Waste Management 30 (2010) 2649–2656

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

LCA comparison of windrow composting of yard wastes with use as alternative daily cover (ADC)

Rob van Haaren [a,*], Nickolas J. Themelis [b], Morton Barlaz [c]

[a] Dept. of Earth and Environmental Engineering, Columbia University, 500 West 120th Street, Room 918, New York, NY 10027, USA
[b] Earth Engineering Center, Columbia University, 500 West 120th Street, Room 918, New York, NY 10027, USA
[c] Dept. of Civil, Construction, & Environmental Engineering, North Carolina State University, Box 7908, Raleigh, NC 27695-7908, USA

ARTICLE INFO

Article history:
Received 8 March 2010
Accepted 7 June 2010
Available online 7 July 2010

ABSTRACT

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.

1. Introduction

In 2001, the California Assembly passed a bill that allows for use of yard wastes as alternative daily cover (ADC) to be counted as part of the recycling effort of a community (Haughey, 2001). The reason for this was recognition of the fact that many landfill operators did not have enough soil available on site and therefore had to transport it for use as ADC. This was costly and also had a negative environmental impact due to use of fossil fuels for transportation of soil (CIWMB, 2009). This legislation has been criticized by some over the years, on the basis of the assumption that windrow composting has a lower environmental impact than the use of yard wastes as ADC in landfills. Therefore, the objective of this research was to compare the environmental impacts of these two methods using Life-Cycle Analysis; and also to provide some insight as to the costs associated with both processing methods.

1.1. Windrow composting

Windrow composting is carried out in piles of 2–3 m high, 3–5 m wide and up to a hundred meters long, so as to keep the temperatures within the pile high and also allow some oxygen flow to the core. The windrows are turned periodically to allow for heat release and expose the material in the core to atmospheric air. Usually, windrow turners are equipped with watering nozzles to maintain the required moisture level. Modern windrow composting facilities provide for collection and treatment of the leachate that is formed in the process. The same is the case for sanitary landfills, as discussed in the next section.

Windrows are less costly than other composting technologies, such as in-vessel composting (van Haaren, 2009). However, it is more difficult to control undesirable gaseous emissions and odors. For this reason, and also to avoid attracting birds and vermin, the windrow feedstock usually does not include food wastes. However, small portions of food wastes are found in yard wastes collected from communities, due to inadequate separation at the source. The odors released by these impurities have caused problems with residents near some windrow facilities (van Haaren, 2009).

In normal windrow composting practice, oxygen may not penetrate throughout the body of the windrow. Therefore, some anaerobic reaction may take place, resulting in methane formation. However, with adequate turning, the amount of methane generated in windrows is very small (Komilis and Ham, 2004).

1.2. Using yard wastes as alternative daily cover

EPA regulations require that a 15-cm (6 in.) thick layer of soil be placed daily over the newly landfilled material, so as to reduce the emission of odors and keep birds, insects and vermin from reaching the MSW (EPA, 2009). Soil daily cover is the common practice for landfills; however, tarps and spray-on mulch mixes are also used as ADC. In 2001, the California Assembly passed a bill that allows for use of yard wastes as ADC to be counted as part of the recycling effort of a community (Haughey, 2001). Currently, an estimated 2.1 million tons of source-separated yard wastes are shredded and used annually as ADC in landfills (Stephens, 2007; Kaufman and Themelis, 2009). According to EPA, the required ADC thickness for yard waste is 9 in. (22 cm). This layer however, compacts in

---

[*] Corresponding author. Present address: Center of Life-Cycle Analysis, 500 West 120th St., #918, Columbia University, New York, NY 10027, USA.
E-mail address: rv2216@columbia.edu (R. van Haaren).

0956-053X/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.wasman.2010.06.007

the landfill to about two inches (5 cm), when additional MSW is deposited over the ADC layer. The 9:2 compaction factor is based on density figures found in a waste characterization study (Theodore et al., 2008). Because of this, use of yard waste as ADC instead of soil conserves landfill space.

Conditions within a landfill are mainly anaerobic. The water needed to generate the methane from the biomass wastes is contained within the MSW or is provided by precipitation and recirculation of leachate. The depth of a typical landfill cell varies considerably, from 20 to 80 m, depending on the landfill geometry and cell size. The height of daily deposition in a cell varies but a typical value is three meters. EPA regulations require that landfill gas (LFG) collection wells be installed within two years after placement of the final cover or five years after starting to dispose waste in a cell. However, at many landfills gas collection systems are installed sooner, after an intermediate cover has been placed.

The working landfill cell is prepared with an impervious liner at the bottom of the cell and leachate collection system, to prevent leach water from contaminating surface or groundwater. When the cell reaches its final height, the final cover is placed after the gas collection system is installed. The EPA requires landfills over a certain size to collect and use or flare landfill gas under the Clean Air Act (EPA, 2009).

In order to save space, some landfills scrape off some of the soil used for daily cover before the next layer of MSW is deposited and the soil is then re-used. On the basis of information provided by landfill operators, this study assumed that the volume ratio of MSW to soil daily cover is 9:1.

