

**METHOD FOR ESTIMATING GREENHOUSE GAS EMISSION REDUCTIONS FROM
DIVERSION OF ORGANIC WASTE FROM LANDFILLS TO COMPOST FACILITIES**

FINAL DRAFT

May 2017

Industrial Strategies Division
Transportation and Toxics Division

California Air Resources Board

California Environmental Protection Agency

DRAFT

TABLE OF CONTENTS

EXECUTIVE SUMMARY	<u>1</u>
1. BACKGROUND	<u>2</u>
2. METHODS	<u>3</u>
2.1 Composting Emissions	<u>3</u>
2.1.1 Transportation Emissions (T_e)	<u>4</u>
2.1.2 Process Emissions (P_e)	<u>4</u>
2.1.3 Fugitive Emissions (F_e)	<u>5</u>
2.2 Compost Emission Reductions	<u>5</u>
2.2.1 Net Avoided Emissions from Landfilling (ALF_b)	<u>6</u>
2.2.2 Decreased Soil Erosion (E_b)	<u>8</u>
2.2.3 Reduced Fertilizer Use (F_b)	<u>8</u>
2.2.4 Reduced Herbicide Use (H_b)	<u>9</u>
2.2.5 Conversion Factor (C_{use})	<u>9</u>
2.3 Compost Emission Reduction Factor	<u>10</u>
3. RESULTS AND DISCUSSION	<u>10</u>
3.1 Composting Emissions	<u>10</u>
3.1.1 Transportation Emissions (T_e)	<u>10</u>
3.1.2 Process Emissions (P_e)	<u>11</u>
3.1.3 Fugitive Emissions (F_e)	<u>12</u>
3.1.4 Summary of Emissions	<u>14</u>
3.2 Compost Emission Reductions	<u>14</u>
3.2.1 Net Avoided Emissions from Landfilling (ALF_b)	<u>14</u>
3.2.2 Decreased Soil Erosion (E_b)	<u>17</u>
3.2.3 Reduced Fertilizer Use (F_b)	<u>17</u>
3.2.4 Reduced Herbicide Use (H_b)	<u>18</u>
3.2.5 Conversion Factor (C_{use})	<u>18</u>
3.2.6 Summary of Emission Reductions	<u>19</u>
3.2 Final Compost Emission Reduction Factor	<u>19</u>
3.4 Variability Analysis	<u>20</u>
4. SUMMARY	<u>23</u>
5. Changes in Biogenic Emissions	<u>23</u>
6. NOTES AND REFERENCES	<u>27</u>

Method for Estimating Greenhouse Gas Emission Reductions from Diversion of Organic Waste from Landfills to Compost Facilities

EXECUTIVE SUMMARY

This document explains a life-cycle method to quantify the California-specific greenhouse gas emission reductions from using compost as well as the greenhouse gas emissions associated with compost management. By diverting organic wastes to composting facilities, methane emissions from landfills are avoided. Additionally, compost application to agricultural fields increases soil health while providing multiple co-benefits such as, reducing the amount of synthetic fertilizer needed, decreasing soil erosion, and reducing the use of herbicides. Although not quantified in this report, other composting application benefits include the energy saved through reduced water use, increased crop yield, and increased microbial activity which result in healthier soils. The management of compost material also results in greenhouse gas emissions. These emissions occur during the collection of the initial feedstock and delivery of the compost, the use of energy and water to manage the compost pile, and as microorganisms convert the initial feedstock to compost. The following equation is used to calculate the compost emission reduction factor (CERF):

$$\text{CERF} = (\text{ALF}_b + ((\text{E}_b + \text{F}_b + \text{H}_b) * \text{C}_{\text{use}})) - \text{E}_{\text{total}}$$

where,

- CERF = Compost emission reduction factor (MTCO₂E/ton of feedstock)
ALF_b = Emission reductions associated with the avoidance of methane emissions at landfills (MTCO₂E/ton of feedstock)
E_b = Emission reduction associated with decreased soil erosion (MTCO₂E/ton of compost)
F_b = Factor to account for the reduced fertilizer use (MTCO₂E/ton of compost)
H_b = Factor to account for the reduced herbicide use (MTCO₂E/ton of compost)
C_{use} = Conversion factor used to convert from tons of compost to tons of feedstock
E_{total} = Emissions due to the composting process (MTCO₂E/ton of feedstock)

The CERF generated for this method was determined for three types of organic compostable waste types: food waste, yard trimmings, and mixed organics, the latter of which is a combination of the other two types proportioned based on the 2008 CalRecycle statewide waste characterization study*. The resulting CERF values are **0.62, 0.44, and 0.56 MTCO₂E/ton of feedstock** (wet weight) for food waste, yard trimmings, and mixed organics respectively.

* *The 2014 waste characterization study (<http://www.calrecycle.ca.gov/publications/Documents/1546/20151546.pdf>) was not included in this report. The data from the study will be included into the next version of the CERF.*

1. BACKGROUND

From 1990 to 2013, the amount of organic waste composted in the United States increased over 420 percent from about 4 to almost 20 million tons.¹ Composting is a decomposition process that converts an initial feedstock of organic waste (i.e. food scraps, yard trimmings, branches, leaves, grass, and organic municipal solid waste) into an organic-rich soil amendment called compost. Compost application to soil systems has many benefits, which include, but are not limited to, increased soil carbon concentrations, decreased density, increased porosity, increased resistance to erosion, provision of secondary nutrients and micro-nutrients not available in many common fertilizers, increased soil microbiology which may protect against pests and diseases, and the potential to decrease the use of synthetic fertilizers.^{1-7, 44, 79} In recent years, efforts have begun to quantify the above compost benefits in terms of greenhouse gas reductions.⁸⁻¹²

The quantification of greenhouse gas (GHG) emission reductions from compost application requires a life-cycle approach. A life-cycle approach accounts for emissions or emission reductions at the manufacturing, use or end-of-life stages for a single product.¹³ Composting is unique because using its end-product reduces energy requirements in other products' life cycle stages. For example, by decreasing soil density, compost application on lands may reduce the fuel requirements for tillage, but this has not yet been quantified. Compost use can also decrease the amount of industrially produced fertilizer needed to produce a particular yield. Applying compost can also reduce the amount of water needed to irrigate a crop. In the proposed method, the GHG emission reductions are quantified compared to a baseline scenario of waste landfilling, and includes benefits from compost used as an amendment to an agricultural soil system. For this analysis, emissions associated with the composting process, such as transportation, and machinery use, and its beneficial end uses in avoiding landfill GHG emissions, reduced soil erosion, and fertilizer and herbicide use will be quantified.

This life-cycle method quantifies the net GHG benefits of composting in relation to a baseline scenario of landfilling, and has consistent elements when compared with other recent compost analyses in the literature. The United States Environmental Protection Agency (USEPA) Waste Reduction Model (WARM) quantifies the compost GHG benefit by accounting for the net emissions from the composting process and summing them with the benefit of soil carbon storage, and also includes a comparison of net emissions relative to a baseline of landfilling.¹⁴ Studies by Martinez-Blanco et al (2009) and Blengini (2008) assess similar parameters as the WARM model, but also include fertilizer benefits.¹⁵⁻¹⁶ However, these studies do not attempt to quantify the GHG benefits associated with a decline in soil erosion and pesticide use, and do not compare composting to a landfilling baseline scenario.

