

Projet d'aménagement d'un lieu d'enfouissement  
technique à Hébertville-Station

6212-03-052

De : Savoie, Patrice  
Date d'envoi : mercredi 5 juin 2013 15:49:42  
À : Poliquin, Renée (BAPE)  
Objet : TR : BAPE  
Transféré automatiquement par une règle

Bonjour,

Pour donner suite à votre demande du 30 mai (DQ16), veuillez trouver ci-joint la réponse ainsi qu'un document d'appui à celle-ci.

Bonne fin de journée!

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-----Message d'origine-----

De : Bourret, Michel  
Envoyé : 5 juin 2013 15:40  
À : Savoie, Patrice  
Cc : Trudel, Claude  
Objet : RE : BAPE

Bonjour Patrice,

Tu trouveras ci-joint un document de référence de l'USEPA portant sur le sujet questionné par le BAPE.

Selon ce rapport, un lieu de compostage n'émet pas de GES. Toujours selon ce rapport, un LET avec captage et brûlage ou valorisation du biogaz n'émet également pas de GES, il agirait même comme un puits d'emmagasinement du carbone.

La biométhanisation, réalisé en milieu fermé, avec valorisation du méthane généré n'émet pas non plus de GES, le méthane étant détruit à 100 %.

Ces données peuvent sembler surprenantes, mais à la lecture du rapport (chapitres 4 et 6), on comprend pourquoi c'est ainsi.

À+

Michel Bourret, ing. M.Sc.



# Solid Waste Management and Greenhouse Gases

A Life-Cycle Assessment of Emissions and Sinks

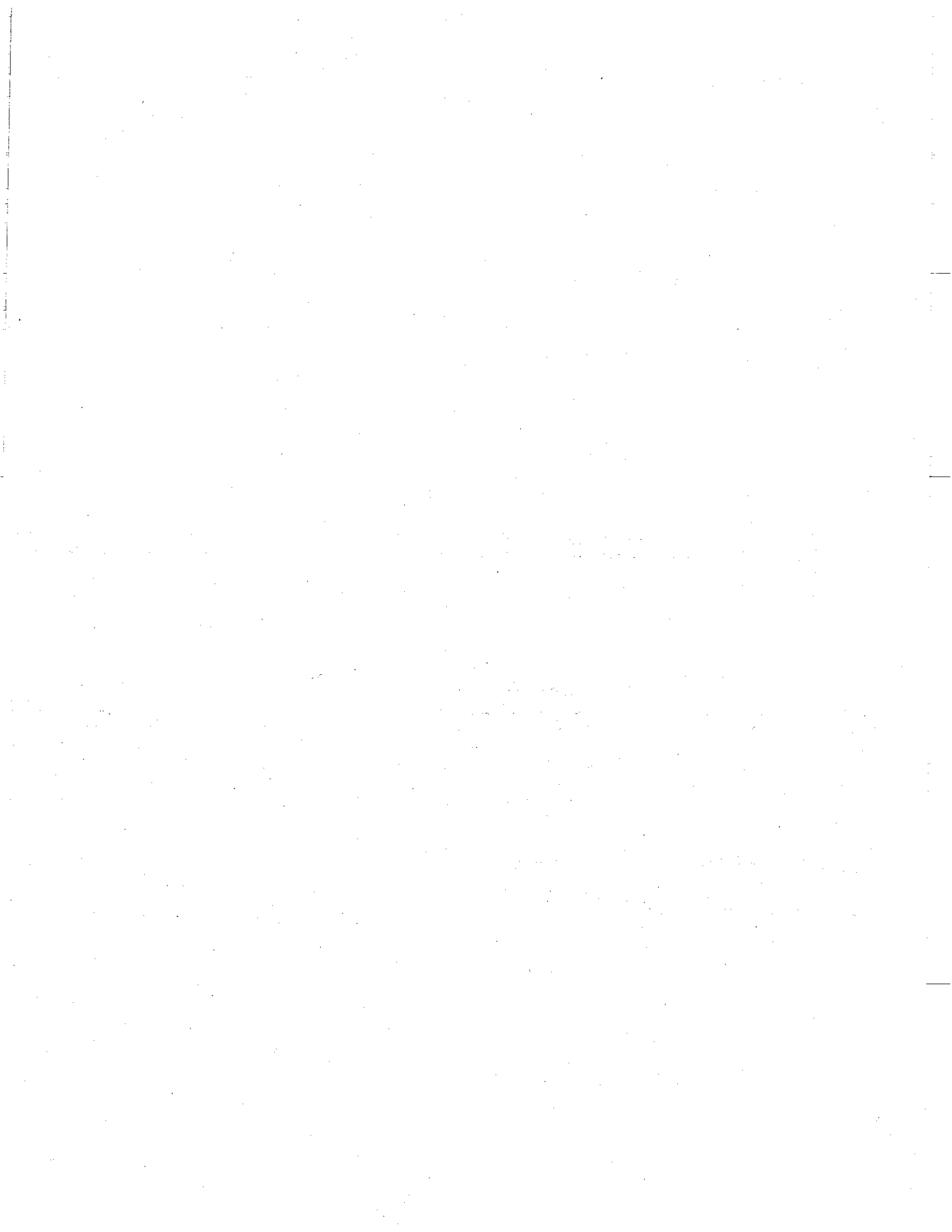
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RECYCLE

**SOLID WASTE MANAGEMENT AND GREENHOUSE GASES**  
**A Life-Cycle Assessment of Emissions and Sinks**

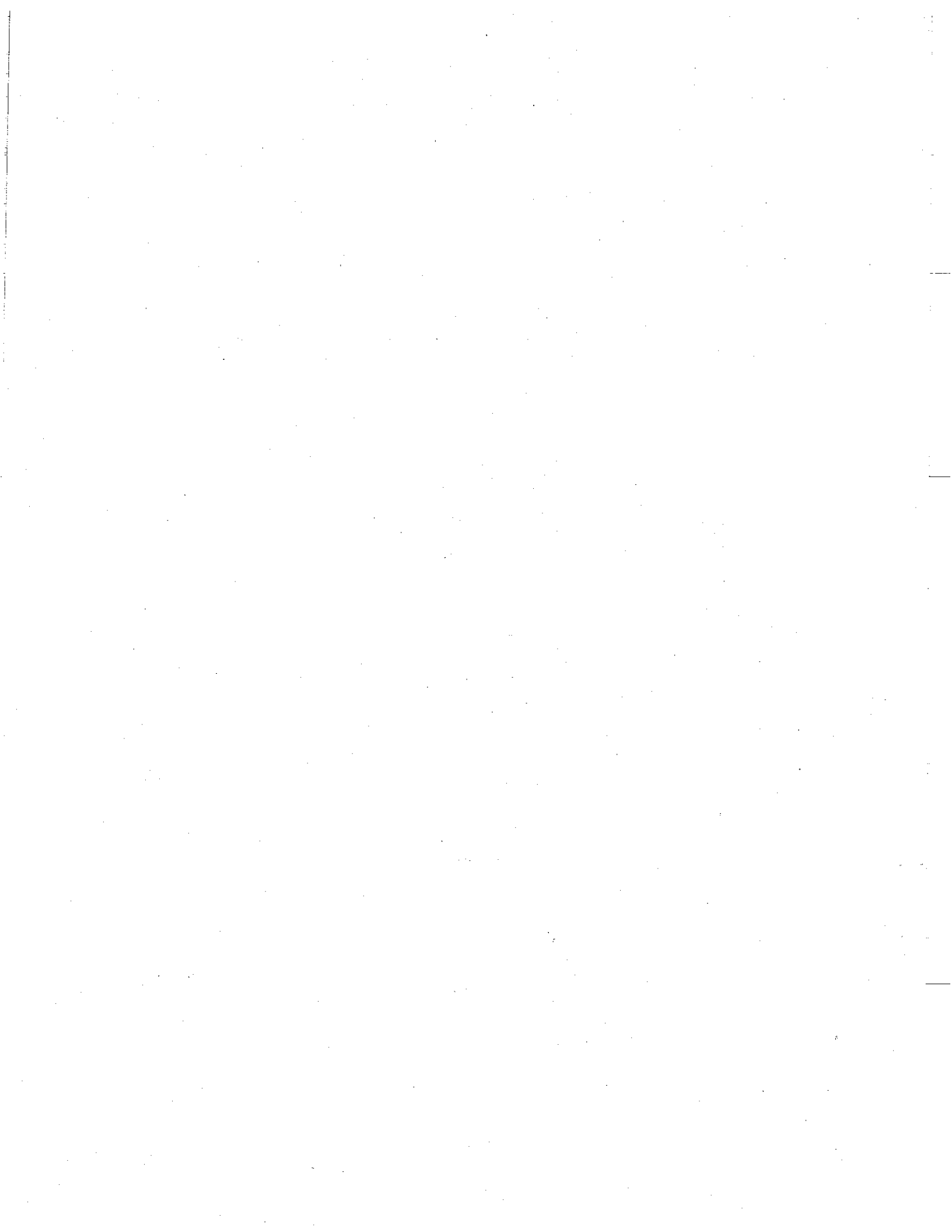
**3<sup>rd</sup> EDITION**

September 2006

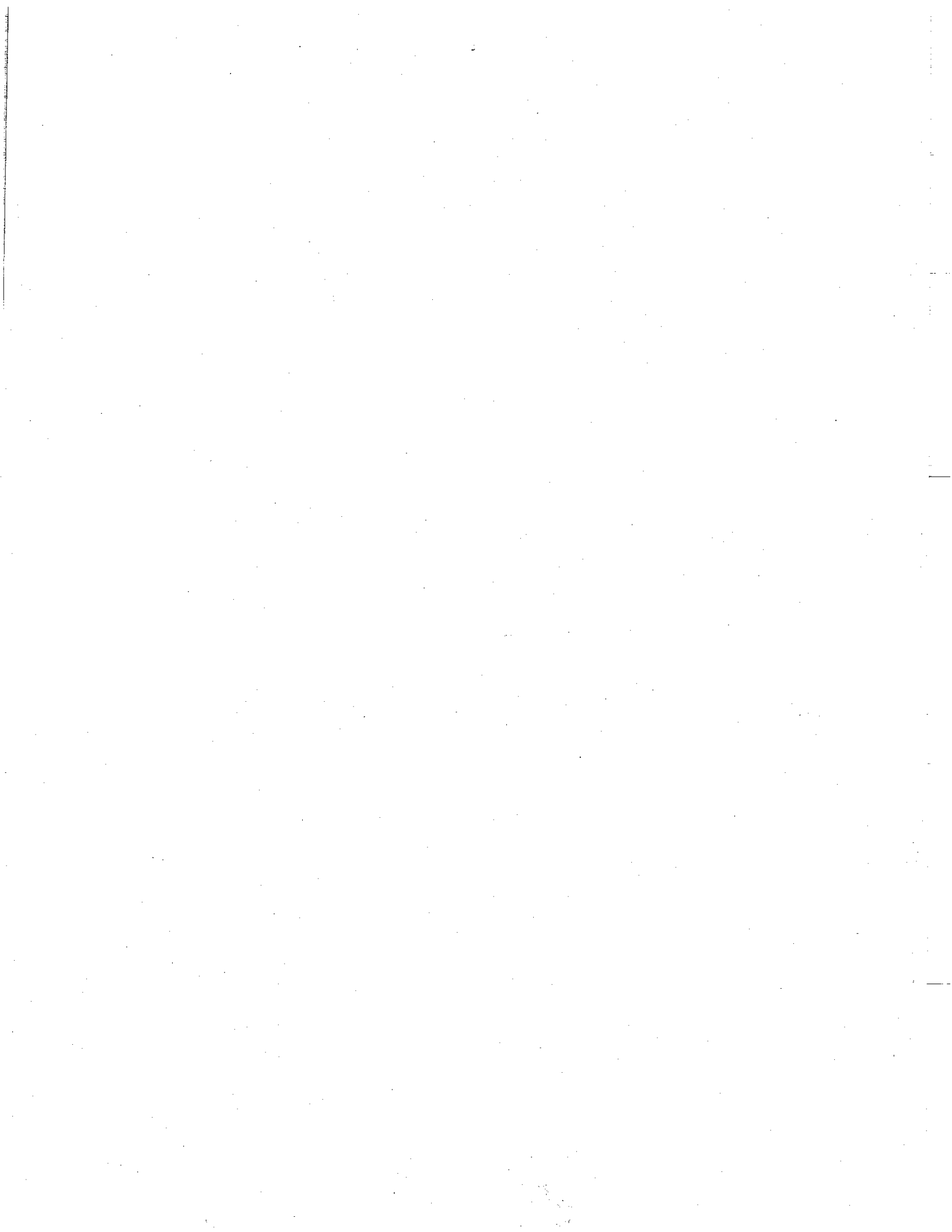


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## 4. COMPOSTING

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This chapter presents estimates of GHG emissions and sinks from composting yard trimmings and food discards (henceforth, organics).<sup>1</sup> It examines only emissions and sinks from centralized (e.g. municipal) composting, rather than from backyard composting or other localized composting operations. The chapter is organized as follows:

Section 4.1 presents an estimate of potential anthropogenic GHG emissions from composting;

Section 4.2 quantifies the potential carbon storage benefits of applying compost to soils;

Section 4.3 presents net GHG emissions from composting; and

Section 4.4 discusses the limitations of this analysis.

Composting may result in (1) CH<sub>4</sub> emissions from anaerobic decomposition; (2) long-term carbon storage in the form of undecomposed carbon compounds; and (3) nonbiogenic CO<sub>2</sub> emissions from collection and transportation of the organic materials to the central composting site, and from mechanical turning of the compost pile.<sup>2</sup> Composting also results in biogenic CO<sub>2</sub> emissions associated with decomposition, both during the composting process and after the compost is added to the soil. Because this CO<sub>2</sub> is biogenic in origin, however, it is not counted as a GHG in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*<sup>3</sup> (as explained in Section 1.4.2) and is not included in this accounting of emissions and sinks.

Research suggests that composting, when managed properly, does not generate CH<sub>4</sub> emissions, but it does result in some carbon storage (associated with application of compost to soils), as well as minimal CO<sub>2</sub> emissions from transportation and mechanical turning of the compost piles. In order to maintain consistency with other chapters in this report, EPA selected point estimates from the range of emission factors—covering various compost application rates and time periods—developed in the analysis. The point estimates were chosen based on a “typical” compost application rate of 20 tons of compost per acre, averaged over three soil-crop scenarios. The carbon storage values for the year 2010 were selected to be consistent with the time between onset of the program and carbon storage effect as simulated in the forest carbon storage estimates presented in Chapter 3 of this report. Overall, EPA estimates that centralized composting of organics results in net GHG storage of 0.05 MTCE/wet ton of organic inputs composted and applied to agricultural soil.

