COMPOSTING

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

1. A SUMMARY OF THE GHG IMPLICATIONS OF COMPOSTING

During composting, microbial decomposition aerobically transforms organic substrates into a stable, humus-like material (Brown and Subler 2007). Although small-scale composting, such as backyard composting, occurs across the United States, WARM models composting only in central composting facilities with windrow piles because data for small-scale composting or other large-scale operations are insufficient.[2] WARM includes composting as a materials management option for yard trimmings, food waste, PLA, and mixed organics.

As modeled in WARM, composting results in some carbon storage (associated with application of compost to agricultural soils), carbon dioxide (CO_2) emissions from transportation and mechanical turning of the compost piles, in addition to fugitive emissions of methane (CH_4) and nitrous oxide (N_2O) produced during decomposition.[3] To estimate the carbon storage from compost application, EPA selected point estimates from the range of emission factors covering various compost application rates and time periods. EPA chose the point estimates based on a typical compost application rate of 20 short tons of compost per acre, averaged over four soil-crop scenarios.[4] EPA selected the carbon storage values for the year 2010 to maintain consistency with the forest carbon storage estimates discussed in the Forest Carbon Storage chapter.[5] Overall, EPA estimates that centralized composting of mixed organics results in net carbon storage of 0.14 $MTCO_2E$ per wet short ton of organic inputs composted and applied to agricultural soil.

2. CALCULATING THE GHG IMPACTS OF COMPOSTING

The stages of a composting operation with the potential to affect GHG flux include the following processes:

- Collecting and transporting the organic materials to the central composting site.
- Mechanical turning of the compost pile.

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[1] Composting is not included as a material management pathway for paper because of insufficient information on the GHG implications of composting paper products.

[2] Windrows are a widely used method for composting yard trimmings and municipal solid waste, and they are considered to be the most cost-effective composting technology (EPA, 1994; Coker, 2006).

[3] These fugitive emission sources were added in June 2014 to WARM Version 13.

[4] EPA ran the composting simulation on two sites included in CENTURY: an eastern Colorado site with clay loam soil and a southwestern Iowa site with silty clay loam soil. EPA simulated two harvest regimes on each site, one where corn is harvested for silage and 95 percent of the above-ground biomass is removed and the other one where corn is harvested for grain and the stover is left behind to decompose on the field.

[5] For consistency with the paper recycling/source reduction analysis of forest carbon storage, EPA analyzed the GHG implications of composting at the year 2010. EPA chose 2010 in the paper recycling/source reduction and forest carbon analyses because it represented a delay of 5 to 15 years from the onset of the simulated period of incremental recycling.

- Non-CO_2 GHG emissions during composting (primarily CH_4 and N_2O).
- Storage of carbon after compost application to soils.

Composting also results in biogenic CO_2 emissions associated with decomposition, both during the composting process and after the compost is added to the soil. Because this CO_2 is biogenic in origin, however, it is not counted as a GHG in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* and is not included in this accounting of emissions and sinks.[6]

Exhibit 1: Components of the Composting Net Emission Factor for Food Waste, Yard Trimmings, and Mixed Organics

	Composting of Post-Consumer Material			
Material Type	**Transportation to Composting**	**Fugitive Emissions**	**Soil Carbon Storage**	**Net Emissions (Post-Consumer)**
PLA	0.04	0.07	-0.24	-0.13
Food Waste	0.04	0.05	−0.24	-0.15
Food Waste (meat only)	0.04	0.05	-0.24	-0.15
Food Waste (non-meat)	0.04	0.05	-0.24	-0.15
Beef	0.04	0.05	-0.24	-0.15
Poultry	0.04	0.05	-0.24	-0.15
Grains	0.04	0.05	-0.24	-0.15
Bread	0.04	0.05	-0.24	-0.15
Fruits and Vegetables	0.04	0.05	-0.24	-0.15
Dairy Products	0.04	0.05	-0.24	-0.15
Yard Trimmings[a]	0.04	0.07	−0.24	−0.12
Grass	0.04	0.07	−0.24	−0.12
Leaves	0.04	0.07	−0.24	−0.12
Branches	0.04	0.07	−0.24	−0.12
Mixed Organics	0.04	0.07	−0.24	−0.14

[a] Yard trimmings represent a 50-percent, 25-percent, and 25-percent weighted average of grass, leaves and branches, respectively, based on U.S. waste generation data from EPA (2014).

Exhibit 1 shows the three components of the net emission factor for food waste, yard trimmings, PLA, and mixed organics. Because of resource and model resolution constraints, the two approaches EPA used in WARM to calculate carbon storage from compost application model only finished compost and do not distinguish between compost feedstocks; therefore, the emission factors for each organic's input are the same. The following sections provide further detail on the sources and methods used to develop these emission factors. Section 2.1 describes how WARM accounts for GHG emissions during transportation of composting materials and the physical turning of the compost. Section 2.2 describes the estimates of fugitive emissions of CH_4 and N_2O for composting within WARM. Section 2.3 details the methodology for calculating the carbon storage resulting from compost application in soils, and Sections 2.4 and 2.5 describe in greater detail the components of carbon storage.