This method evaluates the emission reduction benefits and emissions associated with the composting process and the agricultural use of its end-products, as compared to a baseline scenario of waste landfilling with gas collection. The emissions considered will be transportation (feedstock collection and delivery of finished product), process

emissions (feedstock manipulation during the production of compost,) and fugitive emissions (CH₄ and N₂O emissions from the composting material). The greenhouse gas emission benefits will include avoided methane emissions from landfilling, reduced soil erosion, and a decrease in fertilizer and herbicide use. Whenever feasible, studies from California composting operations and compost application will be used. The quantification of each of these variables will lead to a compost emission reduction factor (CERF) for three categories of organic waste: food scraps, yard trimmings, and mixed organic waste.

This paper concludes with a discussion of the potential change in biogenic carbon dioxide (CO₂) emissions that result when organic material is composted rather than landfilled.

2. METHODS

The boundary, or life-cycle stages used to quantify the compost emission reduction factor, for this method establishes the greenhouse gas emission reductions of compost application and greenhouse gas emissions from composting organic waste, as compared to a baseline scenario of landfilling. This section describes the emissions from the composting process and secondly discusses the avoided landfill emissions and the emission reductions associated with using compost as an agricultural amendment that were considered in this method. If compost is used as an agricultural amendment, all of the benefits discussed below are applicable. A survey completed by CalRecycle indicates that the majority (~ 73 percent) of compost application in California occurs for uses that would benefit from all of the variables discussed below (see section 2.2).¹⁸ These include agricultural, landscape, and nursery applications.

2.1 Composting Emissions

There are three main emission sources that occur during the composting process: transportation emissions occurring from the collection of the initial feedstock and delivery of the finished compost; energy and water emissions from the composting management process; and fugitive emissions from unintended anaerobic decomposition of the feedstocks within the overall aerobic system. The significance of each emission is important because it detracts from the overall emission benefit of compost use; however these emissions must also be compared to emissions that would occur in the baseline scenario of landfilling. The emissions that are discussed in this method are consistent with the emissions in studies evaluating the GHG emissions from composting.^{15, 16, 19} Biogenic carbon dioxide (CO₂) emissions from the degradation of organic material (i.e. branches and food scraps) during the composting process are not counted to maintain consistency with ARB inventory accounting.⁶⁰

The overall emissions from composting are represented by the following equation:

$$E_{\text{total}} = T_e + P_e + F_e \quad (1)$$

where,

- E_{total} = Total emissions from composting (MTCO₂E/ton of feedstock)
- T_e = Net additional transportation emissions from composting as compared to landfilling (MTCO₂E/ton of feedstock)
- P_e = Net additional process emissions from composting as compared to landfilling (MTCO₂E/ton of feedstock)
- F_e = Fugitive emissions from composting (MTCO₂E/ton of feedstock)

2.1.1 Transportation Emissions (T_e)

The transportation emissions (fossil fuel CO₂ emissions from diesel) associated with composting occurs during the collection of the organic feedstock to the composting facility and the delivery of the finished compost to the end user. The total distance travelled (inbound and outbound), in combination with an emission factor that indicates the amount of greenhouse gas emitted per distance travelled (g CO₂/ton-mile), gives an approximation of the emissions for transportation. The inbound and outbound distances vary across the state and depend on the collection method and customer proximity to the composting facility. Discussions with CalRecycle staff led to the identification of six geographically representative compost facilities across the state.²⁰ Average transportations distances were obtained from a survey of Northern, Central and Southern California composters. The emission factor used was generated from Appendix G of the ARB's Statewide Truck and Bus Regulation (101 g CO₂/ton-mile).²¹

Transportation emissions associated with composting are compared to estimates of transportation emissions associated with landfilling. Any significant net difference in estimated transportation emissions between the composting and landfilling scenario are included in the emissions equation as the (T_e) parameter.

2.1.2 Process Emissions (P_e)

Process emissions from the composting process were from the energy required to grind material (electricity), turn and manage the compost pile (diesel) and the emissions associated with water use on the compost pile. California-specific data sources for this parameter were obtained from a personal communication with CalRecycle staff.²⁰

Process emissions associated with composting are compared to estimates of process emissions associated with landfilling. Any significant net difference in estimated process emissions between the composting and landfilling scenario are included in the emission equation as the (P_e) parameter.

2.1.3 Fugitive Emissions (F_e)

Fugitive emissions arise from methane (CH_4) and nitrous oxide (N_2O) releases during the composting process. Methane is produced in anaerobic pockets of a compost pile, while nitrous oxide is a product of nitrification or denitrification.²² Even though the overall emissions of these two GHGs is low relative to carbon dioxide, their emissions are significant because their global warming potential (GWP) is 25 and 298 times greater than CO_2 for CH_4 and N_2O , respectively.²³ Numerous research articles discuss the release of CH_4 and N_2O emissions from composting. The list of studies include both manure²⁴⁻²⁶ and organic waste²⁷⁻²⁹ composting piles. However, manure is not normally contained in a commercial organic waste stream, so data from these studies were not used for this analysis. Studies were selected for inclusion based on criteria such as whether the composting feedstock and methods were consistent and representative of composting management practices in California, and whether the emissions sampling procedures used in the study were appropriate for estimating the fugitive emissions emanating from the surface of compost piles (rather than, for instance, sampling gas from directly inside the compost piles). The selected studies represent California composting methods, and include three California-specific studies. The values from the selected papers that discussed CH_4 (n=6) and N_2O (n=4) emissions were averaged together.

2.2 Compost Emission Reductions

The greenhouse gas emission reduction benefits include both the avoided emissions that would otherwise occur if the organic material had been disposed in a landfill, calculated based on the initial organic feedstock, as well as the benefits from agronomic use of compost, which are calculated based on the finished compost product. The final reduction benefit is reported by converting the compost application benefit to units of initial organic feedstock. The addition of compost to soils produces many benefits that contribute to soil and plant health. While this analysis evaluates only the principle benefits from a GHG perspective, more benefits may occur from compost application (such as increased crop yield and increased below ground biomass when applied to rangelands).^{39,76,80,81} More research is needed to be able to quantify the GHG benefits from these composting applications.

A previous version of this study quantified and included emission reductions from carbon storage in soils.⁵⁸ The previous version's carbon storage factor represented the net amount of carbon from the organic compost feedstock that was stored in soil for at least 30 years following application of the compost on agricultural soils. Because the new version of this study is quantifying emission reduction benefits of composting as compared to a baseline scenario of landfilling, the carbon storage factor is not included as an emission reduction benefit. Instead, changes in biogenic CO_2 emissions are evaluated for composting as compared to landfilling. The biogenic CO_2 emissions are not included in the total composting emission reduction factor; however section 5 contains a discussion of biogenic emission changes. This approach ensures consistency with the carbon flows accounting approach used by ARB GHG inventory

accounting, and is equitable in the treatment of the slowly degrading and/or passive carbon pools that can be stored in landfills and soils for long periods of time.

