management Method	Composite Conceptual Environmental Cost/(Benefit)	LCIA Results - Potential Impact Increase/(Decrease) Per Tonne Red Deer Leaf & Yard Waste						
		Climate Change	Human Respiratory	Human Toxicity	Human Carcino-gencitiy	Eco-toxicity	Acidifi-cation	Eutrophi-cation
	($/tonne)	(kg eCO_2)	(kg $ePM_{2.5}$)	(kg eToluene)	(kg eBenzene)	(kg e2,4-D)	(kg eSO_2)	(kg eN)
Aerobic Composting	($3)	(190)	0.10	13	< 0.005	0.45	0.83	0.11
LFGTE	$66	141	0.73	366	0.17	2.57	3.58	2.63
Mass Burn WTE	$71	455	0.39	268	0.24	4.72	2.82	2.61
	MEBCalc™ Default Conceptual Costs	$40/tonne eCO_2	$10,000/tonne $ePM_{2.5}$	$118/tonne eToluene	$3,030/tonne eBenzene	$3,280/tonne e2,4-D	$410/tonne eSO_2	$4/tonne eN

The sources and derivation of the default conceptual environmental costs for each impact are discussed in Appendix B. To illustrate the sensitivity of the composite valuation to the costs assigned to the various impacts, the project team varied the cost for climate impacts from the baseline conceptual default of $40 per tonne cost for carbon dioxide equivalent emissions down to a low of $10 and up to a high of $80. The $10 per tonne cost for carbon dioxide emissions is at the low end of the $10 to $13.50 range of current values for offset credits in Alberta.

At the $10 cost for GHG emissions, aerobic composting has a cost of $2 per tonne, while landfill and WTE have costs of $62 and $57, respectively. At the higher cost of $80, composting has an environmental benefit of $11 per tonne, while the landfill and WTE disposal methods would entail an environmental cost of $72 and $89 per tonne, respectively.

One can also change various management method parameters to check the rankings sensitivity for the three management methods. For example, as discussed for mixed MSW in Morris' 2010 article in the journal *Environmental Science & Technology*, burying tends to beat burning in terms of climate impact, except in the most favorable case scenario of very high energy and heat recovery efficiency for WTE or in the case of very low landfill methane capture. In the case of Red Deer LYW the landfill methane capture rate above which landfill is better for the climate is between 50% and 60% for typical WTE net electrical energy conversion efficiencies between 20% and 25%.

VIII. ORGANICS LCAS LITERATURE LIST

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Appendix A

Adhikari, B.K.; Tremier, A.; Martinez, J.; Barrington, S. Hone and community composting for on-site treatment of urban organic waste: perspective for Europe and Canada. *Waste Management & Research* 2010, 28(11), 1039-1053

As a result of urbanization and economic prosperity, which has accelerated the generation of municipal solid waste (MSW) along with its organic fraction, the management of MSW is a challenge faced by urban centres worldwide, including the European Union (EU) and Canada. Within a concept of waste recovery, the source separation and on-site treatment of urban organic waste (UOW) can resolve some of the major economic issues faced by urban centres along with the environmental and social issues associated with landfilling. In this context and in a comparison with the traditional landfilling practice, this paper examines on-site UOW composting strategies using a combination of centralized composting facilities, community composting centres and home composting. This study consisted of a feasibility and economic study based on available data and waste management costs. The results indicate that on-site treatment of UOW using practices such as home and community composting can lower management costs by 50, 37 and 34% for the rich European countries (annual GDP over US$25000), the poorer European countries (annual GDP under US$25 000), and Canada, respectively. Furthermore, on-site composting can reduce greenhouse gas emissions by 40% for Europe and Canada, despite gas capture practices on landfill sites. However, the performance of home composters and the quality of the compost products are issues to be further addressed for the successful implementation of UOW on-site composting.

Alberta Environment Climate Change Policy Unit, *Specified Gas Emitters Regulation – Quantification Protocol for Aerobic Composting Projects (Version 1.1)* 2008, Edmonton, Alberta

This quantification protocol is written for the aerobic composting project developer. Some familiarity with, or general understanding of, waste management practices including aerobic composting is expected.
The opportunity for generating carbon offsets with this protocol arises from directly avoiding methane emissions from materials anaerobically decomposed in landfills. Specifically, this protocol covers the diversion of organic residues from landfill for biological decomposition to a condition sufficiently stable for nuisance-free storage and for safe use in land application.

Amlinger, F.; Peyr, S.; Cuhls, C. Greenhouse gas emissions from composting and mechanical biological treatment. *Waste Management & Research* 2008, 26(1), 47-60

In order to carry out life-cycle assessments as a basis for far-reaching decisions about environmentally sustainable waste treatment, it is important that the input data be reliable and sound. A comparison of the potential greenhouse gas (GHG) emissions associated with each solid waste treatment option is essential. This paper addresses GHG emissions from controlled composting processes. Some important methodological prerequisites for proper measurement and data interpretation are described, and a common scale and dimension of emission data are proposed so that data from different studies can be compared. A range of emission factors associated with home composting, open windrow composting, encapsulated composting systems with waste air treatment and mechanical biological waste treatment (MBT) are presented from our own investigations as well as from the literature.
The composition of source materials along with process management issues such as aeration, mechanical agitation, moisture control and temperature regime are the most important factors controlling methane (CH4), nitrous oxide (N2O) and ammoniac (NH3) emissions. If ammoniac is not stripped during the initial rotting phase or eliminated by acid scrubber systems, biofiltration of waste air provides only limited GHG mitigation, since additional N2O may be synthesized during the oxidation of NH3, and only a small amount of CH4 degradation occurs in the biofilter. It is estimated that composting contributes very little to national GHG inventories generating only 0.01–0.06% of global emissions. This analysis does not include emissions from preceding or post-treatment activities (such as collection, transport, energy consumption during processing and land spreading), so that for a full emissions account, emissions from these activities would need to be added to an analysis.

Andersen, J.K.; Christensen, T.H.; Scheutz, C. Substitution of peat, fertilizer and manure by compost in hobby gardening: User surveys and case studies. *Waste Management* 2010, 30(12), 2483-2489

Four user surveys were performed at recycle centres (RCs) in the Municipalities of Aarhus and Copenhagen, Denmark, to get general information on compost use and to examine the substitution of peat, fertiliser and manure by compost in hobby gardening. The average driving distance between the users' households and the RCs was found to be 4.3 km and the average amount of compost picked up was estimated at 800 kg per compost user per year. The application layer of the compost varied (between 1 and 50 cm) depending on the type of use. The estimated substitution (given as a fraction of the compost users that substitute peat, fertiliser and manure with compost) was 22% for peat, 12% for fertiliser and 7% for manure (41% in total) from the survey in Aarhus (n = 74). The estimate from the survey in Copenhagen (n = 1832) was 19% for peat, 24% for fertiliser and 15% for manure (58% in total). This is the first time, to the authors' knowledge, that the substitution of peat, fertiliser and manure with compost has been assessed for application in hobby gardening. Six case studies were performed as home visits in addition to the Aarhus surveys. From the user surveys and the case studies it was obvious that the total substitution of peat, fertiliser and manure was not 100%, as is often assumed when assigning environmental credits to compost. It was more likely around 50% and thus there is great potential for improvement. It was indicated that compost was used for a lot of purposes in hobby gardening. Apart from substitution of peat, fertiliser and manure, compost was used to improve soil quality and as a filling material (as a substitute for soil). Benefits from these types of application are, however, difficult to assess and thereby quantify.

Andersen, J.K.; Boldrin, A.; Christensen, T.H.; Scheutz, C. Greenhouse gas emissions from home composting of organic household waste. *Waste Management* 2010, 30(12), 2475-2482

The emission of greenhouse gases (GHGs) is a potential environmental disadvantage of home composting. Because of a lack of reliable GHG emission data, a comprehensive experimental home composting system was set up. The system consisted of six composting units, and a static flux chamber method was used to measure and quantify the GHG emissions for one year composting of organic household waste (OHW). The average OHW input in the six composting units was 2.6–3.5 kg week1 and the temperature inside the composting units was in all cases only a few degrees (2–10 C) higher than the ambient temperature. The emissions of methane (CH4) and nitrous oxide (N2O) were quantified as 0.4–4.2 kg CH4 Mg1 input wet waste (ww) and 0.30–0.55 kg N2OMg1 ww, depending on the mixing frequency. This corresponds to emission factors (EFs) (including only CH4 and N2O emissions) of 100–239 kg CO2-eq. Mg1 ww. Composting units exposed to weekly mixing had the highest EFs, whereas the units with no mixing during the entire year had the lowest emissions. In addition to the higher emission from the frequently mixed units, there was also an instant release of CH4 during mixing which was estimated to 8–12% of the total CH4 emissions. Experiments with higher loads of OHW (up to 20 kg every fortnight) entailed a higher emission and significantly increased overall EFs (in kg substance per Mg1 ww). However, the temperature development did not change significantly. The GHG emissions (in kg CO2-eq. Mg1 ww) from home composting of OHW were found to be in the same order of magnitude as for centralised composting plants.

Andersen, J.K.; Boldrin, A.; Christensen, T.H.; Scheutz, C. Mass balances and life-cycle inventory for a garden waste windrow composting plant (Aarhus, Denmark). *Waste Management & Research* 2010, 28(11), 1010-1020

A comprehensive life-cycle inventory of all consumptions and emissions of environmental relevance was made for the windrow composting plant treating garden waste in Aarhus (Denmark). The flows of materials and substances within the facility were balanced using the mass-balance model STAN. The overall fuel and electricity use at the facility (3.04 L diesel Mg1 wet waste (ww) and 0.2kWh Mg1 ww) was low whereas the emissions of CH4 and N2O from the windrows (2.4 to 0.5 kg CH4–C Mg1ww and 0.06 to 0.03 kg N2O–N Mg1 ww) were relatively high compared to data reported in similar studies. The loss of carbon during the 14-month-long composting was 56%. CH4 made up 2.1% of the C lost. Loss of nitrogen-containing compounds was identified as the most sensible and uncertain parameter and could be relevant for global warming (N2O emissions), acidification (NH3 emissions), and eutrophication (NH3 and NO 3 emissions). The compost produced had a very low content of heavy metals and was suitable for use in gardens and/or agriculture.

Arsova, L.; Themelis, N.J.; Barlaz, M. Digesting the state of AD Technologies. *Waste Management World* 2010, 11(5)

Anaerobic digestion (AD) is one of the oldest biochemical technologies we have, but until the 1970s it was practiced on an industrial scale only at wastewater treatment plants. In the last few decades AD has also been applied to the management of source-separated organic wastes. It is generally considered to be environmentally preferable to landfill because, in addition to conserving land and generating a biogas rich in methane, it produces compost that can be used for soil conditioning.

Anaerobic digestion of source-separated food wastes is a proven technology in Europe and has experienced significant growth during the last 15 years. However, there are only two AD plants in North America, both of them serving the population of Toronto, Canada.

Boldrin, A.; Hartling, K.R.; Laugen, M.; Christensen, T.H. Environmental inventory modeling of the use of compost and peat in growth media preparation. *Resources, Conservation and Recycling* 2009-10, 54(12), 1250-1260

Compost produced from biological treatment of organic waste has a potential for substituting peat in growth media preparation. The life-cycle-inventories (LCIs) of the two alternatives were compared using LCA-modeling (EASEWASTE) considering a 100-year period and a volumetric substitution ratio of 1:1. For the compost alternative, the composting process, growth media use, and offsetting of mineral fertilizers were considered. For the peat alternative, peatland preparation, excavation, transportation, and growth media use were considered. It was assumed that for compost 14% of the initial carbon was left in the soil after 100 years, while all carbon in peat was mineralized. With respect to greenhouse gas emissions, the former is considered a saving, while the later is considered an emission, because peat in a peatland is considered stored biogenic carbon. The leaching during the growth media use was assessed by means of batch leaching tests involving 4 compost samples and 7 peat samples. The compost leached 3–20 times more heavy metals and other compounds than the peat. The life-cycle-assessment showed that compost performs better regarding global warming (savings in the range of 70–150 kg CO2-eq. Mg^{-1}) and nutrient enrichment (savings in the range of 1.7–6.8 kg NO3 Mg^{-1} compost), while peat performs better in some toxic categories, because of the lower content of heavy metals.

Boldrin, A.; Andersen, J.K.; Moller, J.; Christensen, T.H.; Favoino, E. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. *Waste Management & Research* 2009, 27(8), 800-812

Greenhouse gas (GHG) emissions related to composting of organic waste and the use of compost were assessed from a waste management perspective. The GHG accounting for composting includes use of electricity and fuels, emissions of methane and nitrous oxide from the composting process, and savings obtained by the use of the compost. The GHG account depends on waste type and composition (kitchen organics, garden waste), technology type (open systems, closed systems, home composting), the efficiency of off-gas cleaning at enclosed composting systems, and the use of the compost. The latter is an important issue and is related to the long-term binding of carbon in the soil, to related effects in terms of soil improvement and to what the compost substitutes; this could be fertilizer and peat for soil improvement or for growth media production. The overall global warming factor (GWF) for composting therefore varies between significant savings (–900 kg CO2-equivalents tonne–1 wet waste (ww)) and a net load (300 kg CO2-equivalents tonne–1 ww). The major savings are obtained by use of compost as a substitute for peat in the production of growth media. However, it may be difficult for a specific composting plant to document how the compost is used and what it actually substitutes for. Two cases representing various technologies were assessed showing how GHG accounting can be done when specific information and data are available.

Brown, S.; Cotton, M. Changes in soil properties and carbon content following compost application: Results of on-farm sampling. *Compost Science* (in press) 2010

A field survey was conducted to quantify the benefits of applying compost to agricultural soils in California. Soil samples were collected from farm sites with a history of compost use. Soils were analyzed for total organic carbon and nitrogen, Mehlich III extractable nutrients, bulk density, microbial activity (measured as CO2 evolution), water infiltration rate and gravimetric water at 1 bar tension. Across all sites, compost application increased soil organic carbon by 3x in comparison to control soils.

Significant changes were also observed in soil microbial activity (2.23 x control), gravimetric water (1.57 x control), and bulk density (0.87 x control). Nutrient availability in compost amended soils was similar to availability in conventionally managed soils. Infiltration times were significantly reduced in compost amended soils in comparison to control soils. High rates of compost application showed more significant benefits in comparison low rates of compost application and control soils. At lower application rates, compost amended soils were statistically similar to controls for most variables. Increases in water holding capacity were significant in coarser textured soils in comparison to finer textured soils. Results from this sampling confirm results from replicated field trials on benefits associated with compost use in agricultural soils.

Brown, S.; Cotton, M.; Messner, S.; Berry, F.; Norem, D. *Methane avoidance from composting*. Issue paper prepared for Climate Action Reserve 2009

The objective of this issue paper is to reflect and summarize existing research, data, and quantification methodologies related to diverting organic waste from a landfill to a compost facility where it degrades aerobically rather than anaerobically, thus reducing or eliminating methane emissions.

This paper may be used to inform public stakeholder discussions in the development of an actual protocol for quantifying and crediting emission reductions.

Brown, S.; Kurtz, K.; Bary, A.; Cogger, C. Quantifying benefits associated with land application of organic residuals in Washington State. 2010 In review

Organic soil amendments derived from components of municipal solid waste offer the potential to increase soil carbon content while simultaneously improving soil physical properties. However, traditional life cycle assessments of organic residuals include limited consideration of benefits associated with land application. Discussions of sustainable land management and soil carbon sequestration also generally do not consider residuals application in their analysis. This study was conducted to quantify soil carbon storage, nitrogen concentration, available phosphorus and water holding capacity across a range of sites with different histories and management practices in Washington State. Composts or biosolids had been applied to each site either annually at agronomic rates or at a one-time high rate. Site ages ranged from 2 - 18 years. For all but one site sampled, addition of organic amendments resulted in significant increases in soil carbon storage. Rates of carbon storage per dry Mg of amendment ranged from 0.014 (not significant) in a long- term study of turf grass to 0.54 in a commercial organic pear orchard with a long history of compost use. Soils with the lowest carbon levels showed the highest levels of carbon storage (R2 = 0.37, p< 0.001). Excess C stored per ha with use of amendments in comparison with conventionally managed fields ranged from 8 to 72 Mg ha-1. Sites with multiple application rates showed a linear response with increased carbon storage at increased amendment application rates. For sites with data over time, carbon content increased with time or stabilized after an initial period of net mineralization. Significant increases in soil water holding capacity and available P were also observed at several of the sites. Increases in soil total nitrogen concentration were observed at all sites. These results indicate that organic amendments offer a tool to increase soil carbon and nitrogen reserves, available P, and soil water storage. Based on the results of this sampling, land application of organic residuals in Washington State appears to be a sustainable waste management practice as well as land management practice.