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[6] For more information on biogenic carbon emissions, see the text box, "CO_2 Emissions from Biogenic Sources" in the WARM Background and Overview chapter.

2.1 CO_2 FROM TRANSPORTATION OF MATERIALS AND TURNING OF COMPOST

WARM includes emissions associated with transporting and processing the compost in aerated windrow piles. Transportation energy emissions occur when fossil fuels are combusted to collect and transport yard trimmings and food waste to a composting facility, and then to operate the composting equipment that turns the compost.[7] To calculate these emissions, WARM relies on assumptions from FAL (1994), which are detailed in Exhibit 2.

Exhibit 2: Emissions Associated with Transporting and Turning Compost

Material Type	Diesel Fuel Required to Collect and Transport One Short Ton (Million Btu)[a]	Diesel Fuel Required to Turn the Compost Piles (Million Btu)[a]	Total Energy Required for Composting (Million Btu)	Total CO_2 Emissions from Composting ($MTCO_2E$)
Organics	0.36	0.22	0.58	0.04

[a] Based on estimates in Table I-17 in FAL, 1994, p.132.

2.2 FUGITIVE EMISSIONS OF CH_4 AND N_2O DURING COMPOSTING

2.2.1 Background on Fugitive Emissions from Composting

During the composting process, microbial activity decomposes waste into a variety of compounds, some of which are emitted from the compost pile as gases. The amount and type of end products formed during these reactions depends on many factors, including the original nutrient balance and composition of the waste, the temperature and moisture conditions of the compost, and the amount of oxygen present in the pile. These processes result in the generation of small amounts of CH_4 and N_2O gases, which contribute to the net GHG emissions associated with the composting pathway.

The scientific literature suggests that there is a wide range of emissions for fugitive gases generated during composting. Local factors can strongly influence the existence and extent of CH_4 and N_2O emissions from composting piles. These local factors include:

- *Aeration*
- *Density of compost*
- *Frequency of turning*
- *Feedstock composition*
- *Climate (temperature and precipitation)*
- *Size of compost piles*

After reviewing a large number of studies, EPA found that Amlinger et al. (2008) provided the most applicable results for WARM and forms the basis of EPA's estimates of fugitive emissions for composted waste in WARM. The study characterizes CH_4 and N_2O emissions for both biowaste and green waste in well-managed compost windrows across several weeks. Biowaste is composed of separated organic household waste, including food waste. Green waste, or garden waste, is composed primarily of plant waste such as grass and yard trimmings. In WARM, food waste is classified as a bio-

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[7] EPA did not count transportation emissions from delivery of finished compost from the composting facility to its final destination.

waste for the purposes of estimating fugitive emissions, whereas yard trimmings is classified as a green waste. Mixed organics and PLA are considered a representative blend of compostable waste, and use a weighted average of the biowaste and green waste emission factors for the relative shares of each waste type composted within the United States.

The three best data points available from Amlinger et al. (2008) are the 21 week value for green waste and the 12 week values for biowaste. Although composting times vary between facilities, most commercial composting facilities process compost in 6 to 12 weeks (CWMI 1998), with purely green waste requiring a longer composting time of 14 to 18 weeks (Zanker Road Resource Management, Undated).

2.2.2 Methane Generated from Composting

There is a consensus within the scientific literature that CH_4 is emitted in measurable quantities even in well-managed compost piles. Amlinger et al. (2008) conducted an exhaustive review of literature on emissions from composting and supplemented it with their own findings. They found CH_4 emissions occurring across feedstock types even when the piles were managed, although emissions were variable even within the same treatment. In their own experiments, Amlinger et al. (2008) found that CH_4 emissions for green waste feedstock were 0.0139 $MTCO_2E$ per wet ton of fresh matter (FM). The Amlinger study found that CH_4 emissions from biowaste were lower at 0.0066 and 0.0055 $MTCO_2E$ per wet ton of FM, at 9 weeks and 12 weeks, respectively. For biowaste, EPA selected the 12 week value for WARM because the CO_2 equivalent result increases with time of composting and the results stabilized in later weeks of composting.

Exhibit 3: Fugitive CH_4 Emissions from Composting Biowaste and Green Waste

Compost Feedstock	CH_4 Emissions ($MTCO_2E$/ton)
Biowaste	0.0055
Green waste	0.0139

2.2.3 Nitrous Oxide Generated from Composting

Knowledge of the mechanism of N_2O emissions from composting is significantly less developed than that of either CO_2 or CH_4 emissions. N_2O is formed during both incomplete ammonium oxidation and incomplete denitrification processes, but there is debate over which process is most important in composting (Lou and Nair 2009). While CH_4 is usually detected near the bottom of piles where oxygen is absent, N_2O often forms closer to the surface. For green waste, Amlinger recorded a value of 0.0609 $MTCO_2E$/ton of FM, whereas for biowaste the authors recorded results of 0.0092 and 0.0396 $MTCO_2E$/ton of FM, at 9 weeks and 12 weeks respectively. For biowaste, EPA selected the 12 week value for WARM because the CO_2 equivalent result increases with time of composting and the results stabilized in later weeks of composting.