Reduced water use is also an area where the GHG benefits have been quantified in the previous version of this study. Studies show that compost application decreases the density of soil due to an increase in soil porosity.³²⁻³⁴ Increases in porosity and surface area creates more binding spots for water, leading to higher water retention rates when compared to an unamended soil.^{33,34} The physical characteristics that allow for the increased water retention are directly due to the carbon content of the compost.⁴ A decay pattern similar to carbon loss in compost was therefore used for modeling the water use benefits.¹⁴

The previous version of this paper used a study conducted by the University of California – Riverside which addressed the water retention benefits from compost application.³⁵ The data collected from the study was used to calculate the compost application benefit in the reduced energy needed to transport water to the compost-amended soil. The emission factor calculated for water use was 1.5 MTCO₂e per acre-foot (AF).³⁶ This value is based on a statewide embedded energy in water value of 3.2 MWh/AF. We did not use this study to quantify the energy saved from water use and will consider adding water savings in subsequent revisions of the CERF.

The composting application benefits described in this method are listed in the equation below:

$$B_{total} = ALF_b + ((E_b + F_b + H_b) * C_{use}) \quad (2)$$

where,

- B_{total} = Total emission reduction benefit due to compost use (MTCO₂E/ton of feedstock)
- ALF_b = Emission reductions associated with the avoidance of methane emissions at MSW landfills (MTCO₂E/ton of feedstock)
- E_b = Emission reduction associated with decreased soil erosion (MTCO₂E/ton of compost)
- F_b = Factor to account for the reduced fertilizer use (MTCO₂E/ton of compost)
- H_b = Factor to account for the reduced herbicide use (MTCO₂E/ton of compost)
- C_{use} = Conversion factor used to convert from tons of compost to tons of feedstock.

2.2.1 Net Avoided Emissions from Landfills (ALF_b)

Methane (CH₄) is generated in landfills when microbial respiration reactions occur under the anaerobic conditions present in landfills. Nitrous oxide (N₂O) emissions from degrading organic materials are poorly understood and are assumed to be zero. More research is needed to verify this assumption. Landfilled organic (compostable)

materials such as food waste and yard trimmings decompose primarily under anaerobic conditions following a brief aerobic decomposition phase, and produce significant quantities of landfill gas (LFG) which consists of approximately equal parts CH₄ gas and biogenic CO₂ gas.¹⁴ Produced landfill CH₄ will eventually be released to the atmosphere if not oxidized by landfill cover material or captured and destroyed by a landfill gas collection and control system.

Landfill gas collection systems are present at a majority of landfills in California. It is estimated that upwards of 95% of the waste-in-place (WIP) in the state is located in landfills with gas collection and control systems.⁶⁰ For this reason, this avoided landfill methane calculation assumes that all landfills from which organic waste is diverted have an active gas collection and control system in place.

In order to quantify the net avoided methane emissions that result from diversion of compostable organics, this analysis relies on use of the IPCC first order decay (FOD) model, the same model adapted by ARB for use as the Landfill Emissions Tool and prescribed for modeling emissions per the ARB Local Government Operations Protocol.^{51,53,60} The IPCC FOD model was adapted for this analysis to quantify the net methane emissions that would occur over a one-hundred-year timeframe from the landfill disposal of one short ton of waste deposited in year one. The model was parameterized and run for three primary compostable waste types: food waste, yard trimmings, and a category named 'mixed organics,' which is a combination of the first two categories proportioned based on the most recent California Waste Characterization Study.⁶⁵ For each type of waste, the model was run using two different values for the methane oxidation factor, which represents the fraction of the generated methane that is oxidized by the landfill cover material, and two different landfill gas collection efficiency scenarios.

This study uses two values for the oxidation factor (10% and 35%) in an attempt to balance the uncertainty with respect to landfill gas oxidation rates. The first value (10%) is equal to the IPCC and U.S. EPA default oxidation rate, and the second value (35%) represents the upper bound estimate based on recent research findings and revisions made to the US EPA Mandatory Reporting Rule.⁶⁶

The two gas collection scenarios are meant to represent two reasonable estimations for LFG collection efficiencies at California landfills. Both approaches rely on a phased gas collection approach as described in Barlaz et al. (2009) and Kaplan et al. (2009)^{67,71} The phased collection approach assumes that collection efficiency increases (from zero) in the years following the initial placement of waste in an open landfill cell as the gas collection system is installed and expanded, and the cell cover material transitions from daily cover to intermediate cover to final cover. Very high collection efficiencies up to 95% may occur at the point at which a landfill cell is closed and capped with a final cover material.⁶⁷ Because the 'phased' approach applies increasing collection efficiencies from zero to 95%, this approach takes into account the emission that would occur from open face of the landfill prior to gas collection system placement, as well as the closed cells of a landfill where higher collection efficiencies occur.

It is important to note that the gas collection scenarios used in this document are based on studies that represent common landfill practices in California and throughout the nation, and take into account the varying ages of landfills, local climate parameters, and the diversity of emission control technologies and best management practices. California-specific information is needed to determine a more representative level of gas collection efficiencies that are more applicable to California landfills. To begin this process, ARB and CalRecycle are currently considering additional research to better quantify both CH₄ and N₂O emissions from landfills as well as the gas collection efficiencies of landfills in California.

For each waste type, the average of the four model runs was used as the avoided landfill methane emission value for that waste type. The results of the analysis are discussed in section 3.2.1.

2.2.2 Decreased Soil Erosion (E_b)

When mixed into soil, compost has the ability to decrease erosion and is widely used as an erosion control device at construction sites, along highways and in agricultural applications.^{4,32,38} Compost decreases erosion because of its ability to absorb and retain water in its pore holes. This method evaluated the erosion control benefits from agricultural applications. This benefit was quantified by accounting for the emissions associated with replacing eroded soil with compost. Erosion control is also related to carbon content, density and water retention so a decay pattern similar to carbon loss in compost was used for erosion control.

A study completed by the University of California-Riverside was used to evaluate the soil erosion.³⁵ This study evaluated two sites: a site damaged by a fire and a construction site. The construction site used seeded compost, but the researchers noted that there was no seed growth during the sampling events so the seeded compost mimicked unseeded compost.³⁵ An average erosion between the construction site and fire affected site was used in the calculation. The difference in soil retention between the control and compost-amended site was considered the soil benefit. The experimental plot values were extrapolated to represent a hectare of application and converted to a unit representative of soil saved per ton of compost. The emission factor for replacing one ton of eroded soil was 0.070 MTCO₂E/ton of feedstock (Section 3.1). The emission factor represents the emissions associated with producing compost to replace the soil lost to erosion.