Brown, S.; Kruger, C.; Subler, S. Greenhouse gas balance for composting operations. *Journal of Environmental Quality* 2008, 37, 1396-1410

The greenhouse gas (GHG) impact of composting a range of potential feedstocks was evaluated through a review of the existing literature with a focus on methane (CH4) avoidance by composting and GHG emissions during composting. The primary carbon credits associated with composting are through CH4 avoidance when feedstocks are composted instead of landfilled (municipal solid waste and biosolids) or lagooned (animal manures). Methane generation potential is given based on total volatile solids, expected volatile solids destruction, and CH4 generation from lab and field incubations. For example, a facility that composts an equal mixture of manure, newsprint, and food waste could conserve the equivalent of 3.1 Mg CO2 per 1 dry Mg of feedstocks composted if feedstocks were diverted from anaerobic storage lagoons and landfills with no gas collection mechanisms. The composting process is a source of GHG emissions from the use of electricity and fossil fuels and through GHG emissions during composting. Greenhouse gas emissions during composting are highest for high nitrogen materials with high moisture contents. These debits are minimal in comparison to avoidance credits and can be further minimized through the use of higher carbon: nitrogen feedstock mixtures and lower-moisture-content mixtures. Compost end use has the potential to generate carbon credits through avoidance and sequestration of carbon; however, these are highly project specific and need to be quantified on an individual project basis.

Butler, J.; Hooper, P. Down to earth: An illustration of life cycle inventory good practice with reference to the production of soil conditioning compost. *Resources, Conservation and Recycling* 2010, 55(2), 135-147

The need to minimize the environmental impacts of production and consumption are increasingly being recognised by governments, industry and the general public. Biodegradable waste composting is able to make a contribution to this need, not only in reducing the biodegradable waste being landfilled, but also lessening the horticultural industry's and gardeners' reliance on peat based compost, whilst the application of compost to land has the potential to enhance soil and biomass carbon sequestration.

As a result of the consequent interest in the potential environmental benefits accruing from composting, there have been a number of studies attempting to measure the gains from composting the biodegradable fraction of commercial and household waste streams. However, a review of such studies reveal that there is much scope for improvement in defining the product process and in data accuracy, as well as the technical framework employed to construct the life cycle inventory stage. These shortcomings can invalidate life cycle impact assessments, and at worst lead to invalid management and operational decisions based on their findings.

This study addresses the inventory process deficiencies, and issues of data reliability and completeness, contained in much of the published compost production life cycle assessment literature. It provides a comprehensive cradle to grave inventory of the soil conditioning compost produced by a social enterprise company in Manchester, England. Based on the specifics of the system model, it provides the basis for valid comparisons of the environmental benefits of producing soil-conditioning compost from biodegradable municipal waste with other composting and waste management options. Overall energy use has been calculated as 1034 MJ/tonne of compost, equivalent to 633 MJ/tonne for processing the wet feedstock, with the processing inventory stage accounting for 57%.

Cadena, E.; Colon, J.; Sanchez, A.; Font, X.; Artola, A. A methodology to determine gaseous emissions in a composting plant. *Waste Management* 2009, 29(11), 2799-2807

Environmental impacts associated to different waste treatments are of interest in the decision-making process at local, regional and international level. However, all the environmental burdens of an organic waste biological treatment are not always considered. Real data on gaseous emissions released from full-scale composting plants are difficult to obtain. These emissions are related to the composting technology and waste characteristics and therefore, an exhaustive sampling campaign is necessary to obtain representative and reliable data of a single plant. This work proposes a methodology to systematically determine gaseous emissions of a composting plant and presents the results obtained in the application of this methodology to a plant treating source-separated organic fraction of municipal solid waste (OFMSW) for the determination of ammonia and total volatile organic compounds (VOC). Emission factors from the biological treatment process obtained for ammonia and VOC were 3.9 kg Mg OFMSW1 and 0.206 kg Mg OFMSW1 respectively. Emissions associated to energy use and production were also quantified (60.5 kg CO2 Mg OFMSW1 and 0.66 kg VOC Mg OFMSW1). Other relevant parameters such as energy and water consumption and amount of rejected waste were also determined. A new functional unit is presented to relate emission factors to the biodegradation efficiency of the composting process and consists in the reduction of the Respiration Index of the treated material. Using this new functional unit, the atmospheric emissions released from a composting plant are directly related to the plant specific efficiency.

Cadena, E.; Colon, J.; Artola, A.; Sanchez, A.; Font, X. Environmental impact of two aerobic composting technologies using life cycle assessment. *International Journal of Life Cycle Assessment* 2009, 14(5), 401-410

Background, aim, and scope Composting is a viable technology to treat the organic fraction of municipal solid waste (OFMSW) because it stabilizes biodegradable organic matter and contributes to reduce the

quantity of municipal solid waste to be incinerated or land-filled. However, the composting process generates environmental impacts such as atmospheric emissions and resources consumption that should be studied. This work presents the inventory data and the study of the environmental impact of two real composting plants using different technologies, tunnels (CT) and confined windrows (CCW).
Materials and methods Inventory data of the two composting facilities studied were obtained from field measurements and from plant managers. Next, life cycle assessment (LCA) methodology was used to calculate the environmental impacts. Composting facilities were located in Catalonia
(Spain) and were evaluated during 2007. Both studied plants treat source separated organic fraction of municipal solid waste. In both installations the analysis includes environmental impact from fuel, water, and electricity consumption and the main gaseous emissions from the composting process itself (ammonia and volatile organic compounds).
Results and discussion Inventory analysis permitted the calculation of different ratios corresponding to resources consumption or plant performance and process yield with respect to 1 t of OFMSW. Among them, it can be highlighted that in both studied plants total energy consumption necessary to treat the OFMSW and transform it into compost was between 130 and 160 kWh/t OFMSW. Environmental impact was evaluated in terms of global warming potential (around 60 kg CO2/t OFMSW for both plants), acidification potential (7.13 and 3.69 kg SO2 eq/t OFMSW for CT and CCW plant respectively), photochemical oxidation potential (0.1 and 3.11 kg C2H4 eq/t OFMSW for CT and CCW plant, respectively), eutrophication (1.51 and 0.77 kg PO3_ 4 /t OFMSW for CT and CCW plant, respectively), human toxicity (around 15 kg 1,4-DB eq/t OFMSW for both plants) and ozone layer depletion (1.66×10^{-5} and 2.77×10^{-5}kg CFC−11eq/t OFMSW for CT and CCW plant, respectively).
Conclusions This work reflects that the life cycle perspective is a useful tool to analyze a composting process since it permits the comparison among different technologies. According to our results total energy consumption required for composting OFMSW is dependent on the technology used (ranging from 130 to 160 kWh/t OFMSW) as water consumption is (from 0.02 to 0.33 m3 of water/t OFMSW).
Gaseous emissions from the composting process represent the main contribution to eutrophication, acidification and photochemical oxidation potentials, while those contributions related to energy consumption are the principal responsible for global warming.
Recommendations and perspectives This work provides the evaluation of environmental impacts of two composting technologies that can be useful for its application to composting plants with similar characteristics. In addition, this study can also be part of future works to compare composting with other OFMSW treatments from a LCA perspective. Likewise, the results can be used for the elaboration of a greenhouse gasses emissions inventory in Catalonia and Spain.

California Integrated Waste Management Board (CIWMB). ***Life Cycle Assessment and Economic Analysis of Organic Waste Management and Greenhouse Gas Reduction Options*** **2009, prepared for CIWMB by RTI International, R.W. Beck, Sally Brown, Matthew Cotton, Sacramento, CA**

The California Integrated Waste Management Board (hereafter referred to as the Board) estimates that organics comprise approximately 73 percent1 of the State's municipal solid waste (MSW) stream, including food scraps, yard trimmings, wood waste, and mixed paper. This statistic established organics management as a top priority for the Board2. Organic waste is also important in the context of greenhouse gas (GHG) emissions and climate action plans because it creates methane in landfills, which are the largest source of anthropogenic methane emissions in the United States. The State has a number of legislated mandates driving more sustainable waste management that can lead to the reduction of GHG emissions, such as SD 6.1 which mandates the diversion of 15 million tons of organic waste from landfills by the year 2020.
The overall goal of this project is to identify and quantify (to the fullest extent possible) the lifecycle environmental and costs aspects associated with alternatives to manage organic wastes and recyclables currently being disposed of in landfills in California. These alternatives include composting, chipping and grinding, recycling, anaerobic digestion (AD), biomass-to-energy (BTE), and waste-to-energy (WTE). The results and findings from this project are intended to provide data and information to the Board to support the development of recommendations and policies for organic wastes and recyclables management efforts in the coming years.
The study also focused on three specific California regions in an attempt to capture regional variations in cost and environmental attributes. Ultimately, the findings of this project were intended to facilitate the understanding of tradeoffs between different waste management alternatives so that GHG emission

reduction goals can be met in the most cost-effective manner and zero waste achieved. The goal was not to make absolute conclusions about the economic and/or environmental preference of alternatives but rather to better understand the potential relative economic and environmental performance that may result from alternatives to manage organic wastes and recyclable currently disposed of in landfills.

Chen, T-C.; Lin, C-F. Greenhouse gas emissions from waste management practices using life cycle inventory model. *Journal of Hazardous Materials* 2008, 155, 23-31

When exploring the correlation between municipal solid waste management and greenhouse gas emission, the volume and physical composition of the waste matter must be taken into account. Due to differences in local environments and lifestyles the quantity and composition of waste often vary. This leads to differences in waste treatment methods and causes different volumes of greenhouse gases (GHGs), highlighting the need for local research. In this study the Life Cycle Inventory method was used with global warming indicator GHGs as the variables. By quantifying the data and adopting a region-based approach, this created a model of household MSWM in Taipei City, a metropolitan region in Taiwan. To allow analysis and comparison a compensatory system was then added to expand the system boundary. The results of the analysis indicated that out of all the solid waste management sub-models for a function unit, recycling was the most effective method for reducing GHG emissions while using kitchen food waste as swine feeding resulted in the most GHG emissions. As for the impact of waste collection vehicles on emissions, if the efficiency of transportation could be improved and energy consumption reduced, this will help solid waste management to achieve its goal of reducing GHG emissions.

CM Consulting, *Measuring the benefits of composting source separated organics in the Region of Niagara* 2007, Prepared for the Region of Niagara by CM Consulting, December 2007

Assessing the value of various management options for organic waste (leaf & yard, brush and food waste) in the Region of Niagara requires an understanding of the environmental and human health implications at each stage of each option; from collection to processing to end-use applications.

The following report provides the ‘true costs’ or ‘full cost accounting’ associated with the environmental and human health impacts of composting, landfill and energy from waste (EFW) for 47,178 tonnes of organic waste projected to be managed in the Region of Niagara.

More specifically, the ‘true costs’ provided in this study represent the cost of operations off-set by the economic environmental benefit of each option.

This environmental benefit or cost is the sum of the monetized value of various pollutants, like greenhouse gas emissions (eCO2); human health particulates (ePM2.5); human health toxics (eToluene); human health carcinogens (eBenzene); Eutrophication (eN); Acidification (eSO2); and Ecosystems Toxicity (e2,4-D).

The environmental benefit also includes the monetized value of avoided pollutants as a result of finished compost replacing pesticides and synthetic fertilizers. In addition, the environmental benefit includes the avoided pollution associated with substituting natural gas with electricity produced in an EFW facility. Because the pollution of the substituted natural gas is not created, it is therefore considered as “avoided” and an environmental benefit of EFW. Finally, any carbon sequestration (absorption) that occurs in landfill and compost is also considered as an environmental benefit.

Colon, J.; Martinez-Blanco, J.; Gabarrell, X.; Artola, A.; Sanchez, A.; Rieradevall, J.; Font, X. Environmental Assessment of home composting. *Resources, Conservation and Recycling* 2009-10, 54(11), 893-904

In this study the environmental burdens of home composting were determined using the life cycle assessment (LCA) tool. Data used for the LCA study such as gas emissions (CH4, N2O, NH3 and volatile organic compounds (VOCs)), tools and composter characteristics were obtained from an experimental home composting process of leftovers of raw fruits and vegetables (LRFV). Stable compost with a high content of nitrogen and organic matter was obtained. Neither pathogens nor phytotoxic compounds were found in the final compost. In relation to gaseous emissions, only volatile organic compounds (0.32 kg VOC/Mg LRFV) were detected, even though ammonia, methane and nitrous oxide emissions were also measured. Regarding environmental burdens, the composter was the major contributor to the total home composting process impact for the impact categories of abiotic depletion, ozone layer depletion, and cumulative energy demand. Gaseous emissions (based on our own measurements and literature data) caused the greatest contribution to the acidification, eutrophication, global warming and photochemical oxidation potentials.

Damgaard, A.; Riber, C.; Fruergaard, T.; Hulgaard, T.; Christensen, T.H. Life-cycle-assessment of the historical development of air pollution control and energy recovery in waste incineration. *Waste Management* 2010, 30(7), 1244-1250

Incineration of municipal solid waste is a debated waste management technology. In some countries it is the main waste management option whereas in other countries it has been disregarded. The main discussion point on waste incineration is the release of air emissions from the combustion of the waste, but also the energy recovery efficiency has a large importance.

The historical development of air pollution control in waste incineration was studied through lifecycle-assessment modeling of eight different air pollution control technologies. The results showed a drastic reduction in the release of air emissions and consequently a significant reduction in the potential environmental impacts of waste incineration. Improvements of a factor 0.85–174 were obtained in the different impact potentials as technology developed from no emission control at all, to the best available emission control technologies of today (2010).

The importance of efficient energy recovery was studied through seven different combinations of heat and electricity recovery, which were modeled to substitute energy produced from either coal or natural gas. The best air pollution control technology was used at the incinerator. It was found that when substituting coal based energy production total net savings were obtained in both the standard and toxic impact categories. However, if the substituted energy production was based on natural gas, only the most efficient recovery options yielded net savings with respect to the standard impacts. With regards to the toxic impact categories, emissions from the waste incineration process were always larger than those from the avoided energy production based on natural gas. The results shows that the potential environmental impacts from air emissions have decreased drastically during the last 35 years and that these impacts can be partly or fully offset by recovering energy which otherwise should have been produced from fossil fuels like coal or natural gas.

Davidsson, A.; Gruvberger, C.; Christensen, T.H.; Hansen, T.L.; Jansen, J. C. Methane yield in source-sorted organic fraction of municipal solid waste. *Waste Management* 2007, 27(3), 406-414

Treating the source-separated organic fraction of municipal solid waste (SS-OFMSW) by anaerobic digestion is considered by many municipalities in Europe as an environmentally friendly means of treating organic waste and simultaneously producing methane gas. Methane yield can be used as a parameter for evaluation of the many different systems that exist for sorting and pre-treating waste.

Methane yield from the thermophilic pilot scale digestion of 17 types of domestically SS-OFMSW originating from seven full-scale sorting systems was found. The samples were collected during 1 year using worked-out procedures tested statistically to ensure representative samples. Each waste type was identified by its origin and by pre-sorting, collection and pre-treatment methods. In addition to the pilot scale digestion, all samples were examined by chemical analyses and methane potential measurements. A VS-degradation rate of around 80% and a methane yield of 300–400 Nm3 CH4/ton VS in were achieved with a retention time of 15 days, corresponding to 70% of the methane potential.

The different waste samples gave minor variation in chemical composition and thus also in methane yield and methane potential. This indicates that sorting and collection systems in the present study do not significantly affect the amount of methane produced per VS treated.

De Feo, G.; Malvano, C. The use of LCA in selecting the best MSW system. *Waste Management* 2009, 29(6), 1901-1915

This paper focuses on the study of eleven environmental impact categories produced by several municipal solid waste management systems (scenarios) operating on a provincial scale in Southern Italy. In particular, the analysis takes into account 12 management scenarios with 16 management phases for each one. The only difference among ten of the scenarios (separated kerbside collection of all recyclables, glass excepted, composting of putrescibles, RDF pressed bales production and incineration, final landfilling) is the percentage of separated collection varying in the range of 35–80%, while the other two scenarios, for 80% of separate collection, consider different alternatives in the disposal of treatment residues (dry residue sorting and final landfilling or direct disposal in landfill). The potential impacts induced on the environmental components were analysed using the life cycle assessment (LCA) procedure called ''WISARD'' (Waste Integrated System Assessment for Recovery and Disposal). Paper recycling was the phase with the greatest influence on avoided impacts, while the collection logistics of dry residue was the phase with the greatest influence on produced impacts. For six impact categories (renewable and total energy use, water, suspended solids and oxydable matters index, eutrophication and hazardous waste production), for high percentages of separate collection a management system based on recovery and recycling but without incineration would be preferable.