2. Methodology of Life-Cycle Analysis

The LCA was conducted using the SimaPro LCA software program (PRE Consultants, 2009). It consists of an extensive database of products and processes that provide an inventory of energy and material resources used and of chemical compounds emitted (waterborne, airborne and into the soil) during manufacturing a product or operating a process. This software program allows users to create their own database, by selecting relevant data entries from the SimaPro database or adding data to it. In the next stage, the user can select an appropriate method for the type of environmental impact of interest. The Eco-Indicator 99 v2.05 method used in this study examines the environmental impacts involved in three principal categories (health effects, ecosystem effects and resource conservation). As discussed in a later section of this report, the effect on climate change is one of the categories that were found to be important in this study. The SimaPro program generates a bar chart where all impacts are weighted, by means of appropriate weighting factors, and then integrates these impacts into one number for each of the products or processes under comparison. More detailed information about this software program and methodology can be found on the SimaPro website (PRE Consultants, 2009).

Most of the data and also the methodology used in this study are generated from studies done in Europe. Where possible, American databases (Franklin USA 98) were used in the LCA, but it is important to note that some health and ecosystem effects can be over or underestimated due to a difference in factors like: population density, local vegetation species and specific weather conditions affecting the concentration distribution. Because of limitations in available weighting and normalization values for the United States, this study uses the European factors.

The focus in this study is on the resource uses and air emissions from the operations. This is because the emissions to groundwater and soil are negligible in modern disposal facilities as is discussed in Sections 1.2 and 2.2.

Table 1
Average composition and heating value of yard wastes in the US (after Tchobanoglous et al., 1993).

%	Moisture	Volatile matter	Fixed carbon	Non-combustible	kJ/kg as collected
Yard wastes	60	30	9.5	0.5	6050

Table 2
Major chemical elements in typical dry yard wastes in the US (Tchobanoglous et al., 1993).

%	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur
Yard wastes	46	6	38	3.4	0.3

The functional unit use in this study was one Mg (metric ton) of source-separated yard wastes (also called “green wastes”). The typical composition and calorific value of yard wastes are shown in Table 1; the typical elemental composition is shown in Table 2.

The chemical composition of yard wastes can be calculated from the fractional mass composition shown in Table 2 and the atomic weights of the elements:

$$(C_{3.83}H_{5.95}O_{2.38}N_{0.24}S_{0.009})_n$$

2.1. Ammonification and nitrogen losses

The C:N ratio is an important parameter for ammonification to occur during composting. An initial C:N ratio of 20:1 to 40:1 is recommended for fast composting rates (Graves and Hattemer, 2000).

The carbon to nitrogen ration of yard wastes is calculated to be 15.8. Therefore, ammonia can be formed during windrow composting. In fact, an experimental study of composting yard wastes (Insam et al., 2002) showed that 4–35% of the initial nitrogen content was emitted as ammonia. Projecting this to the nitrogen available in one Mg of yard waste in this study (34 kg-N per dry Mg of yard waste, i.e. 13.6 kg-N per wet Mg), showed that between 0.54 and 4.76 kg of ammonia may be emitted. In this study, ammonia emissions have ecological environmental impacts in the eutrophication/acidification categories and, also, in the respiratory inorganics category of health impacts.

2.2. System boundaries of the methods and software inputs

2.2.1. Windrow composting

The boundaries set in the yard waste composting facility (YWCF) in the study by Komilis and Ham (2004) are shown in the flowsheet of Fig. 1.

The total energy requirements are 29 kWh/Mg and include fuel (71%) and electricity (29%); this compares to the 19.7 kWh of energy needed per Mg of feedstock reported by White et al. (1995). It should be noted that the state-of-art in windrow composting includes a windrow turner and not a front end loader as was used in the study by Komilis and Ham. The use of a windrow turner would decrease the amount of fuel needed for operations, since it is far more effective than a simple front end loader. A study conducted by the Agtech Center (Nelson, 2010), showed that specialized windrow turners also provide a better compost product than agricultural front end loaders. Electricity is included in SimaPro as the average mix of US-generated electricity and the fuel is assumed to be diesel. The associated diesel emissions are included in the airborne emissions. The air emissions inventory is shown in Table 3.

Table 3 shows that 2.5 kg of ammonia were released per 1000 kg of yard waste. This is approximately 18% of the initial nitrogen mass in the feedstock. Waterborne emissions were also obtained from the same study (Table 4).

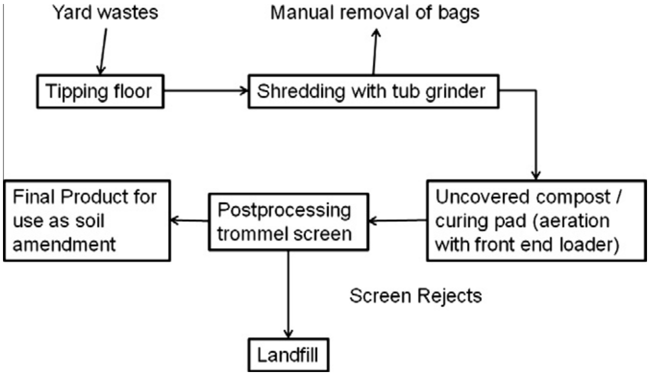

Fig. 1. Overview of the yard waste composting facility process. The yard wastes first pass the tipping floor, then they are shredded and bags are removed. After that, the actual composting takes place and thereafter, screen rejects are removed (Komilis and Ham, 2004).

Table 3
Air emissions per Mg of yard waste feedstock, obtained from life-cycle inventory of Komilis and Ham (2004).