2.2.3 Reduced Fertilizer Use (F_b)

The nitrogen content of compost, along with phosphorous and potassium contributions, provide an opportunity to reduce the amount of fertilizer applied to agricultural systems.³⁹⁻⁴² Other studies have shown that the use of compost does not entirely alleviate the need to apply fertilizers to agricultural soils.⁴³ The greenhouse gas benefit

for this variable was quantified as the avoided synthetic nitrogen, potassium, and phosphorous production from compost use.

The nitrogen, potassium and phosphorous contents of fertilizer degrade more rapidly than carbon.¹⁰ A study by Favoino and Hogg (2008) indicated that nitrogen from compost is used over a 10-year time period.¹⁰ The study also assumed that nitrogen was “conserved” in the soil over time so the available nitrogen over a 10-year time period was actually greater than the initial nitrogen content.¹⁰ Instead of assuming a 30 percent decay rate as Favoino and Hogg (2008),¹⁰ this method used a value to 38 percent over a period of 10 years to ensure the nitrogen availability did not include the “conserved” nitrogen content. It was assumed that the decay of potassium and phosphorous were similar to nitrogen.

Data was obtained from an independent compost lab that tested nutrient and trace metal concentrations from compost in California.⁴⁴ The 10-year decay curve was applied to this data set. The emission factor used for each type fertilizer (N, P, or K) was based on the avoided life cycle emissions from fertilizer production that would have occurred in the absence of compost use. The emission factors for N, P, and K are 8.9, 1.8 and 0.96 kg CO₂E/kg, respectively.^{9,45}

2.2.4 Reduced Herbicide Use (H_b)

Herbicide use in agricultural fields prevents weeds from growing in unwanted areas. Studies indicate that compost replaces the use of herbicide by forming a crust over the top of the soil, making it difficult for weeds to penetrate the surface.⁴⁶ These benefits are limited and may last only one year, but allow for the reduced use or alleviation of herbicide use.⁴⁷

Reduced herbicide use was determined from a study from Roe et al (1993).⁴⁶ The herbicide benefit quantified by this study was multiplied by an emission factor for a pesticide (A life-cycle analysis was not available for a herbicide, so a pesticide was used as a proxy).⁴⁸ Other studies were found that dealt with reduced herbicide use and composting, but were not applicable because the data was not sufficiently quantitative.^{49,50}

2.2.5 Conversion Factor (C_{use})

The composting benefits were quantified in terms of MTCO₂E reduced per ton of applied compost. The conversion factor was used to convert from compost applied to original feedstock composted. This conversion factor is based on numerous studies that report the initial amount of feedstock composted and final amount of composted material.^{9,16,28}

2.3 Compost Emission Reduction Factor

The compost emission reduction factor (CERF) is the sum of compost process emissions (E_{total}) and compost application emission benefits (B_{total}):

$$CERF = B_{total} - E_{total} \quad (3)$$

where,

CERF = Compost emission reduction factor (MTCO₂E/ton of feedstock)

E_{total} = Total emissions from the composting process (MTCO₂E/ton of feedstock)

B_{total} = Total emission benefits due to the application of compost (MTCO₂E/ton of feedstock)

3. RESULTS AND DISCUSSION

This section presents the emissions from the composting process and the emission reduction benefits from applying compost to a non-amended soil. Included in this section will be an analysis of the sensitivity of these values in the context of determining an accurate CERF for use in California.

3.1 Composting Emissions

Composting emissions are calculated in three different categories: emissions from transportation (inbound (collection) and outbound (delivery)), process emissions (turning, etc.) and fugitives (pile management). To remain consistent with the approach of quantifying net compost emission reductions compared to a baseline scenario of landfilling, the transportation emissions and process emissions from composting are compared to estimated transportation and process emissions from landfilling. The calculated values are reported below.

3.1.1 Transportation Emissions (T_e)

Transportation emissions occur when the compost feedstocks are collected (inbound) and when the finished compost product is distributed (outbound). Table 1 shows the location of composting facility and inbound and outbound transportation averages obtained from six representative compost distributors across California.²⁰

Table 1. Feedstock collection (inbound) and compost delivery (outbound) transportation distances.

Location	Inbound (miles)	Outbound (miles)
Oxnard	5	15
Rancho Cucamonga	30	30
San Jose	37	26
Northern California (various locations)	50	50
San Diego	108	N/A
Southern San Joaquin	55	20
Average	47.5	28.2
Sum	75.7	
Emissions	0.008 MTCO₂/ton	

The sum of the inbound and outbound travel miles was multiplied by an emission factor of 101 g CO₂/ton-mile.²¹ The resulting average transportation emissions for the collection of feedstock and delivery of compost to the end user are **0.008 MTCO₂E/ton of feedstock**. Two European studies reported inbound distances of nine¹⁵ and sixteen¹⁶ miles. These values are slightly lower than the values used in this method and represent a 0.003 MTCO₂E/ton of feedstock deviation (on the lower side).

U.S. EPA assumes 1.8 gallons of diesel are used per ton MSW for estimating transportation emissions from landfilling.¹⁴ Using the emission factor of 10.21 kg CO₂/gallon for diesel,¹⁷ this results with estimated transportation emissions of 18.4 kg CO₂/ton waste, or 0.0184 MTCO₂/ton waste. Because the fuel data used by U.S. EPA is based on 1994 data, it may be overestimating diesel fuel use per ton of MSW given transportation efficiency gains achieved since 1994. Therefore, this value should be considered an upper bound for landfill transportation emissions. Nevertheless, for composting transportation emissions to be significantly greater than landfilling emissions, average inbound or outbound distances would have to be substantially greater. For example, an increase in average inbound plus outbound distance of 100 miles would be equivalent to an increase in emissions from 0.008 MT CO₂e to 0.0175 MT CO₂/ton waste, which is close to the upper bound landfill estimate as calculated by using U.S. EPA diesel use assumptions. For this reason, landfilling and composting are considered to be functionally equivalent with regards to transportation emissions. Therefore, the transportation emissions term is equal to zero for the composting emissions calculation.

3.1.2 Process Emissions (P_e)

Composting is completed under varying conditions with specific physical parameters. Data from a Central Valley compost facility indicates that there is about 0.29 gallons of diesel and 250 gallons of water used per ton of initial feedstock for an outdoor windrow (Table 2).²⁰ The data reported in Table 2 represents the overall fuel use per ton of feedstock (activity column of Table 2). Each activity was multiplied by the

corresponding emission factor. The overall emission contributions were summed and averaged to obtain the final emission value (Table 2, last column).

Table 2. Process emissions from compost production.

Facility	Activity	Emission Factor	Emissions (MTCO ₂ E/ton of feedstock) ^a
<i>Outdoor windrow #1</i>	0.29 gal diesel/ton	10.2 kg CO ₂ E/gal ^b	0.003
<i>Outdoor windrow #2</i>	0.24 gal diesel/ton	10.2 kg CO ₂ E/gal ^b	0.002
<i>Outdoor windrow #3</i>	0.56 gal diesel/ton	10.2 kg CO ₂ E/gal ^b	0.006
	7.2 kWh/ton	0.419 kgCO ₂ E/kWh ^c	0.003
Average			0.007

^a In order to obtain the total value, an average for each process emission type was taken, when applicable. For example, the average diesel fuel use was taken between outdoor windrow samples 1-3 while, the electricity value from outdoor windrow 3 only was used. ^{bc} Reference 51.