### 4.1 POTENTIAL GHG EMISSIONS

Two potential types of GHG emissions are associated with composting: (1) CH<sub>4</sub> from anaerobic decomposition, and (2) nonbiogenic CO<sub>2</sub> from transportation of compostable materials and turning of the compost piles.

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<sup>1</sup> Although paper and mixed MSW can be composted, EPA did not analyze the GHG implications of composting them because of time and resource constraints.

<sup>2</sup> CO<sub>2</sub> emissions from delivery of compost to its final destination were not counted because compost is a marketable product, and CO<sub>2</sub> emissions from transportation of other marketable, finished goods to consumers have not been counted in other parts of this analysis.

<sup>3</sup> EPA. 2005. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC. EPA 430-R-05-003.

#### 4.1.1 CH<sub>4</sub>

To research the issue of CH<sub>4</sub> emissions, EPA first conducted a literature search for articles on CH<sub>4</sub> generation from composting. Because CH<sub>4</sub> emissions from composting are addressed only occasionally in the literature, EPA contacted several composting experts from universities and USDA to discuss the potential for CH<sub>4</sub> generation, based on the nature of carbon flows during composting. The CH<sub>4</sub> analysis presented here is based on their expert opinions.

The researchers EPA contacted stated that well-managed compost operations usually do not generate CH<sub>4</sub> because they typically maintain an aerobic environment with proper moisture content to encourage aerobic decomposition of the materials. The researchers also noted that even if CH<sub>4</sub> is generated in anaerobic pockets in the center of the compost pile, the CH<sub>4</sub> is most likely oxidized when it reaches the oxygen-rich surface of the pile, where it is converted to CO<sub>2</sub>. Several of the researchers commented that anaerobic pockets are most apt to develop when too much water is added to the compost pile. They noted that this problem rarely occurs because compost piles are much more likely to be watered too little rather than too much.

EPA concluded from the available information that CH<sub>4</sub> generation from centralized compost piles is essentially zero.

#### 4.1.2 CO<sub>2</sub> from Transportation of Materials and Turning of Compost

This study estimated the indirect CO<sub>2</sub> emissions associated with collecting and transporting organics to centralized compost facilities, and turning the compost piles. EPA began with estimates developed by FAL for the amount of diesel fuel required to (1) collect and transport 1 ton of organics<sup>4</sup> to a central composting facility (363,000 Btu) and (2) turn the compost pile (221,000 Btu).<sup>5</sup> EPA then converted these estimates to units of MTCE per ton of organics, based on a carbon coefficient of 0.02 MTCE per million Btu of diesel fuel. This resulted in an estimate of 0.01 MTCE of indirect CO<sub>2</sub> emissions per ton of material composted in a centralized facility.

## 4.2 POTENTIAL CARBON STORAGE

EPA also evaluated the effect of compost application on soil carbon storage. Information on carbon storage associated with compost derived specifically from yard trimmings or food discards was not found. Nevertheless, it is reasonable to expect that these materials have similar fates in terms of their stored carbon, even though their initial moisture and carbon contents differ.

To develop carbon storage estimates for composted organics, EPA researched the processes that affect soil carbon storage, reviewed the results of experiments on the soil carbon impacts of applying organic amendments (e.g., compost, manure, biosolids, and crop residues), and interviewed experts on the potential carbon storage benefits of composting organics as compared to other methods of disposal. During this process, four hypotheses were proposed regarding the benefits of applying organics compost to soil:

- (1) Many soils have been depleted in organic matter through cultivation and other practices. Adding compost can raise soil carbon levels by increasing organic matter inputs. Soils degraded by intensive crop production, construction, mining, and other activities lose organic matter when decomposition rates and removals of carbon in harvests exceed the rate of new inputs of organic materials. Adding compost shifts the balance so that soil organic carbon levels are restored to higher levels. Some of the compost carbon is retained by the system.

<sup>4</sup> Measured on a wet weight basis, as MSW is typically measured.

<sup>5</sup> Franklin Associates, Ltd. 1994. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful), pp. I-27, 30, and 31.

- (2) Nitrogen in compost can stimulate higher productivity, thus generating more crop residues. This "fertilization effect" would increase soil carbon due to the larger volume of crop residues, which serve as organic matter inputs.
- (3) The composting process leads to increased formation of stable carbon compounds (e.g., humic substances, aggregates) that then can be stored in the soil for long (>50 years) periods of time. Humic substances make up 60–80 percent of soil organic matter and are made up of complex compounds that render them resistant to microbial attack.<sup>6</sup> In addition to humic substances, soil organic carbon may be held in aggregates (i.e., stable organo-mineral complexes in which carbon is bonded with clay colloids and metallic elements) and protected against microbial attack.<sup>7</sup>
- (4) The application of compost produces a multiplier effect by qualitatively changing the dynamics of the carbon cycling system and increasing the retention of carbon from noncompost sources. Some studies of other compost feedstocks (e.g., farmyard manure, legumes) have indicated that the addition of organic matter to soil plots can increase the potential for storage of soil organic carbon. The carbon increase apparently comes not only from the organic matter directly, but also from retention of a higher proportion of carbon from residues of crops grown on the soil. This multiplier effect could enable compost to increase carbon storage by more than its own direct contribution to carbon mass accumulation.

EPA's research efforts did not yield any primary data that could be used to develop quantitative estimates of the soil carbon storage benefits of compost. Therefore, modeling approaches to investigate the possible effects of compost application on soil carbon storage were developed. Section 4.2.2 describes application of the CENTURY model to quantify soil carbon restoration and nitrogen fertilization associated with compost application to carbon-depleted soils. EPA conducted a bounding analysis, described in Section 4.2.6, to address the third hypothesis, incremental humus formation. Although several of the experts contacted cited persuasive qualitative evidence of the existence of a multiplier effect, EPA was unable to develop an approach to quantify this process. In that sense, the carbon storage estimates are likely to be conservative (i.e., understate carbon storage rates), at least for soils with high silt and/or clay content where this process is most likely to apply.

EPA's analyses of soil carbon restoration, nitrogen fertilization, and incremental humus formation apply relatively simple models of very complex processes. These processes probably are controlled by a number of biological, physicochemical, and compost management factors, such as application (i.e., silviculture, horticulture, agriculture, and landscaping); application rate; regional and local climatic factors; soil type; and, to a lesser extent, compost feedstock (e.g., grass, leaves, branches, yard trimmings, food discards). In addition, the results are time-dependent, so the year in which benefits are assessed has an effect on the magnitude of carbon storage.

Note that the framework used here describes the soil carbon benefits of composting relative to landfilling and combustion. In all three management methods, yard trimmings are collected and removed from soils in residential or commercial settings. This removal may result in some loss of organic carbon from the "home soil." An estimate of the "absolute" soil carbon storage value would net out whatever loss occurs due to the removal of the yard trimmings. This effect is probably a negligible one, however, and EPA was unable to find empirical data on it. Because the decrement in carbon in "home soil" applies equally to all three management practices, and emission factors are intended to be viewed relative to other management practices (see Chapter 8), neglecting the carbon loss from the home soil does not compromise the validity of the results.

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<sup>6</sup> N. Brady and R. Weil. 1999. *The Nature and Properties of Soils* (Upper Saddle River, NJ: Prentice Hall).

<sup>7</sup> R. Lal et al. 1998. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, MI: Sleeping Bear Press, Inc).

#### 4.2.1 Modeling Soil Carbon Restoration and Nitrogen Fertilization

As mentioned above, this analysis included an extensive literature review and interviews with experts to consider whether the application of compost leads to long-term storage of carbon in soils. After determining that neither the literature review nor discussions with experts would yield a basis for a quantitative estimate of soil carbon storage, EPA evaluated the feasibility of a simulation modeling approach. EPA initially identified two simulation models with the potential to be applied to the issue of soil carbon storage from compost application: CENTURY<sup>8</sup> and the Rothamsted C (ROTHC-26.3)<sup>9</sup> model. Both are peer-reviewed models whose structure and application have been described in scores of publications. They share several features:

- Ability to run multiyear simulations;
- Capability to construct multiple scenarios covering various climate and soil conditions and loading rates; and
- Ability to handle interaction of several soil processes, environmental factors, and management scenarios such as carbon:nitrogen (C:N) ratios, aggregate formation, soil texture (e.g., clay content), and cropping regime.

Given the extensive application of CENTURY in the United States, its availability on the Internet, and its ability to address many of the processes important to compost application, it was decided to use CENTURY rather than ROTHC-26.3.

#### 4.2.2 CENTURY Model Framework

CENTURY is a Fortran model of plant-soil ecosystems that simulates long-term dynamics of carbon, nitrogen, phosphorus, and sulfur. It tracks the movement of carbon through soil pools—active, slow, and passive—and can show changes in carbon levels due to the addition of compost.

In addition to soil organic matter pools, carbon can be found in surface (microbial) pools and in above- and below-ground litter pools. The above-ground and below-ground litter pools are divided into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. Carbon additions to the system flow through the various pools and can exit the system (e.g., as CO<sub>2</sub>, dissolved carbon, or through crop removals).

The above-ground and below-ground litter pools are split into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. The active pool of soil organic matter includes living biomass, some of the fine particulate detritus,<sup>10</sup> most of the nonhumic material, and some of the more easily decomposed fulvic acids. The active pool is estimated to have a mean residence time (MRT)<sup>11</sup> of a few months to 10 years.<sup>12</sup> The slow pool includes resistant plant material (i.e., high lignin content) derived from the structural pool and other slowly decomposable and chemically resistant components. It has an MRT of 15–100 years.<sup>13</sup> The passive pool of soil organic matter includes very stable materials remaining in the soil for hundreds to thousands of years.<sup>14</sup>

<sup>8</sup> Metherell, A., L. Harding, C. Cole, W. Parton. 1993. CENTURY Agroecosystem Version 4.0, Great Plains System Research Unit Technical Report No. 4, USDA-ARS Global Climate Change Research Program (Colorado State University: Fort Collins, CO).

<sup>9</sup> This model was developed based on long-term observations of soil carbon at Rothamsted, an estate in the United Kingdom where organic amendments have been added to soils since the 19<sup>th</sup> century.

<sup>10</sup> Detritus refers to debris from dead plants and animals.

<sup>11</sup> The term "mean residence time" is used interchangeably with "turnover time" and is the average time in which a unit (e.g., a carbon atom) resides within a "state" where there is both an input and an output. MRT is only strictly defined at steady-state (i.e., inputs = outputs), but as most soils systems have a continuing input of carbon and an

CENTURY does not simulate increased formation of humic substances associated with organic matter additions, nor does it allow for organic matter additions with high humus content to increase the magnitude of the passive pool directly. (Because CENTURY does not account for these processes, EPA developed a separate analysis, described in Section 4.2.6.)

CENTURY contains a submodel to simulate soil organic matter pools. Additional submodels address nitrogen, phosphorus, sulfur, the water budget, leaching, soil temperature, and plant production, as well as individual submodels for various ecosystems (e.g., grassland, cropland). The nitrogen submodel addresses inputs of fertilizer and other sources of nitrogen, mineralization of organic nitrogen, and uptake of nitrogen by plants.

#### 4.2.3 Inputs

The CENTURY model simulates the long-term dynamics of various plant-soil ecosystems (e.g., grassland, agricultural land, forest, and savanna). The model uses a series of input files to specify modeling conditions: crop, harvest, fertilization, cultivation, organic matter addition, irrigation, grazing, fire, tree type, tree removal, site, and weather statistics. A schedule file is used to specify the timing of events.

For this analysis, EPA developed a basic agricultural scenario where land was converted from prairie to farmland (growing corn) in 1921 and remains growing corn through 2030. More than 30 scenarios were then run to examine the effect of several variables on soil carbon storage:

- Compost application rate and frequency;
- Site characteristics (rainfall, soil type, irrigation regime);
- Fertilization rate; and
- Crop residue management.

Compost application rates were adjusted using the organic matter (compost) files for each compost application rate included in the analysis. EPA compared the effect of applying compost annually for 10 years (1996–2005) at seven different application rates: 1.3, 3.2, 6.5, 10, 15, 20, and 40 wet tons compost/acre (corresponding to 60–1,850 grams of carbon per square meter).<sup>15</sup> EPA also investigated the effect of compost application frequency on the soil carbon storage rate and total carbon levels. The model was run to simulate compost applications of 1.3 wet tons compost/acre and 3.2 wet tons compost/acre every year for 10 years (1996–2005) and applications of 1.3 wet tons compost/acre and 3.2 wet tons compost/acre applied every five years (in 1996, 2001, and 2006). The simulated

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approximately equal output through decomposition and transfer to other pools, MRT is often used to describe carbon dynamics in soils. Mathematically, it is the ratio of (a) mass in the pool to (b) throughput of carbon. For example, if a given carbon pool has a mass of 1,000 kg and the inflow is 1 kg/yr, the MRT is  $1,000 \text{ kg} / (1 \text{ kg/yr}) = 1,000 \text{ yr}$ .

<sup>12</sup> Metherell et al. 1993, Brady and Weil 1999.

<sup>13</sup> *Ibid.*

<sup>14</sup> *Ibid.*

<sup>15</sup> The model requires inputs in terms of the carbon application rate in grams per square meter. The relationship between the carbon application rate and compost application rate depends on three factors: the moisture content of compost, the organic matter content (as a fraction of dry weight), and the carbon content (as a fraction of organic matter). Inputs are based on values provided by Dr. Harold Keener of Ohio State University, who estimates that compost has a moisture content of 50 percent, an organic matter fraction (as dry weight) of 88 percent, and a carbon content of 48 percent (as a fraction of organic matter). Thus, on a wet weight basis, 21 percent of compost is carbon.

compost was specified as having 33 percent lignin,<sup>16</sup> 17:1 C:N ratio,<sup>17</sup> 60:1 carbon-to-phosphorus ratio, and 75:1 carbon-to-sulfur ratio.<sup>18</sup> EPA also ran a scenario with no compost application for each combination of site-fertilization-crop residue management. This scenario allowed EPA to control for compost application, i.e., to calculate the change in carbon storage attributable only to the addition of compost.

The majority of inputs needed to specify a scenario reside in the site file. The input variables in this file include the following:

- Monthly average maximum and minimum air temperature;
- Monthly precipitation;
- Lignin content of plant material;
- Plant nitrogen, phosphorus, and sulfur content;
- Soil texture;
- Atmospheric and soil nitrogen inputs; and
- Initial soil carbon, nitrogen, phosphorus, and sulfur levels.

Several sets of detailed site characteristics from past modeling applications are available to users. EPA chose two settings: an eastern Colorado site with clay loam soil and a southwestern Iowa site with silty clay loam soil. Both settings represent fairly typical Midwestern corn belt situations where agricultural activities have depleted soil organic carbon levels. The Colorado scenario is available as a site file on the CENTURY Web site.<sup>19</sup> Dr. Keith Paustian, an expert in the development and application of CENTURY, provided the specifications for the Iowa site (as well as other input specifications and results for several of the runs described here).