De Gioannis, G.; Muntoni, A.; Cappai, G.; Milia, S. Landfill gas generation after mechanical biological treatment of municipal solid waste: Estimation of gas generation rate constants. *Waste Management* 2009, 29(3), 1026-1034

Mechanical biological treatment (MBT) of residual municipal solid waste (RMSW) was investigated with respect to landfill gas generation. Mechanically treated RMSW was sampled at a full-scale plant and aerobically stabilized for 8 and 15 weeks. Anaerobic tests were performed on the aerobically treated waste (MBTW) in order to estimate the gas generation rate constants (k, y1), the potential gas generation capacity (Lo, Nl/kg) and the amount of gasifiable organic carbon. Experimental results show how MBT allowed for a reduction of the non-methanogenic phase and of the landfill gas generation potential by, respectively, 67% and 83% (8 weeks treatment), 82% and 91% (15 weeks treatment), compared to the raw waste. The amount of gasified organic carbon after 8 weeks and 15 weeks of treatment was equal to 11.01 ± 1.25 kg C/tMBTW and 4.54 ± 0.87 kg C/tMBTW, respectively, that is 81% and 93% less than the amount gasified from the raw waste. The values of gas generation rate constants obtained for MBTW anaerobic degradation (0.0347–0.0803 y1) resemble those usually reported for the slowly and moderately degradable fractions of raw MSW. Simulations performed using a prediction model support the hypothesis that due to the low production rate, gas production from MBTW landfills is well-suited to a passive management strategy.

De La Cruz, F.B.; Barlaz, M.A. Estimation of waste component-specific landfill decay rates using laboratory-scale decomposition data. *Environmental Science & Technology* 2010, 44(12), 4722-4728

The current methane generation model used by the U.S. EPA (Landfill Gas Emissions Model) treats municipal solid waste (MSW) as a homogeneous waste with one decay rate. However, component-specific decay rates are required to evaluate the effects of changes in waste composition on methane generation. Laboratory-scale rate constants,k_{lab}, for the major biodegradable MSW components were used to derive field-scale decay rates (k_{field}) for each waste component using the assumption that the average of the field-scale decay rates for each waste component, weighted by its composition, is equal to the bulk MSW decay rate. For an assumed bulk MSW decay rate of 0.04 yr-1, k_{field} was estimated to be 0.298, 0.171, 0.015, 0.144, 0.033, 0.02, 0.122, and 0.029 yr-1, for grass, leaves, branches, food waste, newsprint, corrugated containers, coated paper, and office paper, respectively. The effect of landfill waste diversion programs on methane production was explored to illustrate the use of component-specific decay rates. One hundred percent diversion of yard waste and food waste reduced the year 20 methane production rate by 45%. When a landfill gas collection schedule was introduced, collectable methane was most influenced by food waste diversion at years 10 and 20 and paper diversion at year 40.

EPA, *Composting (chapter accompanying version 11 of WARM released October 2010)* 2010, Washington, DC: U.S. Environmental Protection Agency

This guidance document describes the development of composting emission factors for EPA's Waste Reduction Model (WARM). Included are estimates of the net greenhouse gas (GHG) emissions from composting of yard trimmings and food scraps, as well as mixed organics.1

EPA, *Organics: Yard Trimmings and Food Scraps (chapter accompanying version 11 of WARM released October 2010)* 2010, Washington, DC: U.S. Environmental Protection Agency

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for yard trimmings and food scraps beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with these two organic material types in the following three materials management options: composting, landfilling and combustion. Exhibit 1 shows the general outline of materials management pathways for these materials in WARM.

EPA, *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks (third edition)* 2006, Washington, DC: U.S. Environmental Protection Agency

In the 21st century, management of municipal solid waste (MSW) continues to be an important environmental challenge facing the United States. In 2003, the United States generated 236.2 million tons1 of MSW, an increase of 15 percent over 1990 generation levels and 168 percent over 1980 levels.2 Climate change is also a serious issue, and the United States is embarking on a number of voluntary actions to reduce the emissions of greenhouse gases (GHGs) that can intensify climate change. By presenting material-specific GHG emission factors for various waste management options, this report examines the interrelationship between MSW management and climate change.

Among the efforts to slow the potential for climate change are measures to reduce emissions of carbon dioxide (CO2) from energy use, decrease emissions of methane (CH4) and other non-carbon-dioxide GHGs, and promote long-term storage of carbon in forests and soil. Management options for MSW provide many opportunities to affect these processes, directly or indirectly. This report integrates information on the GHG implications of various management options for some of the most common materials in MSW. To EPA's knowledge, this work represents the most complete national study on GHG emissions and sinks from solid waste management practices. The report's findings may be used to support a variety of programs and activities, including voluntary reporting of emission reductions from waste management practices.

Eunomia Research & Consulting Ltd. *Meeting Ireland's Waste Targets: The Role of MBT*, 2008, Final report for Greenstar by Eunomia Research & Consulting, Bristol, UK

Ireland currently stands at a critical stage in the development of its waste management infrastructure. The European policy framework presents stiff challenges which the country must meet. To do so, it needs to move quickly.

It is the agenda in respect of residual waste treatment which remains contentious. Incineration has been, for the past decade, the technology of choice in this regard from the perspective of national policy and most of the regional waste management plans.1 Yet, a decade on from the early regional waste management plans, no facility has been built, though planning consents and licences have been granted for some facilities. Recent decisions around the proposed incinerator at Poolbeg have been hotly contested, in the public and the political sphere.

In a previous report, we noted that there might be an alternative approach which could be less contentious, potentially more environmentally beneficial, and possess the useful characteristic of being capable of being constructed quickly. Mechanical biological treatment (MBT) has been, and is being used, in its various guises, across Europe. Such treatments have the potential to form a major part of Ireland's residual waste treatment mix. Certain policy issues are, however, currently holding back widespread uptake and utilisation of these technologies.

This report has set out to shed some light on:

- What 'MBT'-type activity is currently occurring in Ireland?
- Which policies support, or could be adapted to support, MBT in Ireland?
- What might be done to foster the development of MBT in Ireland? and
- What role might MBT play in Ireland in the future, and how would its deployment affect

Ireland's ability to meet key waste management targets and objectives?

Eunomia Research & Consulting Ltd. *Economic Analysis of Options for Managing Biodegradable Municipal Waste* 2002, prepared for the European Commission by Eunomia Research & Consulting, Bristol, UK

ECOTEC Research and Consulting Limited (ECOTEC), in association with Eunomia Research & Consulting, HDRA Consultants Ltd (UK), Zentrum für Rationelle Energieanwendung und Umwelt GmbH (ZREU) (Centre for Rational Use of Energy and Environment Ltd.) (Germany), Scuola Agraria del Parco di Monza (Italy), and LDK Consultants (Greece), has been asked by the European Commission to carry out an Economic Analysis of Options for Managing Biodegradable Municipal Waste. This takes place at a time when many countries, especially those that are heavily dependent upon landfill, are considering options of this nature in the context of the Article 5 targets in the Council Directive on the Landfill of Waste (the Landfill Directive).1

The main objective of the study is to conduct an economic evaluation that considers both private and social welfare costs and benefits, of existing options for managing the biodegradable fraction of municipal solid waste.

Although all management options (anaerobic digestion, composting, landfilling, incineration, etc.) are considered in the study, the main emphasis is on the separate collection and recycling of the biodegradable fraction of MSW. The study focuses on the Member States of the European Union and on the first wave of Accession countries, i.e. the Czech Republic, Poland, Hungary, Estonia, Slovenia and Cyprus.

Favoino, E.; Hogg, D. The potential role of compost in reducing greenhouse gases. *Waste Management & Research* 2008, 26(1), 61-69

The contribution of the agricultural sector to emissions of climate change gases is becoming better understood. At the same time, the potential role of the sector as a means through which to tackle climate change, widely neglected in the past, is becoming more widely acknowledged. The absorption potential of agricultural soils could contribute significantly to constraining growth in greenhouse gas emissions, while also contributing to improvements in soil quality in some areas. In addition to the measures listed above, other benefits of compost application may have some relevance. Some of these measures include replacement of chemical fertilizers (implying avoidance of greenhouse gases related to their production) reduced use of pesticides (avoiding emissions associated with their production), improved tilth and workability (less consumption of fuels). Typically, life-cycle analyses (LCAs) exhibit limitations related to assessing the effects of 'time-limited' carbon sequestration in soils. This has tended to obscure the potentially important effect of composting, in which biogenic carbon is held in soils for a period of time before the carbon is released. The paper seeks to understand these effects and offers comments on the contribution of biological treatments to tackling climate change issues. Key issues include the replacement of fertilizers, reduction of N2O emissions, and peat replacement.

Finnveden, G.; Johansson, J.; Lind, P.; Moberg, A. Life cycle assessment of energy from solid waste – Part 1: General methodology and results. *Journal of Cleaner Production* 2005, 13(3), 213-229

The overall goal of the present study is to evaluate different strategies for treatment of solid waste in Sweden based on a life cycle perspective. Important goals are to identify advantages and disadvantages of different methods for treatment of solid waste, and to identify critical factors in the systems, including the background systems, which may significantly influence the results. Included in the study are landfilling, incineration, recycling, digestion and composting. The waste fractions considered are the combustible and recyclable or compostable fractions of municipal solid waste. The methodology used is life cycle assessment (LCA). The results can be used for policy decisions as well as strategic decisions on waste management systems. A waste hierarchy suggesting the environmental preference of recycling over incineration over landfilling is often put forward and used in waste policy making. LCAs can be used to test the waste hierarchy and identify situations where the hierarchy is not valid. Our results indicate that the waste hierarchy is valid as a rule of thumb. The results also suggest that a policy promoting recycling of paper and plastic materials, preferably combined with policies promoting the use of plastics replacing plastics made from virgin materials, leads to decreased use of total energy and emissions of gases contributing to global warming. If the waste can replace oil or coal as energy sources, and neither biofuels nor natural gas are alternatives, a policy promoting incineration of paper materials may be successful in reducing emissions of greenhouse gases.

Fruergaard, T.; Astrup, T. Optimal utilization of waste-to-energy in an LCA perspective. *Waste Management* 2011, in press

Energy production from two types of municipal solid waste was evaluated using life cycle assessment (LCA): (1) mixed high calorific waste suitable for production of solid recovered fuels (SRF) and (2) source separated organic waste. For SRF, co-combustion was compared with mass burn incineration. For organic waste, anaerobic digestion (AD) was compared with mass burn incineration. In the case of mass burn incineration, incineration with and without energy recovery was modeled. Biogas produced from anaerobic digestion was evaluated for use both as transportation fuel and for heat and power production. All relevant consequences for energy and resource consumptions, emissions to air, water and soil, upstream processes and downstream processes were included in the LCA. Energy substitutions were considered with respect to two different energy systems: a present-day Danish system based on fossil fuels and a potential future system based on 100% renewable energy. It was found that mass burn incineration of SRF with energy recovery provided savings in all impact categories, but co-combustion was better with respect to Global Warming (GW). If all heat from incineration could be utilized, however, the two alternatives were comparable for SRF. For organic waste, mass burn incineration with energy recovery was preferable over anaerobic digestion in most impact categories. Waste composition and flue gas cleaning at co-combustion plants were critical for the environmental performance of SRF treatment, while the impacts related to utilization of the digestate were significant for the outcome of organic waste treatment. The conclusions were robust in a present-day as well as in a future energy system. This indicated that mass burn incineration with efficient energy recovery is a very environmentally competitive solution overall.

Haight, M. Assessing the environmental burdens of anaerobic digestion in comparison to alternative options for managing the biodegradable fraction of municipal solid wastes. *Water Science & Technology* 2005, 52(1-2), 553-559

Biological treatment processes including anaerobic digestion (biogasification) and composting are increasingly being considered by waste management officials and planners as alternatives for managing the mainly organic residues of municipal solid wastes (MSW). The integrated waste management model which is based upon the application of life-cycle analysis was employed to compare the environmental burdens of landfilling, composting and anaerobic digestion of MSW at a mid-sized Canadian community. Energy consumption (or recovery), residue recoveries and emissions to air and water were quantified. Scenario comparisons were analyzed to demonstrate that the environmental burdens associated with anaerobic digestion are reduced in comparison with the alternative options. The major benefit occurs as a result of the electricity produced from burning the biogas and then supplying the ‘green power’ to the local electrical grid.

Ham, R.K.; Komilis, D. *A laboratory study to investigate gaseous emissions and solids decomposition during composting of municipal solid wastes* 2002, report EPA 600/R-02-XX prepared for US Environmental Protection Agency, Washington, DC

A materials flow analysis was performed for composting municipal solid waste (MSW) and specific biodegradable organic components of MSW. This work is part of an overall U.S. Environmental Protection Agency (EPA) project providing cost, energy, and materials flow information on different methods to reduce, recycle, treat, or dispose of MSW. This information will be used by managers to optimize MSW management. Calculating energy and material flows, emissions, and costs associated with different methods and mixes of methods for handling MSW or for different components of MSW will provide basic information to guide decisionmakers.

Composting is aerobic decomposition of a substrate, in this case MSW or components of MSW. The purpose of this work was to quantify and model energy and material flows into a typical compost facility and material flows out of it. This work required laboratory experiments because material flows in particular were not known for general MSW or its components.

The results indicate that MSW (at 25% inorganics) and the three largest decomposable components of MSW (i.e., food wastes, mixed paper, and yard wastes) will lose 47, 66, 35, and 48%, respectively, of their dry weight upon “complete” composting. This will produce 730, 1,340, 560, and 800 kg of carbon dioxide (CO2) per dry U.S. ton of MSW, food wastes, mixed paper, and yard wastes, respectively. Corresponding ammonia releases are 0.42, 49, 2.4, and 5.4 kg per dry ton. Volatile organic compound (VOC) releases were quantified for 12 targeted VOCs, and additional VOCs were found but not quantified. The results are modeled for facilities accepting various combinations of MSW components (or MSW of various compositions).

Hansen, T.L.; Jansen, J.C.; Davidsson, A.; Christensen, T.H. Effects of pre-treatment technologies on quantity and quality of source-sorted municipal organic waste for biogas recovery. *Waste Management & Research* 2007, 27(3), 398-405

Source-sorted municipal organic waste collected from different dwelling types in five Danish cities and pre-treated at three different plants was sampled and characterized several times during one year to investigate the origin of any differences in composition of the pretreated waste introduced by city, pre-treatment technology, dwelling type or annual season.

The investigated pre-treatment technologies were screw press, disc screen and shredder + magnet. The average quantity of pre-treated organic waste (biomass) produced from the incoming waste varied between the investigated pre-treatment technologies: 59%, 66% and

98% wet weight, respectively (41%, 34% and 2% reject, respectively). The pre-treatment technologies showed differences with respect to distribution of the chemical components in the waste between the biomass and the rejected material (reject), especially for dry matter, ash, collection bag material (plastic or paper) and easily degradable organic matter. Furthermore, the particle size of the biomass was related to the pre-treatment technology. The content of plastic in the biomass depended both on the actual collection bag material used in the system and the pre-treatment technology. The sampled reject consisted mostly of organic matter. For cities using plastic bags for the source-separated organic waste, the expected content of plastic in the reject was up to 10% wet weight (in some cases up to 20%).

Batch tests for methane potential of the biomass samples showed only minor variations caused by the factors city, pre-treatment technology, dwelling type and season when based on the VS content of the waste (overall average 459 STP m3/t VS). The amount of methane generated from 1 t of collected waste was therefore mainly determined by the efficiency of the chosen pre-treatment technology described by the mass distribution of the incoming waste between biomass and reject.