Emissions to air	Amount (kg)
Particulates	0.018
Nitrogen oxides	0.16
Hydrocarbons, unspecified	0.035
Sulfur dioxide	0.035
Carbon monoxide	0.082
Carbon dioxide, biogenic	350
Carbon dioxide, fossil	7.3
Ammonia	2.5
Hydrogen chloride	2.5×10^{-7}
Methane, biogenic	2.3×10^{-5}
Lead	2.3×10^{-9}

Table 4
Water emissions per Mg of yard waste feedstock, obtained from the life-cycle inventory of Komilis and Ham.

Emissions to water	Amount (kg)
Suspended solids, unspecified	2×10^{-5}
Solved solids	0.021
BOD5, Biological Oxygen Demand	2.1×10^{-5}
COD, Chemical Oxygen Demand	1×10^{-4}
Oils, unspecified	2.5×10^{-4}
Sulfuric acid	1.5×10^{-3}
Iron	3.7×10^{-4}
Chromium	6.9×10^{-9}
Lead	3.1×10^{-9}
Zinc	4.5×10^{-8}
Solids, inorganic	0.26

These emissions are associated with the combustion of fuel and electricity use. It is assumed that this windrow composting plant has a leachate collection system that stores the slurry waste in a pond or an enclosed vessel before it is treated.

2.2.1.1. Avoided production of fertilizer. The compost product of windrow composting can be used as soil conditioner/fertilizer. This has a beneficial effect on the overall environmental impact of a process, since the production of chemical fertilizers consumes chemicals and energy. The effectiveness of the compost product can be compared to that of an average fertilizer, taking into account the release rate of the nutrients and accounting for the elements by means of a mass balance: Assuming a mass loss for windrow composting of 20% from the initial feedstock (Breitenbeck and Schellinger, 2004), a moisture content (by mass) of 34.8% for the compost product (White et al., 1995), and mass percentages of N, P, and K nutrients of 2%, 0.3% and 0.8%, respectively (Cogger et al., 2002). To account for the lower availability of the nutrients in compost material compared to fertilizer, an additional factor of 0.3 is applied to the nutrient content (Levis, 2008). In this way, the effectiveness of the compost product can be compared to a typical synthetic fertilizer. Fertilizers are usually characterized by means of their "NPK number", which denotes their nitrogen (as N), phosphorus (as P_2O_5) and potassium (as K_2O) content. For instance, taking into account the atomic weight of the three elements, a (17–17–17) fertilizer contains 17% N, 7.4% P and 14.1% K.

On the basis of the above numbers, it is calculated that one Mg of wet yard waste would yield a fertilizer with an 0.7–0.2–0.3 NPK number. This is 51 times less effective on a nutrient mass basis than a metric ton of (17–17–17) fertilizer. It is important in the LCA study to include the fact that the use of compost replaces fertilizers. Therefore, the calculated mass of each nutrient in fertilizer that is avoided, because of the use of compost, is entered in the SimaPro analysis. Table 5 shows the avoided products for each element.

Favoino and Hogg (2008) estimated that one Mg of dry matter compost product would replace 19 kg N fertilizer and, of course, avoid the use of energy needed for the production of the fertilizer. Assuming a mass loss of 20% during the composting process, he found that 15.2 kg N fertilizer would be replaced by 1 Mg of input feedstock. If Favoino had taken into account the lower availability of compost fertilizer and calculated this figure on a wet product basis, at 34.8% moisture content by mass (White et al., 1995), the 15.2 kg N would be reduced to 3.3 kg N. This compares well with the 3.5 kg N calculated in the model used for this study.

In addition to its nutrient value, compost has other benefits including increased soil organic matter and water holding capacity, and reduced pesticide requirements (Favoino and Hogg, 2008). While important and recognized, these benefits could not be quantified in this analysis.

2.2.2. Use of yard wastes as alternative daily cover

This method was assessed by looking at the differences between use of soil or of yard wastes as alternative daily cover in a landfill. The major factors of resource and energy use are included in this study by using an air emission model, estimates for soil excavation and avoided fossil fuel burning.

2.2.2.1. Air emissions and landfill gas collection. Much of the biogas generated in sanitary landfills (LFG) can be captured and used in a gas engine or turbine to generate electricity. The yard waste that is used as ADC in a landfill also decays partially and generates biogas. In order to determine the fraction of the yield of methane that can be expected from the yard waste, a decay model was used. Methane production was calculated by using the same formulation as used by the US EPA in the landfill gas emissions model (LandGem) (US EPA, 2005). The model considers three constituents of yard waste: grass (40%), leaves (40%) and branches (20%). All were assumed to contain 50% moisture by mass.

Table 5
Avoided products of the compost product of one Mg of yard waste processed in the windrow composting facility.

Fertilizer effectiveness (avoided products) of windrow compost product	Amount (kg) per Mg of feedstock
Fertilizer (N)	3.5
Fertilizer (P)	0.5
Fertilizer (K)	1.4

The decay function is expressed as follows:

$$Q_n = k \cdot L_0 \cdot \sum_{i=0}^{n} \sum_{j=0.0}^{0.9} \frac{M_i}{10} \cdot e^{-k \cdot t_{i,j}} \quad (1)$$

where Q_n is the CH_4 generation rate ($m^3\ yr^{-1}$) in year n; k is the waste decay rate (yr^{-1}); L_0 is the CH_4 generation potential (m^3 CH_4 Mg^{-1} wet waste); M_i is waste mass placement in year i (Mg); j is the deci-year time increment; and t is time (yr). For this application, the model was only run for the deposition of one year's waste. The used L_0 and k for the components are displayed in Table 6.