EPA also varied the fertilization rate. As discussed earlier, one of the hypotheses was that the mineralization of nitrogen in compost could stimulate crop growth, leading to production of more organic residues, which in turn would increase soil organic carbon levels. The strength of this effect would vary depending on the availability of other sources of nitrogen (N). To investigate this hypothesis, different rates of synthetic fertilizer addition ranging from zero up to a typical rate to attain average crop yield—90 pounds (lbs.) N/acre for the Colorado site, 124 lbs. N/acre for the Iowa site—were analyzed. EPA also evaluated fertilizer application at half of these typical rates.

Finally, two harvest regimes were simulated, one where the corn is harvested for silage (where 95 percent of the above-ground biomass is removed) and the other where corn is harvested for grain (where the “stover” is left behind to decompose on the field). These simulations enabled EPA to isolate the

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<sup>16</sup> Percent lignin was estimated based on the lignin fractions for grass, leaves, and branches specified by compost experts (particularly Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University, and lignin fractions reported in M.A. Barlaz, “Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills,” EPA 600/R-97-071, 1997. FAL provided an estimate of the fraction of grass, leaves, and branches in yard trimmings in a personal communication with ICF Consulting, November 14, 1995. Subsequently, FAL obtained and provided data showing that the composition of yard trimmings varies widely in different states. The percentage composition used here (50 percent grass, 25 percent leaves, and 25 percent branches on a wet weight basis) is within the reported range.

<sup>17</sup> The C:N ratio was taken from Brady and Weil, 1999, *The Nature and Property of Soils: Twelfth Edition* (Upper Saddle River, NJ: Prentice Hall).

<sup>18</sup> C:P and C:S ratios were based on the literature and conversations with composting experts, including Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University.

<sup>19</sup> The Natural Resource Ecology Laboratory at Colorado State University, CENTURY Soil Organic Matter Model, Version 5.0, available at: <http://www.nrel.colostate.edu/projects/century5>

effect of the carbon added directly to the system in the form of compost, as opposed to total carbon inputs (which include crop residues).

#### 4.2.4 Outputs

CENTURY is capable of providing a variety of output data, including carbon storage in soils, CO<sub>2</sub> emissions due to microbial respiration, and monthly potential evapotranspiration. The outputs EPA chose were carbon levels for each of the eight soil pools: structural carbon in surface litter, metabolic carbon in surface litter, structural carbon in soil litter, metabolic carbon in soil litter, surface pool, active pool, slow pool, and passive pool. The output data cover the period from 1900 through 2030. In general, EPA focused on the difference in carbon storage between a baseline scenario, where no compost was applied, and a with-compost scenario. EPA calculated the difference between the two scenarios to isolate the effect of compost application. Output data in grams of carbon per square meter were converted to MTCE by multiplying by area (in square meters).

To express results in units comparable to those for other sources and sinks, EPA divided the increase in carbon storage by the short tons of organics required to produce the compost.<sup>20</sup> That is, the factors are expressed as a carbon storage rate in units of MTCE per wet short ton of organic inputs (not MTCE per short ton of compost).

#### 4.2.5 Results

The carbon storage rate declines with time after initial application. The rate is similar across application rates and frequencies, and across the site conditions that were simulated. Exhibit 4-1 displays results for the Colorado and Iowa sites, for the 10-, 20-, and 40-ton per acre application rates. As indicated on the graph, the soil carbon storage rate varies from about 0.08 MTCE per wet ton organics immediately after compost application (in 1997) to about 0.02 MTCE per ton in 2030 (24 years after the last application in 2006).

The similarity across the various site conditions and application rates reflects the fact that the dominant process controlling carbon retention is the decomposition of organic materials in the various pools. As simulated by CENTURY, this process is governed by first-order kinetics, i.e., the rate is independent of organic matter concentration or the rate of organic matter additions.

Several secondary effects, however, result in some variation in the carbon storage rate.<sup>21</sup> EPA had hypothesized that where a crop's demand for nitrogen exceeds its availability from other sources, mineralization of compost nitrogen can stimulate increased productivity. Simulation of this effect showed that where there is a shortage of nitrogen, compost application can result in higher productivity, which translates into higher inputs of crop residues to the soil. These higher inputs in turn increase the carbon storage rate per unit of compost inputs. This effect is a relatively modest one, however.

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<sup>20</sup> EPA assumes 2.1 tons of yard trimmings are required to generate 1 ton of composted yard trimmings. Thus, to convert the results in this report (in MTCE per wet ton yard trimmings) to MTCE per wet ton of compost, multiply by 2.1. To convert to MTCE per dry ton compost, multiply values in this report by 4.2 (assuming 50 percent moisture content).

<sup>21</sup> In addition to the nitrogen fertilization effect, compost also affects moisture retention in soils, which in turn modifies the water balance relations simulated by CENTURY.

**Exhibit 4-1**  
**Soil Carbon Storage--Colorado and Iowa sites; 10, 20, and 40 tons-per-acre Application Rates**

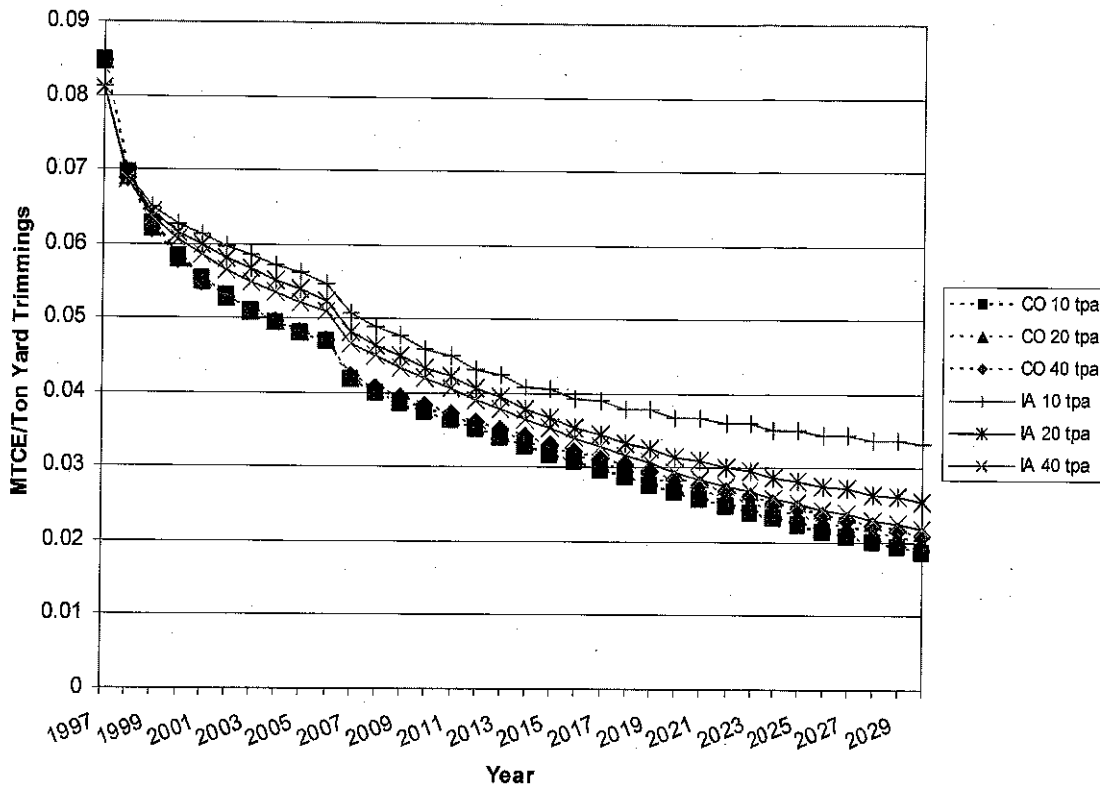


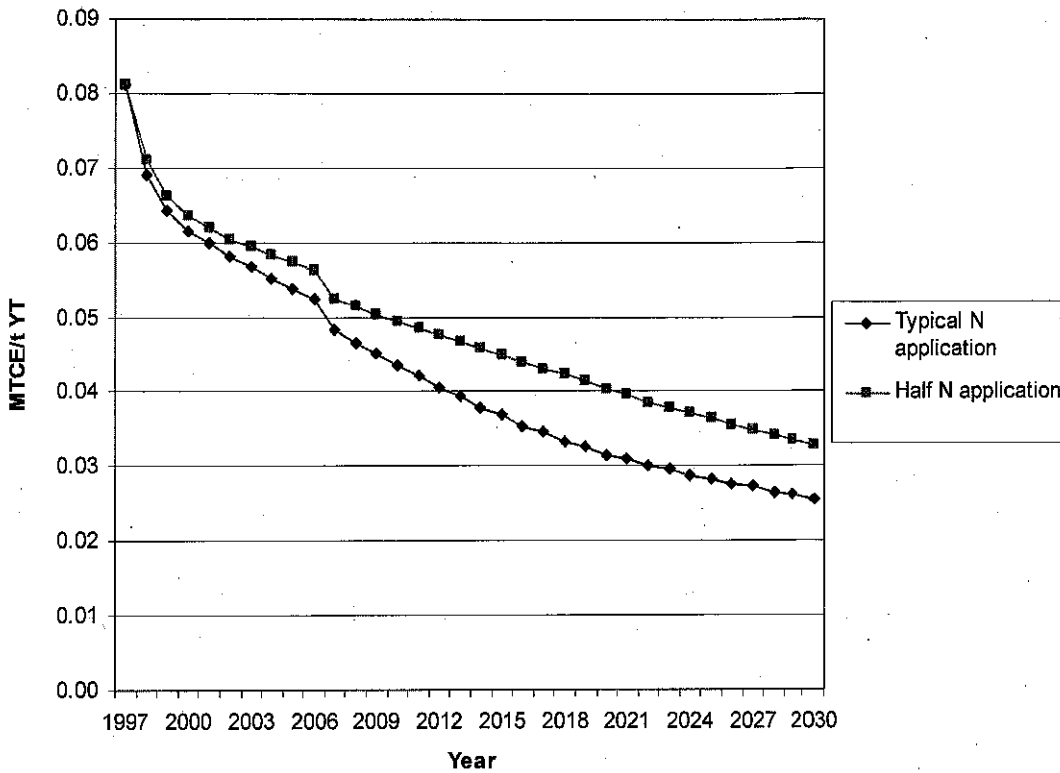
Exhibit 4-2 shows the carbon storage rate for the Iowa site and the effect of nitrogen fertilization. The two curves in the exhibit both represent the difference in carbon storage between (a) a with-compost scenario (20 tons per acre) and (b) a baseline where compost is not applied. The nitrogen application rates differ in the following ways:

- The curve labeled “Typical N application” represents application of 124 lbs. per acre, for both the compost and baseline scenario. Because the nitrogen added via compost has little effect when nitrogen is already in abundant supply, this curve portrays a situation where the carbon storage is attributable solely to the organic matter additions in the compost.
- The curve labeled “Half N application” represents application of 62 lbs. per acre. In this scenario, mineralization of nitrogen added by the compost has an incremental effect on crop productivity compared to the baseline. The difference between the baseline and compost application runs reflects both organic matter added by the compost and additional biomass produced in response to the nitrogen contributed by the compost.

The difference in incremental carbon storage rates between the two fertilization scenarios is less than 0.01 MTCE per ton, indicating that the nitrogen fertilization effect is small. Note that this finding is based on the assumption that farmers applying compost also will apply sufficient synthetic fertilizer to maintain economic crop yields. If this assumption is not well-founded, or in situations where compost is applied as a soil amendment for road construction, landfill cover, or similar situations, the effect would be larger.



**Exhibit 4-2 Incremental Carbon Storage as a Function of Nitrogen Application Rate**



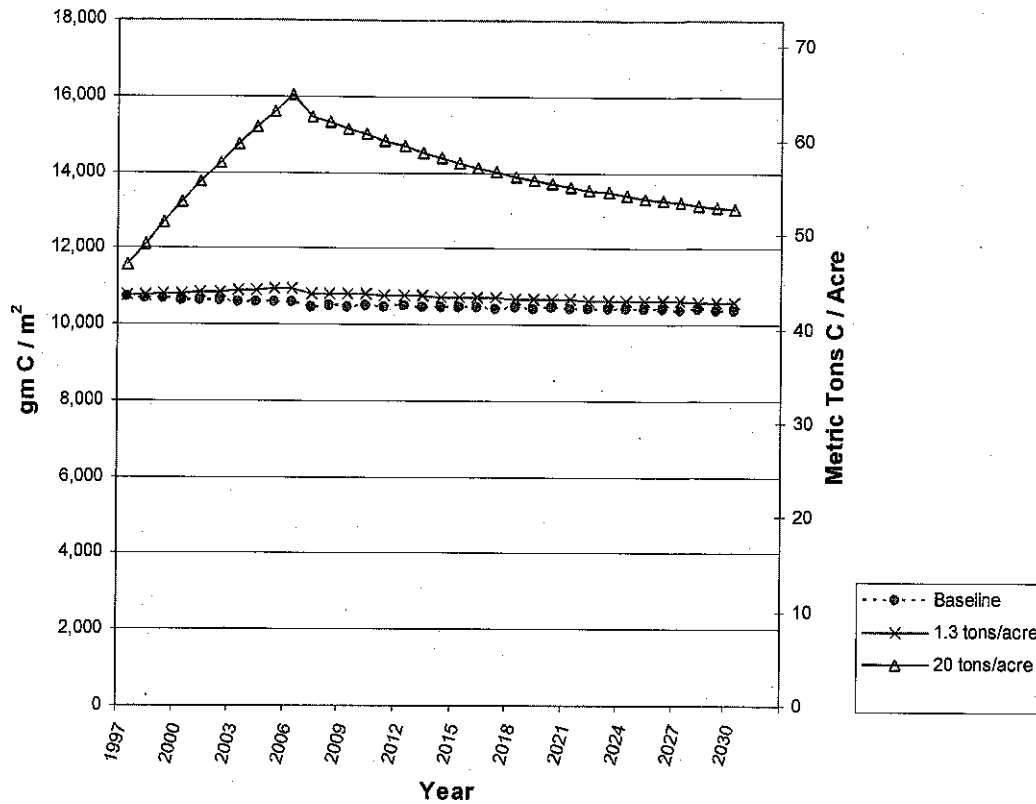
When viewed from the perspective of total carbon, rather than as a storage rate per ton of inputs to the composting process, both soil organic carbon concentrations and total carbon stored per acre increase with increasing application rates (see Exhibit 4-3). Soil organic carbon concentrations increase throughout the period of compost application, peak in 2006 (the last year of application), and decline thereafter due to decomposition of the imported carbon. Exhibit 4-3 displays total carbon storage (including baseline carbon) in soils on the order of 40 to 65 metric tons per acre (the range would be higher with higher compost application rates or longer term applications).