Hansen, T.L.; Bhander, G.S.; Christensen, T.H.; Brun, S.; Jensen, L.S. Life cycle modeling of environmental impacts of processed organic municipal solid waste on agricultural land (EASEWASTE). *Waste Management & Research* 2006, 24(2), 153-166

A model capable of quantifying the potential environmental impacts of agricultural application of composted or anaerobically digested source-separated organic municipal solid waste (MSW) is presented. In addition to the direct impacts, the model accounts for savings by avoiding the production and use of commercial fertilizers. The model is part of a larger model, Environmental Assessment of Solid Waste Systems and Technology (EASEWASTE), developed as a decision support model, focusing on assessment of alternative waste management options. The environmental impacts of the land application of processed organic waste are quantified by emission coefficients referring to the composition of the processed waste and related to specific crop rotation as well as soil type. The model contains several default parameters based on literature data, field experiments and modeling by the agro-ecosystem model, Daisy. All data can be modified by the user allowing application of the model to other situations. A case study including four scenarios was performed to illustrate the use of the model. One tonne of nitrogen in composted and anaerobically digested MSW was applied as fertilizer to loamy and sandy soil at a plant farm in western Denmark. Application of the processed organic waste mainly affected the environmental impact categories global warming (0.4–0.7 PE), acidification (–0.06 (saving)–1.6 PE), nutrient enrichment (–1.0 (saving)–3.1 PE), and toxicity. The main contributors to these categories were nitrous oxide formation (global warming), ammonia volatilization (acidification and nutrient enrichment), nitrate losses (nutrient enrichment and groundwater contamination), and heavy metal input to soil (toxicity potentials). The local agricultural conditions as well as the composition of the processed MSW showed large influence on the environmental impacts. A range of benefits, mainly related to improved soil quality from long-term application of the processed organic waste, could not be generally quantified with respect to the chosen life cycle assessment impact categories and were therefore not included in the model. These effects should be considered in conjunction with the results of the life cycle assessment.

Hellweg, S.; Hofstetter, T.B.; Hungerbuhler, K. Modeling waste incineration for life-cycle inventory analysis in Switzerland. ***Environmental Modeling and Assessment*** **2001, 6(4), 219-235**

This paper proposes a mathematical model for life-cycle inventory analysis (LCI) of waste incineration in Switzerland. In order to model conventional and new incineration technologies adequately, fundamental aspects of the different technologies relevant for the LCI are discussed. The environmental impact of these technologies strongly depends on the assessment of the long-term emissions of the solid incineration residues and is therefore related to value based decisions about the time horizon considered. The article illustrates that the choice of the landfill model has a significant influence on the results of life-cycle assessment of waste incineration.

Hubbe, M.A.; Nazhad, M.; Sanchez, C. Composting as a way to convert cellulosic biomass and organic waste into high-value soil amendments: A review. ***BioResources*** **2010, 5(4), 2808-2854**

Plant-derived cellulosic materials play a critical role when organic wastes are composted to produce a beneficial amendment for topsoil. This review article considers publications dealing with the science of composting, emphasizing ways in which the cellulosic and lignin components of the composted material influence both the process and the product. Cellulose has been described as a main source of energy to drive the biological transformations and the consequent temperature rise and chemical changes that are associated with composting. Lignin can be viewed as a main starting material for the formation of humus, the recalcitrant organic matter that provides the water-holding, ion exchange, and bulking capabilities that can contribute greatly to soil health and productivity. Lignocellulosic materials also contribute to air permeability, bulking, and water retention during the composting process. Critical variables for successful composting include the ratio of carbon to nitrogen, the nature of the cellulosic component, particle size, bed size and format, moisture, pH, aeration, temperature, and time. Composting can help to address solid waste problems and provides a sustainable way to enhance soil fertility.

ICF Consulting, ***Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions: MEMO: Updated Environment Canada Waste Management and Greenhouse Gas Emission Spreadsheet Model,*** **2008, prepared for Environment Canada and Natural resources Canada by ICF Consulting, Toronto, ON**

This memorandum presents a brief summary of the changes made to update and improve upon the waste management and greenhouse gas (GHG) emission spreadsheet model, originally created by ICF for Environment Canada in 2005. The overall objective of this effort was to provide a simplified downloadable Excel model that strikes a balance between versatility and complexity on one hand, and user-friendliness on the other.

ICF Consulting, ***Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions: 2005 Update*** **2005, prepared for Environment Canada and Natural resources Canada by ICF Consulting, Toronto, ON**

This report represents the culmination of a series of projects to develop and refine life-cycle GHG emission factors for specific materials commonly occurring in the Canadian residential and IC&I waste stream. The original report, “Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions” (ICF 2001) described the net GHG emissions for selected materials, across a partial life cycle, ending with various waste management fates. This report – the “2005 Update” – presents the efforts of previous work and results of research undertaken more recently. The most recent research has included the addition of several materials that are common in the residential and IC&I waste streams and where the potential of alternative waste management options are of interest to Environment Canada and Natural Resources Canada (NRCan): electronics, white goods, copper wire, and tires. In addition, this report reflects efforts to improve the modeling of paper recycling by simulating open loop recycling – i.e., where the second generation products differ from the product being recycled.

The emission factors provided in this report also reflect the use of more recent data to calculate emissions from electricity use.

Much of the life-cycle methodology and some of the data employed in this project, and some of the passages in this report, are drawn directly from research performed for the U.S. Environmental Protection Agency, Office of Solid Waste (EPA 2002). This work, conducted since 1993 by ICF Consulting and others, has led to development of GHG emission factors for recycling, composting, combustion, and landfilling, focuses on U.S. conditions. The Canadian emission factors build and expand on this work by (1) utilizing Canadian data wherever possible, (2) including anaerobic digestion (AD) among the waste management options, (3) including several new material types not yet investigated in the United States (e.g., electronics, white goods), (4) disaggregating upstream energy use by life-cycle stage, and (5) characterizing provincial electricity generation fuel mixtures to more accurately reflect the geographic distribution of manufacturing for each of the materials.

ICF Consulting, *Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions* 2001, prepared for Environment Canada by ICF Consulting, Torrie-Smith Associates and Enviros-RIS, Toronto, ON

As policy makers seek to reduce greenhouse gas (GHG) emissions, many in Canada and elsewhere have found that mitigation opportunities related to waste management are both significant and cost effective. Several analyses at the local and national scales have suggested that potential reductions are on the same scale as energy efficiency and electricity repowering. To better evaluate these opportunities, emission factors are needed for key materials and waste management techniques.

This report describes the development of emission factors for GHG emissions and sinks for a set of specific materials commonly occurring in the Canadian municipal waste stream. Most of the effort in this project has been devoted to developing a spreadsheet model to produce these emission factors. This report is intended to meet the following objectives:

1. Present the methodological framework used to estimate life-cycle GHG impacts of waste management in Canada; 2. Describe the data and assumptions used for each waste management type; and 3. Identify limitations and areas for further research.

In keeping with the priorities in the project, we have intended the documentation to be relatively brief and to address only the most important elements of the project. We refer the reader to the spreadsheet model for details on the calculations and data elements used in the emission factors.

Much of the methodology and some of the data employed in this project, and many of the passages in this report, are drawn directly from research performed for the U.S. Environmental Protection Agency,

Office of Solid Waste.1 This work, conducted since 1993 by ICF Consulting and others, has led to development of GHG emission factors for source reduction, recycling, composting, combustion, and landfilling, and focuses on U.S. conditions. The current project builds and expands on this work by including anaerobic digestion and using data on Canadian conditions (e.g., energy intensity, fuel mix) wherever possible within the time and resource constraints of the project. The data sources, assumptions and methodology are described in the remainder of this report.

Jansen, J.C.; Spliid, H.; Hansen, T.L.; Svard, A; Christensen, T.H. Assessment of sampling and chemical analysis of source-separated organic household waste. *Waste Management* 2004, 24, 541-549

The quality of the waste sampling procedure and chemical analysis was evaluated in a research program on characterization of organic waste obtained after disc screening of source-separated organic household waste. The sampling procedures focused on a truckload of waste and involved several steps of subsampling including shredding, mixing, blending, high-speed-blending, drying and milling prior to analysis of the organic waste with respect to ash content, crude fibers, crude fat, crude protein, sugar, starch, enzyme-digestible organic matter, P, N, C, H, S and calorific value. The statistical evaluation of the procedures involved 10 samples of the same truckload of waste obtained by splitting the sample at each level in the procedure according to a staggered, incomplete nested statistical design. Furthermore, one sample was analysed six times over a period of approximately one year. The statistical evaluation showed that no single step in the sampling procedure contributed with excessive variance and that the variance caused by the sampling procedure was approximately the same as the variance in the chemical analysis observed over a year. The variance varied with the analytical parameter but for most parameters the uncertainty was satisfactorily low (of the order of 3–10% expressed as the relative standard deviation, which is considered to be satisfactory for waste characterization).

Komilis, D.P. A kinetic analysis of solid waste composting at optimal conditions. *Waste Management* 2006, 26(1), 82-91

Six municipal solid waste (MSW) and yard waste components (food waste, mixed paper, yard waste, leaves, branches, grass clippings) were aerobically decomposed to measure the extent of decomposition under near optimal conditions. Decomposition was characterized by at least two principal stages, for most components, as was indicated by the carbon dioxide production rates. An aerobic biodegradation conceptual model is presented here based on the principle that solids hydrolysis is the rate-limiting step during solid waste composting. The mineralizable solid carbon of each solid waste component was assumed to comprise the readily, the moderately and the slowly (or refractory) hydrolysable carbons, each hydrolyzing at different rates to aqueous (water soluble) carbon. Aqueous carbon mineralizes to CO2 at rapid rates that are not rate-limiting to the process. Solids hydrolysis rate constants were calculated after fitting the experimentally determined carbon dioxide production rate data to model results. Hydrolysis rates for the readily hydrolysable carbon in all components ranged from approximately 0.06 to 0.1 d1; hydrolysis rates for the moderately hydrolysable carbon ranged from 0.005 to 0.06 d1. Leaves, branches and grass clippings did not have a readily hydrolysable carbon fraction, whilst the leaves and branches had the largest slowly hydrolysable carbon fractions (70%, 82%, respectively, of the total solid organic carbon). Grass and yard waste did not contain slowly hydrolysable carbon fractions. Food waste had the largest readily hydrolysable carbon fraction and produced the highest amount of CO2 among all substrates. Moderately hydrolysable solid carbon fractions ranged from 16% to 90% of the total solid organic carbon for all substrates used.

Komilis, D.P.; Ham, R.K. Carbon dioxide and ammonia emissions during composting of mixed paper, yard waste and food waste. *Waste Management* 2006, 26(1), 62-70

The objective of the work was to provide a method to predict CO2 and NH3 yields during composting of the biodegradable fraction of municipal solid wastes (MSW). The compostable portion of MSW was simulated using three principal biodegradable components, namely mixed paper wastes, yard wastes and food wastes. Twelve laboratory runs were carried out at thermophilic temperatures based on the principles of mixture experimental and full factorial designs. Seeded mixed paper (MXP), seeded yard waste (YW) and seeded food waste (FW), each composted individually, produced 150, 220 and 370 g CO2–C, and 2.0, 4.4 and 34 g NH3–N per dry kg of initial substrate, respectively. Several experimental runs were also carried out with different mixtures of these three substrates. The effect of seeding was insignificant during composting of food wastes and yard wastes, while seeding was necessary for composting of mixed paper. Polynomial equations were developed to predict CO2 and NH3 (in amounts of mass per dry kg of MSW) from mixtures of MSW. No interactions among components were found to be significant when predicting CO2 yields, while the interaction of food wastes and mixed paper was found to be significant when predicting NH3 yields.

Komilis, D.P.; Ham, R.K. Life-cycle inventory of municipal solid waste and yard waste windrow composting in the United States. *Journal of Environmental Engineering* 2004, 130(11), 1390-1400

This paper presents a life-cycle inventory (LCI) for solid waste composting. Three LCIs were developed for two typical municipal solid waste (MSW) composting facilities (MSWCFs) and one typical yard waste (YW) composting facility (YWCF). Municipal solid waste was assumed to comprise three organic components, food wastes, yard wastes, and mixed paper, as well as various inorganic components. Total costs, combined precombustion, and combustion energy requirements and 29 selected material flows—also referred to as LCI coefficients—were calculated by accounting for both the processes involved in originally producing, refining and transporting a material used in the facility as well as consumption during normal facility operation. Total costs ranged from $15/ t to $50/ t and energy requirements from 29 kw h/ t to 167 kw h/ t for a YWCF and a high quality MSW composting facility, respectively. More than 90% of the overall CO2 emissions in all facilities were due to the biological decomposition of the organic substrate, while the rest was due to fossil fuel combustion.

Komilis, D.P.; Ham, R.K. *Life-cycle inventory and cost model for mixed municipal and yard waste composting* 2000, report EPA/R-99/XXXX prepared for US Environmental Protection Agency, Washington, DC

Life cycle inventories (LCIs) are used to evaluate overall materials and energy flows of processes or systems. EPA is conducting research to evaluate the cost and environmental burdens of different municipal solid waste (MSW) management systems, based on the development of models for each of the processes that constitute the system (EPA, 1999). This work's objective is to develop a model to estimate cost, energy and material requirements, and environmental releases for mixed MSW and yard waste (YW) compost operations.

MSW components studied include branches, leaves, grass, food, waste, and newsprint. Thirty-nine model coefficients, including total cost, total energy, air emissions, waterborne effluents, and solid wastes were tracked and ultimately expressed on a per unit wet mass basis of a mixture of MSW or YW entering an MSW or YW composting facility. The boundary of the model includes the composting facility as well as application of the compost to land.

Using "typical" composting facility designs, the predicted total cost is $16/ton for a yard waste composting facility (YWCF), $28/ton for a low-quality MSW compost facility (LQCF), and $49/ton for a high-quality MSW compost facility (HQCF), all 1998 dollars. Costs are comparable to actual values of composting facilities in the United States. Total energy requirements, including precombustion and combustion energies, are 102,000, 330,000, and 570,000 Btu/ton for the YWCF, LQCF, and HQCF, respectively.

More than 90 percent of the total emitted CO_2 is due to solid waste decomposition with the rest being emitted due to fossil fuel combustion and precombustion for all facilities. For an HQCF, approximately 35 percent of the total energy requirements is due to diesel fuel combustion, 58 percent to electricity generation, and 7 percent to diesel fuel manufacturing and delivery processes.

The model cost and energy predictions are sensitive to the compost retention time and odor-control design elements, because each factor accounts for a large fraction of the total capital costs of MSW composting facilities. Labor costs, electricity, and diesel costs account for 70, 16.6, and 8 percent of total operating costs.

Kranert, M.; Gottschall, R.; Bruns, C.; Hafner, G. Energy or compost from green waste? – A CO_2-based assessment. *Waste Management* 2010, 30(4), 697-701

The emission of greenhouse gases (GHGs) is a potential environmental disadvantage of home composting. Because of a lack of reliable GHG emission data, a comprehensive experimental home composting system was set up. The system consisted of six composting units, and a static flux chamber method was used to measure and quantify the GHG emissions for one year composting of organic household waste (OHW). The average OHW input in the six composting units was 2.6–3.5 kg week 1 and the temperature inside the composting units was in all cases only a few degrees (2–10 C) higher than the ambient temperature. The emissions of methane (CH_4) and nitrous oxide (N_2O) were quantified as 0.4–4.2 kg CH_4 Mg 1 input wet waste (ww) and 0.30–0.55 kg N_2OMg 1 ww, depending on the mixing frequency. This corresponds to emission factors (EFs) (including only CH_4 and N_2O emissions) of 100–239 kg CO_2-eq. Mg 1 ww. Composting units exposed to weekly mixing had the highest EFs, whereas the units with no mixing during the entire year had the lowest emissions. In addition to the higher emission from the frequently mixed units, there was also an instant release of CH_4 during mixing which was estimated to 8–12% of the total CH_4 emissions. Experiments with higher loads of OHW (up to 20 kg every fortnight) entailed a higher emission and significantly increased overall EFs (in kg substance per Mg 1 ww). However, the temperature development did not change significantly. The GHG emissions (in kg CO_2-eq. Mg 1 ww) from home composting of OHW were found to be in the same order of magnitude as for centralised composting plants.

Kranert, M.; Hafner, G.; Gottschall, R.; Bruns, C. Comparison of the energy recovery and usage of compost from green waste: What is the impact on primary resources? *Compost and digestate: sustainability, benefits, impacts for the environment and for plant production* 2008, Proceedings of the international congress CODIS 2008, Research Institute of Organic Agriculture FiBL, Solothurn, Switzerland, February 2008.