Exhibit 4: Fugitive N_2O Emissions from Composting Biowaste and Green Waste

Compost Feedstock	N_2O Emissions ($MTCO_2E$/ton)
Biowaste	0.0396
Green waste	0.0609

2.2.4 Summary of Fugitive Emissions Generated from Composting

Combining CH_4 and N_2O emissions, the net fugitive emissions from composting comprise 0.0451 and 0.0748 $MTCO_2E$/ton for biowaste and green waste, respectively. For mixed organics, WARM uses a weighted emission factor that considers the relative amounts of biowaste and green waste composted in the United States.[8] As the composting waste stream is predominantly yard waste, the weighted emission estimate is much closer to the value for green waste, at 0.0724 $MTCO_2E$/ton. For an overview of fugitive emissions by material type, see Exhibit 5.

Exhibit 5: Total Fugitive Emissions from Composting, by Material Type

Material Type	Fugitive Emissions ($MTCO_2E$/ton)
PLA	0.0724
Food Waste	0.0451
Yard Trimmings	0.0748
Grass	0.0748
Leaves	0.0748
Branches	0.0748
Mixed Organics	0.0724

2.3 CARBON STORAGE RESULTING FROM COMPOST APPLICATION TO SOILS

2.3.1 Background on Carbon Storage in Soils

The stock of carbon in soils is the result of a balance between inputs (usually plant matter) and outputs (primarily CO_2 flux during decomposition of organic matter). The entire portion of carbon held in the soil and undergoing decomposition is collectively referred to as “soil organic matter” (SOM) or “soil organic carbon” (SOC). SOC is a mixture of different organic compounds that decompose at vastly differing rates. Soils contain thousands of different SOC compounds that microbial degradation or abiotic condensation reactions transform into new structures. The more complex of these molecular soil structures tend to have a low decomposition rate and often are identified as humus (Davidson and Janssens, 2006). Strong evidence exists that SOC decomposition decreases with increasing depth (Meersmans et al., 2009). The top layers of soil generally contain organic matter (such as plant residues) that decomposes quickly, meaning that carbon in this portion of the soil is likely to be relatively young. The carbon dynamics in deeper soil layers and the driving factors behind vertical distribution of SOC are poorly understood.

During composting, microbes degrade the original waste materials into organic compounds through a variety of pathways. During this decomposition, approximately 80 percent of the initial

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[8] According to the 2012 EPA MSW Facts and Figures report, 8% of the waste composted in the United States in 2011 was comprised of food waste, whereas the remaining 92% consisted of yard waste (EPA 2014).

organic matter is emitted as CO_2 (Beck-Friis et al., 2000). The remainder of the organic compounds eventually stabilize and become resistant to further rapid microbial decomposition (i.e., recalcitrant) (Francou et al., 2008). Mature compost is characterized as containing a high percentage of these stable, humic substances. When the compost is mature, nearly all of the water-soluble compounds (such as dissolved organic carbon) will have leached out (Bernal et al., 1998).

While EPA is currently researching the mechanisms and magnitude of carbon storage, WARM assumes that carbon from compost remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils and carbon stored in non-reactive humus compounds. WARM calculates the carbon storage impact of each carbon storage path separately and then adds them together to estimate the carbon storage factor associated with each short ton of organics composted.

2.3.2 Soil Carbon Storage Calculation

To calculate soil carbon storage, EPA simulated soil organic matter pools using the Century model, which is described in Section 2.4. EPA ran more than 30 scenarios with varied compost application rates and frequency, site characteristics, fertilization rates, and crop residue management. Based on this analysis, EPA concluded that while a single compost application does initially increase soil carbon, the carbon storage rate declines with time after the application. Using a timeframe of 10 years to calculate carbon storage, only a fraction of the initial carbon added remained in the soil at the end of that time period. EPA included this fraction of added carbon per short ton of compost that remained present in the soil after 10 years in the WARM composting emission factor, as shown in Exhibit 1.[9]

2.3.3 Alternative Carbon Storage Hypotheses

When EPA first incorporated into WARM composting as a materials management option, the agency conducted research but could not identify sufficient primary data that could be used to develop quantitative estimates of the soil carbon storage benefits of compost. EPA developed modeling approaches to investigate the possible effects of compost application on soil carbon storage. In addition to the humus formation and depleted soils mechanisms mentioned earlier, EPA considered the following two possible mechanisms for the effect of compost on soil carbon:

- Nitrogen in compost may stimulate higher productivity, thus generating more crop residues. This fertilization effect would increase soil carbon because of the larger volume of crop residues, which serves as organic matter input.
- 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 non-compost 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.

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[9] Note that if the time frame is extended to longer periods (and many of the recent discussions of agricultural and forestry offsets in the context of carbon credits would indicate that 10 years is well below the consensus time horizon), the fraction of added carbon per ton of compost that remains present in the soil would be smaller. Although the selection of an appropriate time frame is not the subject of this documentation, EPA may later revisit the choice of time frame.