The modeled landfill in this study is assumed to have a landfill gas collection system installed two years after the cell is covered. Eight ADC layers are deposited before the final cover is placed and the gas collection system is installed. The working landfill cells are assumed to be filled evenly at the rate of 1500 Mg/day, and cover a total area of 19 hectares (47 acres). With a total capacity of roughly 4.6 million cubic meters (6 million cubic yards) it will take approximately four years to fill up this cell. The collection of landfill gas in this time period is assumed to increase incrementally: During the first two years, gases (methane and carbon dioxide) generated by the decay process are emitted to the atmosphere; in the third year, 25% of the gases are collected and the rest are emitted; in the fourth year, the collection efficiency is 50%; after the fourth year, 75% is collected and this continues until the end of the modeled time frame (20 years). This system of phased collection is representative of current practice at landfills in the United States (Barlaz et al., 2009).

Especially because most of the methane is generated in the first years of the degradation process, it is important to take this into account. This was not done in a study by the research group of Los Angeles County Sanitation District (LACSD, 2008) who assumed an overall LFG collection efficiency of 91%.

Table 6
Methane generation potential (L_0), decay rate (k) and carbon storage factor (CSF) for the three components of yard waste.

Component:	L_0 (l/dry kg)	k (yr^{-1})	CSF (kg C/kg dry mass)
Grass	135.9	0.233	0.24
Leaves	43.7	0.017	0.335
Branches	62.6	0.003	0.38

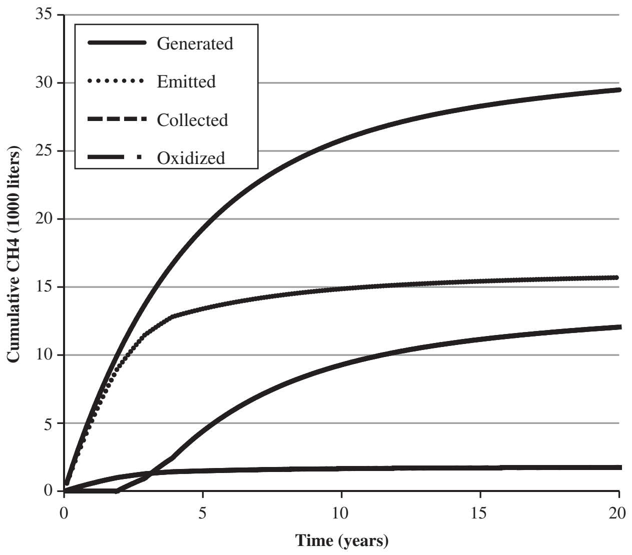

Fig. 2. Proportion of landfill gas generated, emitted, oxidized and collected over a time period of 20 years per kg of feedstock (using LFG generation model based on US EPA LandGEM).

The results from the model (Fig. 2) show that, per Mg of yard waste, 15,690 l of methane are emitted into the air and 12,100 l are collected, over 20 years. A small fraction (10%) of the generated methane is assumed to be oxidized in the process. The collected gas corresponds to 458 MJ of thermal energy in the form of natural gas.

According to the model and assuming that LFG contains equal volumes of CH_4 and CO_2, 54.5 kg of CO_2 are emitted per Mg of yard waste. Part of the carbon content of the yard waste is stored in the landfill. The total stored carbon was determined using the carbon storage factor (CSF) for each component (Table 6). This results in 153 kg-C stored/Mg wet yard waste. In the software, this is accounted for by adding 561 kg of stored CO_2, using a factor of (44/12) to convert C to CO_2.

It should be noted that there will be some emissions of trace gases associated with the anaerobic decomposition of yard waste as documented in Staley et al. (2006). However, these emissions were not included in our analysis. There is huge uncertainty in emissions from volatiles and so quantification would not necessarily improve the overall analysis.

2.2.2.2. Avoided soil excavation. When yard wastes are used as a daily cover instead of soil, the excavation of soil is avoided. The required thickness of the daily cover is 15 cm (6-in.) for soil and 22.5 cm (9-in.) for source-separated yard waste (SSYW) (EPA, 2009). Because of the large difference in bulk density of soil and SSYW, the use of SSYW represents a considerable saving in energy and labor. With a yard waste and soil density of 200 kg/m^3 (Theodore et al., 2008) and 1600 kg/m^3 (Blouin et al., 2004), respectively, 3.3 m^3 of soil are avoided for each metric ton of yard waste used as ADC. In terms of tonnages in the landfill, this would mean that the mass ratio of cover to MSW is reduced from 1:4.5 for soil, to about 1:27 for yard waste. These ratios are derived by assuming a covered MSW layer of 1.35 m and we assumed a 9:1 MSW to soil volume ratio.

2.3. Results

The above inventories of emissions and energy uses were included in the Life-Cycle Analysis. A summary of the inputs can be found in the Appendix A. The result is the impact assessment of windrow composting and ADC use of yard wastes as ADC shown in Fig. 3 below. SimaPro converted the emissions and energy uses to environmental impact categories according to Eco-Indicator 99 and the different methods can be compared in this way. The y-axis of the figure is expressed in terms of Ecopoints, a means of measuring different kinds of environmental impacts. One hundred Ecopoints are defined as the total environmental burden ("damage") caused by an average European citizen over the course of one year. The thick black horizontal line is the zero-line, which denotes what effects are beneficial for the environment (below the zero-line) and what are the damages to the environment (above the zero-line). The impact categories that are significant in the results are:

- Respiratory inorganics: damage to respiratory system resulting from winter smog, caused by dust, NO_x and SO_x emissions
- Fossil fuels: resource depletion of fossil fuels
- Acidification/eutrophication: damage to ecosystem quality, as a result of emissions of acidifying substances to air
- Climate change: damage resulting from an increase of diseases and death caused by climate change.