Besides the energy recovery, a positive influence on greenhouse gases emissions can be achieved through material recovery and use of green waste – especially as compost and as turf-substitute –

although this procedure is currently not supported in Germany. A direct comparison of the two alternatives is not yet available in the current scientific literature. Aim of the research project was to create a data base containing all relevant data about green waste and its products, amongst others soil conditioner, substitute for fertilizer, turf, fuel from biomass etc., with particular regard to carbon dioxide. A comparative balancing of different technical plants shows that the use of compost from green waste as a substitute for turf can save the same amount of CO2 as the energy recovery of this green waste. The range is between 130 kg up to 1190 kg CO2-saving per Mg of green waste. In this respect both possibilities seem therefore equal. The research project, already examined by the Universität Stuttgart, in cooperation with Humus and soil cantor (HEKO), Neu-Eichenberg is financed by the EdDE (Entsorgungsverband der Deutschen Entsorgungswirtschaft).

Levis, J.W.; Barlaz, M.A.; Themelis, N.J.; Ulloa, P. Assessment of the state of food waste treatment in the United States and Canada. *Waste Management* 2010, 30(8-9), 1486-1494

Currently in the US, over 97% of food waste is estimated to be buried in landfills. There is nonetheless interest in strategies to divert this waste from landfills as evidenced by a number of programs and policies at the local and state levels, including collection programs for source separated organic wastes (SSO). The objective of this study was to characterize the state-of-the-practice of food waste treatment alternatives in the US and Canada. Site visits were conducted to aerobic composting and two anaerobic digestion facilities, in addition to meetings with officials that are responsible for program implementation and financing. The technology to produce useful products from either aerobic or anaerobic treatment of SSO is in place. However, there are a number of implementation issues that must be addressed, principally project economics and feedstock purity. Project economics varied by region based on landfill disposal fees. Feedstock purity can be obtained by enforcement of contaminant standards and/or manual or mechanical sorting of the feedstock prior to and after treatment. Future SSO diversion will be governed by economics and policy incentives, including landfill organics bans and climate change mitigation policies.

Llamsanguan, C.; Gheewala, S.H. Environmental assessment of energy production from municipal solid waste incineration. *International Journal of Life Cycle Assessment* 2007, 12(7), 537-543

Background, Aims and Scope. During the combustion of municipal solid waste (MSW), energy is produced which can be utilized to generate electricity. However, electricity production from incineration has to be evaluated from the point view of the environmental performance.
In this study, environmental impacts of electricity production from waste incineration plant in Thailand are compared with those from Thai conventional power plants.
Methods. The evaluation is based on a life cycle perspective using life cycle assessment (LCA) as the evaluation tool. Since MSW incineration provides two services, viz., waste management and electricity production, the conventional power production system is expanded to include landfilling without energy recovery, which is the most commonly used waste management system in Thailand, to provide the equivalent function of waste management.
Results. The study shows that the incineration performs better than conventional power plants vis-à-vis global warming and photochemical ozone formation, but not for acidification and nutrient enrichment.
Discussion. There are some aspects which may influence this result.
If landfilling with gas collection and flaring systems is included in the analysis along with conventional power production instead of landfilling without energy recovery, the expanded system could become more favorable than the incineration in the global warming point of view. In addition, if the installation of deNOx process is employed in the MSW incineration process, nitrogen dioxide can be reduced with a consequent reduction of acidification and nutrient enrichment potentials. However, the conventional power plants still have lower acidification and nutrient enrichment potentials.
Conclusions. The study shows that incineration could not play the major role for electricity production, but in addition to being a waste management option, could be considered as a complement to conventional power production. To promote incineration as a benign waste management option, appropriate deNOx and dioxin removal processes should be provided. Separation of high moisture content waste fractions from the waste to be incinerated and improvement of the operation efficiency of the incineration plant must be considered to improve the environmental performance of MSW incineration.

Recommendations. This study provides an overall picture and impacts, and hence, can support a decision-making process for implementation of MSW incineration. The results obtained in this study could provide valuable information to implement incineration. But it should be noted that the results show the characteristics only from some viewpoints.
Outlook. Further analysis is required to evaluate the electricity production of the incineration plant from other environmental aspects such as toxicity and land-use.

Lou, X.F.; Nair, J. The impact of landfilling and composting on greenhouse gas emissions – A review. *Bioresource Technology* 2009, 100(16), 3792-3798
Municipal solid waste is a significant contributor to greenhouse gas emissions through decomposition and life-cycle activities processes. The majority of these emissions are a result of landfilling, which remains the primary waste disposal strategy internationally. As a result, countries have been incorporating alternative forms of waste management strategies such as energy recovery from landfill gas capture, aerobic landfilling (aerox landfills), pre-composting of waste prior to landfilling, landfill capping and composting of the organic fraction of municipal solid waste. As the changing global climate has been one of the major environmental challenges facing the world today, there is an increasing need to understand the impact of waste management on greenhouse gas emissions. This review paper serves to provide an overview on the impact of landfilling (and its various alternatives) and composting on greenhouse gas emissions taking into account streamlined life cycle activities and the decomposition process. The review suggests greenhouse gas emissions from waste decomposition are considerably higher for landfills than composting. However, mixed results were found for greenhouse gas emissions for landfill and composting operational activities. Nonetheless, in general, net greenhouse gas emissions for landfills tend to be higher than that for composting facilities.

Lundie, S.; Peters, G.M. Life cycle assessment of food waste management options. *Journal of Cleaner Production* 2005, 13(3), 275-286
This environmental assessment of alternative means for managing food waste is based on the life cycle assessment (LCA) methodology. It covers the service provided by a household in-sink food waste processor (FWP) unit, and alternatives to it. The three alternatives considered are home composting, landfilling food waste with municipal waste (‘‘codisposal’’) and centralised composting of green (food and garden) waste.
The functional unit is defined as management of the food waste produced by a Sydney household in one year. The environmental assessment includes eight environmental indicators and impact categories. This LCA study identifies an environmentally preferable option as well as the key environmental issues. If operated aerobically, home composting has the least environmental impact in all impact categories. The environmental performance of the codisposal option is relatively good, except with respect to climate change and eutrophication potential. The FWP performed well in terms of energy usage, climate change and acidification potentials, although it makes a large contribution to eutrophication and toxicity potentials. Demonstration of the relatively high water consumption of the FWP is an important outcome of this LCA study, as Australia is the driest inhabited continent on earth. Compared with the other three options, centralised composting has a relatively poor environmental performance due to the energy-intense waste collection activities it requires. Implementing a separate collection and transportation system for organic waste results in relatively high environmental impacts due to the frequency of collections and the small quantities of green waste collected per household. Compared with European cities, significantly larger distances have to be travelled in Sydney, differentiating this LCA from previous work.
Non-recurrent impacts of the FWP are identified as causing large contributions to the overall result for this waste management option due to the types of materials used and the low operational capacities of the FWP. Finally, although home composting is clearly the best option in terms of the categories examined in this LCA, there is an important caveat to this result. If operated without due care, home composting loses its allure due to the high greenhouse gas emissions consequent to anaerobic methanogenesis. Although home composting has the capacity to be the best food waste management option, it can also perform worst in relation to a subject in which Australia is already at the bottom of its class.

Manfredi, S.; Tonini, D.; Christensen, T.H. Contribution of individual waste fractions to the environmental impacts from landfilling of municipal solid waste. *Waste Management* 2010, 30 (3), 433-440

A number of LCA-based studies have reported on the environmental performance of landfilling of mixed waste, but little is known about the relative contributions of individual waste fractions to the overall impact potentials estimated for the mixed waste. In this paper, an empirical model has been used to estimate the emissions to the environment from landfilling of individual waste fractions. By means of the LCA-model EASEWASTE, the emissions estimated have been used to quantify how much of the overall impact potential for each impact category is to be attributed to the individual waste fractions. Impact potentials are estimated for 1 tonne of mixed waste disposed of in a conventional landfill with bottom liner, leachate collection and treatment and gas collection and utilization for electricity generation. All the environmental aspects are accounted for 100 years after disposal and several impact categories have been considered, including standard categories, toxicity-related categories and groundwater contamination.

Amongst the standard and toxicity-related categories, the highest potential impact is estimated for human toxicity via soil (HTs; 12 mPE/tonne). This is mostly caused by leaching of heavy metals from ashes (e.g. residues from roads cleaning and vacuum cleaning bags), batteries, paper and metals. On the other hand, substantial net environmental savings are estimated for the categories Global Warming (GW; 31 mPE/tonne) and Eco-Toxicity in water chronic (ETwc; 53 mPE/tonne). These savings are mostly determined by the waste fractions characterized by a high content of biogenic carbon (paper, organics, other combustible waste). These savings are due to emissions from energy generation avoided by landfill gas utilization, and by the storage of biogenic carbon in the landfill due to incomplete waste degradation.

Martinez-Blanco, J.; Colon, J.; Gabarrell, X.; Font, X.; Sanchez, A., Artola, A.; Rieradevall, J. The use of life cycle assessment for the comparison of biowaste composting at home and full scale. *Waste Management* 2010, 30 (6), 983-994

Six municipal solid waste (MSW) and yard waste components (food waste, mixed paper, yard waste, leaves, branches, grass clippings) were aerobically decomposed to measure the extent of decomposition under near optimal conditions. Decomposition was characterized by at least two principal stages, for most components, as was indicated by the carbon dioxide production rates. An aerobic biodegradation conceptual model is presented here based on the principle that solids hydrolysis is the rate-limiting step during solid waste composting. The mineralizable solid carbon of each solid waste component was assumed to comprise the readily, the moderately and the slowly (or refractory) hydrolysable carbons, each hydrolyzing at different rates to aqueous (water soluble) carbon. Aqueous carbon mineralizes to CO2 at rapid rates that are not rate-limiting to the process. Solids hydrolysis rate constants were calculated after fitting the experimentally determined carbon dioxide production rate data to model results. Hydrolysis rates for the readily hydrolysable carbon in all components ranged from approximately 0.06 to 0.1 d1; hydrolysis rates for the moderately hydrolysable carbon ranged from 0.005 to 0.06 d1. Leaves, branches and grass clippings did not have a readily hydrolysable carbon fraction, whilst the leaves and branches had the largest slowly hydrolysable carbon fractions (70%, 82%, respectively, of the total solid organic carbon). Grass and yard waste did not contain slowly hydrolysable carbon fractions. Food waste had the largest readily hydrolysable carbon fraction and produced the highest amount of CO2 among all substrates. Moderately hydrolysable solid carbon fractions ranged from 16% to 90% of the total solid organic carbon for all substrates used.

Martinez-Blanco, J.; Munoz, P.; Anton, A.; Rieradevall, J. Life cycle assessment of compost from municipal organic waste for fertilization of tomato crops. *Resources, Conservation and Recycling* 2008-09, 53(6), 340-351

Several authors have assessed the positive repercussions of compost application in soil and the benefits of composting process, although most previous works focused only on a specific aspect of the whole life cycle of compost. The aim of this paper was to determine the environmental impacts associated to the use of compost, from the collection of organic municipal solid waste to its application to tomato crops, and to compare these results with mineral fertilizer application, using the environmental tool of life cycle assessment. Three fertilizing systems were defined, arising from the dosages of mineral and organic fertilizers applied. The environmental performance of the pilot fields and the industrial composting were based on experimental measured data. The use of compost in horticulture demonstrated to be a treatment with fewer impacts than mineral fertilizer, if the avoided loads were considered, although compost production was a critical stage which needs to be optimised. No differences were observed in terms of agricultural production and quality.

Moberg, A.; Finnveden, G.; Johansson, J.; Lind, P. Life cycle assessment of energy from solid waste – Part 2: Landfilling compared to other treatment methods. *Journal of Cleaner Production* 2005, 13(3), 231-240

In the present paper, the validity of the waste hierarchy for treatment of solid waste is tested. This is done by using the tool life cycle assessment on recycling, incineration with heat recovery and landfilling of recyclable waste for Swedish conditions. A waste hierarchy suggesting the environmental preference of recycling over incineration over landfilling is found to be valid as a rule of thumb. There are however assumptions and value choices that can be made that make landfilling more preferable. This is the case for some waste fractions and for some of the environmental impacts studied when only a limited time period is considered. When transportation of waste by passenger car from the households is assumed for the other treatment options but not for landfilling, landfilling also gains in preference in some cases. The paper concludes that assumptions made including value choices with ethical aspects are of importance when ranking waste treatment options. Uncertainties related to the assessment of toxicological impacts can also influence the conclusions.

Mohareb, A.K.; Warith, M.A.; Diaz, R. Modeling greenhouse gas emissions for municipal solid waste management strategies in Ottawa, Ontario, Canada. *Resources, Conservation and Recycling* 2008, 52(11), 1241-1251

Human-induced climate change, through the emission of greenhouse gases, may result in a significant negative impact on Earth. Canada is one of the largest per capita emitters of greenhouse gas, generating 720 megatonnes (Mt) carbon dioxide equivalents (CO2e), or per capita emissions of 23.2 t CO2e. The solid waste sector in Canada was directly responsible for 25Mt CO2e in 2001, of which 23Mt CO2e were produced by landfill gas (LFG). A modeling exercise was undertaken to determine greenhouse gas (GHG) emissions from the waste sector using the waste disposal, recycling, and composting data from Ottawa, Ontario, Canada for the year 2003, as well as the results of an audit of residential units performed in the same year. This evaluation determined that, among the options examined, waste incineration, further source separation of recyclables, and anaerobic digestion of an organic wastes have the greatest benefits for reducing GHG emissions in the City of Ottawa's waste sector. Challenges surrounding the installation of incineration facilities in Canada suggest that improved diversion of recyclable materials and anaerobic digestion of organic materials are the optimal options for the City of Ottawa to pursue.

Moller, J.; Boldrin, A.; Christensen, T.H. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. *Waste Management & Research* 2009, 27(8), 813-824

Anaerobic digestion (AD) of source-separated municipal solid waste (MSW) and use of the digestate is presented from a global warming (GW) point of view by providing ranges of greenhouse gas (GHG) emissions that are useful for calculation of global warming factors (GWFs), i.e. the contribution to GW measured in CO2-equivalents per tonne of wet waste. The GHG accounting was done by distinguishing between direct contributions at the AD facility and indirect upstream or downstream contributions. GHG accounting for a generic AD facility with either biogas utilization at the facility or upgrading of the gas for vehicle fuel resulted in a GWF from –375 (a saving) to 111 (a load) kg CO2-eq. tonne–1 wet waste. In both cases the digestate was used for fertilizer substitution. This large range was a result of the variation found for a number of key parameters: energy substitution by biogas, N2O-emission from digestate in soil, fugitive emission of CH4, unburned CH4, carbon bound in soil and fertilizer substitution. GWF for a specific type of AD facility was in the range –95 to –4 kg CO2-eq. tonne–1 wet waste. The ranges of uncertainty, especially of fugitive losses of CH4 and carbon sequestration highly influenced the result. In comparison with the few published GWFs for AD, the range of our data was much larger demonstrating the need to use a consistent and robust approach to GHG accounting and simultaneously accept that some key parameters are highly uncertain.

Morawski, C. Composting – Best bang for MSW management buck. *BioCycle* 2008, October, 23-27
For many years, life cycle analyses of end-of-life management practices have been available for all of the basic recyclables as well as organics. The life cycle data, usually derived by the U.S. Environmental Protection Agency's WAste Reduction Model (WARM), represents the net greenhouse gas impact of recycling, landfilling or incinerating a variety of material streams. The model calculates emissions in metric tons of carbon equivalent, metric tons of carbon dioxide equivalent and energy units. Mellon University's Economic Input-Output Life Cycle Assessment (LCA) model, measures seven environmental impacts: climate change expressed as CO2 equivalents; human health expressed as particulates, toluene equivalents (toxics), and benzene equivalents (carcinogens); eutrophication expressed as nitrogen equivalents; acidification expressed as sulfur dioxide equivalents; and ecosystem toxicity expressed as herbicide 2,4-D equivalents (based on USEPA's TRACI — Tool for the Reduction and Assessment of Chemical and other environmental Impacts — model). Together, WARM and the Carnegie Mellon LCA tool (USEPA, 2006; EIOICA, 1995) offer the ability to understand the full environmental impact of our decisions on how to manage various components of the waste stream.