This multiplier effect could enable compost to increase carbon storage by more than its own direct contribution to carbon mass accumulation.

EPA concluded from the Century simulations that a shortage of nitrogen can modestly increase crop productivity with compost application, which results in higher inputs of crop residues into the soil and an increased carbon storage rate. As noted in Section 2.4.4, however, our analysis assumes that farmers will supply sufficient synthetic fertilizer to crops to maintain commercial yields, in addition to any compost added, so that the soil carbon effect of nitrogen fertilization resulting from compost is relatively small. 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. More information on these two hypotheses and why they were not included in the final carbon storage emission factor appears in Section 2.4.4.

2.4 CENTURY MODEL FRAMEWORK AND SIMULATIONS

2.4.1 Evaluating Possible Soil Carbon Models

As mentioned earlier, EPA's composting 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: (1) Century and (2) the Rothamsted C (ROTHC-26.3)[10] model. Both are peer-reviewed models that have structure and application that have been described in scores of publications. The models share several features:

- Ability to run multiyear simulations.
- Capability to construct multiple scenarios covering various climate and soil conditions and loading rates.
- 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, EPA decided to use Century rather than ROTHC-26.3.

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[10] 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 19th century.

2.4.2 Century Simulations

For this analysis, EPA developed a basic agricultural scenario in Century where land was converted from prairie to farmland (growing corn) in 1921 and remained growing corn through 2030.[11]

Description of the Century Soil Model

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 as a result of 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_2, 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, most of the non-humic material, and some of the more easily decomposed fulvic acids. The active pool is estimated to have a mean residence time (MRT) of a few months to 10 years (Metherell et al., 1993; Brady and Weil, 1999). 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. The passive pool of soil organic matter includes very stable materials remaining in the soil for hundreds to thousands of years.

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 2.4.)

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.

Several sets of detailed site characteristics from past modeling applications are available to users in Century. 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. EPA then ran more than 30 scenarios to examine the effect of the following variables on soil carbon storage:

- Compost application rate and frequency.

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[11] EPA is conducting research into compost markets, and initial findings indicate that compost is not often used in large-scale agricultural applications, but it is often applied in high-end markets, such as landscaping. Century and other widely vetted soil carbon models, however, do not readily model the effects of composting on soil carbon for non-agricultural scenarios. Because of this lack of data, EPA chose to simulate composting using the large-scale agricultural scenarios available in Century. EPA is researching methods to improve these assumptions.

- Site characteristics (rainfall, soil type, irrigation regime).
- Fertilization rate.
- Crop residue management.

EPA adjusted compost application rates using the organic matter (compost) files for each compost application rate included in the analysis. EPA then 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 short tons compost per acre (corresponding to 60–1,850 grams of carbon per square meter).[12] EPA also investigated the effect of compost application frequency on the soil carbon storage rate and total carbon levels. EPA ran the model to simulate compost applications of 1.3 wet short tons compost/acre and 3.2 wet short tons compost/acre every year for 10 years (1996–2005) and applications of 1.3 wet short tons compost/acre and 3.2 wet short tons compost/acre applied every 5 years (in 1996, 2001, and 2006). The simulated compost was specified as having 33 percent lignin,[13] 17:1 C:N ratio,[14] 60:1 carbon-to-phosphorus ratio, and 75:1 carbon-to-sulfur ratio.[15] 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 that is, to calculate the change in carbon storage attributable only to the addition of compost.

Finally, EPA simulated two harvest regimes, 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 effect of the carbon added directly to the system in the form of compost, as opposed to total carbon inputs, which include crop residues.

2.4.3 Analysis of Compost Application Impacts on Depleted Soils

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

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[12] 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.

[13] EPA estimated the percentage of lignin 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 [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.

[14] The C:N ratio was taken from Brady and Weil (1999).