#### **4.2.6 Incremental Humus Formation**

The third of the four hypotheses describing the benefits of composting, as compared to alternative management methods, is predicated on incremental formation of stable carbon compounds that can be stored in the soil for long periods of time. CENTURY does not simulate this process, i.e., it does not allow for organic matter additions with high humus content to directly increase the magnitude of the passive pool. Therefore, EPA used a bounding analysis to estimate the upper and lower limits of the magnitude of this effect. In this analysis, EPA evaluated the amount of long-term soil carbon storage when organics are composted and applied to soil.

During the process of decomposition, organic materials typically go through a series of steps before finally being converted to CO<sub>2</sub>, water, and other reaction products. The intermediate compounds that are formed, and the lifetime of these compounds, can vary widely depending on a number of factors, including the chemical composition of the parent compound. Parent compounds range from readily degradable molecules such as cellulose and hemicellulose to molecules more resistant to degradation, such as lignin, waxes, and tannins.

**Exhibit 4-3 Total Soil C; Iowa Site, Corn Harvested for Grain**



Composting is designed to promote rapid decomposition of organics, thus reducing their volume. Some evidence suggests that composting produces a greater proportion of humus than that typically formed when organics are left directly on the ground. The conditions in the two phases are different. The heat generated within compost piles favors “thermophilic” (heat-loving) bacteria, which tend to produce a greater proportion of stable, long-chain carbon compounds (e.g., humic substances) than do bacteria and fungi that predominate at ambient soil temperatures.

Increased humus formation associated with compost application is a function of two principal factors:

- (1) The fraction of carbon in compost that is considered “passive” (i.e., very stable); and
- (2) The rate at which passive carbon is degraded to CO<sub>2</sub>.

Estimates for the first factor are based on experimental data compiled by Dr. Michael Cole of the University of Illinois. Dr. Cole found literature values indicating that between 4 and 20 percent of the carbon in finished compost degrades quickly.<sup>22</sup> Dr. Cole averaged the values he found in the literature and estimated that 10 percent of the carbon in compost can be considered “fast” (i.e., readily degradable). The remaining 90 percent can be classified as either slow or passive. EPA was unable to locate experimental data that delineate the fractions of slow and passive carbon in compost; therefore, upper and lower bound estimates based on Dr. Cole’s professional judgment were developed. He suggested values

<sup>22</sup> Very little information is available on the characteristics of compost derived from yard trimmings or food discards. However, Dr. Cole found that the composition of composts derived from other materials is broadly consistent, suggesting that his estimates may be reasonably applied to yard trimmings or food scrap compost.

of 30 percent slow and 60 percent passive, and 45 percent slow and 45 percent passive for the upper and lower bounds on passive content, respectively.<sup>23</sup>

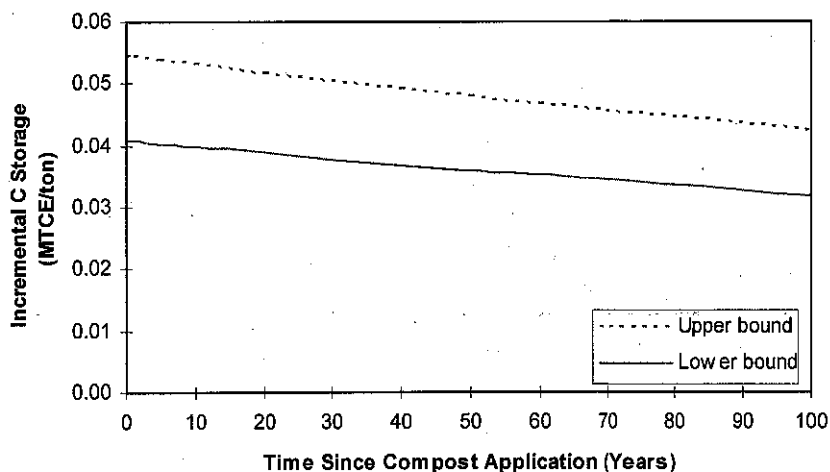
For the second factor, EPA chose a mean residence time for passive carbon of 400 years based on the range of values specified in the literature.<sup>24</sup>

Combining the two bounds for incremental humus formation (60 percent passive and 45 percent passive), EPA estimated the incremental carbon storage implied by each scenario (see Exhibit 4-4).

The upper bound on the incremental carbon storage from composting is more than 0.05 MTCE per wet ton (shown in the top left of the graph); the lower bound is approximately 0.03 MTCE per wet ton (shown in the bottom right of the graph) after about 100 years. Incremental storage is sensitive to the fraction of carbon in compost that is passive but is not very sensitive to the degradation rate (within a 100-year time horizon, over the range of rate constants appropriate for passive carbon).

To select a point estimate for the effect of incremental humus formation, EPA took the average storage value across the two bounding scenarios, when time equals 10 years (i.e., approximately 2010). The resulting value is 0.046 MTCE/ton. The 2010 time frame was chosen for this analysis because the forest carbon estimates presented in Chapter 3 of this report are for the period ending in 2010.

**Exhibit 4-4 Incremental Carbon Storage: MTCE/Wet Ton Versus Time**



<sup>23</sup> EPA focused only on the passive pool because (1) the CENTURY model does not allow for direct input of organic carbon into the passive pool, and (2) the model runs resulted in very little indirect (i.e., via other pools) formation of passive carbon. Although the first factor is also true for the slow pool, the second is not. Had EPA analyzed slow carbon in the same way as passive carbon, there would be potential for double counting (see discussion in Section 4.3).

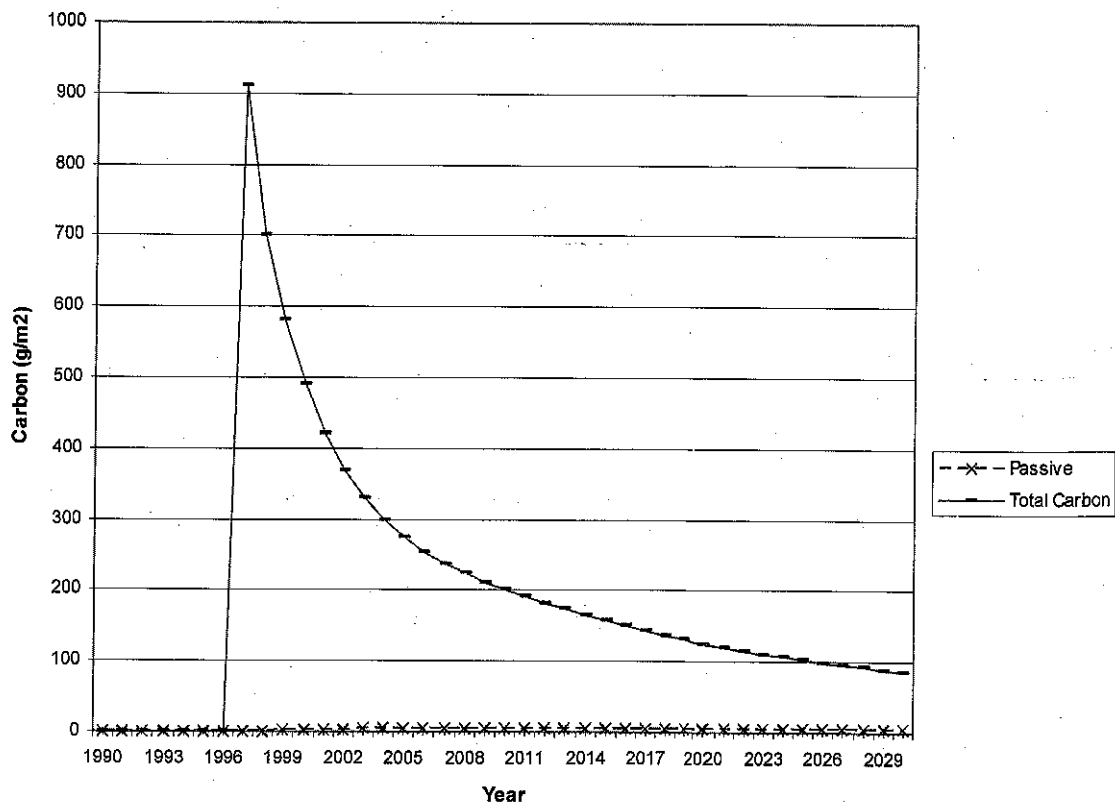
<sup>24</sup> Metherell et al. 1993, Brady and Weil 1999.

### 4.3 NET GHG EMISSIONS FROM COMPOSTING

The approaches described in Section 4.2 were adopted to capture the range of carbon storage benefits associated with compost application. However, this dual approach creates the possibility of double counting. In an effort to eliminate double counting, EPA evaluated the way that CENTURY partitions compost carbon once it is applied to the soil.

To do so, EPA ran a CENTURY model simulation of compost addition during a single year and compared the results to a corresponding reference case (without compost). EPA calculated the difference in carbon in each of the CENTURY pools for the two simulations and found that the change in the passive pool represented less than 0.01 percent of the change in total carbon. Therefore, CENTURY is not adding recalcitrant carbon directly to the passive pool. Next, EPA graphed the change in the passive pool over time to ensure that the recalcitrant compost carbon was not being cycled from the faster pools into the passive pool several years after the compost is applied. As Exhibit 4-5 shows, CENTURY does not introduce significant increments (over the base case) of recalcitrant carbon into the passive pool at any time.

**Exhibit 4-5 Difference in Carbon Storage Between Compost Addition and Base Case Yearly Application with 20 Tons Compost**



Based on the analysis, it appears that CENTURY is appropriately simulating carbon cycling and storage for all but the passive carbon introduced by compost application. Because passive carbon represents approximately 52 percent of carbon in compost (the midpoint of 45 percent and 60 percent), EPA scaled the CENTURY results by 48 percent to reflect the proportion of carbon that can be classified as fast or slow (i.e., not passive).

Exhibit 4-6 shows the soil carbon storage and transportation-related emissions and sinks, and sums these to derive estimates of a net GHG emission factor, using the same sign convention as the broader analysis. A negative value denotes carbon storage; a positive value denotes emissions.

Summing the values corresponding to typical application rate and the 2010 time frame for soil carbon restoration (-0.02 MTCE/ton), increased humus formation (-0.05 MTCE/ton), and transportation emissions (0.01 MTCE/ton), the result is -0.05 MTCE/ton.<sup>25</sup>

**Exhibit 4-6**  
**Net GHG Emissions from Composting**  
**(In MTCE Per Ton of Yard Trimmings Composted)**

Emission/ Storage Factor (for 2010)					
Soil Carbon Restoration			Increased Humus Formation	Transportation Emissions	Net Carbon Flux
Unweighted	Proportion of C that is Not Passive	Weighted Estimate			
-0.04	48%	-0.02	-0.05	0.01	-0.05

#### 4.4 LIMITATIONS

Due to data and resource constraints, this chapter does not explore the full range of conditions under which compost is managed and applied, and how these conditions would affect the results of this analysis. Instead, this study attempts to provide an analysis of GHG emissions and sinks associated with centralized composting of organics under a limited set of scenarios. EPA's analysis was limited by the lack of primary research on carbon storage and CH<sub>4</sub> generation associated with composting. The limited availability of data forced EPA to rely on two modeling approaches, each with its own set of limitations. In addition, the analysis was limited by the scope of the report, which is intended to present life-cycle GHG emissions of waste management practices for selected material types, including food discards and yard trimmings.

##### 4.4.1 Limitations of Modeling Approaches

Due to data and resource constraints, EPA was unable to use CENTURY to evaluate the variation in carbon storage impacts for a wide range of compost feedstocks (e.g., yard trimmings mixed with food discards, food discards alone). As noted earlier, resource constraints limited the number of soil types, climates, and compost applications simulated. The CENTURY results also incorporate the limitations of the model itself, which have been well documented elsewhere. Perhaps most importantly, the model's predictions of soil organic matter levels are driven by four variables: annual precipitation, temperature, soil texture, and plant lignin content. Beyond these, the model is limited by its sensitivity to several factors for which data are difficult or impossible to obtain (e.g., presettlement grazing intensity, nitrogen input during soil development).<sup>26</sup> The model's monthly simulation intervals limit its ability to fully address potential interactions between nitrogen supply, plant growth, soil moisture, and decomposition rates, which may be sensitive to conditions that vary on a shorter time scale.<sup>27</sup> In addition, the model is not designed to capture the hypothesis that, due to compost application, soil ecosystem dynamics change so that more carbon is stored than is actually being added to the soil (i.e., the multiplier effect).

<sup>25</sup> The addends do not sum to the total, due to rounding.

<sup>26</sup> Parton, W., D. Schimel, C. Cole, and D. Ojima. 1987. "Analysis of Factors Controlling Soil Organic Matter Levels in Great Plains Grasslands." *Soil Sci. Soc. Am. J.* Vol. 51 (1173-1179).

<sup>27</sup> Paustian, K., W. Parton, and Jan Persson. 1992. "Modeling Soil Organic Matter in Organic-Amended and Nitrogen-Fertilized Long-Term Plots." *Soil Sci. Soc. Am. J.* Vol. 56 (476-488).

CENTURY simulates carbon movement through organic matter pools. Although the model is designed to evaluate additions of organic matter in general, it is not believed to have been applied in the past to evaluate the application of organics compost. CENTURY is parameterized to partition carbon to the various pools based on ratios of lignin to nitrogen and lignin to total carbon, not on the amount of organic material that has been converted to humus already. EPA addressed this limitation by developing an “add-on” analysis to evaluate humus formation in the passive pool, scaling the CENTURY results, and summing the soil carbon storage values. There is some potential for double counting, to the extent that CENTURY is routing some carbon to various pools that is also accounted for in the incremental humus analysis. EPA believes that this effect is likely to be minor.

The bounding analysis used to analyze increased humus formation is limited by the lack of data specifically dealing with composts composed of yard trimmings or food discards. This analysis is also limited by the lack of data on carbon in compost that is passive. The approach of taking the average value from the two scenarios is simplistic but appears to be the best available option.

#### **4.4.2 Limitations Related to the Scope of the Report**

As indicated above, this chapter presents EPA’s estimates of the GHG-related impacts of composting organics. These estimates were developed within the framework of the larger report; therefore, the presentation of results, estimation of emissions and sinks, and description of ancillary benefits is not comprehensive. The remainder of this section describes specific limitations of the compost analysis.

As in the other chapters of this report, the GHG impacts of composting reported in this chapter are relative to other possible disposal options for yard trimmings (i.e., landfilling and combustion). In order to present absolute GHG emission factors for composted yard trimmings that could be used to compare composting to a baseline of leaving yard trimmings on the ground where they fall, EPA would need to analyze the home soil. In particular, the carbon storage benefits of composting would need to be compared to the impact of removal of yard trimmings on the home soil.