Morris, J. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. *Environmental Science & Technology* 2010, 44(20), 7944-7949
This study uses life cycle assessment (LCA) to compare climate impacts of landfill (LF) and waste-to-energy (WTE) for disposal of municipal solid waste (MSW). To avoid possibly arbitrary assumptions about landfill gas (LFG) capture rates, the study develops a crossover function for LFG capture that indicates the capture rate at which LF and WTE breakeven for climate impacts. Above the crossover rate LF is better for the climate; below WTE is superior. Base case and sensitivity analyses show how this crossover rate is affected by waste composition, electricity conversion efficiency, heat capture, scrap metal recovery, greenhouse gas (GHG) intensity of displaced power, and LCA time horizon. In general, crossover rates are in the 50% to 70% range. Notable exceptions include much higher crossover when WTE has high heat recovery, and much lower crossover for low carbon displaced power. The study also compares GHG emissions for electricity generated by WTE, captured LF methane, coal and natural gas, and concludes that none are carbon neutral. Further, the study tentatively suggests that MSW is a particularly carbon intensive fuel due to GHGs avoidable when readily recyclable materials in MSW are used in manufacturing new products rather than used to generate electricity.

Morris, J. *The Environmental Value of Metro Region Recycling for 2008* 2010, prepared for Metro Sustainability Center, Portland, OR
Metro Sustainability Center contracted with Sound Resource Management Group, Inc. (SRMG) to develop a version of SRMG's Measuring the Environmental Benefits Calculator (MEBCalc^{TM}) specifically parameterized to reflect solid waste management practices in the Metro region. This report discusses the results of applying Metro MEBCalc^{TM} to 2008 recycling in the Metro region. A companion report provides technical documentation for Metro MEBCalc^{TM} and instructions for the calculator's users.

The Metro region recovered 1,235,924 tons of solid wastes in 2008. Metro MEBCalc^{TM} estimates the environmental value of recovery for over 96 percent of materials or 1,191,798 of those tons – including all grades of paper; PET, HDPE and film plastics; ferrous and non-ferrous metals including aluminum and steel cans; glass packaging; electronics; tires; wood; yard debris and food scraps. Not currently included are carpet, gypsum wallboard, paint and used motor oil. Future versions of Metro MEBCalc^{TM} will estimate environmental value for recovering these currently excluded materials as robust environmental data from life cycle assessment studies on them become available.

Morris J.; Bagby, J. Measuring environmental value for natural lawn and garden care practices. *International Journal of Life Cycle Assessment* 2008, 13(3), 226-234
Background, Aims and Scope. Measuring Environmental Value for Natural Lawn and Garden Care Practices provides a life cycle assessment and impacts valuation methodology to quantify environmental (public health and ecological) and water conservation benefits from natural lawn and garden care practices in Seattle. Seattle Public Utilities (SPU) initiated this study as part of a triple-bottom line analysis of its Natural Lawn and Garden Care program.
Methods. The study uses life cycle assessment (LCA) methods, including the Carnegie-Mellon Economic Input-Output Life Cycle Assessment (EIOLCA) tool publicly available on the Internet, to inventory

pollutant generation from a synthetic nutrients and pesticide approach to lawn and garden care compared against a natural/organic care approach. The study applies US Environmental Protection Agency's TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) climate change, acidification, eutrophication, and human health-criteria air pollutant stressor factors, along with the Lawrence Berkeley National Laboratory's CalTOX risk assessment model's human and ecosystem toxicity potentials to roll up the numerous pollutant quantities into six environmental impact categories (global warming potential, human respiratory disease potential, human toxicity potential, ecological toxicity potential, acidification potential and eutrophication potential). The study develops cost valuation estimates for each impact category to produce a dollar estimate of the environmental cost of the two archetypical lawn and garden care methods.

Results. Lawns and gardens account for 25% of Seattle's land area, so lawn and garden care methods potentially have substantial impacts on the city's land- and water-based ecosystems. LCA methods provide an informative methodology for comparing environmental impacts from lawn and garden care practices. These methods reveal the importance of more natural lawn and garden care practices. They also show that resource extraction and manufacturing impacts of pesticides and synthetic fertilizers dominate their on-site use impacts in the case of global warming, but that the reverse holds for human and ecological toxicity, and eutrophication. In addition, releases of particulates, SOx and NOx associated with gasoline-powered lawn mowing are nearly an order of magnitude larger than releases of these pollutants as a result of the production of pesticides and fertilizers.

Discussion. The study proceeds by using available data and research to build a desktop model that characterizes and contrasts two archetypical lawn and garden care practices: (1) Petroleum-based fertilizers and pesticides, a gasoline-powered lawn mower, and substantial irrigation to maintain a traditional weed-free, always-green lawn and garden, versus (2) A backyard compost system to provide lawn and garden nutrients, supplemented moderately by purchased non-synthetic soil amendments, an electricity-powered mower, no pesticides, and drought tolerant lawn and garden species having little need for irrigation.

Conclusions. The study concludes that each household converting from synthetic to natural practices produces nearly $75 in annual ongoing public health, ecological, water conservation and hazardous waste management benefits – between $16 and $21 of environmental benefits from reduced use of synthetic fertilizers and pesticides, $8 of environmental benefits for switching from gas to electricity for lawn mowing, $42 in cost savings due to reduced irrigation, and $5 or $6 from lower hazardous waste management costs. There also is a potential one time avoidance of $31 in construction costs resulting from reduced need for storm water detention and diversion capacity.

Recommendations and Perspectives. This study's estimates of environmental value would benefit from comprehensive information on direct exposure to active ingredients in insecticides during their application. Estimates of impacts are based only on volatilization and runoff of active ingredients after application. Furthermore, the study would benefit from estimates of carbon sequestration in soils promoted by natural lawn and garden care techniques, and on the upstream pollutant releases from production of synthetic versus organic fertilizers. All three of these data gaps suggest that the estimated $75 per single family residence for environmental value is probably a lower bound on benefits from natural lawn and garden care versus more traditional pesticide-and-synthetic-fertilizer-based approaches.

Morris, J. Recycling versus incineration: an energy conservation analysis. *Journal of Hazardous Materials* 1996, 47(1-3), 277-293

This paper shows that for 24 out of 25 solid waste materials, recycling saves more energy than is generated by incinerating mixed solid waste in an energy-from-waste facility. Recycling conserves energy that would otherwise be expended extracting virgin raw materials from the natural environment and transforming them to produce goods that can also be manufactured from recycled waste materials. Furthermore, energy conserved by recycling exceeds electricity generated by energy-from-waste incineration by much more than the additional energy necessary to collect recycled materials separately from mixed solid waste, process recycled materials into manufacturing feedstocks, and ship them to manufacturers, some of whom are located thousands of miles away.

Munster, M.; Meibom, P. Long-term affected energy production of waste to energy technologies identified by use of energy system analysis. *Waste Management* 2010, 30, 2510-2519

Affected energy production is often decisive for the outcome of consequential life-cycle assessments when comparing the potential environmental impact of products or services. Affected energy production is however difficult to determine. In this article the future long-term affected energy production is identified by use of energy system analysis. The focus is on different uses of waste for energy production. The Waste-to-Energy technologies analysed include co-combustion of coal and waste, anaerobic digestion and thermal gasification. The analysis is based on optimization of both investments and production of electricity, district heating and bio-fuel in a future possible energy system in 2025 in the countries of the Northern European electricity market (Denmark, Norway, Sweden, Finland and Germany). Scenarios with different CO2 quota costs are analysed. It is demonstrated that the waste incineration continues to treat the largest amount of waste. Investments in new waste incineration capacity may, however, be superseded by investments in new Waste-to-Energy technologies, particularly those utilising sorted fractions such as organic waste and refuse derived fuel. The changed use of waste proves to always affect a combination of technologies. What is affected varies among the different Waste-to-Energy technologies and is furthermore dependent on the CO2 quota costs and on the geographical scope. The necessity for investments in flexibility measures varies with the different technologies such as storage of heat and waste as well as expansion of district heating networks. Finally, inflexible technologies such as nuclear power plants are shown to be affected.

Pickin, J.; Representations of environmental concern in cost-benefit analysis of solid waste recycling. *Resources, Conservation and Recycling* 2008-09, 53(1-2), 79-85

The value of cost–benefit analysis (CBA) as a decision tool in the area of solid waste recycling is examined, centering on a review of how 37 ‘effect-by-effect’ English language studies attempt to encapsulate the associated environmental issues. I identify five critical areas where CBAs are often inconsistent with each other, with popular views of recycling, or with other areas of policy. These are: the types of environmental impact and their valuation; the relevance of upstream externalities; whether there is a scarcity externality; the economic significance of householder efforts; and the need to drive towards long-term sustainability through eco-restructuring. Rather than the hard rationality it seems to promise, I conclude that CBA with environmental externality measurement and valuation has diverted debate from the public arena into technical complexities that are the preserve of experts, allowing space for analysts’ ideological inclinations to be manifest and for commissioning agencies to procure results that suit their interests. I argue that the best CBAs are those with multiple levels of information, disaggregated environmental data, range values, sensitivity analysis, itemization of excluded or unvalued elements, and, to the extent affordable, valuation by multiple methods. Expressed preference methods may produce valuations that accord with economic theory and are also more in tune with popular opinion.

Reale-Levis, J.; Barlaz, M.A.; Ranjithan, R. A life-cycle analysis of alternatives for the management of commercial and industrial food waste, 2008, North Carolina State University, Raleigh, NC

Currently in the US, food waste that is not buried in a landfill is aerobically composted and the end product has the potential to be used as a soil amendment that can replace mineral fertilizers or other agrochemicals. In Europe, anaerobic digestion of organic wastes is more common. Anaerobic digestion facilities produce methane that can be used as an energy source.

The residual from anaerobic digestion can also be used as a soil amendment similar to what is produced at composting facilities. The objective of this study was to evaluate emissions, energy use, and global warming potential (GWP) associated with alternatives for the management of commercial food waste including aerobic composting, landfill disposal, and anaerobic digestion.

A life-cycle inventory was performed for food waste processed through several different aerobic composting systems of varying complexity, an anaerobic digestion facility, and a landfill with and without energy recovery. The functional unit was one ton of food waste plus 0.6 tons of yard waste. The yard waste was considered because it is used as a bulking agent in food waste composting processes. The CO, SO2, NOx, and Total PM emissions as well as energy use and

GWP for each alternative were calculated. An offset for avoided fertilizer production was considered for the composting and anaerobic digestion alternatives where the food waste residual may be used as a soil amendment. An offset for electrical energy production was considered for the landfill with energy

recovery and the anaerobic digestion alternatives. The analysis is predicated on the assumption that high purity food waste will be provided by the waste generator.
The anaerobic digestion alternative was superior in every category due to the efficient collection of the methane generated and its conversion to energy. The two landfilling alternatives resulted in the highest GWP although the landfill with energy production had the second lowest emissions and energy use. The composting alternatives were superior relative to landfilling without energy recovery in which the gas is managed by flaring. A sensitivity and uncertainty analysis was performed on these results and the anaerobic digestion alternative was determined to be a robust optimal decision.

Recycled Organics Unit, *Greenhouse Gas Emissions from Composting Facilities(second edition)* 2007, prepared for New South Wales Department of Environment and Conservation by Recycled Organics Unit at The University of New South Wales, Sydney, Australia
This study examines windrow composting of garden organics material, as this feedstock material is the dominant compostable material derived from the solid "waste" stream that is processed by the recycled organics industry in New South Wales and is also sought as a feedstock for *waste to energy* applications. Examination of greenhouse gas emissions from composting facilities is necessary to quantify actual emissions from these systems and also to allow comparisons to be made with alternatives such as energy recovery and disposal (e.g. waste to energy, landfill etc.).
Greenhouse gas emissions may be either biogenic or anthropogenic in origin. According to international convention, only greenhouse gas emissions resulting from anthropogenic sources (derived from human activity) are considered in emissions calculations. Emissions that are generated from biogenic processes (emissions that would have happened during the natural decomposition process) are excluded from the analysis.

Recycled Organics Unit, *Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems(second edition)* 2007, prepared for New South Wales Department of Environment and Conservation, Parramatta, NSW, Australia
Numerous local government, industry and state government agencies have expressed a need for Life Cycle Assessment to inform environmental decision making in relation to the streaming and management of solid waste. However, comparative studies to date have not in any significant manner addressed the impacts resulting from the use of recycled organics products such as composts once such products have been applied. As a result, previous comparative studies have tended to exclude such post application impacts from the analysis, effectively excluding a range of significant environmental benefits and reducing the relative environmental value of biological treatment systems.
This study provides a comprehensive Life Cycle Inventory (LCI) for commercial composting systems in Australia, and models the environmental impacts of the commercial composting systems in NSW using rigorous Life Cycle Assessment (LCA) modeling. This study is the first time, internationally, that LCI data for the postapplication impacts of composting systems has been developed in any significant or comprehensive manner. The study has been extensively reviewed by relevant technical experts in Life Cycle Assessment, and by relevant agricultural and environmental scientists in NSW Agriculture and the CSIRO.
The results of this study indicate significant environmental benefits arise from the commercial composting system, including net greenhouse benefits, even where composts are transported significant distances (in this study 600 km) for agricultural application.
Whilst this LCA study is valuable in its own right in identifying and quantifying the environmental externalities of the composting system, the LCI data in this study is also transparently developed and documented to allow for application in future comparative LCA studies.

Rigamonti, L.; Grosso, M.; Giugliano, M. Life cycle assessment of sub-units composing a MSW management system. *Journal of Cleaner Production* 2010, 18(16-17), 1652-1662
This paper summarizes the results of a number of life cycle evaluations that we have carried out in recent years about some of the sub-units (in particular, the recycling of the packaging materials, the treatment of the bio-waste, and the energy recovery from the residual waste) that compose a municipal solid waste management system (MSWMS) and about the MSWMS as a whole.
The range of values estimated for cumulative energy demand (CED), global warming (GWP100), human toxicity, acidification, and photochemical ozone creation indicators according to the different analyses are

presented in the paper for each sub-unit. The assumptions influencing the results have been identified, too. The proper aggregation of sub-units has allowed the estimation of the impacts associated with two integrated MSWMSs implemented in Italy and of the order of magnitude of those associated with a generic MSWMS, similar to those of the two case studies.
The results show that the assumptions that most influence the environmental indicators are those about selection efficiencies and quality deterioration in the recycling of the packaging materials, about process emissions and avoided products in the composting, about the biogas yield and its way of utilization in the anaerobic digestion, and about the efficiency of the plant and the kind of avoided energy in the energy recovery. All the indicators, except GWP100 under certain assumptions, are negative in sign, thus indicating a benefit for the environment thanks to the avoided impact associated with the production of material and energy during the waste management. The estimated order of magnitude of the CED and GWP100 indicators turns out to be respectively thousands of MJ eq. and tens of kg CO2 eq. per tonne of managed waste.

Sheltair Group (Contact: Ron MacDonald), *Life Cycle Assessment (LCA) Considerations for Waste to Energy and Materials Recovery* 2008, prepared for Alberta Environment, Edmonton, AB

This project was executed to define the life cycle considerations of waste management -with specific consideration for waste to energy and recycling, while acknowledging landfilling as a base case. The work included a review of waste related policies, waste generation rates in Alberta, market conditions for recycling, and the analysis frameworks to incorporate life cycle thinking into consideration. Different strategies for waste management may result in different energy consumption and emissions - both at the waste management facility and in other parts of the Life Cycle. Considering the full life cycle for the disposal of municipal solid waste acknowledges indirect benefits of a project that accrue such as avoided emissions for energy production or virgin material production. These accrue through either energy recovery or enhanced recycling, respectively.
Many of the indirect benefits do not accrue to the waste system operator, but rather are realized by Albertans in general or people outside Alberta. For example recycling reduces the production of virgin materials and may reduce energy consumption or emissions at the location of the product production.

Smith, S.R.; Jasim, S. Small-scale composting of biodegradable household waste: overview of key results from a 3-year research programme in West London. *Waste Management & Research* 2009, 27(10), 941-950

Home composting (HC) is recognized by both local and national Governments for its contribution to reducing household waste disposal in landfill. However, the quantitative impact of HC on the diversion of household waste from landfill is uncertain. An overview of key results is presented from a 3-year research programme on HC in the West London area of Runnymede Borough Council (RBC), Surrey, UK. The amount of biodegradable household waste diverted from landfill disposal by HC was measured in a 2-year monitoring study involving 64 homeowners. The total average annual waste input to a standard 290 L HC bin was approximately 370 kg per household. The average relative mass inputs of kitchen, paper and garden waste were 29, 2 and 69%, respectively. A survey of the study area indicated that approximately 20% of households were engaged in HC and, based on inputs to HC bins, this corresponded to an overall recycling/diversion rate equivalent to 20% of household biodegradable waste. Temperature and gas composition measurements indicated organic matter decomposition by HC was aerobic and only traces of CH4 were occasionally detected. A field trial examined the end-use of composted products for the growth of Petunia grandiflora. Flower production increased with home-produced composts in comparison with peat-amended or untreated control soil. Compost chemical composition, bioaerosol emissions and vector attraction were also investigated.