The values used for the process emissions in this method were compared to multiple studies completed in Europe.^{9,15,16} These studies indicate that direct diesel emissions from shredders, front loaders, and turning equipment is generally in the range of 0.03 - 1.4 gallon/ton of feedstock.⁹ This range is consistent with the above diesel emissions shown in Table 2. Landfill process emissions include emissions from landfill construction, waste placement, gas and leachate management, operations, and long term maintenance. Estimates of process emissions from U.S. landfills range from 0.007 MTCO₂/ton⁷⁰ to 0.018 MT CO₂/ton.¹⁴

Because process emissions from composting likely fall within the same range as process emissions from landfilling, and are relatively insignificant to the total emission reduction estimate, landfilling and composting are considered to be functionally equivalent in regards to process emissions. For this reason, the process emissions term is equal to zero for the composting emissions calculation.

3.1.3 Fugitive Emissions (F_e)

Fugitive CH₄ and N₂O emissions were compiled from various selected studies and averaged together for this method.^{15,19,22,27-29} The majority of the references were taken from a study completed by the Intergovernmental Panel on Climate Change (IPCC), but additional studies were added to take into account more recent data, as well as to include studies specific to composting methods and feedstocks utilized in California.^{15,29,53} Tables 3 and 4 show each study used to generate the average for methane and nitrous oxide emissions respectively from a compost pile.

Table 3. Fugitive CH₄ emissions from composting.

Reference	Feedstock	Emission factor (g _{CH₄} /kg)
Beck-Friis et al (2000) ^a	Household organic mixed with coarsely chipped branches and bushes	7.63
Hellmann et al (1997) ^b	Organic MSW with bush, leaves and grass clippings	0.17
Amlinger et al (2008) ^c	Green waste, sewage sludge and biowaste	0.21
San Joaquin Valley Air Pollution Control District (2013) ^d	Central California Green waste	2.90
South Coast Air Quality Management District (2001) ^e	Southern California Green waste	0.41
South Coast Air Quality Management District (2001) ^f	Southern California Green waste	0.45
	Average	1.96
	Emissions	0.049 MTCO₂E/ short ton

^a Reference 22; ^b Reference 28; ^c Reference 19; ^d Reference 15; ^e Reference 27; ^f Reference 29;

Table 4. Fugitive N₂O emissions from composting.

Reference	Feedstock	Emission factor (g _{N₂O} /kg)
Beck-Friis et al (2000) ^a	Household organic mixed with coarsely chipped branches and bushes	0.1
Hellmann et al (1997) ^b	Organic MSW with bush, leaves and grass clippings	0.022
Amlinger et al (2008) ^d	Green waste and grass	0.13
San Joaquin Valley Air Pollution Control District (2013) ^c	Central California Green waste	0.046
	Average	0.075
	Emissions	0.021 MTCO₂E/ short ton

^a Reference 22; ^b Reference 28; ^c Reference 15;

The values used in this method for fugitive methane and nitrous oxide emissions are consistent with other literature values. For example, the IPCC reports that CH₄

emissions are 4 g CH₄/kg of compost and N₂O emissions are 0.3 g N₂O/kg of compost.⁵³ The N₂O value is lower than the IPCC values and may be due to the feedstock types used in this method compared to the IPCC. When composting certain feedstock, such as manure, N₂O emissions were higher than this method.²⁴⁻²⁶

3.1.4 Summary of Emissions

Table 5 presents the total emissions (E_{total}) from the composting process.

Table 5. Summary of composting emissions (E_{total}).

Emission type	Emission (MTCO ₂ E/ton of feedstock)
Transportation emissions (T_e)	0
Process emissions (P_e)	0
Fugitive CH ₄ emissions (F_e)	0.049
Fugitive N ₂ O emissions (F_e)	0.021
Total	0.070

3.2 Compost Use Emission Reductions

Emission reductions occur due to reduced landfill methane emissions and due to the application and end use of the composted product. For this paper, the benefits of avoided landfill emissions, reduced fertilizer use, reduced herbicide use, and decreased soil erosion were used to quantify the GHG emissions. Other benefits to composting applications have been shown to include the increase in soil water retention, increased crop yield, and increased microbial activity. However, due to difficulties in applying these GHG emission reduction benefits to composting alone, these were not included in the calculations.³⁹

The section below quantifies the greenhouse gas benefit of applying compost to a soil system. Instead of presenting a single value, a range for each benefit (when possible) will be given.

3.2.1 Net Avoided Emissions from Landfills (ALF_b)

The degree to which methane emissions are avoided due to composting depends largely on the characteristics of the type of waste composted. Organic wastes that contain a higher fraction of anaerobically degradable organic carbon will have higher net methane generation per ton of material. With the use of phased gas collection assumptions, the rate of decay of the waste type is a sensitive parameter for determining methane emissions, as the higher the rate of decay, the more methane gas will be generated early after waste disposal in the landfill cell *prior* to the gas collection system achieving higher gas collection efficiencies. Table 6 below contains the key parameters used for parameterizing the model.

Table 6. FOD model parameters.

Parameter	Waste Type	Value	Note
Decay rate (<i>k</i>) (yr ⁻¹)	Food waste	0.072	Reference 14
	Yard trimmings	0.068	Reference 14, 61
	Mixed Organics	0.072	Reference 14, 62
Degradable Organic Carbon (DOC) (Mt C/t waste)	Food waste	0.135	Reference 60
	Yard trimmings	0.287	Reference 60, 61
	Mixed Organics	0.176	Reference 60, 62
Anaerobically Degradable Organic Carbon (ANDOC) (MT C/t Waste)	Food waste	0.117	Reference 60
	Yard trimmings	0.063	Reference 60, 61
	Mixed Organics	0.101	Reference 60, 62
Oxidation factor (Ox) (fraction)	All	0.1 and 0.35	Reference 63,69,75
Gas Collection Efficiency (GCe)	All	Typical Phased: <ul style="list-style-type: none"> • 0 (yr. 1-2) • 50% (yr. 3) • 75% (yr. 4-10) • 95% (yr. 11-100) 	Reference 67
		Phased with gas collection shutdown at year 60: <ul style="list-style-type: none"> • 0 (yr. 1-2) • 50% (yr. 3) • 70% (yr. 4,5) • 80% (yr. 6-60) • 0% (yr. 61-100) 	Reference 71, 74
Decomposition Delay (<i>M</i>)	All	6 months	Reference 53
Gas Combustion Efficiency (flare)	All	99.77%	Reference 78
Global Warming Potential for Methane (GWP)	All	25	Consistent with California GHG Inventory

Table 7: Calculation Results in units of MTCO_{2e}/Short ton input

Waste Type	'Typical' Phased Gas Collection		Phased with Gas Collection Shutdown		Average
	Oxidation Factor		Oxidation Factor		
	10%	35%	10%	35%	
Food Waste	0.377	0.272	0.525	0.379	0.388
Yard Trimmings	0.197	0.142	0.283	0.204	0.207
'Mixed Organics'	0.324	0.234	0.452	0.326	0.334
Total LFG Collection Efficiency*	78.5%		70.0%		74.3%

* As noted before, the gas collection efficiencies used in this document are based on studies representing a variety of landfill conditions, locations, years of operation, and degrees of controls. Further California-specific information is needed in determining a more representative level of gas collection efficiencies from California landfills. ARB and CalRecycle are currently considering additional research to better quantify both CH₄ and N₂O emissions as well as the gas collection efficiencies of landfills in California.