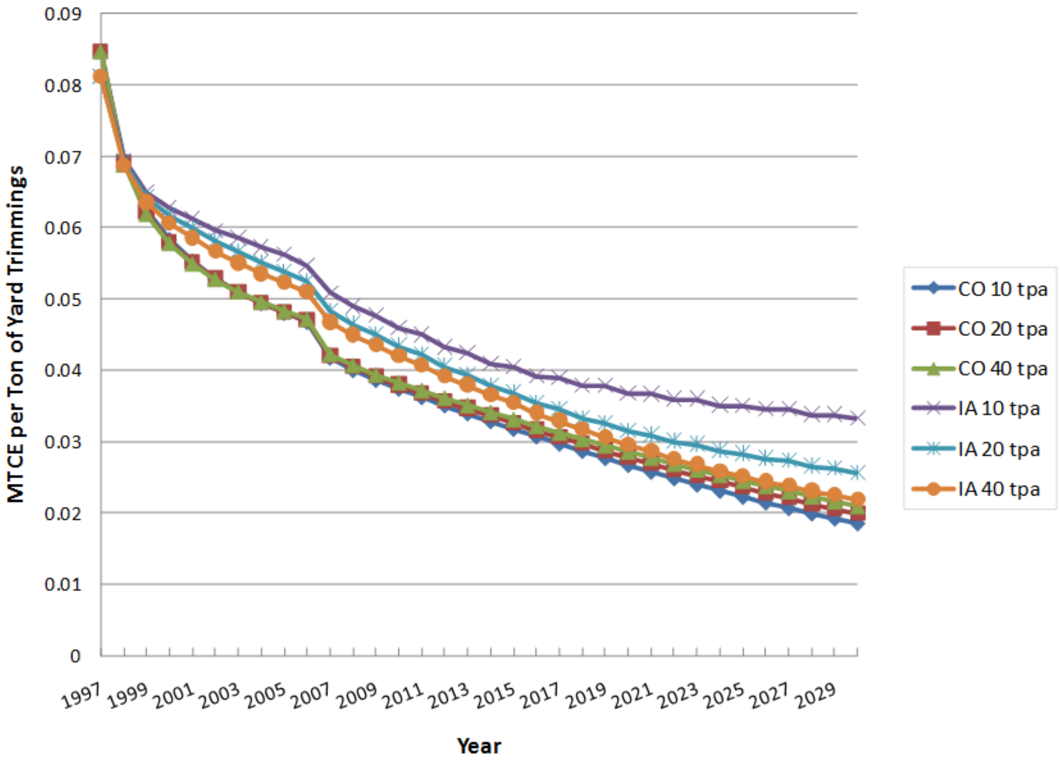
[15] C:P and C:S ratios were based on the literature and conversations with composting experts, including Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University.

compost application. EPA converted output data in grams of carbon per square meter to $MTCO_2E$ by multiplying by area in square meters and multiplying by the molecular weight ratio of CO_2 to carbon.

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.[16] That is, the factors are expressed as a carbon storage rate in units of $MTCO_2E$ per wet short ton of organic inputs (not $MTCO_2E$ per short ton of compost).

As Exhibit 6 illustrates, EPA's Century analysis found that 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 6 shows 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 (0.30 $MTCO_2E$) per wet ton yard trimmings immediately after compost application in 1997 to about 0.02 MTCE (0.07 $MTCO_2E$) per ton in 2030, 24 years after the last application in 2006.

Exhibit 6: Soil Carbon Storage—Colorado and Iowa Sites; 10, 20, and 40 Tons-per-Acre Application Rates



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

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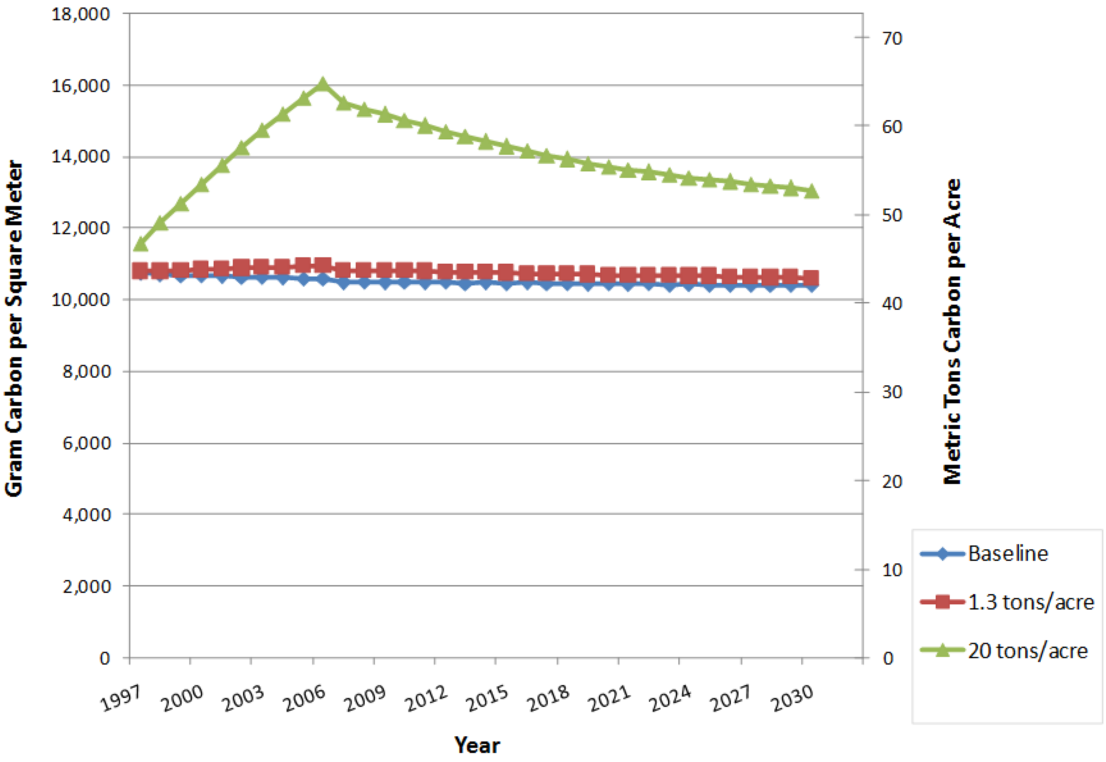
[16] EPA assumes 2.1 tons of yard trimmings are required to generate 1 ton of composted yard trimmings; thus, to convert the results in WARM (in $MTCO_2E$ per wet ton yard trimmings) to $MTCO_2E$ per wet ton of compost, multiply by 2.1. To convert to $MTCO_2E$ per dry ton compost, multiply values in WARM by 4.2 (assuming 50 percent moisture content).