Sound Resource Management Group, *Environmental Life Cycle Assessment of Waste Management Strategies with a Zero Waste Objective: Study of the Solid Waste Management System in Metro Vancouver, British Columbia* 2009, prepared for Belkorp Environmental Services Inc., Vancouver, BC

An increasingly complex set of environmental, economic and social pressures is driving change in the solid waste management industry in North America. These pressures include:

- The impact of Climate Change and the increasing awareness of the role of “waste” and “wasting” in the production of greenhouse gas emissions;

• Diminishing world fossil fuel energy supplies;
• Increasing limitations of government to prevent and control the volume and toxicity of products in the waste stream and a growing need to shift responsibility to the product manufacturer; and
• A growing public desire to set ambitious waste prevention and diversion goals thereby minimizing the need for waste disposal facilities in the long term.

Pressures such as these are driving change in public and private strategic planning for solid waste diversion and disposal systems. Notably, conventional approaches and mixes of municipal waste management facilities and services no longer sufficiently address broader public concerns and ambitions for environmental sustainability and zero waste. However, determining preferable strategic directions in this complex and changing industry is very challenging.

With these challenges in mind, Belkorp Environmental Services Inc. (BESI) commissioned Sound Resource Management Group (Olympia, WA) to conduct a comprehensive life cycle analysis (LCA) study of solid waste management in the Metro Vancouver region of British Columbia. The intent of the study was to provide BESI with guidance in developing a long term waste management business strategy based on adopting a zero waste objective.

BESI's interest in seeking such guidance arises from the company's experience and current involvement in the recycling and disposal industries in the region, and the Metro Vancouver regional government's adoption of a zero waste philosophy in a revised long-term 'Waste Management Plan'. Wastech Services Ltd., a subsidiary of BESI, handles municipal solid waste under contract to the regional government, operating four waste transfer stations and the Cache Creek landfill. Wastech also operates a cardboard baling facility, a wood waste recycling facility and recycling depots at each of the transfer stations.

TSH Engineers Architects and Planners (Technical Report Coordinator: Michael Cant), *Municipal Solid Waste (MSW) Options: Integrating Organics Management and Residual Treatment/Disposal* 2006, prepared for Municipal Waste Integration Network and Recycling Council of Alberta, Edmonton, AB

Municipal Solid Waste (MSW) Options: Integrating Organics Management and Residual Treatment/Disposal will assist municipalities in moving their integrated waste management systems to the "next level" in order to further conserve resources, reduce environmental impacts, reduce greenhouse gas emissions, produce energy, lessen dependence on landfills and improve social acceptability.

The report provides evaluations of the following Organics Management and Residual Treatment/Disposal options:

• composting;
• anaerobic digestion;
• sanitary landfill.
• bioreactor landfill; and
• thermal treatment;

The indicators used in the evaluations included: environmental, social, economic, energy and greenhouse gases.

The community sizes evaluated included populations of 20,000, 80,000 and 200,000.

United Nations Environmental Programme (UNEP). *Waste and climate change: Global trends and strategy framework* 2010, UNEP Division of Technology, Industry and Economics, International Environmental Technology Centre, Osaka/Shiga, Japan

Every waste management practice generates GHG, both directly (i.e. emissions from the process itself) and indirectly (i.e. through energy consumption). However, the overall climate impact or benefit of the waste management system will depend on net GHGs, accounting for both emissions and indirect, downstream GHG savings. The actual magnitude of these emissions is difficult to determine because of poor data on worldwide waste generation, composition and management and inaccuracies in emissions models. Although currently OECD countries generate the highest levels of methane, those of developing nations are anticipated to increase significantly as better waste management practices lead to more anaerobic, methane producing conditions in landfills.

Estimates of GHG emissions from waste management practices tend to be based on life-cycle assessment (LCA) methods. LCA studies have provided extremely useful analyses of the potential climate impacts and benefits of various waste management options. However, due to data availability and resources, LCA studies are primarily focused on scenarios appropriate for developed countries. Due to the key, underlying assumptions on which these assessments are based (such as local/regional waste composition, country-specific energy mix, technology performance, etc.) the results are not necessarily transferable to other countries. This makes it generally impossible to make global comparisons regarding the GHG performance of different waste management technologies.

The climate benefits of waste practices result from avoided landfill emissions, reduced raw material extraction and manufacturing, recovered materials and energy replacing virgin materials and fossil-fuel energy sources, carbon bound in soil through compost application, and carbon storage due to recalcitrant materials in landfills. In particular, there is general global consensus that the climate benefits of waste avoidance and recycling far outweigh the benefits from any waste treatment technology, even where energy is recovered during the process.

Although waste prevention is found at the top of the 'waste management hierarchy' it generally receives the least allocation of resources and effort. The informal waste sector makes a significant, but typically ignored contribution to resource recovery and GHG savings in cities of developing nations.

A range of activities focused on waste and climate change are currently being led by international organisations, including UNEP. There is clear recognition of the considerable climate benefit that could be achieved through improved management of wastes. UNEP is involved in a variety of relevant partnerships and programmes, such as Integrated Waste Management, Cleaner Production, and Sustainable Consumption and Production. There is also strong interest in Clean Development Mechanism (CDM) projects in the waste sector. CDM activity has focused mainly on landfill gas capture (where gas is flared or used to generate energy) due to the reduction in methane emissions that can be achieved. However, there is a lack of a cohesive approach, which has resulted in gaps, duplication, and regional disparity is programmes offered. A central mechanism is needed to collaborate with existing organisations to ensure accessibility to and dissemination of relevant information across the globe, effective use of resources to achieve climate benefit through integrated waste management, promotion of best practice, and rapid transfer of simple, effective, proven technologies and knowledge to developing countries.

Valerio, F. Environmental impacts of post-consumer material managements: Recycling, biological treatments, incineration. *Waste Management* 2010, 30(11), 2354-2361

The environmental impacts of recycling, mechanical biological treatments (MBT) and waste-to-energy incineration, the main management strategies to respond to the increasing production of post-consumer materials are reviewed and compared. Several studies carried out according to life-cycle assessment (LCA) confirm that the lowest environmental impact, on a global scale, is obtained by recycling and by biological treatments (composting and anaerobic fermentations) if compost is used in agriculture. The available air emission factors suggest that, on a local scale, mechanical biological treatments with energy recovery of biogas, may be intrinsically safer than waste-to-energy incinerators. Several studies confirm the capability of biological treatments to degrade many toxic xenobiotic contaminating urban wastes such as dioxins and polycyclic aromatic hydrocarbons, an important property to be improved, for safe agricultural use of compost. Further LCA studies to compare the environmental impact of MBTs and of waste-to-energy incinerators are recommended.

Van Haaren, R.; Themelis, N.J.; Barlaz, M. LCA comparison of windrow composting of yard wastes with use as an alternative daily cover (ADC). *Waste Management* 2010, 30(12), 2649-2656

This study compared the environmental impacts of composting yard wastes in windrows with using them in place of soil as alternative daily cover (ADC) in landfills. The Life Cycle Assessment was made using the SimaPro LCA software and showed that the ADC scenario is more beneficial for the environment than windrow composting. ADC use is also a less costly means of disposal of yard wastes. This finding applies only in cases where there are sanitary landfills in the area that are equipped with gas collection systems and can use yard wastes as alternative daily cover. Otherwise, the environmentally preferable method for disposal of source-separated yard wastes is composting rather than landfilling.

Van Opstal, B. Role of anaerobic digestion in Toronto's organics diversion plan. 2010, Presentation to Canadian Waste Sector Symposium, Toronto, Ontario, November 2010

This slide show discusses the role of anaerobic digestion in Toronto's Organics Diversion Plan: including

Overview of Toronto SWM Programs, Background -Green Bin organics program, Background –Dufferin, AD Facility, Future expansion of AD capacity, Biogas utilization and Rationale.

Weitz, K.; Barlaz, M.; Ranjithan, R.; Brill, D.; Thorneloe, S.; Ham, R. Life cycle management of municipal solid waste. *International Journal of Life Cycle Assessment* 1999, 4(4), 195-201
Life-cycle assessment concepts and methods are currently being applied to evaluate integrated municipal solid waste management strategies throughout the world. The Research Triangle
Institute and the U.S. Environmental Protection Agency are working to develop a computer-based decision support tool to evaluate integrated municipal solid waste management strategies in the United States. The waste management unit processes included in this tool are waste collection, transfer stations, recovery, com~ post, combustion, and landfill. Additional unit processes included are electrical energy production, transportation, and remanufacturing. The process models include methodologies for environmental and cost analysis. The environmental methodology calculates life cycle inventory type data for the different unit processes. The cost methodology calculates annualized construction and equipment capital costs and operating costs per ton processed at the facility. The resulting environmental and cost parameters are allocated to individual components of the waste stream by process specific allocation methodologies. All of this information is implemented into the decision support tool to provide a life-cycle management evaluation of integrated municipal solid waste management strategies

Winkler, J.; Bilitewski, B. Comparative evaluation of life cycle assessment models for solid waste management. *Waste Management* 2007, 27(8), 1021-1031
This publication compares a selection of six different models developed in Europe and America by research organizations, industry associations and governmental institutions. The comparison of the models reveals the variations in the results and the differences in the conclusions of an LCA study done with these models. The models are compared by modeling a specific case – the waste management system of Dresden, Germany – with each model and an in-detail comparison of the life cycle inventory results. Moreover, a life cycle impact assessment shows if the LCA results of each model allows for comparable and consecutive conclusions, which do not contradict the conclusions derived from the other models' results. Furthermore, the influence of different level of detail in the life cycle inventory of the life cycle assessment is demonstrated.
The model comparison revealed that the variations in the LCA results calculated by the models for the case show high variations and are not negligible. In some cases the high variations in results lead to contradictory conclusions concerning the environmental performance of the waste management processes. The static, linear modeling approach chosen by all models analysed is inappropriate for reflecting actual conditions. Moreover, it was found that although the models' approach to LCA is comparable on a general level, the level of detail implemented in the software tools is very different.

Wright, A.L.; Provin, T.L.; Hons, F.M.; Zuberer, D.A.; White, R.H. Compost impacts on dissolved organic carbon and available nitrogen and phosphorous in turfgrass soil. *Waste Management* 2008, 28(6), 1057-1063
Compost application to turfgrass soils may increase dissolved organic C (DOC) levels which affects nutrient dynamics in soil. The objectives of this study were to investigate the influence of compost source and application rate on soil organic C (SOC), DOC, NO3, and available P during 29 months after a one-time application to St. Augustinegrass [Stenotaphrum secundatum (Walt.) Kuntze] turf. Compost sources had variable composition, yet resulted in few differences in SOC, DOC, and NO3 after applied to soil. Available NO3 rapidly decreased after compost application and was unaffected by compost source and application rate. Available P increased after compost application and exhibited cyclical seasonal patterns related to DOC. Compost application decreased soil pH relative to unamended soil, but pH increased during the course of the study due to irrigation with sodic water. Increasing the compost application rate increased SOC by 3 months, and levels remained fairly stable to 29 months. In contrast, DOC continued to increase from 3 to 29 months after application, suggesting that compost mineralization and growth of St. Augustinegrass contributed to seasonal dynamics. Dissolved organic C was 75%, 78%, and 101% greater 29 months after application of 0, 80, and 160 Mg compost ha1, respectively, than before application. Impacts of composts on soil properties indicated that most significant effects occurred within a few months of application. Seasonal variability of SOC, DOC, and available P was likely related to St. Augustinegrass growth stages as well as precipitation, as declines occurred after precipitation events.

Yang, W.; Macdonald, R.; Fichtner, K. *Life cycle assessment of organics management: An LCA evaluation of scenarios for managing source separated organics from the Greater Vancouver Region* 2007, Greater Vancouver Regional District and The Sheltair Group, Vancouver, BC

Key findings are:

• The diversion of organics alters the composition of the waste stream resulting in a higher heat content of the remaining waste, slightly reduced WTEF throughput (by tonne), slightly increased GHG emissions at the WTEF, and reduced landfill gas generation at the two landfill locations.

• The emissions from the activities of separation (extra collection effort) and processing the organics (composting, digestion) are small compared to the other emissions sources such as the WTEF and the landfills.

• Separation of organics generally results in reduced emissions of greenhouse gas and air contaminants due to reduced landfill gas generation at the landfills.

• Recoverable heat and electricity are created at the landfills and the WTEF(s) in all scenarios. These provide some offset of the direct GHG emissions of these facilities and displace some electricity and natural gas energy sources elsewhere.

• The diversion of organics does not add substantially to the petroleum fuel energy requirements as the additional fuel for collection is somewhat offset by reduced requirements for MSW collection.

APPENDIX B

A Brief Description of MEBCalc™

MEBCalc™ is an Excel-based workbook model that computes an LCIA based on user inputs of waste materials types and quantities, distances to processing and disposal facilities as well as distances to end use markets, and other community specific parameters of a solid waste management system. Figure 1, Product Life Cycle Phases, indicates the LCA approach used by MEBCalc™.[8] The figure portrays environmental flows across a product's life cycle in terms of energy and material inputs and energy and pollution outputs (to air, water and land). The typical product's life cycle involves:

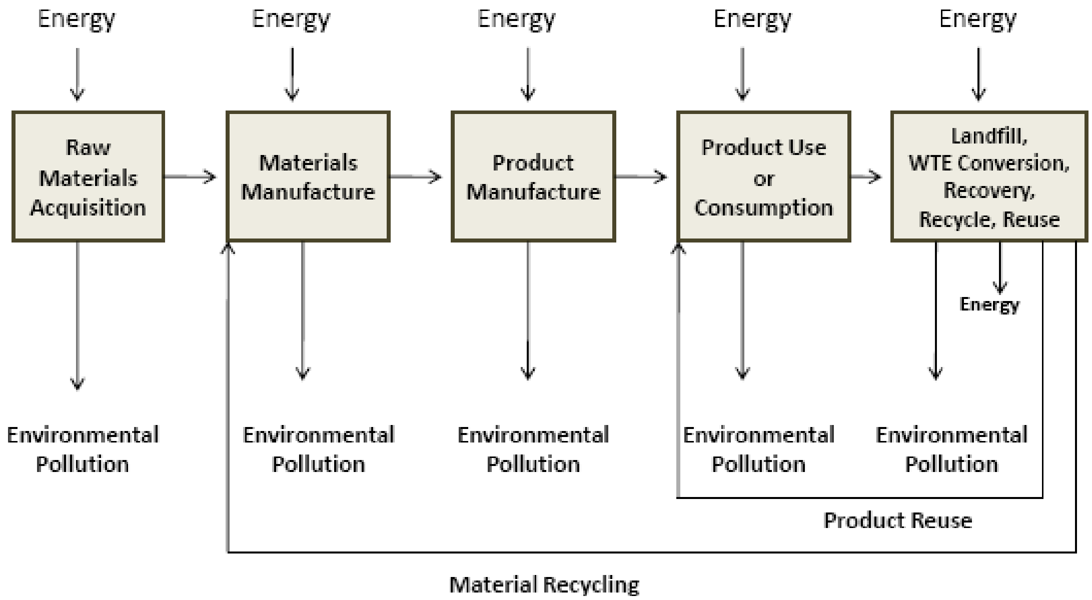
- extracting raw materials from nature's ecosystems,
- refining those virgin resources into industrial feedstocks,
- manufacturing the product from these feedstock,
- using the product by consumers, and
- disposition of product discards by recycling, recovery or disposal.

The first three phases (extraction, refining and manufacturing) are often termed the *upstream phase* in the product life cycle. The last phase (recycling, composting, waste-to-energy, landfill) is often termed the *downstream* or post-consumer phase.

The feedback loops in Figure 1 show how recycling and composting bypass a portion of the upstream phase. This conserves the energy already embodied in products and reduces the waste and pollution that result when new goods and services are produced. Most of the environmental benefit of recycling and composting comes from energy and pollution reductions in the upstream phase when recycled materials replace raw materials and compost replaces petroleum-based fertilizers. In addition, compost provides some product use phase benefits when reduced use of pesticides decreases human exposure to toxics from pesticide applications, as well as when reduced use of synthetic fertilizers reduces eutrophication of waterways as a result of decreased runoff of water soluble nitrogen in synthetic fertilizer.