As mentioned in Section 4.4.1, due to data and resource constraints, the analysis considers a small sampling of feedstocks and a single compost application (i.e., agricultural soil). EPA analyzed two types of compost feedstocks—yard trimmings and food discards—although sewage sludge, animal manure, and several other compost feedstocks also may have significant GHG implications. Similarly, it was assumed that compost was applied to degraded agricultural soils, despite widespread use of compost in land reclamation, silviculture, horticulture, and landscaping.

This analysis did not consider the full range of soil conservation and management practices that could be used in combination with compost and the impacts of those practices on carbon storage. Some research indicates that adding compost to agricultural soils in conjunction with various conservation practices enhances the generation of soil organic matter to a much greater degree than applying compost alone. Examples of these conservation practices include conservation tillage, no tillage, residue management, crop rotation, wintering, and summer fallow elimination. Research suggests that allowing crop residues to remain on the soil rather than turning them over helps to protect and sustain the soil while simultaneously enriching it. Alternatively, conventional tillage techniques accelerate soil erosion, increase soil aeration, and hence lead to greater GHG emissions.<sup>28</sup> Compost use also has been shown to increase soil water retention; moister soil gives a number of ancillary benefits, including reduced irrigation costs and reduced energy used for pumping water. Compost can also play an important role in the adaptation strategies that will be necessary as climate zones shift with climate change and some areas become more arid.

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<sup>28</sup> R. Lal et al. 1998. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, MI: Sleeping Bear Press, Inc).

As is the case in other chapters, the methodology used to estimate GHG emissions from composting did not allow for variations in transportation distances. EPA recognizes that the density of landfills versus composting sites in any given area would have an effect on the extent of transportation emissions derived from composting. For example, in states that have a higher density of composting sites, the hauling distance to such a site would be less and would require less fuel than transportation to a landfill. Alternatively, transporting compost from urban areas, where compost feedstocks may be collected, to farmlands, where compost is typically applied, potentially would require more fuel because of the large distance separating the sites.

Emission factors presented in this chapter do not capture the full range of possible GHG emissions from compost. Some of the nitrogen in compost is volatilized and released into the atmosphere as N<sub>2</sub>O shortly after application of the compost. Based on a screening analysis, N<sub>2</sub>O emissions were estimated to be less than 0.01 MTCE per wet ton of compost inputs.

Addressing the possible GHG emission reductions and other environmental benefits achievable by applying compost instead of chemical fertilizers, fungicides, and pesticides was beyond the scope of this report. Manufacturing those agricultural products requires energy. To the extent that compost may replace or reduce the need for these substances, composting may result in reduced energy-related GHG emissions. Although EPA understands that compost is generally applied for its soil amendment properties rather than for pest control, compost has been effective in reducing the need for harmful or toxic pesticides and fungicides.<sup>29</sup>

In addition to the carbon storage benefits of adding compost to agricultural soils, composting can lead to improved soil quality, improved productivity, and cost savings. As discussed earlier, nutrients in compost tend to foster soil fertility.<sup>30</sup> In fact, composts have been used to establish plant growth on land previously unable to support vegetation. In addition to these biological improvements, compost also may lead to cost savings associated with avoided waste disposal, particularly for feedstocks such as sewage sludge and animal manure.

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<sup>29</sup> For example, the use of compost may reduce or eliminate the need for soil fumigation with methyl bromide (an ozone-depleting substance) to kill plant pests and pathogens.

<sup>30</sup> N. Brady and R. Weil. 1999.

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## 6. LANDFILLING

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This chapter presents estimates of GHG emissions and carbon storage from landfilling the materials considered in this analysis. For this study, EPA estimated the CH<sub>4</sub> emissions, transportation-related CO<sub>2</sub> emissions, and carbon storage that will result from landfilling each type of organic waste and mixed MSW. The analysis is based on three key GHG accounting principles:<sup>1</sup>

- When food discards, yard trimmings, paper, and wood are landfilled, anaerobic bacteria degrade the materials, producing CH<sub>4</sub> and CO<sub>2</sub>. CH<sub>4</sub> is counted as an anthropogenic GHG, because even though it is derived from sustainably harvested biogenic sources, degradation would not result in CH<sub>4</sub> emissions if not for deposition in landfills. The CO<sub>2</sub> is not counted as a GHG in this context because if it were not emitted from landfills, it would be produced through natural decomposition. Because metals and glass do not contain carbon, they do not generate CH<sub>4</sub> when landfilled. Plastics, carpet, PCs, clay bricks, concrete, fly ash, and tires do not biodegrade measurably in anaerobic conditions, and therefore do not generate any CH<sub>4</sub>.
- Transportation of waste materials to a landfill results in anthropogenic CO<sub>2</sub> emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes.
- Because food discards, yard trimmings, and paper are not completely decomposed by anaerobic bacteria, some of the carbon in these materials is stored in the landfill. Because this carbon storage would not normally occur under natural conditions (virtually all of the organic material would degrade to CO<sub>2</sub>, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic sink. However, carbon in plastic that remains in the landfill is not counted as stored carbon, because it is of fossil origin.

EPA developed separate estimates of emissions from (1) landfills without gas recovery systems, (2) those that flare CH<sub>4</sub>, (3) those that combust CH<sub>4</sub> for energy recovery, and (4) the national average mix of these three categories. The national average emission estimate accounts for the extent to which CH<sub>4</sub> will be flared at some landfills and combusted onsite<sup>2</sup> for energy recovery at others.<sup>3</sup>

From the standpoint of postconsumer GHG emissions, landfilling some materials—including newspaper and phonebooks—results in net storage (i.e., carbon storage exceeds CH<sub>4</sub> plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present. At the other extreme, office paper, textbooks, and food discards result in net emissions regardless of landfill gas collection and recovery practices. The remaining materials have net postconsumer emissions that are either very low (all materials have transportation-related emissions of 0.01 MTCE per ton, regardless of whether gas collection is present) or borderline, depending on whether the landfill has gas recovery (e.g., mixed MSW has net emissions at landfills without gas recovery, but net carbon storage at landfills with gas recovery).

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<sup>1</sup> These principles are described in broad terms in Section 1.4 of this report.

<sup>2</sup> Although gas from some landfills is piped to an offsite power plant and combusted there, for the purposes of this report, the assumption was that all gas for energy recovery was combusted onsite.

<sup>3</sup> Currently, most landfill CH<sub>4</sub> recovery in the United States—both for flaring and electricity—is occurring in response to a 1996 EPA rule that requires a well-designed and well-operated landfill gas collection system at landfills that (1) have a design capacity of at least 2.5 million metric tons and 2.5 million cubic meters; (2) are calculated to emit more than 50 metric tons of non-CH<sub>4</sub> organic compounds per year; and (3) received waste on or after November 11, 1987 (*Federal Register*, Vol. 61, No. 49, p. 9905, March 12, 1996). For the year 2003, an estimated 59 percent of landfill CH<sub>4</sub> was generated at landfills with landfill gas recovery systems subject to these requirements or installed on a voluntary basis (U.S. Environmental Protection Agency, 2005. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*).

## 6.1 CH<sub>4</sub> GENERATION AND CARBON STORAGE FOR ORGANIC MATERIALS

This section starts with a review of the principal processes that influence the fate of organic carbon in the landfill environment and then describes the experimental basis for and derivation of the estimates of CH<sub>4</sub> emissions and carbon storage used in this report.

### 6.1.1 Carbon Stocks and Flows in Landfills

Exhibit 6-1 shows the carbon flows within a landfill system. Carbon entering the landfill can have one of several fates: exit as CH<sub>4</sub>, exit as CO<sub>2</sub>, exit as volatile organic compounds (VOCs), exit dissolved in leachate, or remain stored in the landfill.<sup>4</sup>

After entering landfills, a portion of the organic materials decomposes and eventually is transformed into landfill gas and/or leachate. Aerobic bacteria initially decompose the waste until the available oxygen is consumed. This stage usually lasts less than a week and is followed by the anaerobic acid state, in which carboxylic acids accumulate, the pH decreases, and some cellulose and hemicellulose decomposition occurs. Finally, during the methanogenic state, bacteria further decompose the organic material into CH<sub>4</sub> and CO<sub>2</sub>.

The rate of decomposition in landfills is affected by a number of factors, including: (1) waste composition; (2) factors influencing microbial growth (moisture, available nutrients, pH, temperature); and (3) whether the operation of the landfill retards or enhances waste decomposition. Most studies have shown the amount of moisture in the waste, which can vary widely within a single landfill, to be a critical factor in the rate of decomposition.<sup>5</sup> As a result, there is increasing interest in the operation of landfills as bioreactors, in which leachate and possibly other liquids are recirculated to enhance decomposition and gas production.<sup>6</sup> Bioreactor technologies, which optimize landfill moisture content in order to accelerate waste decomposition, have emerged as a leading technology for facilitating rapid decomposition of organic wastes and cost-effective CH<sub>4</sub> collection.

Of the various components of the landfill carbon system, by far the most research to date has been conducted on the transformation of landfill carbon into CH<sub>4</sub>.<sup>7,8</sup> This interest has been spurred by a number of factors, including EPA's 1996 rule requiring large landfills to control landfill gas emissions (40 Code of Federal Regulations Part 60, Subparts Cc and WWW), the importance of CH<sub>4</sub> emissions in GHG inventories, and the market for CH<sub>4</sub> as an energy source. CH<sub>4</sub> production occurs in the methanogenic stage of decomposition, as methanogenic bacteria break down the fermentation products from earlier decomposition processes. Since CH<sub>4</sub> emissions result from waste decomposition, the quantity and duration of the emissions is dependent on the same factors that influence waste degradability (e.g., waste composition, moisture).

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<sup>4</sup> The exhibit and much of the ensuing discussion are taken directly from Freed, J.R., K. Skog, C. Mintz, and N. Glick. 2004. "Carbon Storage due to Disposal of Biogenic Materials in U.S. Landfills." *Proceedings of the Third Annual Conference on Carbon Sequestration*, U.S. Department of Energy. Available at [www.carbonsq.com](http://www.carbonsq.com).

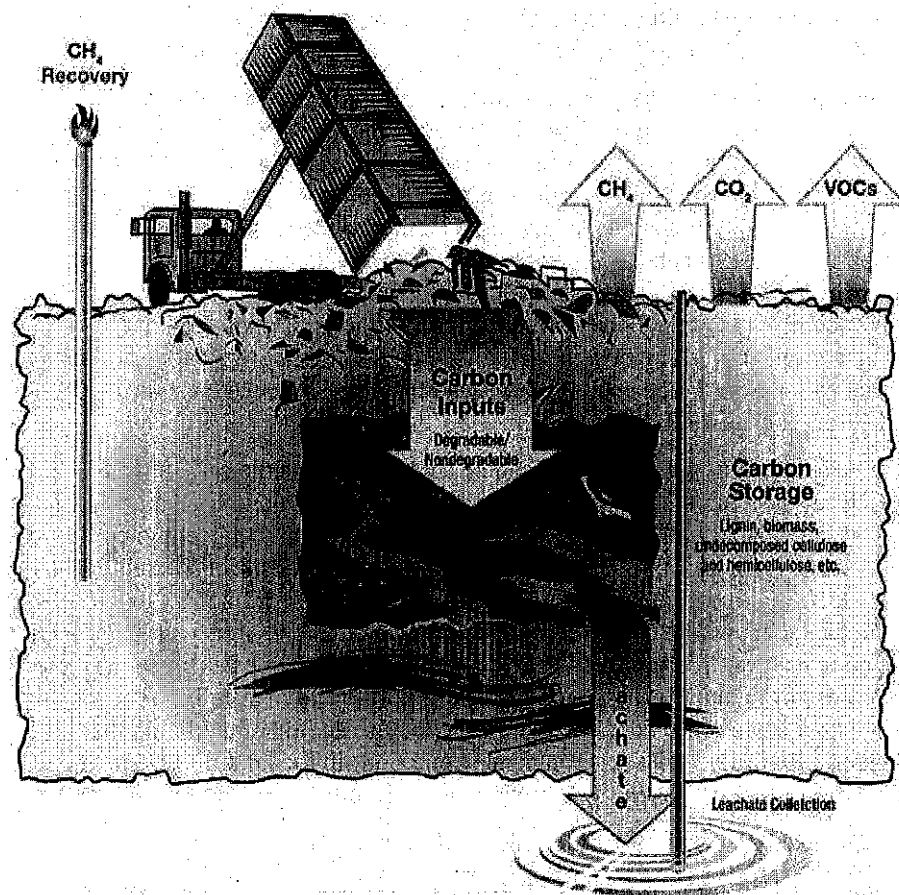
<sup>5</sup> Barlaz, M. A., R.K. Ham, and D.M. Schaefer. 1990. "Methane Production From Municipal Refuse: A Review of Enhancement Techniques and Microbial Dynamics," *Critical Reviews in Environmental Control*, 19(6):557.

<sup>6</sup> Pacey, J., D. Augenstein, R. Morck, D. Reinhart, R. Yazdani. 1999. The Bioreactive Landfill. *MSW Management*, September/October 1999.

<sup>7</sup> Bingemer, H G. and P J Crutzen, 1987. "The Production of Methane from Solid Wastes." *Journal of Geophysical Research* 90(D2): 2181-2187.

<sup>8</sup> Barlaz, M., W. Eleazer, W. Odle, X. Qian, Y. Wang. 1997. "Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills," U.S. Environmental Protection Agency 600/R-97-071.

## Exhibit 6-1 Landfill Carbon Mass Balance



Carbon dioxide is produced in the initial aerobic stage and anaerobic acid stage of decomposition. However, relatively little research has been conducted to quantify CO<sub>2</sub> emissions during these stages. Emissions during the aerobic stage are generally assumed to be a small proportion of total organic carbon inputs, and a screening level analysis indicates that less than 1 percent of carbon is likely to be emitted through this pathway.<sup>9</sup> Once the methanogenic stage of decomposition begins, landfill gas *as generated* is composed of approximately 50 percent CH<sub>4</sub> and 50 percent CO<sub>2</sub>.<sup>10</sup> But landfill gas *as collected* generally has a higher CH<sub>4</sub> concentration than CO<sub>2</sub> concentration (sometimes as much as a 60 percent:40 percent ratio), because some of the CO<sub>2</sub> is dissolved in the leachate as part of the carbonate system (CO<sub>2</sub> ↔ H<sub>2</sub>CO<sub>3</sub> ↔ HCO<sub>3</sub><sup>-</sup> ↔ CO<sub>3</sub><sup>2-</sup>).

To date, very little research has been conducted on the role of VOC emissions in the landfill carbon mass balance. Given the thousands of compounds entering the landfill environment, tracking the biochemistry by which these compounds ultimately are converted to VOC is a complex undertaking. Existing research indicates that ethane, limonene, *n*-decane, *p*-dichlorobenzene, and toluene may be

<sup>9</sup> Freed et al. 2004. Op cit.