Information on these and other impact categories can be found in the SimaPro Database manual (PRE Consultants, 2008).

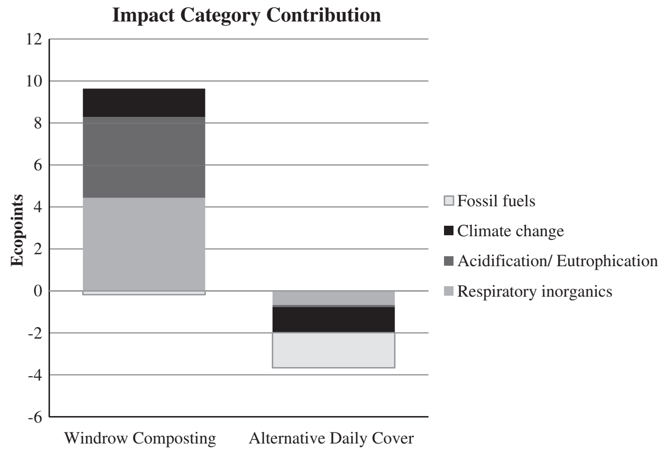

Fig. 3. Categorized results of the environmental impact assessment of the windrow composting (left) and ADC method (right). Bars above the zero-line represent environmental burdens, bars below represent benefits. The smallest contributing categories have been left out.

Table 7
Process contributions, in 'EcoPoints', to environmental impact scores of windrow composting and ADC use of yard wastes. Negative values represent environmental benefits.

Substance	Compartment	Windrow Composting	Alternative daily cover
Ammonia	Output air	7.85	0.00
Carbon dioxide, in air (sequestration)	Input raw	0.00	−2.29
Natural gas, 46.8 MJ per kg	Input raw	0.07	−1.55
Carbon dioxide, biogenic	Output air	1.43	0.22
Methane, biogenic	Output air	0.00	0.96
Sulfur oxides	Output air	0.06	−0.45
Energy, from natural gas	Input raw	−0.43	0.00
Nitrogen oxides	Output air	0.32	−0.26
Oil, crude, 42 MJ per kg, in ground	Input raw	0.20	−0.02
Remaining substances		−0.03	−0.25
Total		9.46	−3.64

Fig. 3 presents in graphical form the results of the Life-Cycle Analysis using the SimaPro program.

Using yard waste as an alternative daily cover (ADC) has a lower overall environmental impact than windrow composting. Methane emission in the first two years of operation is the main contributor to negative impact on the environment. Table 7 shows the individual scores of each process and the list of contributions to the total scores by each process. It can be seen that ammonia (2.5 kg air emissions) is the biggest contributor in the windrow composting scenario.

The lower carbon dioxide emission from landfilling is due to the fact that not all carbon is reacted in a landfill. The benefit from extracted landfill gas is that it replaces natural gas from fossil fuels (Natural gas, 46.8 MJ per kg). As stated earlier, the heating value of the extracted landfill gas is 458 MJ/Mg of yard waste and this results in a −1.55 Ecopoint contribution to the ADC scenario. Similarly, the negative number for 'Energy, from natural gas' in the windrow composting scenario is due to the avoidance of using fossil fuel in the production of fertilizers. The −0.45 contribution to ADC from sulfur oxides is due to the avoided use of fossil fuels from the collected landfill gas.

The impact on climate change for both methods is found to favor the use of ADC (−255 kg CO_2-eq) versus windrow composting (333 kg CO_2-eq) using the IPCC 100 yr Global Warming Potential (PRE Consultants, 2008). Carbon storage of the yard waste is the biggest contributor: without accounting for the storage in the landfill, the climate change impacts are approximately the same. The difference in climate change impact is in line with an earlier study by the Los Angeles County Sanitation District where they reported emission reductions for the ADC method to be 7–8 times higher than for windrow composting. However, in that study, fugitive methane emissions from ADC practices were not taken into account and they assumed a 91% landfill gas collection efficiency (LACSD, 2008). In addition, the LACSD study assumed that windrow composting contributed to methane emissions, while the studies quoted earlier in this paper showed that with adequate turning of the piles, methane emissions from windrows are very low.

3. Cost comparison of windrow composting and ADC use

In addition to comparing the environmental impact of these two methods of organic waste processing, it is essential to also put these methods side by side in terms of capital and operating costs. The final unit of comparison for each technology is $/metric ton of feedstock. This number includes repayment of the capital cost of the plant (annualized over 15 years at an assumed 6% interest rate) plus operating and maintenance (O&M) costs.

The capital cost per Mg of processing capacity usually decreases with annual throughput. In this case, an annual capacity of 40,000 metric tons/year was assumed. Costs were divided into initial investment and O&M and costs. Because of the lack of data, assumptions were made about cost categories using data available from other systems. The costs of the land are included under the category 'Site Lease'. Tipping fees for both landfills and composting plants are subject to local land costs. For a fair assessment, it was assumed that both the composting plant as well as the landfill are located in a similar region, in terms of site lease and land costs. The final results of the calculations were then compared with sources found in composting reports and surveys. The revenue from the end product of windrow composting was not taken into account in this study, since the quality of the products of various composting technologies differ widely from plant to plant, as do the prices for which the end products are sold.