[8] The model is discussed and reviewed in two trade journal articles by team member Clarissa Morawski – The New 'Eco-Currency': New model monetizes environmental benefits and reveals new cost savings in waste diversion, *Solid Waste & Recycling*, December/January 2008; and Composting – Best bang for MSW management buck, *Biocycle*, October 2008. Many of the LCA techniques and management method parameters used in the calculator are discussed in the following three peer-reviewed articles by team member Jeffrey Morris – Morris, J (2005), Comparative LCAs for curbside recycling versus either landfilling or incineration with energy recovery, *International Journal of Life Cycle Assessment* 10(4) 273-284; Morris, J; Bagby, J (2008), Measuring environmental value for natural lawn and garden care practices, *International Journal of Life Cycle Assessment* 13(3) 226-234; and Morris, J (2010), Bury or burn North American MSW? LCAs provide answers for climate impacts & climate neutral power potential, *Environmental Science & Technology* 44(20) 7944-7949.

Figure 1: Product Life Cycle Phases



MEBCalc™ includes a "best-of" compendium of life cycle data from a number of environmental life cycle inventory and assessment models, including:

- US EPA's WARM life cycle inventory spreadsheet calculator for greenhouse gas (GHG) emissions and the associated report (EPA 2006).[9]
- US EPA's MSW Decision Support Tool (DST) and database.[10]
- Carnegie Mellon University Green Design Institute's Economic Input-Output Life Cycle Assessment model.[11]
- US NIST's BEES model.[12]
- US EPA's TRACI model.[13]

MEBCalc™ also uses life cycle data from the Consumer Environmental Index (CEI) model developed for the Washington State Department of Ecology[14], as well as from peer-reviewed journal articles.

In addition, the calculator relies on:

- A life cycle inventory for wood wastes developed recently for Seattle Public Utilities.[15]
- Franklin Associates report on environmental impacts of recycling glass into containers, fiberglass and aggregate.[16]

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[9] WARM is available at http://www.epa.gov/climatechange/wycd/waste/calculators/Warm_home.html .
[10] Both the DST and the database are available through Research Triangle Institute.
[11] Available at http://www.eiolca.net .
[12] Available at http://www.bfrl.nist.gov/oae/software/bees/model.html .
[13] Information about TRACI is available at http://www.epa.gov/nrmrl/std/sab/traci/ .
[14] The CEI model is discussed in Morris, J; Matthews, H S (2007), Development of a consumer environmental index and results for Washington State consumers, *Journal of Industrial Ecology*, 14(3) 399-421.
[15] Available in the monograph Morris, J (2008), Environmental impacts for clean wood waste management methods: Preliminary results, prepared for Seattle Public Utilities, Seattle, WA.

- R. W. Beck reports on conversion technologies and anaerobic digestion.[17]

MEBCalc™ estimates pollution reductions that are caused across all phases of product life cycles by diverting material discards to recycling, composting, or use as industrial fuels. The calculator accounts for the effects of recovery on waste management system pollution emissions from collection vehicles, recyclables processing facilities, composting facilities, disposal facilities, shipping of processed materials to end users, and production of recycled-content and virgin-content products by those end users.

MEBCalc™ evaluates the potential effects of recovery for seven categories of impacts to public health, the environment and ecosystems:

- Climate change – characterizes the potential increase in greenhouse effects due to anthropogenic emissions. Carbon dioxide (CO_2) from combustion of fuels is the most common source of greenhouse gases (GHGs). Methane from anaerobic decomposition of organic material is another large source of greenhouse gases.
- Human respiratory disease and death from particulates – characterizes potential human health impacts from anthropogenic releases of coarse particles known to aggravate respiratory conditions such as asthma, releases of fine particles that can lead to more serious respiratory symptoms and disease, and releases of particulate precursors such as nitrogen oxides and sulfur oxides.
- Human disease and death from toxics -- characterizes potential human health impacts from releases of chemicals that are toxic to humans. There are a large number of chemical and heavy metal pollutants that are toxic to humans, including 2,4-D, benzene, DDT, formaldehyde, permethrin, toluene, chromium, copper, lead, mercury, silver, and zinc.
- Human disease and death from carcinogens -- characterizes potential human health impacts from releases of chemicals that are carcinogenic to humans. There are a large number of chemical and heavy metal pollutants that are carcinogenic to humans, including 2,4-D, benzene, DDT, formaldehyde, kepone, permethrin, chromium, and lead.
- Eutrophication -- characterizes the potential environmental impacts from addition of mineral nutrients to the soil or water. In both media, the addition of mineral nutrients, such as nitrogen and phosphorous, can yield generally undesirable shifts in the number of species in ecosystems and a reduction in ecological diversity. In water, nutrient additions tend to increase algae growth, which can lead to reductions in oxygen and death of fish and other species.
- Acidification -- characterizes the potential environmental impacts from anthropogenic releases of acidifying compounds, principally from fossil fuel and

[16] Available in the monograph Franklin Associates (1998), Environmental and economic analysis of glass container recycling from Portland's curbside collection program, Final Report. Prepared for City of Portland, Portland, Or.

[17] Available in the reports by RW Beck (2004), Anaerobic digestion feasibility study, Final Report, Prepared for Bluestem Solid Waste Agency and Iowa Department of Natural Resources; and RW Beck (2007), Comparative evaluation of waste export and conversion technologies disposal options – Internal Draft, Prepared for King County Department of Natural Resources and Parks Solid Waste Division, Seattle, WA.

biomass combustion, which affect trees, soil, buildings, animals and humans. The main pollutants involved in acidification are sulfur, nitrogen and hydrogen compounds – e.g., sulfur oxides, sulfuric acid, nitrogen oxides, hydrochloric acid (HCL), and ammonia.

- Ecosystems toxicity -- characterizes the relative potential for chemicals released into the environment to harm terrestrial and aquatic ecosystems, including wildlife. There are a large number of chemical and heavy metal pollutants that are toxic to ecosystems, including 2,4-D, benzene, DDT, ethyl benzene, formaldehyde, kepone, permethrin, toluene, chromium, copper, lead, silver, and zinc.

Life cycle analysis and environmental risk assessments provide the methodologies for connecting pollution of various kinds to these seven categories of environmental damage. For example, releases of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and other pollutants cause global warming which leads to climate change. The IPCC has conducted and reviewed scientific data to determine the strength of each pollutant relative to carbon dioxide in causing global warming. For example, over a hundred year time frame methane is 25 times and nitrous oxide 298 times more harmful than CO_2. Based on these global warming potential factors we can aggregate the emissions of all greenhouse gas pollutants into a single indicator quantity for global warming potential. This quantity is CO_2 equivalents (herein denoted eCO_2 or CO_2E).

Similar scientific efforts enable us to express the quantity of pollutant releases in terms of a single indicator quantity for the other six categories of environmental damage. This greatly simplifies reporting and analysis of different levels of pollution. By categorizing pollution impacts into a handful of categories, the environmental costs and benefits model is able to reduce the complexity of following trends for hundreds of pollutants. This simplifies life for policy makers. The trade-off is that we have to sort through complex pollutant aggregation and weighting methodologies. The MEBCalc™ model used herein relies on the methodologies used by the IPCC, US EPA's TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) model and the Lawrence Berkeley National Laboratory's CalTOX model.[18]

The methodology for aggregating pollutants into environmental impact categories yields total pollution reductions in terms of an indicator pollutant for each impact category. These indicators are:

- Climate change – carbon dioxide equivalents (eCO_2),
- Human health-particulates – particulate matter less than 2.5 microns equivalents ($ePM_{2.5}$),
- Human health-toxics – toluene equivalents (eToluene),
- Human health-carcinogens – benzene equivalents (eBenzene),
- Eutrophication – nitrogen equivalents (eN),
- Acidification – sulfur dioxide equivalents (eSO_2), and
- Ecosystems toxicity – herbicide 2,4-D equivalents (e2,4-D).

[18] See a description of the CalTOX model, references, and downloadable manual and software at http://eetd.lbl.gov/IED/ERA/caltox/index.html .

Conceptual Valuation of Life Cycle Environmental Impacts

The final step in estimating an environmental value for recovery is, then, to determine a dollar value for the damage to public health and/or ecosystems caused by each of the indicator pollutants. The following list shows these estimated damage valuations. The remainder of this section discusses the sources and justifications for these conceptual valuations.

- eCO_2 -- $40 per ton.
- ePM2.5 -- $10,000 per ton.
- eToluene -- $118 per ton.
- eBenzene -- $3,030 per ton.
- eN -- $4 per ton.
- eSO2 -- $410 per ton.
- e2, 4-D -- $3,280 per ton.

The cost of greenhouse gas emissions (eCO_2)

There is a very wide range in estimated costs for greenhouse gas emissions and valuations for the benefits of reductions in those emissions. The low end for valuations is the trading price for voluntary greenhouse gas emission reductions. Operating much as the markets in sulfur dioxide emissions permits do, several markets are available for trading voluntary greenhouse gas emissions reduction pledges. One of these is the Chicago Climate Exchange (CCX). Trading values on the CCX for CO_2 reductions have been between $1 and $4 per ton of carbon dioxide over the past several years. Values on European carbon markets have been ten times higher than trading prices on the CCX due to the mandatory CO_2 emissions caps imposed on European greenhouse gas generators.

The upper end of the range for estimated costs of climate change is found in recent studies such as the review of the economics of climate change conducted by Nicholas Stern.[19] That study determined that a reasonable estimate for the cost of current greenhouse gas emissions was $85 per metric ton, based on the risk of catastrophic environmental impacts and the resultant costs to the economy in the future if substantial reductions in greenhouse gas emissions are not implemented today.

MEBCalc™ uses $40 per ton for the cost of greenhouse gas emissions. This is in the middle of the range between market values for voluntary emissions reductions and estimated costs of severe climate change impacts if today’s emissions levels are not substantially reduced.

The cost of particulates emissions ($ePM_{2.5}$)

Eastern Research Group reports the following:

“Epidemiological studies have linked exposure to increased particulate matter (PM) levels to mortality and morbidity from chronic bronchitis and cardio-vascular disease. Time-series data from the 20 largest U.S. cities indicate a linear relationship between particulate air pollution and

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[19] Stern, N (2007), *The Economics of Climate Change: The Stern Review*, Cambridge University Press, Cambridge, England and New York, NY.

mortality.[20] The number of years of life lost from premature death, and wellbeing lost from illness, due to PM exposure depends on the age distribution and size of the exposed population. Many factors enter into the assessment of illness from PM exposure including weather, types of emissions, and health of the population. These analyses must be conducted at a local level in order to incorporate all of these factors."

"National estimates of the "per ton" benefits of reducing PM emissions are not often calculated. The importance of local factors in the effects of PM emissions makes such broad estimates highly uncertain. In order to compare the benefits and costs of regulations that federal agencies had chosen not to monetize, the Office of Management and Budget (OMB) calculated a broad national value of the benefits of reducing PM emissions by one ton of $10,000 to $100,000 ($2001).[21] OMB based this estimate on the 1997 NAAQS benefit assessment, though their method is not described."[22]

Based on this analysis by Eastern Research Group, MEBCalc™ incorporates a cost valuation of $10,000 per ton for emissions of $PM_{2.5}$.

The cost of human toxics emissions (eToulene)

As with the valuation of the costs of greenhouse gas emissions, there is a wide range in the estimated costs for emissions of pollutants that are toxic to humans. Eastern Research Group found estimates ranging up to $2,700 per ton of eToluene for the human health costs of toxic air pollutant emissions. MEBCalc™'s very conservative estimate of monetary costs for toxic air emissions is based on a peer-reviewed study on the health effects of atmospheric emissions of mercury. That study was sponsored by the Northeast States for Coordinated Air Use Management (NESCAUM) and conducted by scientists at the Harvard Center for Risk Analysis.[23] The study evaluated neurological and possible cardiovascular health impacts from exposure to methyl mercury through fish consumption, where atmospheric releases of mercury result in depositions of mercury in water bodies within and bordering the U.S. These depositions lead to increases in methyl mercury concentrations in fish.

The NESCAUM study evaluated three main health effects from methyl mercury exposure – neurological decrements associated with intrauterine exposure, myocardial effects associated with adult exposure, and elevated childhood blood pressure and cardiac rhythm effects associated with *In Utero* exposure. MEBCalc™ relies on the economic cost estimated in the study for only the first effect. The decrease in cognitive ability as a result of intrauterine exposure to methyl mercury is well documented and understood, whereas research on the other two health effects is not yet as extensive or thoroughly peer-reviewed.

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[20] M. J. Daniels, et al. 2000. Estimating particulate matter mortality dose-response curves and threshold levels: An analysis of daily time series for the 20 largest U. S. cities. *American Journal of Epidemiology*, 10:606-617.

[21] Office of Management and Budget, Office of Information and Regulatory Affairs. 2005. *Validating Regulatory Analysis: 2005 report to Congress on the costs and benefits of federal regulations and unfunded mandates on state, local, and tribal entities*.

[22] Eastern Research Group (2006), Draft Report: Cost benefit analysis for six "pure" methods for managing leftover latex paint - data, assumptions and methods. Prepared for the Paint Product Stewardship Initiative.

[23] Rice, G; Hammitt, J K (2005), Economic valuation of human health benefits of controlling mercury emissions from U.S. coal-fired power plants. Prepared for Northeast States Coordinated Air Use Management (NESCAUM) by the Harvard Center for Risk Analysis, Boston, MA.

The NESCAUM study's neurotoxicity health cost estimate for exposure to methyl mercury from consumption of fish that have bioaccumulated that toxin as a result of mercury air pollution is $10.5 million in year 2000 dollars per ton of mercury emitted to the atmosphere. Inflating that estimate to current dollars and converting the cost to toluene emissions, the indicator substance for human toxicity, yields $118 per ton of eToluene for the cost of pollutant emissions that are toxic to human health. This is the value MEBCalc™ attributes to reductions in human toxicity that are caused by diverting material resources from disposal to recycling and composting.

The cost of human carcinogenic emissions (eBenzene)

Eastern Research Group reports research suggesting that the cost to human health from benzene exposure could be 950 times greater than toluene. Given a valuation of $118 per ton for toluene, this ratio implies that benzene's valuation should be more than $100,000 per ton. This cost valuation is extremely high. MEBCalc™ uses $3,030 per ton, which is about 10% above the midpoint of the range $0.06 to $6.00 per kilogram for expected health risks from benzene releases that is also discussed in the Eastern Research Group study.

The cost of eutrophying emissions (eN)

In soil or waterways, the addition of large quantities of mineral nutrients, such as nitrogen and phosphorous, results in generally undesirable shifts in the number of species in ecosystems and a reduction in ecological diversity. In water, it tends to increase algae growth, which can lead to lack of oxygen and therefore death of species such as fish. MEBCalc™'s estimate of the cost of releases of nutrifying compounds is based on EPA's cost-effectiveness analysis for the NPDES regulation on effluent discharges from concentrated animal feeding operations. That analysis estimated that costs up to $4.41 per metric ton of nitrogen ($4.00 per short ton) removed from wastewater effluents were economically advantageous.[24]

The cost of acidifying emissions (eSO_2)

We estimate the value of acidification reductions at $410 per ton. This is the average of 2005 ($690), 2006 ($860), 2007 ($433), 2008 ($380), 2009 ($62) and 2010 ($36) market clearing spot prices in EPA's annual acid rain sulfur dioxide emissions permit allowances auction under the Clean Air Act.

The cost of ecosystem toxics emissions (e2, 4-D)

A study estimated the toxicity cost to plants and wildlife from application of a pound of 2, 4-D herbicide at $1.64.[25] This is an updated estimate from Joe Kovach, Integrated Pest Management Program at Ohio State University, based on his 1992 research on putting an

[24] US Environmental Protection Agency, Office of Research and Development (2002), Economic analysis of the final revisions to the National Pollutant Discharge Elimination System regulation and the effluent guidelines for concentrated animal feeding operations. EPA-812-R-03-002, Washington, DC.

[25] Kovach J; Petzoldt C; Degni J; Tette J (1992). A method to measure the environmental impact of pesticides. Integrated Pest Management Program, Cornell University, New York State Agricultural Experimentation Station, Geneva, NY (Available through Online Publications of the New York State IPM Program at http://www.nysipm.cornell.edu/publications).

environmental price to pesticide use.[26] The estimate includes costs for impacts on fish, birds, bees and beneficial arthropods, but not the estimated costs developed by Kovach for impacts on human health as a result of groundwater contamination. That human health cost is captured in the human toxicity potential impact category.

[26] Pesticide wash-off may be higher in a hilly urban environment than in a flat agricultural field. To the extent that Kovach relied on agricultural crop studies, his estimate of the cost to non-target plants and wildlife may underestimate the cost of pesticide applications in an urban environment.