<sup>10</sup> Bingemer, H. G. and P. J. Crutzen, 1987. Op. cit.

among the most abundant landfill VOCs.<sup>11</sup> Hartog (2003) reported non-CH<sub>4</sub> volatile organic compound concentrations in landfill gas at a bioreactor site in Iowa, averaging 1,700 parts per million (ppm) carbon by volume in 2001 and 925 ppm carbon by volume in 2002.<sup>12</sup> If the VOC concentrations in landfill gas are generally of the order of magnitude of 1,000 ppm, VOCs would have a small role in the overall carbon balance, as concentrations of CH<sub>4</sub> and CO<sub>2</sub> will both be hundreds of times larger.

Leachate is produced as water percolates through landfills. Factors affecting leachate formation include the quantity of water entering the landfill, waste composition, and the degree of decomposition. Because it may contain materials capable of contaminating groundwater, leachate (and the carbon it contains) is typically collected and treated before being released to the environment, where it eventually degrades into CO<sub>2</sub>. However, leachate is increasingly being recycled into the landfill as a means of inexpensive disposal and to promote decomposition while the containment system is operating at peak efficiency.<sup>13</sup> Research shows that this recirculation can increase the mass of organics collected by the system and consequently enhance aqueous degradation.<sup>14</sup> Although a significant body of literature exists on landfill leachate formation, little research is available on the carbon implications of this process. Based on a screening analysis, Freed et al. (2004) found that loss as leachate may occur for less than one percent of total carbon inputs to landfills.

In mass balance terms, carbon storage can be characterized as the carbon that remains after accounting for the carbon exiting the system as landfill gas or dissolved in leachate. On a dry weight basis, municipal refuse contains 30–50 percent cellulose, 7–12 percent hemicellulose, and 15–28 percent lignin.<sup>15</sup> Although the degradation of cellulose and hemicellulose in landfills is well documented, lignin does not degrade to a significant extent under anaerobic conditions.<sup>16</sup> In fact, although cellulose and hemicellulose biodegradation does occur, the extent of decomposition varies with landfill conditions, and these materials do not appear to completely degrade based on a number of excavation studies.<sup>17</sup> In addition, the presence of lignin actually prevents some cellulose and hemicellulose biodegradation. Thus, landfills in effect store some of the cellulose and hemicellulose and all of the lignin that is buried initially. The amount of storage will vary with environmental conditions in the landfill; pH and moisture content have been identified as the two most important variables controlling decomposition.<sup>18</sup>

### 6.1.2 Measured and Estimated CH<sub>4</sub> Generation and Carbon Storage

The focus of this report is on comparing waste management options for specific materials within the solid waste stream. Although a large body of research exists on CH<sub>4</sub> generation from mixed solid wastes, only a few investigators—most notably Dr. Morton Barlaz and coworkers at North Carolina State University—have measured the behavior of specific waste wood, paper, food waste, and yard trimming components.

<sup>11</sup> Eklund B., E. Anderson, B. Walker, and D. Burrows. 1998. "Characterization of landfill gas composition at the Fresh Kills municipal solid-waste landfill." *Environ Sci Technol* 32:2233-2237.

<sup>12</sup> Hartog, C.L. 2003. The Bluestem Bioreactor. Briefing presented at the Bioreactor Workshop, sponsored by USEPA, Feb 27-28, 2003, Arlington, VA.

<sup>13</sup> Chan G., L. Chu, and M. Wong. 2002. "Effects of leachate recirculation on biogas production from landfill co-disposal of municipal solid waste, sewage sludge and marine sediment." *Environmental Pollution* 118(3). 393–399.

<sup>14</sup> Warith, M. A., W. Zekry, and N. Gawri. 1999. "Effect of leachate recirculation on municipal solid waste biodegradation," *Water Quality Research Journal of Canada* Volume 34, No. 2, pp. 267–280.

<sup>15</sup> Hilger, H., and M. Barlaz. 2001. "Anaerobic decomposition of refuse in landfills and methane oxidation in landfill cover soils," *Manual of Environmental Microbiology*, 2nd Ed., Am. Soc. Microbiol., Washington, D. C., pp. 696–718.

<sup>16</sup> Colberg, P.J. 1988. "Anaerobic microbial degradation of cellulose lignin, oligolignols, and monoaromatic lignin derivatives." p. 333–372. In A.J.B. Zehnder (ed.) *Biology of anaerobic microorganisms*. New York: Wiley.

<sup>17</sup> Ham, R.K., and Bookter T.J. 1982. "Decomposition of solid waste in test lysimeters." *J.Env. Eng.* 108: 1147.

<sup>18</sup> Barlaz, M. A., R. Ham, and D. Schaefer. 1990. Op cit.

Barlaz<sup>19</sup> developed a series of laboratory experiments designed to measure biodegradation of these materials in a simulated landfill environment, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). Specific waste components (e.g., grass, branches, leaves, paper) were dried, analyzed for cellulose, hemicellulose, and lignin content, weighed, placed in two-liter plastic containers (i.e., reactors), and allowed to decompose anaerobically under moist conditions (Eleazer, et al. 1997).<sup>20</sup> The reactors were seeded with a small amount of well-decomposed refuse containing an active population of microorganisms. Phosphate and nitrogen concentrations were maintained at sufficient levels to assure that they were not limiting factors for biodegradation. The reactors were allowed to run until either no more CH<sub>4</sub> was produced or an extrapolation of gas production data indicate that the reactors had produced 95 percent of the CH<sub>4</sub> that would ultimately be emitted if allowed to run forever. At the end of the experiment, the contents of the reactors were dried, weighed, and analyzed for cellulose, hemicellulose, lignin, and (in the case of grass only) protein content. The carbon in these residual components is assumed to represent carbon that would remain undegraded over the long term in landfills; i.e., it would be stored.

Thus, these experiments provide three key outputs on a material-by-material basis: initial carbon content (namely, the sum of carbon in the cellulose, hemicellulose, lignin, and protein components), cumulative CH<sub>4</sub> emissions (over the course of the experiment), and carbon stored (as of the end of the experiment).<sup>21</sup>

As described in the preceding section, the principal elements in the landfill carbon balance are:

- Initial carbon content;
- Carbon output as CH<sub>4</sub> (CH<sub>4</sub>-C);
- Carbon output as CO<sub>2</sub> (CO<sub>2</sub>-C); and
- Residual carbon (i.e., landfill carbon storage, LF C).

Of these elements, the only one missing in the Barlaz experiments is CO<sub>2</sub> emissions. In a simple system where the only carbon fates are CH<sub>4</sub>, CO<sub>2</sub>, and carbon storage, the carbon balance can be described as

$$\text{CH}_4 - \text{C} + \text{CO}_2 - \text{C} + \text{LF C} = \text{Initial C}$$

If the only decomposition is anaerobic, then CH<sub>4</sub>-C = CO<sub>2</sub>-C.<sup>22</sup> Thus, the carbon balance can be expressed as

$$2 \times \text{CH}_4 - \text{C} + \text{LF C} = \text{Initial C}$$

Exhibit 6-2 shows the measured experimental values, in terms of the percentage of initial carbon, for each of the materials analyzed (see columns "b" and "d"). The exhibit also displays the implied biogas yield (= 2 × CH<sub>4</sub> - C, column "c"), and the sum of outputs (= 2 × CH<sub>4</sub> - C + LF C) as a percentage of initial carbon (see column "e"). As column "e" shows, the balance between carbon outputs and carbon inputs generally was not perfect; the imbalance ranges from 0 percent of initial carbon for newsprint to 34 percent of initial carbon for office paper, and is attributable to measurement uncertainty in the analytic techniques.

<sup>19</sup> Barlaz, M.A., 1998. "Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills." *Global Biogeochemical Cycles* 12 (2), 373-380.

<sup>20</sup> Eleazer, W.E., W.S. Odle, III, Y.S. Wang, and M.A. Barlaz. 1997. "Biodegradability of municipal solid waste components in laboratory-scale landfills." *Env. Sci. Tech.* 31(3):911-917.

<sup>21</sup> It should be noted that VOCs are also emitted, but are estimated to account for less than one percent of carbon flux from landfills. (Freed, J.R., K. Skog, N. Glick, C. Mintz. 2004. *Carbon Storage due to Disposal of Biogenic Materials in U.S. Landfills*. Proceedings of the Third Annual Conference on Carbon Sequestration. U.S. Dept of Energy, National Energy Technology Lab.)

<sup>22</sup> The molar ratio of CH<sub>4</sub> to CO<sub>2</sub> is 1:1 for carbohydrates (e.g., cellulose, hemicellulose). For proteins, the molar ratio is 1.65 CH<sub>4</sub> per 1.55 CO<sub>2</sub>; for protein it is C<sub>3.2</sub>H<sub>5</sub>ON<sub>0.86</sub> (Barlaz et al. 1989). Given the predominance of carbohydrates, for all practical purposes, the overall ratio is 1:1.

For the emission factors used in this report, adjustments were made to the measured values so that exactly 100 percent of the initial carbon would be accounted for. After consultation with Dr. Barlaz, the following approach was adopted:

- For materials where carbon outputs were *less than* initial carbon, the “missing” carbon was assumed to be emitted as equal molar quantities of CH<sub>4</sub> and CO<sub>2</sub>. In these cases (corrugated cardboard, office paper, food discards, leaves, branches, and mixed MSW) the CH<sub>4</sub>-C was increased with respect to the measured values as follows:

$$(\text{Initial C} - \text{LF C}) / 2 = \text{CH}_4 - \text{C}$$

This calculation assumes that CO<sub>2</sub>-C = CH<sub>4</sub>-C. In essence, the adjustment approach was to increase biogas production. The resulting values are italicized in column “g” of Exhibit 6-2.

- For materials where carbon outputs were *greater than* initial carbon (coated paper and grass), the measurements of initial carbon content and CH<sub>4</sub> mass were assumed to be accurate. Here, the adjustment approach was to decrease carbon storage. Thus, landfill carbon storage was calculated as the residual of initial carbon content minus (2 × CH<sub>4</sub>-C). The resulting values are italicized in column “h” of Exhibit 6-2.

**Exhibit 6-2  
Experimental and Adjusted Values for CH<sub>4</sub> Yield and Carbon Storage.<sup>a</sup>**

	Initial Carbon Content, % Of dry Matter	Measured Yield as a % Of Initial Carbon	Implied Yield Of Biogas (CH <sub>4</sub> +CO <sub>2</sub> ) as Proportion Of Initial Carbon	Measured Proportion of Initial Carbon Stored	Output as % of Initial Carbon	Adjustment Approach	Adjusted Yield of CH <sub>4</sub> as Proportion Of Initial Carbon	Adjusted Proportion Of Initial Carbon Stored
	a	b	c (=2×b)	d	e (=c+d)	f	g	h
<i>Paper and Paperboard</i>								
Corrugated	46%	16%	32%	55%	88%	inc biogas	22%	55%
Newsprint	49%	8%	15%	85%	100%	NA	8%	85%
Office Paper	40%	27%	54%	12%	66%	inc biogas	44%	12%
Coated Paper	34%	12%	25%	99%	124%	reduce LF C	12%	75%
Food Discards	50%	30%	59%	16%	75%	inc biogas	42%	16%
<i>Yard Trimmings</i>								
Grass	44%	16%	32%	71%	103%	reduce LF C	16%	68%
Leaves	41%	7%	14%	72%	86%	inc biogas	14%	72%
Branches	49%	6%	13%	77%	90%	inc biogas	12%	77%
MSW	42%	11%	22%	52%	74%	inc biogas	24%	52%

<sup>a</sup> CH<sub>4</sub> generation estimates are from Eleazer, et al. (1997), op cit. Carbon storage and initial carbon content values are from Barlaz (1998), op cit. All values for leaves (initial carbon content, CH<sub>4</sub> generation, and carbon storage) are from updated experiments reported in a letter report from M.A. Barlaz to J.R. Freed (of ICF Consulting) dated June 29, 2005.

**Exhibit 6-3**  
**CH<sub>4</sub> Yield for Solid Waste Components**

Material	Initial Carbon Content (%)	Final (Adjusted) C Emitted as CH <sub>4</sub> (%)	Final (Adjusted) CH <sub>4</sub> Yield (MTCE/dry ton)	Final (Adjusted) CH <sub>4</sub> Yield (MTCE/wet ton)
Corrugated Cardboard	47	22	0.80	0.688
Magazines/Third-class Mail	34	12	0.32	0.278
Newspaper	49	08	0.28	0.244
Office Paper	40	44	1.35	1.198
Food Discards	51	42	1.63	0.445
Yard Trimmings				0.264
Grass	45	16	0.55	0.150
Leaves	49	14	0.44	0.281
Branches	49	12	0.44	0.355
Mixed MSW	42	24	0.76	0.580

**Exhibit 6-4**  
**Carbon Storage for Solid Waste Components**

(a) Material	(b) Ratio Of Carbon Storage to Dry Weight (gm C/dry gm)	(c) Ratio Of Dry Weight to Wet Weight (dry gm/wet gm)	(d) (d = b × c) Ratio Of Carbon Storage to Wet Weight (gm C/wet gm)	(e) Amount Of Carbon Stored (MTCE per Wet Ton)
Corrugated Cardboard	0.26	0.95	0.25	0.22
Magazines/Third-class Mail	0.26	0.95	0.25	0.22
Newspaper	0.42	0.95	0.40	0.36
Office Paper	0.05	0.95	0.05	0.04
Food Discards	0.08	0.30	0.02	0.02
Yard Trimmings				0.19
Grass	0.30	0.30	0.09	0.08
Leaves	0.30	0.70	0.21	0.19
Branches	0.38	0.90	0.34	0.31
Mixed MSW	0.22	0.84	0.18	0.17

**Explanatory Notes:**

(1) Because MSW is typically measured in terms of its wet weight, it was required to convert the ratios for carbon stored as a fraction of dry weight to carbon stored as a fraction of wet weight. To do this conversion, EPA used the estimated ratio of dry weight to wet weight for each material. These ratios are shown in column "c" of the exhibit. For most of the materials, EPA used data from an engineering handbook.<sup>23</sup> For grass, leaves, and branches, EPA used data provided by Dr. Barlaz.

(2) For consistency with the overall analysis, EPA converted the carbon storage values for each material to units of MTCE stored per short ton of waste material landfilled. The resulting values are shown in column "e" of the exhibit.

The CH<sub>4</sub> yields in column "g" of Exhibit 6-2 can be converted to yields expressed in MTCE/short ton (to be consistent with units in the rest of the report), as shown in Exhibit 6-3. Similarly, the carbon storage proportions listed in percentages in Exhibit 6-2 are converted to MTCE/wet ton in Exhibit 6-4.

<sup>23</sup> Tchobanoglous, George, Hilary Theisen, and Rolf Eliassen. 1977. *Solid Wastes: Engineering Principles and Management Issues* (New York: McGraw-Hill Book Co.), pp. 58 and 60.