As observed in the calculation results shown in Table 7, the waste components with higher decay rates (food waste and 'mixed organics') have the highest avoided emissions. Equally as important is the amount of total anaerobically degradable carbon in each type of waste (ANDOC). Yard waste has high total carbon per short ton of material (0.287 MT C/ ton), but only 28.7 percent of the carbon will decompose in an anaerobic landfill environment.¹⁴ Therefore, much of the carbon in yard waste does not readily decompose to create methane gas. On the opposite end of the spectrum is food waste. Food waste (as measured on a wet basis) is high in moisture and relatively low in carbon content (0.135 MT C/ton), however the majority of the carbon in food waste (86.5 percent) will rapidly decompose to create methane. Predictably, the mixed organics category falls in between food waste and yard waste. The input parameters for the mixed organics category were determined by weighting the parameters of individual components (food waste, grass, leaves, sticks/branches) by their relative 'waste disposed' fractions based the most recent CalRecycle statewide waste characterization study.⁶⁵ Because the 'disposed' organics waste stream is dominated by rapidly degrading food waste and grass/leaves, collectively making up 88 percent of the 'mixed waste' category, using a weighted average decay rate value results with a waste stream that is relatively rapidly degrading (with a decay rate only slightly less than food waste) and with only a slightly lower ANDOC than a ton of food waste alone.⁶⁴ Therefore the mixed waste parameterization resulted with a modeled waste stream with a methane potential closer to that of food waste rather than yard waste.

Recent literature suggests the possibility that decay rates may be higher than indicated using the typical default values used by U.S. EPA.⁷³ It should be noted that higher decay rates would greatly impact the outcome of this calculation and could substantially increase total estimated emission reductions from avoided landfill methane. In addition, uncertainties in other landfill parameter values (oxidation factors, gas collection assumptions, and decomposition delay) have the potential to alter the emission reduction calculation results.

3.2.2 Decreased Soil Erosion (E_b)

Decreased erosion from addition of compost to soils is directly related to carbon content and water retention rates.³¹ The curve in Figure 1 was used to determine the erosion capacity of compost. For initial inputs to the decay curve, the California-specific study by Crohn (2010) was used.³⁵ Compost applied to the fire affected site and construction site reduced soil erosion by 91 and 328 lbs/ton of compost on a 1-year timescale, respectively. This corresponds to a 30-year soil retention benefit of 1750 and 6300 lbs of soil/ton of compost for the fire affected and construction sites.

The emission factor used for this production was generated from the emissions associated with the composting process (Table 4). The emission factor is 0.07 MTCO₂E/ton of soil, which equates to an average savings of **0.14 MTCO₂E/ton of compost** and a range of 0.06-0.22 MTCO₂E/ton of compost (after being multiplied by the pounds of soil saved) over a 30-year time period.

The values used in this method are slightly higher than two other studies.^{32,38} The values in the existing studies range from 33-64 lbs/ton of compost on the 1-year timescale.^{32,38} However, these studies simulated single rain events, while the study by Crohn (2010), looked at multiple rain events over a longer time period.

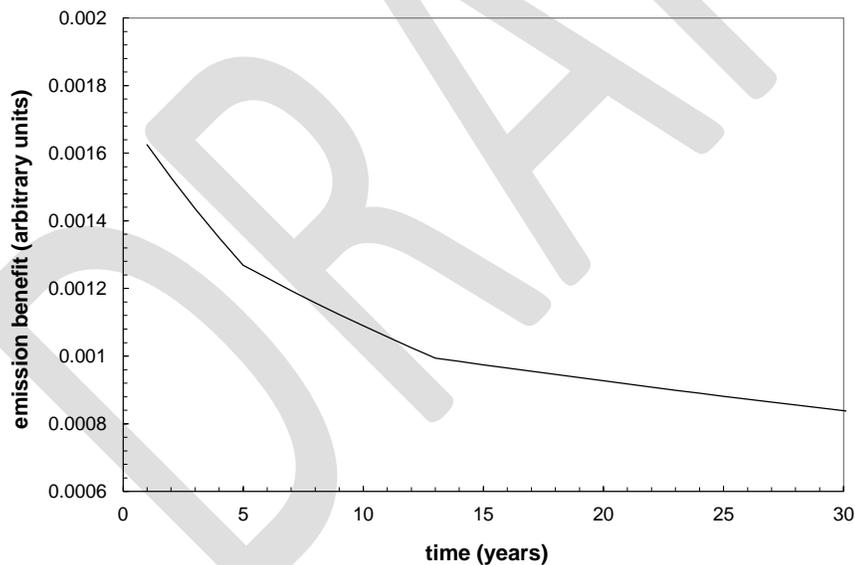


Figure 1. Decay curve used for decreased erosion benefits (E_b) of composting.

3.2.3 Reduced Fertilizer Use (F_b)

Fertilizer use in non-compost amended agricultural fields is often costly and leads to deleterious effects on soil health.³ Amending a soil with compost has the ability to decrease the fertilizer requirement, but not totally eliminate the application.⁴³ Table 8 presents the NPK fertilizer benefits from compost application.

Table 8. Fertilizer benefit from compost application.^a

Fertilizer	Percent Weight (%)	Mass, 1-year (kg/ton of compost)	Mass, 10-year (kg/ton of compost)	Benefit, 10-year (MTCO ₂ E/ton of compost)
Nitrogen (avg) ^b	1	9.1	24	0.21
Nitrogen (range) ^c	0.4-1.5	4.0-13.6	10.6-35.9	0.094-0.32
Phosphorous (avg) ^d	0.8	7.3	19.3	0.035
Phosphorous (range) ^c	0.0-1.6	0.1-14.5	0.3-38.3	0.0005-0.07
Potassium (avg) ^e	0.7	6.4	16.9	0.017
Potassium (range) ^c	0.3-1.3	2.7-11.9	7.1-31.4	0.007-0.03
Average				0.26
Range				0.1-0.42

^a Reference 44. ^b n = 1215. ^c Range is based on a confidence level of 68% or one standard deviation (1σ). ^d n = 1356. ^e n = 1354.