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.

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 7). Soil organic carbon concentrations increase throughout the period of compost application, peak in 2006 (the last year of application), and decline thereafter as a result of decomposition of the imported carbon. Exhibit 7 shows 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.)

Exhibit 7: Total Soil C; Iowa Site, Corn Harvested for Grain



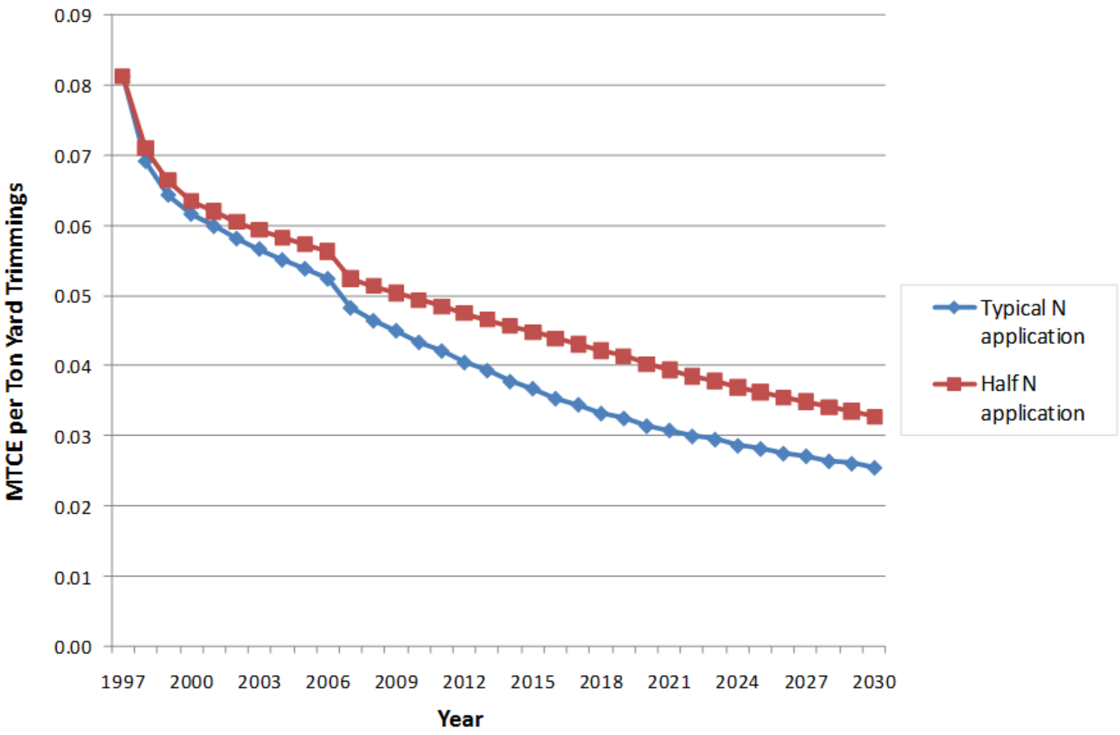
2.4.4 Century Simulation of Nitrogen Fertilization Effect

While the decomposition of organic materials is the primary process driving soil carbon retention, EPA's Century analysis also revealed several secondary effects of compost application, including the effects of compost application on nitrogen availability and moisture retention. EPA performed additional Century simulations to quantify the nitrogen fertilization effect, or the hypothesis that mineralization of nitrogen in compost could stimulate crop growth, leading to production of more organic residues and increased soil organic carbon levels. The strength of this effect varies, depending on the availability of other sources of nitrogen (N). To investigate this hypothesis, EPA analyzed different rates of synthetic fertilizer addition ranging from zero up to a typical rate to attain average crop yield (Colorado site: 90 lbs. N/acre; Iowa site: 124 lbs. N/per acre). EPA also evaluated fertilizer application at half of these typical rates.

Exhibit 8 shows the carbon storage rate for the Iowa site and the effect of nitrogen fertilization. The two curves in the exhibit represent the difference in carbon storage between a with-compost scenario (20 tons per acre) and 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 scenarios. Because the nitrogen added through the 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.