3.1. Costs of windrow composting

Turned windrow composting is common practice in the US. However, some plants are more sophisticated than others and therefore investment costs range considerably. For instance, preparation of the site that includes paving is a significant part of the total investment but it is not a necessity for a composting plant. Komilis and Ham (2004) reported paving costs of $180,000 per hectare for a 100 Mg/day composting plant. About 5.5 hectares were used for the plant so the total paving job was $1,000,000, amounting to a third of the total cost. Of course, paving and effluent containment lowers the potential environmental impact of the facility. The same study was used as a source of data for the LCA study, so the costs are in line with the damage assessment. Table 8 shows the different cost categories adapted to a 110 Mg/day facility (or approximately 40,000 metric tons per year).

The total cost for a 40,000 Mg/year plant was then annualized assuming a 15 year lifetime and 6% interest of repayment. This resulted in a total cash flow of $5,635,000. In order to calculate the dollars per Mg, this amount was divided by the total tonnage processed in the plant's lifetime, resulting to about $9/Mg. Note that this does not include the cost for land property, which is included in the O&M costs discussed below.

Table 8
Breakdown of costs for the windrow composting method for a 110 Mg/day facility (Komilis and Ham, 2004).

Capital cost category	Cost
Paving	$1,100,000
Grading	$82,500
Fencing	$22,000
Building	$550,000
Leachate system	$110,000
Engineering cost	$550,000
Tub grinder	$275,000
Windrow turner	$220,000
Legal	$165,000
Screens	$220,000
Front end loader	$198,000
Total	$3,492,500

Table 9
Operation and maintenance costs for a 40,000 Mg/year windrow composting plant.

O&M cost category	Cost
Labor	$187,000
Overhead	$77,000
Windrow turner	$27,500
Tub grinder	$55,000
Screens	$5500
Front end loader	$5500
Building	$5500
Site lease	$110,000
Total	$473,000

Table 11
Capital and operation and maintenance (O&M) costs per metric ton of handled waste for the two different methods.

Cost per Mg of input feedstock ($)	Windrow composting	Alternative daily cover on landfill
Capital cost	9	Included
O&M cost	12	Included
Total cost per Mg	21	14 (tipping fee)

Operation and maintenance for a 40,000 Mg/year windrow composting add up to about $473,000 annually, or $12/Mg. Labor (including overhead) and site lease are the biggest contributors to the operation costs with amounts of $264,000 and $110,000, respectively. Table 9 shows the O&M costs of such a facility.

The range of costs in windrow composting was studied by Steuteville and reported in the magazine BioCycle in 1995 (Steuteville, 1995). Although the data is outdated, it shows the difference in costs per Mg due to extra steps in the process (shredding and screening). Displayed below is a table with the results of his survey. The total cost per Mg in our analysis amounts to $21 per Mg, which is in line with the values for facilities equipped with screening and shredding in Steuteville (see Table 10).

3.2. Costs of using yard wastes as ADC

For the ADC scenario, there is no need to build a plant to process the waste. The method replaces the use of soil in a landfill with waste. For the landfill owner, this means that there is no need to dig up as much soil, plus there is more landfill space to use in an existing landfill. Two separate streams of waste go into the landfill, municipal solid waste (MSW) and source-separated yard waste (ADC). These materials are charged different tipping fees. For example, a landfill in Azusa, California, charges $14/Mg for incoming yard waste that is used as ADC (Azusa, 2009). At the Sycamore landfill, tipping fees for yard wastes are much higher: $35/Mg. At the San Diego Miramar landfill, the gate fee is $22/Mg for yard wastes (Sycamore and Miramar landfill, 2010). In comparison, the median MSW tipping fee in the year 2000 in California was $34/Mg (CIWMB, 2000).

With regard to the total cost of ADC scenario, it depends from what perspective costs are evaluated. If the company owns a landfill, then a decision to use yard waste as ADC can save in capital and operating costs for heavy machinery. Less soil excavators and dump trucks will be needed and the front end loaders and landfill crawlers used to spread out the daily cover will keep their function but they will be spreading out a different material. Typical prices of soil excavators and dump trucks are $250,000 (Caterpillar 345 CL excavator) and $100,000 (Caterpillar 740 Articulated Dump truck) (ironplanet.com, 2009). According to EMCON, the cost to import and place soil on a landfill is about $2 per cubic yard (EMCON, 1997). Assuming a 1-million cubic yard landfill, approximately $500,000 would be spent on depositing soil. Shredding of MSW typically costs $8/Mg, with approximately $4/Mg for both O&M and capital costs (Fitzgerald, 2009).

The value of space in a landfill is also important in considering the difference between using soil and ADC. With a $30/Mg tipping fee for MSW at a 1 million cubic yard landfill, the value of the space saved by using ADC is approximately $3,000,000 (assuming refuse to soil ratio increase from 4:1 to 9:1) (Haughey, 2001). In addition, the landfill owner can charge a tipping fee for the incoming yard waste, as in the case of the landfills mentioned earlier.

If the landfill is not owned by the waste managing company, the yard waste can be brought to the closest landfill. A tipping fee of $14/Mg is assumed for the total costs (like the Azusa, CA landfill) for the ADC scenario, without including transport costs.

The capital costs and O&M costs of the processing methods are shown in Table 11.