The results from this method compare well with existing literature studies. The average fertilizer benefit from these studies was 0.17 MTCO₂E/ton of compost with a range of 0.14-0.32 MTCO₂E/ton of compost.^{9,10,16}

3.2.4 Reduced Herbicide Use (H_b)

The quantitative results from a study that evaluated the effectiveness of compost at weed suppression were used. In this study, a glyphosate spray was applied to a bell pepper field and compared to other field plots that used compost or no amendment (control). The results indicated that compost was as effective as the herbicide.⁴⁶ Assuming a 100 percent replacement of herbicide by compost, the herbicide reduction value was multiplied by an emission factor that quantified the emissions associated with herbicide production.^{46,48} This produces a measurable, but highly uncertain greenhouse gas benefit (< 0.001 MTCO₂E/ton of compost) due to the large amount of compost needed to achieve the same benefit as a small amount of herbicide. In terms of the overall contribution to the CERF, this benefit is negligible.

3.2.5 Conversion Factor (C_{use})

The conversion factor is used to convert from tons of compost to tons of initial feedstock. This conversion was done on a wet weight basis and is consistent with the method used for the composting emissions from section 3.1. Table 9 summarizes the studies used to determine this value.

Table 9. Conversion factor inputs.

Reference	Feedstock	Conversion Factor
Hellmann et al (1997) ^a	Organic MSW, yard waste	0.66
Blengini et al (2008) ^b	Organic MSW	0.28
Boldrin et al (2009) ^c	Food waste, green waste	0.55
Breitenbeck et al (2004) ^d	Various green wastes	0.81
	Average	0.58
	Range	0.28-0.81

^a Reference 28; ^b Reference 16; ^c Reference 9, ^d Reference 52

3.2.6 Summary of Emission Reductions

Table 10 presents the overall emission benefits from using compost.

Table 10. Summary of composting benefits (B_{total}).

Emission reduction type	Emission reduction (MTCO ₂ E/ton of compost)	Conversion factor	Final emission reduction by waste type (MTCO ₂ E/ton of feedstock)		
			Food Waste	Yard Trimmings	Mixed Organics
Avoided Landfill Emissions	N/A	N/A	0.39	0.21	0.33
Decreased Soil Erosion	0.25	0.58	0.15	0.15	0.15
Decreased Fertilizer Use	0.26	0.58	0.15	0.15	0.15
Decreased Herbicide Use	0.0	0.58	0.0	0.0	0.0
Total	N/A	N/A	0.69	0.51	0.63

3.3 Final Compost Emission Reduction Factor

The CERF is determined by subtracting the composting emissions from the composting emission reductions for each waste type. The results are included in Table 11.

Table 11. CERF values by waste type.

Waste Type	Composting Benefits (B_{total})	Composting Emissions	Final CERF (MT CO₂e/ ton waste input)
Food Waste	0.69	0.07	0.62
Yard Trimmings	0.51	0.07	0.44
Mixed Organics	0.63	0.07	0.56

This leads to a CERF of **0.44 – 0.62 MTCO₂E/ton of feedstock**.

3.4 Variability Analysis

The studies used to calculate each variable that contributed to the CERF were spread over a wide range of values. For instance, the fugitive CH₄ emissions ranged from 0.17 to 7.63 gCH₄/kg (Table 3) and the fertilizer benefits ranged from 0.1-0.42 MTCO₂E/ton of compost (Table 5). This wide range illustrates the uncertainty associated with each of these factors due to variability in the compost processing and in the physical properties of the soil to which the compost is added.

To quantify the range of values for avoided landfill emissions (ALF_b), this method adjusted sensitive parameters of decay rate (k), oxidation rate (OX), and decomposition delay (M) but did not adjust waste characteristic inputs (DOC, ANDOC) because a range could not be determined for these default values. The high range model uses the phased gas collection scenario with shutdown at year 60, and the low range model value uses the phased approach with 95 percent gas collection after installation of the final cover. Decay rate values are generally based on the moisture conditions of the landfill, which is a function primarily of annual rainfall. Per the ARB GHG Inventory, the Waste-In-Place (WIP) weighted average landfill decay rate for California is 0.022 yr⁻¹, which is very close to the EPA default value for a dry (low moisture) landfill (0.020 yr⁻¹).^{14,60} Therefore, the original model runs used the U.S. EPA waste-specific decay rates for 'dry' landfill conditions, which is most representative of California landfills. These decay rates are already on the lowest end of the spectrum, so no change was made to decay rates for the low-range calculation. To estimate a range for high range decay rates, it was noted that recent research suggests decay rates at landfills may be higher than default values indicate. Therefore the high-end estimate uses the higher decay rates equivalent to an 'average' landfill rather than a 'dry' landfill. Table 12 provides the key parameters used and the results of the low/high model runs for ALF_b values.

Table 12. Parameters and results of the avoided landfill variability analysis.

Waste Type	Decay rate (k)		Oxidation (ox)		Decomposition Delay (M)		Result (MT CO ₂ e /ton)	
	Low	High	Low	High	Low	High	Low	High
Food Waste	0.072	0.144	36% ⁷⁷	10%	12 mo.	0 mo.	0.23	0.71
Yard Trimmings	0.068	0.135	36% ⁷⁷	10%	12 mo.	0 mo.	0.12	0.38
Mixed Organics	0.070	0.143	36% ⁷⁷	10%	12 mo.	0 mo.	0.20	0.61

In order to assess the possible range of CERF values, the following equation was used:

$$CERF_{range} = CERF_L \text{ to } CERF_H \quad (4)$$

$$CERF_L = ((\sum B_{totL}) \times C_{useL}) + ALF_L - E_{totH} \quad (5)$$

$$CERF_H = ((\sum B_{totH}) \times C_{useH}) + ALF_H - E_{totL} \quad (6)$$

where,

$CERF_{range}$ = Possible range of the CERF based on evaluation of the lowest and highest compost emissions and benefits (MTCO₂E/ton of feedstock)

$CERF_L$ = Lowest possible CERF (MTCO₂E/ton of feedstock)

$CERF_H$ = Highest possible CERF (MTCO₂E/ton of feedstock)

B_{totL} = Sum of compost benefits based on the lowest values from this method (MTCO₂E/ton of compost) = 0.07 MTCO₂E/ton of compost

C_{useL} = 0.28 ton of feedstock/ton of compost

E_{totH} = Sum of compost emissions based on the highest values from this method (MTCO₂E/ton of feedstock) = 0.21 MTCO₂E/ton of feedstock

B_{totH} = Sum of compost benefits based on the highest values from this method (MTCO₂E/ton of compost) = 0.63 MTCO₂E/ton of compost

C_{useH} = 0.81 ton of feedstock/ton of compost

E_{totL} = Sum of compost emissions based on the lowest values from this method (MTCO₂E/ton of feedstock) = 0.01 MTCO₂E/ton of feedstock

Table 13 provides the results of the variability analysis after factoring in the avoided landfill results.

Table 13. Results of the variability analysis (MT CO₂e/ton).

	Food Waste	Yard Trimmings	Mixed Organics
Low Range	0.09	-0.02	0.06
High Range	1.33	0.99	1.23
Average	0.76	0.49	0.65

Applying the values for each variable, the CERF_{range} is from a minimum of ~ 0 for yard trimmings to a maximum of 1.33 for food waste. The actual calculated values used in the CERF are either slightly above (food waste) or below (yard trimmings, mixed organics) the average of the variability analysis.