Exhibit 8: Incremental Carbon Storage as a Function of Nitrogen Application Rate at the Iowa Site



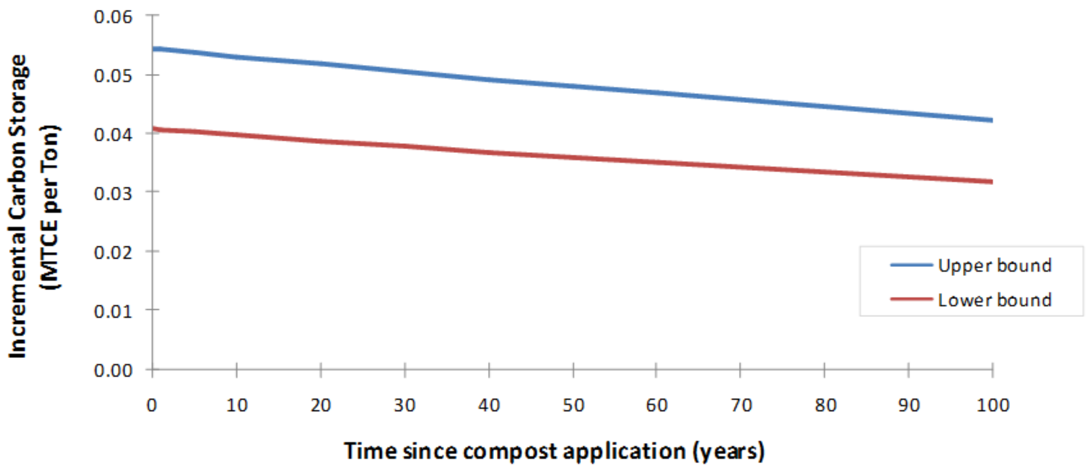
The difference in incremental carbon storage rates between the two fertilization scenarios is less than 0.01 MTCE (0.03 $MTCO_2E$) per ton, indicating that the nitrogen fertilization effect is relatively small. Note that this finding is based on the assumption that farmers applying compost also will apply sufficient synthetic fertilizer to maintain economic crop yields. The effect would be larger 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.

2.5 HUMUS FORMATION CARBON STORAGE

Significant evidence exists that compost contains stable compounds, such as humus, and that the carbon stored in that humus should be considered passive when added to the soil because it breaks down much more slowly than crop residues. As mentioned earlier, the Century model does not allow carbon inputs to flow directly into the passive pools; therefore, EPA used a bounding analysis to estimate the upper and lower limits of this humus formation mechanism of carbon storage. This bounding analysis rested on two primary variables: (1) the fraction of carbon in compost that is considered very stable and (2) the rate at which passive carbon is degraded to CO_2. Based on the expert judgment of Dr. Michael Cole from the University of Illinois, EPA found that between 4 to 20 percent of the carbon in compost degrades very quickly, and the remainder can be considered either slow or passive. Dr. Cole found 400 years to be the average of the reported sequestration times of carbon in the soil. The upper and lower bounds of the rate of carbon storage in soils resulting from the humus effect are shown in Exhibit 9. EPA took an average value of the upper and lower bounds after 10 years to estimate the carbon storage per short ton of compost that was stored in the passive carbon pool after year 10.

In WARM's final calculation, EPA weighed the carbon values from the two carbon storage mechanisms according to the estimated percentage of compost that is passive (assumed to be 52 percent), and then used the total to estimate the sequestration value associated with composting, as shown in Exhibit 11.