Dr. Barlaz's experiment did not specifically test all of the paper grades described in this report. He did evaluate four specific grades: newspaper, corrugated boxes, office paper, and coated paper. EPA identified proxies for five additional material types for which there were no experimental data. Magazines and third-class mail placed in a landfill were assumed to have characteristics similar to those observed for coated paper. Similarly, phonebooks and textbooks were assumed to behave in the same way as newspaper and office paper, respectively. Experimental results for branches were used as a proxy for dimensional lumber and medium-density fiberboard.

As discussed in Section 3.2, EPA included the following three definitions of mixed paper among the materials analyzed in this report:

- Broadly defined mixed paper, which includes almost all printing-writing paper, folding boxes, and most paper packaging;
- Residential mixed paper, which includes the typical mix of papers from residential curbside pick-up (e.g., high-grade office paper, magazines, catalogs, commercial printing, folding cartons, and a small amount of old corrugated containers); and
- Mixed paper from offices, which includes copy and printer paper, stationary and envelopes, and commercial printing.

To develop estimates of CH<sub>4</sub> emissions and carbon storage for these three categories of mixed paper, EPA used the detailed characterization of mixed paper (shown in Exhibit 3-2) developed by FAL, and assigned analogues among the four paper grades tested by Dr. Barlaz. Exhibit 6-5 characterizes the composition of the two products made from mixed paper: boxboard (made using either a broad or a residential mix of recycled paper) and paper towels (made from recycled office paper). Emissions were calculated using these characterizations of the mixed paper grades and the values obtained from Dr. Barlaz's experiment for newspaper, corrugated boxes, office paper, and coated paper.<sup>24</sup>

## 6.2 FATES OF LANDFILL CH<sub>4</sub>

In this analysis, EPA accounted for (1) the oxidation in the landfill of some portion of landfill CH<sub>4</sub> to CO<sub>2</sub>, and (2) the capture of CH<sub>4</sub>, either for flaring or for combustion with energy recovery (in either case, the captured CH<sub>4</sub> is converted to CO<sub>2</sub>).<sup>25</sup> Exhibit 6-6 presents this analysis.

The exhibit begins with the CH<sub>4</sub> generation per wet ton of each material, which is shown in column "b" (the values were simply copied from the last column of Exhibit 6-3). Columns "c" through "k" calculate net GHG emissions from CH<sub>4</sub> generation for each of three categories of landfills: (1) landfills without LFG recovery; (2) landfills with LFG recovery that flare LFG; and (3) landfills with LFG recovery that generate electricity from the LFG. Columns "l" through "n" show CH<sub>4</sub> generation-weighted percentage for each category in 2004.<sup>26</sup> The final column shows the weighted average GHG emissions from CH<sub>4</sub> generation across all types of landfills.

To estimate MSW CH<sub>4</sub> emissions from each category of landfill, EPA first estimated the percentage of landfill CH<sub>4</sub> that is oxidized near the surface of the landfill. Based on estimates in the literature, EPA assumed that 10 percent of the landfill CH<sub>4</sub> generated is either chemically oxidized or

<sup>24</sup> Note that Exhibits 6-2 through 6-4 do not show mixed paper since this was not used as a category by Dr. Barlaz; however, mixed paper is shown in Exhibit 6-8 through Exhibit 6-10.

<sup>25</sup> The CO<sub>2</sub> that is emitted is not counted as a GHG because it is biogenic in origin (as described in "CO<sub>2</sub> Emissions from Biogenic Sources" in Section 1.4.2).

<sup>26</sup> U.S. Environmental Protection Agency, 2006. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004*.



converted by bacteria to CO<sub>2</sub>,<sup>27</sup> and the remaining 90 percent remains as CH<sub>4</sub>, and is either emitted or captured and burned.

**Exhibit 6-5  
Composition of Mixed Paper Categories from Barlaz Experiments (Percent)**

Paper Grade	Broad Definition for Mixed Paper	Mixed Paper from Residential Sources	Mixed Paper from Offices
Corrugated Cardboard <sup>a</sup>	48	53	5
Magazines/Third-class Mail <sup>b</sup>	8	10	36
Newspaper <sup>c</sup>	24	23	21
Office Paper <sup>d</sup>	20	14	38
<b>Total</b>	<b>100</b>	<b>100</b>	<b>100</b>

**Explanatory Notes:**

<sup>a</sup> Includes virgin and recycled corrugated boxes.

<sup>b</sup> Includes coated free sheet paper and coated groundwood paper.

<sup>c</sup> Includes newspaper, uncoated groundwood paper, recycled folding boxes, and set-up boxes.

<sup>d</sup> Includes uncoated free sheet paper, cotton fiber paper, bleached bristols, unbleached kraft folding boxes, bleached kraft folding boxes, bleached bags and sacks, unbleached bags and sacks, and unbleached wrapping paper.

To estimate MSW CH<sub>4</sub> emissions from landfills with LFG recovery, EPA assumed that these landfills have an average LFG recovery efficiency of 75 percent.<sup>28</sup> EPA then calculated avoided utility GHG emissions from landfills where the CH<sub>4</sub> is used for electricity generation. Because energy recovery systems experience down time, during which CH<sub>4</sub> is flared rather than used to generate electricity, a 15 percent system efficiency loss was incorporated into the estimates for avoided utility emissions.<sup>29</sup>

EPA also estimated the percentage of CH<sub>4</sub> generated at each category of landfill in 2003. Research indicates that 59 percent of all landfill CH<sub>4</sub> was generated at landfills with recovery systems, and the remaining 41 percent was generated at landfills without LFG recovery.<sup>30</sup> Of the 59 percent of all CH<sub>4</sub> generated at landfills with LFG recovery, 53 percent (or 31 percent of all CH<sub>4</sub>) was generated at landfills that use LFG to generate electricity, and 47 percent (or 28 percent of all CH<sub>4</sub>) at landfills that flare LFG.<sup>31, 32</sup>

The results are shown in the final column of Exhibit 6-6. The materials with the highest rates of net GHG emissions from CH<sub>4</sub> generation, as shown in column "o"—corrugated boxes, office paper, and

<sup>27</sup> An oxidation rate of 10 percent is cited by Liptay, K., J. Chanton, P. Czepiel, and B. Mosher, "Use of stable isotopes to determine methane oxidation in landfill cover soils," *Journal of Geophysical Research*, April 1998, 103(D7), pp. 8243-8250; and Czepiel, P.M., B. Mosher, P.M. Crill, and R.C. Harriss. 1996. "Quantifying the effects of oxidation on landfill methane emissions," *Journal of Geophysical Research*, 101, pp. 16721-16729. The rate of 10 percent is also recommended by the IPCC.

<sup>28</sup> EPA. 2005. The Landfill Methane Outreach Program (LMOP) has used this figure in its most recent publications [see, for example, *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions* (Washington, D.C.: U.S. Environmental Protection Agency) September 1999].

<sup>29</sup> EPA. 1999. *Landfill Gas-to-Energy Project Opportunities: Background Information on Landfill Profiles*, Office of Air and Radiation, EPA 430-K-99-002, pp. 3-13.

<sup>30</sup> Based on data on year 2004 MSW landfill CH<sub>4</sub> generation and collection data from *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004* with an estimated landfill CH<sub>4</sub> recovery efficiency of 75 percent (from *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*).

<sup>31</sup> *U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*.

<sup>32</sup> The assumption that 59 percent of landfills recovering CH<sub>4</sub> will use it for energy is subject to change over time based upon changes in the cost of recovery and the potential payback. Additionally, new technologies may be developed that use recovered CH<sub>4</sub> for purposes other than generating electricity and direct gas use.

textbooks—also have the highest gross CH<sub>4</sub> generation, as shown in column “b.” The recovery of CH<sub>4</sub> at landfills reduces the CH<sub>4</sub> emissions for each material in proportionate amounts but does not change the ranking of materials by CH<sub>4</sub> emissions. Grass, leaves, branches, and the two wood products have the lowest rates of net GHG emissions from CH<sub>4</sub> generation.

### **6.3 UTILITY CO<sub>2</sub> EMISSIONS AVOIDED**

Exhibit 6-7 presents a list of conversion factors and physical constants used to convert CH<sub>4</sub> combusted for electricity production to avoided CO<sub>2</sub> emissions. Using data on Btu per cubic feet of CH<sub>4</sub>, kWh of electricity generated and delivered per Btu, and kilograms of utility carbon avoided per Btu delivered, EPA estimated that 0.15 MTCE is avoided per MTCE of CH<sub>4</sub> combusted. This figure then was incorporated into Exhibit 6-8 to estimate net GHG emissions from landfills with electricity generation. As mentioned earlier in this chapter, the analysis assumes that 31 percent of CH<sub>4</sub> generated in the United States comes from landfills that combust landfill CH<sub>4</sub> for electricity generation. EPA also assumes a 15 percent system efficiency loss, reflecting the fact that landfill gas-to-energy facilities incur some system “down-time,” as shown in column 1. Landfill CH<sub>4</sub> is assumed to be flared during down-time periods.

### **6.4 NET GHG EMISSIONS FROM LANDFILLING**

To determine the net GHG emissions from landfilling each material, the net GHG emissions from CH<sub>4</sub> generation, carbon storage (treated as negative emissions), and transportation CO<sub>2</sub> emissions were summed. The results are shown in Exhibit 6-8. The four columns under section “e” of the exhibit may be used by local MSW planners to estimate GHG emissions from MSW in a given community.

As the exhibit shows, the postconsumer results for organic materials vary widely. For some materials—in particular newspaper and phonebooks—landfilling results in substantial negative net GHG emissions. For others—including office paper, textbooks, and food discards—net emissions are significant. For the rest, net emissions and reductions are relatively small.

**Exhibit 6-6  
GHG Emissions from CH<sub>4</sub> Generation**

(a) Material	CH <sub>4</sub> from Landfills With LFG Recovery and:										Net CH <sub>4</sub> Generation (MTCE/Wet et.Ton)	Net CH <sub>4</sub> Emissions from Landfilling (MTCE/Wet et.Ton)	Net GHG Emissions From Landfilling (MTCE/Wet et.Ton)	TOTAL					
	CH <sub>4</sub> from Landfills Without CH <sub>4</sub> Recovery					Flaring									Electricity Generation				
	(b) CH <sub>4</sub> Generation (MTCE/Wet Ton)	(c) 90%	(d) Net GHG Emissions From CH <sub>4</sub> Generation (MTCE/Wet Ton)	(e) CH <sub>4</sub> Not Recovered (100% Minus LFG Collection System Efficiency)	(f) CH <sub>4</sub> Not Recovered That Is Not Oxidized to CO <sub>2</sub>	(g) Net GHG Emissions From CH <sub>4</sub> Generation (MTCE/Wet Ton)	(h) Utility CO <sub>2</sub> Emissions Avoided per MTCE CH <sub>4</sub> Combusted (MITCE)	(i) CH <sub>4</sub> Recovered for Electricity Generation Not Utilized Due to System "Down Time"	(j) Utility CO <sub>2</sub> Emissions Avoided (MTCE/Wet et.Ton)	(k) CH <sub>4</sub> From Landfills Without LFG Recovery in 2000					(l) CH <sub>4</sub> From Landfills With LFG Recovery And Flaring in 2000	(m) CH <sub>4</sub> From Landfills With LFG Recovery and Electricity Generation in 2000	(n) CH <sub>4</sub> From Landfills With LFG Recovery and Electricity Generation in 2000	(o) Net CH <sub>4</sub> Emissions from Landfilling (MTCE/Wet et.Ton)	(p) Net Avoided CO <sub>2</sub> Emissions from Landfilling (MTCE/Wet et.Ton)
Corrugated Cardboard	0.688	90%	0.619	25%	90%	0.155	-0.153	0.150	-0.067	41%	28%	31%	0.344	-0.021	0.323				
Magazines/Third-class Mail	0.278	90%	0.250	25%	90%	0.062	-0.153	0.150	-0.027	41%	28%	31%	0.139	-0.008	0.130				
Newspaper	0.244	90%	0.220	25%	90%	0.055	-0.153	0.150	-0.024	41%	28%	31%	0.122	-0.007	0.115				
Office Paper	1.198	90%	1.078	25%	90%	0.270	-0.153	0.150	-0.117	41%	28%	31%	0.599	-0.037	0.562				
Phonebooks	0.244	90%	0.220	25%	90%	0.055	-0.153	0.150	-0.024	41%	28%	31%	0.122	-0.007	0.115				
Textbooks	1.198	90%	1.078	25%	90%	0.270	-0.153	0.150	-0.117	41%	28%	31%	0.599	-0.037	0.562				
Dimensional Lumber	0.355	90%	0.320	25%	90%	0.080	-0.153	0.150	-0.035	41%	28%	31%	0.178	-0.011	0.167				
Medium-density Fiberboard	0.355	90%	0.320	25%	90%	0.080	-0.153	0.150	-0.035	41%	28%	31%	0.178	-0.011	0.167				
Food Discards	0.445	90%	0.400	25%	90%	0.100	-0.153	0.150	-0.043	41%	28%	31%	0.222	-0.014	0.209				
Yard Trimmings	0.264	90%	0.238	25%	90%	0.059	-0.153	0.150	-0.026	41%	28%	31%	0.132	-0.008	0.124				
Grass	0.150	90%	0.136	25%	90%	0.034	-0.153	0.150	-0.015	41%	28%	31%	0.075	-0.005	0.070				
Leaves	0.281	90%	0.253	25%	90%	0.063	-0.153	0.150	-0.027	41%	28%	31%	0.141	-0.009	0.132				
Branches	0.355	90%	0.320	25%	90%	0.080	-0.153	0.150	-0.035	41%	28%	31%	0.178	-0.011	0.167				
Mixed Paper <sup>a</sup>																			
Broad Definition Residential Definition Office Paper Definition	0.651	90%	0.59	25%	90%	0.146	-0.153	0.150	-0.063	41%	28%	31%	0.325	-0.020	0.305				
Office Paper Definition	0.616	90%	0.55	25%	90%	0.139	-0.153	0.150	-0.060	41%	28%	31%	0.308	-0.019	0.289				
Mixed MSW	0.641	90%	0.58	25%	90%	0.144	-0.153	0.150	-0.062	41%	28%	31%	0.321	-0.020	0.301				
	0.580	90%	0.522	25%	90%	0.131	-0.153	0.150	-0.056	41%	28%	31%	0.290	-0.018	0.272				

<sup>a</sup> The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

## 6.5 LIMITATIONS

Perhaps the most important caveat to the analysis of GHG emissions and storage associated with landfilling is that the results are based on a single set of laboratory experiments, those conducted by Dr. Morton Barlaz. Although researchers other than Dr. Barlaz have conducted laboratory studies that track the degradation of mixed MSW, his experiments were the only ones EPA identified that rigorously tested materials on an individual basis. Dr. Barlaz is recognized as an expert on the degradation of different fractions of MSW under anaerobic conditions, and his findings with respect to the CH<sub>4</sub> potential of mixed MSW are within the range used by landfill gas developers. Nevertheless, given the sensitivity of the landfill results to estimated CH<sub>4</sub> generation and carbon storage, EPA recognizes that more research is needed in this area.