The ADC method has the lowest cost ($14/Mg). This figure is the yard waste tipping fee of a typical landfill in California. However, from the perspective of the landfill owner, the use of yard waste as daily cover will actually result in additional revenues, because of the increased refuse capacity and the lower use of soil, in combination with a tipping fee as an extra income.

Table 10
Results of a cost survey done on composting plants in BioCycle magazine (Steuteville, 1995).

Facility	Throughput (Mg/yr)	Operating ($/Mg)	Capital ($/Mg)	Total ($/Mg)	Description
Atlantic Co., NJ	22,000	11.8	10.2	22	Materials shredded and screened
Bozeman, MT	2000	6.5	1.5	8	No shredding or screening
Bluestem SWA, IA	70,000	7	4.2	11.2	All materials shredded and screened
Des Moines, IA	23,500	n/a	n/a	20–25	All materials shredded, most screened
Lehigh County, PA	17,000	8.1	10.4	18.5	Only brush shredded, most screened
St. Petersburg, FL	16,600	n/a	n/a	25.6	Composted mulch
Three Rivers, MI	2700	n/a	n/a	17.2	Materials shredded, not screened

4. Conclusions

This LCA study has shown that the use of yard waste as alternative daily cover (ADC) in place of soil is environmentally preferable to windrow composting because it avoids the excavation and use of soil as ADC and also ammonia emissions to the atmosphere. Besides that, sequestered carbon in the landfill contributes beneficially to climate change. The avoided fossil fuel use, for digging up and moving the soil, is of nearly the same magnitude as the composting benefit of avoiding the manufacturing of fertilizer replaced by the compost product minus the fossil fuel use in windrow composting. Of course, this finding applies only in cases where there are sanitary landfills in the area that 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.

The effects of the transportation of yard wastes, either to composting facilities or to landfills, were assumed to be the same and thus were not included in the LCA comparison. However, preliminary calculations showed that transport is a minor contributor to the overall impact assessment. For example, the biogenic emissions from biodegradation are far greater than the emissions associated with trucking the wastes a distance of 100 km.

The effect of avoided fertilizer production on the overall score was found to be smaller than 10%, or 0.7 EcoPoints. The uncertainty in the factor of 0.3 that was applied to account for the lower nutrient availability is therefore of only minor effect to the overall result.

Also, in this study it was assumed that in the ADC scenario yard wastes would replace a six-inch layer of soil. However, in some US landfills tarpaulins or other types of ADC are being used instead of soil. LCA comparison of ADC with such covers was beyond the scope of this study.

In terms of costs, the alternative daily cover method is less costly than windrow composting. The biggest factor is the need for a new facility in windrow composting, while the ADC scenario merely replaces the use of soil on a landfill. Despite the wide range in landfill gate fees tipping fees ($14–$35 per Mg), the actual cost of yard waste disposal in a landfill is less than that of windrow composting.

Acknowledgements

The authors gratefully acknowledge sponsorship of this study by the Council for Sustainable Use of Resources (www.surcouncil.org) and the Earth Engineering Center of Columbia University (www.eecny.org).

Appendix A

The assumed inputs for windrow composting and ADC use of yard wastes are shown below. The method used is Eco-Indicator 99 (E) V2.05/Europe EI 99 E/E. Software: SimaPro 7.

SimaPro 7 LCA input entries, respective amounts, and source database.

Entry	Amount	Unit	Database
Yard waste windrow composting	1000	kg	
Avoided products			
Fertilizer (N)	3.47	kg	LCA Food DK
Fertilizer (P)	0.53	kg	LCA Food DK
Fertilizer (K)	1.4	kg	LCA Food DK
Materials/fuels			
Diesel, burned in diesel-electric generating set/GLO S	20.59	kWh	EcoInvent
Electricity/heat			
Electricity avg. kWh USA	8.41	kWh	Franklin USA 98
Emissions to air			
Particulates	0.018	kg	Undefined
Nitrogen oxides	0.16	kg	Undefined
Hydrocarbons, unspecified	0.035	kg	Undefined
Sulfur dioxide	0.035	kg	Undefined
Carbon monoxide	0.082	kg	Undefined
Carbon dioxide, biogenic	350	kg	Undefined
Carbon dioxide, fossil	7.3	kg	Undefined
Ammonia	2.5	kg	Undefined
Hydrogen chloride	2.50*E*−07	kg	Undefined
Methane, biogenic	0.000023	kg	Undefined
Lead	2.30*E*−09	kg	Undefined
Emissions to water			
Suspended solids, unspecified	0.00002	kg	Undefined
Solved solids	0.021	kg	Undefined
BOD5, Biological Oxygen Demand	0.000021	kg	Undefined
COD, Chemical Oxygen Demand	0.0001	kg	Undefined
Oils, unspecified	0.00025	kg	Undefined
Sulfuric acid	0.0015	kg	Undefined
Iron	0.00037	kg	Undefined
Ammonia	2.90*E*−06	kg	Undefined
Chromium	6.90*E*−09	kg	Undefined
Lead	3.10*E*−09	kg	Undefined
Zinc	4.50*E*−08	kg	Undefined
Solids, inorganic	0.26	kg	Undefined
Yard waste as alternative daily cover on landfill	1000	kg	All waste types
Inputs from nature			
Carbon dioxide, from air	561	kg	Undefined
Avoided products			
Excavation, skid-steer loader/RER S	3.3	m^3	EcoInvent
Heat from nat. gas FAL	458	MJ	Franklin USA 98
Emissions to air			
Methane, biogenic	11.24	kg	Undefined
Carbon dioxide, biogenic	54.5	kg	Undefined

References

Barlaz, M.A., Chanton, J.P., Hater, G.R., 2009. Controls on landfill gas collection efficiency: instantaneous and lifetime performance. J. Air Waste Manag. Assoc. 59, 1399–1404.