Exhibit 9: Carbon Storage Resulting from Humus Effect, Bounding Estimate

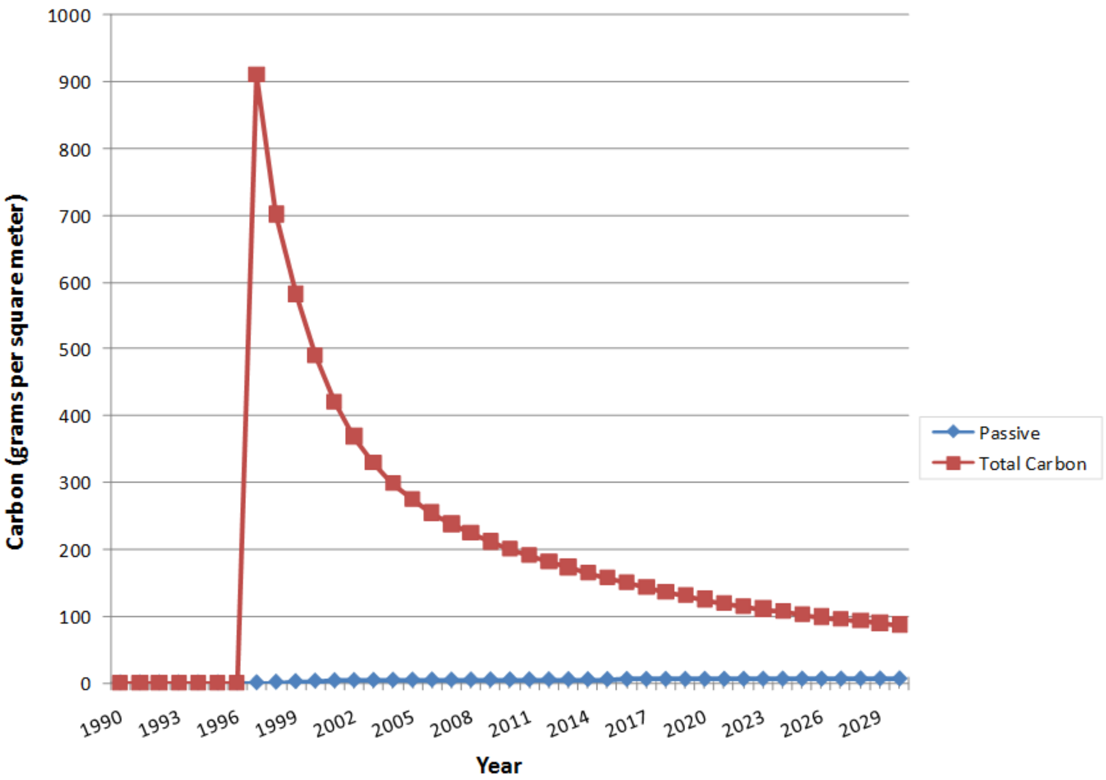


2.5.1 Eliminating the Possibility of Double-Counting

EPA adopted the approach of adding the humus formation effect to the direct carbon storage effect to capture the range of carbon storage benefits associated with compost application; however, this dual approach creates the possibility of double counting because the Century simulation may include both the direct carbon storage and humus formation effects. In an effort to eliminate double counting, EPA evaluated the way that Century partitions compost carbon after 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 10 shows, Century does not introduce significant increments over the base case of recalcitrant carbon into the passive pool at any time.

Exhibit 10: 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).

2.5.2 WARM Composting Results

Exhibit 11 shows the two carbon storage mechanisms included in WARM's analysis of the GHGs associated with composting. The resulting net storage value relies on three main input values: the direct carbon storage, the carbon stored resulting from humus formation, and the percentage of carbon in compost assumed to be passive, or resistant to degradation.

Exhibit 11: The Soil Carbon Restoration Effect, the Increased Humus Formation Effect, and the Transportation Emissions for the Typical Compost Application Rate of 20 Short Tons per Acre

	Soil Carbon Restoration					
Scenario	**Unweighted**	**Proportion of C that Is Not Passive (%)**	**Weighted Estimate**	**Increased Humus Formation**	**Transportation Emissions**	**Net Carbon Flux**
Annual application of 20 short tons of compost per acre	-0.04	0.48	-0.07	-0.17	0.04	-0.20

3. LIMITATIONS

Because of 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. The lack of primary research on carbon storage associated with composting limited EPA's analysis. 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 WARM, which is intended to present life-cycle GHG emissions of waste management practices for selected material types, including food discards and yard trimmings.

3.1 LIMITATIONS OF MODELING APPROACHES

Because of 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 important, 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) (Parton et al., 1987). 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 (Paustian et al., 1992). In addition, the model is not designed to capture the hypothesis that, because of the compost application, soil ecosystem dynamics change and more carbon is stored than is added to the soil (i.e., the multiplier effect).

Century simulates carbon movement through organic matter pools. Although the model is designed to evaluate additions of organic matter in general, EPA does not believe that it has 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 it appears to be the best available option.

3.2 LIMITATIONS RELATED TO THE SCOPE OF THE EMISSION FACTORS

As indicated earlier, this chapter describes EPA's estimates of the GHG-related impacts of composting organics. EPA developed these estimates within the framework of the larger WARM development effort; 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 noted in the other documentation chapters, the GHG impacts of composting reported in this chapter are calculated using a methodology that facilitates comparison between composting and other possible disposal options for yard trimmings (i.e., landfilling and combustion). 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 2, the lack of data and resources constrained EPA's analysis and, therefore, the analysis considers a small sampling of feedstocks and a specific application scenario (i.e., degraded 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 also 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 (Lal et al., 1998). 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 and some areas become more arid.

As is the case in other chapters, the methodology EPA 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 smaller and thus 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, could require more fuel because of the large distance separating the sites.

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. For example, nutrients in compost tend to foster soil fertility (Brady and Weil, 1999). In fact, composts have been used to establish plant growth on land previously unable to support vegetation.

3.3 ONGOING RESEARCH TO IMPROVE COMPOSTING ESTIMATES

EPA is researching several aspects of the composting analysis to improve existing assumptions based on updated research that is emerging. EPA's literature review focused on the following key topics: potential end uses and markets for compost, the shares of compost currently used in different applications in the United States, humus formation, the carbon storage timeframe, the multiplier effect, and other environmental benefits of composting.

Research on the potential end uses and markets for compost suggested that the horticultural/landscaping markets appear to be the most popular markets for compost in the United States. While data quantifying the size of these markets are limited, this finding suggests that the assumptions underlying the current WARM modeling may need to be re-examined. Further research into this subject may be warranted to determine exactly how compost is used in these urban or higher-end markets.

During EPA's research on carbon storage mechanisms, the agency uncovered new field research that may provide a basis for using primary data to quantify the carbon storage emission factor. If EPA decides to calculate a new carbon sequestration value based on field data, both the Century and bounding analyses will be superseded by this approach. EPA has also conducted extensive research into potential GHG emissions from composting. Preliminary research indicates that small amounts of both CH_4 and N_2O emissions are released during composting, even in well-managed piles.

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 documentation. 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 generally compost is 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.[17] Analyses of these benefits, however, are highly sensitive to

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[17] 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.

assumptions about composting and fertilizer application rates, and information on the typical applications of these two soil additions is lacking.

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