Another important caveat relates to the estimate that 59 percent of MSW landfill CH<sub>4</sub> is generated at landfills with LFG recovery systems. The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate. Because of the high GWP of CH<sub>4</sub>, small changes in the LFG recovery rate (for the national average landfill) could have a large effect on the net GHG impacts of landfilling each material and the ranking of landfilling relative to other MSW management options. The effects of different rates of LFG recovery are shown in Exhibit 6-9. Column "b" of the exhibit shows net GHG emissions if 20 percent of waste were disposed of at landfills with recovery. The remaining columns show net GHG emissions at increasing LFG recovery rates, up to a 60 percent rate. As the exhibit shows, the net postconsumer GHG emissions for landfilling mixed MSW decline significantly as recovery increases. At the local level, the GHG emissions from landfilling MSW depend on whether the local landfill has LFG recovery, as shown in Exhibit 6-8.

Because the national average estimate of emissions is based on estimated year 2003 LFG recovery levels, several limitations are associated with the use of this emission factor. First, because landfill CH<sub>4</sub> generation occurs over time and has significant timing delays (i.e., CH<sub>4</sub> generation may not begin until a few years after the waste is deposited in the landfill and can continue for many years after the landfill is closed), the values listed in this chapter represent total CH<sub>4</sub> generated, over time, per ton of waste landfilled. To the extent that LFG recovery rates shift dramatically over time, these shifts are not reflected in the analysis. Second, landfills with LFG recovery may be permitted, under EPA regulations, to remove the LFG recovery equipment when three conditions are met: (1) the landfill is permanently closed, (2) LFG has been collected continuously for at least 15 years, and (3) the landfill emits less than 50 metric tons of non-CH<sub>4</sub> organic compounds per year.<sup>33</sup> Although the removal of LFG recovery equipment will permit CH<sub>4</sub> from closed landfills to escape into the atmosphere, the amounts of CH<sub>4</sub> emitted should be relatively small, because of the length of time required for LFG collection before LFG recovery equipment is removed. Third, several methodological issues are associated with applying the CH<sub>4</sub> generation estimates from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (U.S. Inventory) to develop the national average emission factors:<sup>34</sup>

- (1) The generation estimates in the U.S. Inventory include closed landfills (generation is modeled as a function of waste in place), whereas the estimates used in this report apply to ongoing generation (which is routed to open landfills);
- (2) Likewise, both the flaring and landfill gas-to-energy estimates also include closed landfills; and
- (3) The distribution of waste in place is not a perfect proxy for the destination of ongoing waste generation.

<sup>33</sup> *Federal Register*, 1996, Vol. 61, No. 49, p. 9907.

<sup>34</sup> U.S. Department of State, 2002. *U.S. Climate Action Report—2002*. Washington DC, May.

CH<sub>4</sub> oxidation rate and landfill gas collection system efficiency are also important factors driving results. EPA used values of 10 percent and 75 percent, respectively, as best estimates for these factors. Reviewers of previous editions of this report and sources in the literature have reported estimates ranging from about 5 percent to 40 percent for oxidation, and from about 60 to 95 percent for collection system efficiency. EPA investigated the sensitivity of the results to these assumptions, and the results are shown in Exhibit 6-10. To portray the sensitivity as a bounding analysis, EPA used the combinations of variables yielding the upper bound emission factor (5 percent oxidation, 60 percent collection efficiency) and the lower bound (40 percent oxidation, 95 percent efficiency).<sup>35</sup> As the exhibit shows, the materials most sensitive to these variables are those with the highest CH<sub>4</sub> generation potential, i.e., corrugated cardboard, office paper, textbooks, food discards, and mixed paper. Sensitivity varies: the difference between upper and lower bounds ranges from 0.05 MTCE/ton for grass to 0.42 MTCE/ton for office paper and textbooks. The postconsumer emission factors of several materials and mixed material combinations—corrugated cardboard, grass, mixed paper, and mixed MSW—change from having net storage under the lower bound to having net emissions under the upper bound.

Ongoing shifts in the use of landfill cover and liner systems are likely to influence the rate of CH<sub>4</sub> generation and collection. As more landfills install effective covers and implement controls to keep water and other liquids out, conditions will be less favorable for degradation of organic wastes. Over the long term, these improvements may result in a decrease in CH<sub>4</sub> generation and an increase in carbon storage. Moreover, Dr. Barlaz believes that the CH<sub>4</sub> yields from his laboratory experiments are likely to be higher than CH<sub>4</sub> yields in a landfill, because the laboratory experiments were designed to generate the maximum amount of CH<sub>4</sub> possible. If the CH<sub>4</sub> yields from the laboratory experiments were higher than yields in a landfill, the net GHG emissions from landfilling organic materials would be lower than estimated here.

EPA assumed that once wastes are disposed in a landfill, they are never removed. In other words, it was assumed that landfills are never “mined.” A number of communities have mined their landfills—removing and combusting the waste—in order to create more space for continued disposal of waste in the landfill. To the extent that landfills are mined in the future, it is incorrect to assume that carbon stored in a landfill will remain stored. For example, if landfilled wastes are later combusted, the carbon that was stored in the landfill will be oxidized to CO<sub>2</sub> in the combustor.

The estimate of avoided utility GHG emissions per unit of CH<sub>4</sub> combusted assumes that all landfill gas-to-energy projects are electricity producing. In reality, some projects are “direct gas” projects, in which CH<sub>4</sub> is piped directly to the end user for use as fuel. In these cases, the CH<sub>4</sub> typically replaces natural gas as a fuel source. Because natural gas use is less GHG-intensive than average electricity production, direct gas projects will tend to offset fewer GHG emissions than electricity projects will—a fact not reflected in the analysis.

For landfilling of yard trimmings (and other organic materials), EPA assumed that all carbon storage in a landfill environment is incremental to the storage that occurs in a nonlandfill environment. In other words, it was assumed that in a baseline where yard trimmings are returned to the soil (i.e., in a nonlandfill environment), all of the carbon is decomposed relatively rapidly (i.e., within several years) to CO<sub>2</sub>, and there is no long-term carbon storage. To the extent that long-term carbon storage occurs in the baseline, the estimates of carbon storage reported here are overstated, and the net postconsumer GHG emissions are understated.

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<sup>35</sup> Exhibit 6-10 also reports two intermediate combinations, including the best estimate values.

Finally, the analysis is limited by the assumptions that were made at various steps in the analysis, as described throughout this chapter. The key assumptions that have not already been discussed as limitations are the assumptions used in developing "corrected" CH<sub>4</sub> yields for organic materials in MSW. Because of the high GWP of CH<sub>4</sub>, a small difference between estimated and actual CH<sub>4</sub> generation values would have a large effect on the GHG impacts of landfilling and the ranking of landfilling relative to other MSW management options.

**Exhibit 6-7  
Calculation to Estimate Utility GHGs Avoided through Combustion of  
Landfill CH<sub>4</sub>**

Step	Value	Source
Metric tons CH <sub>4</sub> /MTCE CH <sub>4</sub>	0.17	1/((12/44) × Global warming potential of CH <sub>4</sub> )
Grams CH <sub>4</sub> /metric ton CH <sub>4</sub>	1.00E+06	Physical constant
Cubic ft. CH <sub>4</sub> /gram CH <sub>4</sub>	0.05	1/20: 20 grams per cubic foot of CH <sub>4</sub> at standard temperature and pressure
Btu/cubic ft. CH <sub>4</sub>	1,012	EPA 2005. LMOP Benefits Calculator.
kWh electricity generated/Btu	0.00009	1/11,700: EPA 2005. LMOP Benefits Calculator.
Electricity generation efficiency	0.85	EPA 2005. LMOP Net capacity factor for generation units (availability, operating load, parasitic losses).
Kg utility C avoided/kWh generated electricity	2.405E-01	0.24 kg CE/kWh generated electricity, from Exhibit 5-4. This assumes that LFG energy recovery displaces fossil fuel generation.
Metric tons avoided utility C/kg utility C	0.001	1000 kg per metric ton
Ratio of MTCE avoided utility C per MTCE CH <sub>4</sub>	0.15	Product from multiplying all factors

**Exhibit 6-8  
Net GHG Emissions from Landfilling<sup>a</sup>**

(a) Material	(b) Net GHG Emissions from CH <sub>4</sub> Generation (MTCE/Wet Ton)				(c) Net Carbon Storage (MTCE/Wet Ton)	(d) GHG Emissions From Transportation (MTCE/Wet Ton)	(e) (= b + c + d) Net GHG Emissions from Landfilling (MTCE/Wet Ton)			
	Landfills Without LFG Recovery	Landfills With LFG Recovery And Flaring	Landfills With LFG Recovery And Electric Generation	Year 2003 National Average			Landfills Without LFG Recovery	Landfills With LFG Recovery And Flaring	Landfills With LFG Recovery And Electric Generation	Year 2003 National Average
Aluminum Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Steel Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Copper Wire	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Glass	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
HDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
LDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
PET	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Corrugated Cardboard	0.62	0.15	0.09	0.32	-0.22	0.01	0.41	-0.06	-0.13	0.11
Magazines/Third-class Mail	0.25	0.06	0.04	0.13	-0.22	0.01	0.04	-0.15	-0.18	-0.08
Newspaper	0.22	0.05	0.03	0.11	-0.36	0.01	-0.13	-0.30	-0.32	-0.24
Office Paper	1.08	0.27	0.15	0.56	-0.04	0.01	1.05	0.24	0.12	0.53
Phonebooks	0.22	0.05	0.03	0.11	-0.36	0.01	-0.13	-0.30	-0.32	-0.24
Textbooks	1.08	0.27	0.15	0.56	-0.04	0.01	1.05	0.24	0.12	0.53
Dimensional Lumber	0.32	0.08	0.05	0.17	-0.31	0.01	0.02	-0.22	-0.25	-0.13
Medium-density Fiberboard	0.32	0.08	0.05	0.17	-0.31	0.01	0.02	-0.22	-0.25	-0.13
Food Discards	0.40	0.10	0.06	0.21	-0.02	0.01	0.39	0.09	0.05	0.20
Yard Trimmings	0.24	0.06	0.03	0.12	-0.19	0.01	0.05	-0.12	-0.15	-0.06
Grass	0.14	0.03	0.02	0.07	-0.08	0.01	0.06	-0.04	-0.05	0.00
Leaves	0.25	0.06	0.04	0.13	-0.19	0.01	0.07	-0.12	-0.14	-0.05
Branches	0.32	0.08	0.05	0.17	-0.31	0.01	0.02	-0.22	-0.25	-0.13
Mixed Paper <sup>b</sup>										
Broad Definition	0.59	0.15	0.08	0.31	-0.22	0.01	0.38	-0.06	-0.13	0.09
Residential Definition	0.55	0.14	0.08	0.29	-0.23	0.01	0.33	-0.08	-0.14	0.07
Office Paper Definition	0.58	0.14	0.08	0.30	-0.18	0.01	0.40	-0.03	-0.09	0.13
Mixed MSW	0.52	0.13	0.07	0.27	-0.17	0.01	0.37	-0.03	-0.08	0.12
Carpet	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Personal Computers	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Clay Bricks	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Concrete	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Fly Ash	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Tires	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01

**Explanatory Notes:**

<sup>a</sup> Please see Exhibit 6-6 for details on calculations.

<sup>b</sup> The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

**Exhibit 6-9**

**Net GHG Emissions from CH<sub>4</sub> Generation at Landfills with Recovery (MTCE/Wet Ton)**

Sensitivity Analysis: Varying the Percentage of Waste Disposed at Landfills with CH <sub>4</sub> Recovery					
(a)	(b)	(c)	(d)	(e)	(f)
Material	17%	20%	49%	55%	60%
Corrugated Cardboard	0.32	0.30	0.15	0.12	0.09
Magazines/Third-class Mail	0.00	0.00	-0.07	-0.08	-0.09
Newspaper	-0.16	-0.17	-0.22	-0.23	-0.24
Office Paper	0.89	0.86	0.60	0.54	0.50
Phonebooks	-0.16	-0.17	-0.22	-0.23	-0.24
Textbooks	0.89	0.86	0.60	0.54	0.50
Dimensional Lumber	-0.03	-0.03	-0.11	-0.13	-0.14
Medium-density Fiberboard	-0.03	-0.03	-0.11	-0.13	-0.14
Food Discards	0.33	0.32	0.22	0.20	0.19
Yard Trimmings	0.02	0.01	-0.04	-0.06	-0.07
Grass	0.04	0.04	0.01	0.00	-0.01
Leaves	0.04	0.03	-0.03	-0.05	-0.06
Branches	-0.03	-0.03	-0.11	-0.13	-0.14
Mixed Paper <sup>a</sup>					
Broad Definition	0.29	0.28	0.13	0.10	0.08
Residential Definition	0.25	0.24	0.10	0.08	0.05
Office Paper Definition	0.32	0.31	0.16	0.13	0.11
Mixed MSW	0.29	0.28	0.15	0.12	0.10

<sup>a</sup>The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.



**Exhibit 6-10**

**Net GHG Emissions from CH<sub>4</sub> Generation at Landfills with Recovery (MTCE/Wet Ton)**

Sensitivity Analysis: Varying Oxidation and Gas Collection Efficiency Rates.				
Oxidation Rate: Collection Efficiency:	40% 95%	25% 85%	10% 75%	5% 60%
Material	Lower-bound Emissions	Conservative (High) Emissions	Best Estimate	Upper-bound Emissions
Corrugated Cardboard	0.18	0.26	0.34	0.42
Magazines/Third-class Mail	0.07	0.10	0.14	0.17
Newspaper	0.06	0.09	0.12	0.15
Office Paper	0.31	0.45	0.60	0.73
Phonebooks	0.06	0.09	0.12	0.15
Textbooks	0.31	0.45	0.60	0.73
Dimensional Lumber	0.09	0.13	0.18	0.22
Medium-density Fiberboard	0.09	0.13	0.18	0.22
Food Discards	0.12	0.17	0.22	0.27
Yard Trimmings	0.07	0.10	0.13	0.16
Grass	0.04	0.06	0.08	0.09
Leaves	0.07	0.10	0.14	0.17
Branches	0.09	0.13	0.18	0.22
Mixed Paper <sup>a</sup>				
Broad Definition	0.17	0.24	0.33	0.40
Residential Definition	0.16	0.23	0.31	0.38
Office Paper Definition	0.17	0.24	0.32	0.39
Mixed MSW	0.15	0.22	0.29	0.36

<sup>a</sup> The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

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