Blouin, V., Schmidt, M., Bulmer, C., Krzic, M., 2004. Soil compaction and water content effects on lodgepole pine seedling growth in British Columbia, SuperSoil Conf.

Breitenbeck, G.A., Schellinger, D., 2004. Calculating the reduction in material mass and volume during composting. Compost Sci. Util. 12 (4).

CIWMB, California Integrated Waste Management Board, 2009. Alternative Daily Cover White Paper, Unpublished Results.

Cogger, C., Bary, A., Sullivan, D.M., 2002. Fertilizing with Yard Trimmings. Washington State University Cooperative Extension.

EMCON, 1997. City of Burbank Landfill No. 3, Alternative Daily Cover Application, June 24.

Favoino, E., Hogg, D., 2008. The potential role of composting in reducing greenhouse gases. Waste Manag. Res. 26, 61–69.

Fitzgerald, G.C., 2009. Technical and Economic Analysis of Pre-shredding Municipal Solid Wastes Prior to Disposal. MS Thesis, Columbia University, Unpublished Results.

Graves, R.E., Hattemer, G.M., 2000. National Engineering Handbook, Ch 2: “Composting”, United States Department of Agriculture (USDA), Washington, DC.

van Haaren, R., 2009. Large Scale Aerobic Composting of Source Separated Organic Wastes: A Comparative Study of Environmental Impacts, Costs, and Contextual Effects. MS Thesis, Columbia University, Unpublished Results.

Haughey, R.D., 2001. Landfill alternative daily cover: conserving airspace and reducing landfill operating cost. J. Waste Manag. Res. 19, 89–95.

Insam, H., Riddech, N., Klammer, S., 2002. Microbiology of Composting. Springer-Verlag, Berlin.

Kaufman, S.M., Themelis, N.J., 2009. Using a direct method to characterize and measure flows of municipal solid waste in the United States. J. Air Waste Manag. Assoc. 59, 1386–1390.

Komilis, D., Ham, R., 2004. Life-cycle inventory of municipal solid waste and yard waste windrow composting in the United States. J. Environ. Eng. 130 (11), 1390–1400.

LACSD, Los Angeles County Sanitation District, 2008. Evaluation of Green Waste Management Impacts on GHG Emissions: Alternative Daily Cover Compared with Composting, Unpublished Results.

Levis, J.W., 2008. A Life-Cycle Analysis of Alternatives for the Management of Waste Hot-Mix Asphalt, Commercial Food Waste, and Construction and Demolition Waste. MS Thesis, North Carolina State University, Unpublished Results.

Staley, B.F., Xu, F., Cowie, S.J., Barlaz, M.A., Hater, G.R., 2006. Release of trace organic compounds during the decomposition of municipal solid waste compounds. Environ. Sci. Technol. 40 (19), 5984–5991.

Steuteville, R., 1995. How much does it cost to compost yard trimmings. BioCycle 37 (9), 39–40.

Sycamore and Miramar landfill, 2010. Phone Interviews with Operating Personnel on January 8th, 2010, Personal Communication.

Tchobanoglous, G., Theisen, H., Vigil, S.A., 1993. Integrated Solid Waste Management: Engineering Principles and Management Issues. McGraw-Hill Education.

Theodore, L., Weiss, K.N., McKenna, J.D., Smith, F.L., Sharp, R.R., Santoleri, J.J., McGowan, T.F., 2008. Perry’s Chemical Engineers’ Handbook, 8 ed. McGraw-Hill (Section 8).

US Environmental Protection Agency, 2005. Landfill Gas Emissions Model (LandGEM) Version 3.02 User’s Guide, Washington, DC.

White, P., Franke, M., Hindle, P., 1995. Integrated Solid Waste Management: A Lifecycle Inventory. Blackie Academic & Professional, London, New York.

Web references

Azusa landfill, 2009. Solid Waste and Recycling Economic and Strategic Study. <http://www.ci.azusa.ca.us/DocumentView.aspx?DID=1953> (Last accessed February 2010).

CIWMB, 2000. CIWMB, California Integrated Waste Management Board, Landfill Tipping Fees. <http://www.calrecycle.ca.gov/Profiles/Facility/Landfill/LFProfile1.asp?COID=1&FACID=01-AA-0009> (Last accessed April 2010).

EPA 2009, Environmental Protection Agency. <http://www.epa.gov/osw/nonhaz/municipal/landfill/rev-rule/dailycov.txt> (Last accessed February 2010). <http://www.epa.gov/landfill/faq-1.htm#q7> (Last accessed February 2010).

Ironplanet.com, 2009. <http://www.ironplanet.com/jsp/find/searchresults.jsp?category=11&command=NewSearch&h=400> (Last Accessed January 2010).

Nelson, V., 2010. Assessment of Windrow Turners, Agtech Centre. <http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/eng9938> (Last accessed March 2010).

PRE Consultants, 2009. <http://www.pre.nl/eco-indicator99/eco-indicator_99.htm> (Last accessed: March 2010).

Stephens, 2007. ’Innovations’ Case Studies: Organics Options. http://www.ciwmb.ca.gov/LGlibrary/Innovations/Organics/Trimmings.htm (Last accessed March 2010).