The CERF obtained from this method has uncertainties due to the lack of general scientific understanding of some physical processes and emissions pathways for landfills and compost piles, potential multiplicative compost application benefits to soil carbon, absence of literature articles, and reliance on non-California specific study locations and default assumptions.

The application of compost to a non-amended soil provides soil benefits (benefits were discussed in this method). Uncertainties occur when researchers attempt to link a specific compost benefit to a modification of soil properties. For example, soil type plays a large role in the magnitude of a compost benefit. It is unclear what factors (type, size, pH, etc.) of the mineral composition of the parent soil impact the compost benefit.

Current compost literature focuses mainly on the fugitive emissions^{15,19,20,27-29} that occur during the composting process. Few studies evaluate the process emissions or the benefits from the end uses of compost. The most prevalent composting benefits discussed in the literature were increased soil carbon storage^{9,14,16} and decreased fertilizer use^{9,10,16,44}. Additionally, the erosion and water use results were extrapolated from laboratory-scale experiments as opposed to macro scale field methods. Extrapolating the data may skew the results, depending on the physical properties of the compost. The herbicide results are based on only one study.⁴⁶ It was difficult to obtain reliable results from a single experiment, plus life-cycle information on herbicides was difficult to obtain and a pesticide life-cycle was used as a proxy.⁴⁸

This method was able find some California-specific compost studies to use for quantification (process emissions, transportation emissions, reduced water use, reduced soil erosion, and reduced fertilizer use). The other studies came from the United States (soil carbon storage and reduced herbicide use) or well-reputed international sources (fugitive emissions were modified from IPCC data).

As additional research is completed, the uncertainties will diminish. In the interim, it is important to understand the shortcomings of this quantification method and apply them in a judicious manner.

4. SUMMARY

This method presents a compost emission reduction factor (CERF) for composting in California. This method accounts for the emissions (transportation, process, and fugitive) from the composting process and the benefits (avoided landfill methane, reduced soil erosion, decreased fertilizer use, and decreased herbicide use) as compared to a baseline scenario of landfilling. A summary of the emissions and emission reductions are shown in Table 14.

Table 14. Summary of compost emission reduction factor (CERF).^a

Emissions			
<i>Emission Type</i>		<i>Emission (MTCO₂E/ton of feedstock)</i>	
Transportation emissions (Te)		0	
Process emissions (Pe)		0	
Fugitive CH ₄ emissions (Fe)		0.049	
Fugitive N ₂ O emissions (Fe)		0.021	
<i>Total Emissions</i>		<i>0.070</i>	
Emission Reductions			
<i>Emission reduction type</i>	<i>Emission reduction (MTCO₂E/ton of compost)</i>	<i>Conversion factor</i>	<i>Final Emission reduction (MTCO₂E/ton of feedstock)</i>
Decreased Soil Erosion (E _b)	0.14	0.58	0.08
Decreased Fertilizer Use (F _b)	0.26	0.58	0.15
Decreased Herbicide Use (H _b)	0.0	0.58	0.0
<i>Emission Reductions without ALF_b</i>			<i>0.23</i>
Avoided Landfill Methane (ALF _b)	<i>Food Waste</i>	<i>Yard Trimmings</i>	<i>Mixed Organics</i>
	0.39	0.21	0.33
CERF	0.62	0.44	0.56

^a The CERF was determined by subtracting the emissions from the emission reductions.

5. Changes in Biogenic Emissions

Organic waste contains varying fractions of biogenic carbon, which is carbon that was removed from the atmosphere via plant respiration and is considered to be part of the natural carbon cycle. Both the type of waste and the method of waste management will determine the quantity and rate at which biogenic carbon is emitted back to the atmosphere as biogenic CO₂. Because this method is relying on a carbon flow accounting system to ensure consistency with the ARB GHG Inventory approach, the amount of biogenic carbon that is returned back to the atmosphere as CO₂ is calculated both for composting and landfill waste management systems. The results are

discussed, however per IPCC and ARB GHG Inventory guidelines, the biogenic CO₂ emissions are not included in the final compost emission reduction factor.

5.1 Biogenic Emissions from Landfilled Organic Waste

Landfilled carbon-bearing waste degrades mainly through anaerobic decomposition. This anaerobic biodegradation process generates approximately equal amounts of CO₂ and CH₄ gas as a byproduct. Some types of waste do not decompose or do so very slowly in anaerobic environments; therefore a significant fraction of organic carbon is stored in the landfill long term. The fraction of carbon that can decompose anaerobically varies by waste type. Woody materials tend to have a high fraction of carbon that does not decompose under anaerobic conditions, whereas food waste and grass clippings have a relatively low fraction of carbon that does not decompose anaerobically.⁶⁰ The waste characteristics for the 'mixed organics' category of waste (which is a combination of food waste and yard trimmings) were used for input into the biogenic CO₂ calculation.

To determine net biogenic emissions of CO₂ from landfilling, this method used the following approach:

1. The total anaerobically degradable carbon (ANDC) was determined by multiplying the total carbon (DOC) by the anaerobically degradable fraction (DOC_f) factor,
2. The total anaerobically degradable carbon was assumed to be equal to the net carbon emitted as either CO₂ or CH₄ over the 100 year time horizon of the FOD model.
3. The total carbon *emitted* as methane was subtracted from the total anaerobically degradable carbon to get the total quantity of carbon emitted as CO₂. Carbon contained in the CH₄ gas that is oxidized by landfill cover material or by combustion by the LFG collection system was assumed to be emitted as biogenic CO₂. Carbon contained in the CH₄ gas that is oxidized by landfill cover material or by combustion by the LFG collection system was assumed to be emitted as biogenic CO₂.

$$\text{Bio_CO2}_{\text{LF}} = \text{Bio_C}_{\text{LF}} \times (44/12) \quad (7)$$

$$\text{Bio_C}_{\text{LF}} = \text{ANDOC} - \text{C}_{\text{methane}} \quad (8)$$

$$\text{ANDOC} = \text{DOC} \times \text{DOC}_f \quad (9)$$

where,

Bio_CO2_{LF} = Estimated biogenic emissions from landfilled organic waste (MT CO₂E/ton of feedstock)

Bio_C_{LF} = Estimated biogenic emissions of carbon from landfilled organic waste (MT C/ton of feedstock)

- ANDOC = Total anaerobically degradable organic carbon (*MT C/ton of feedstock*)
- C_{methane} = Total carbon emitted as methane, which is equal to the average result of the FOD model converted to units of (*MT C/ton of feedstock*)
- DOC = Degradable organic carbon content of waste (*MT C/ton of feedstock*)
- DOC_f = Fraction of the degradable organic carbon content of waste that can decompose under anaerobic conditions (*fraction*)

Table 15 below contains a summary of the biogenic emissions from landfilled organic waste calculated.

Table 15. Summary of results of biogenic emissions from landfilled organic waste.

Waste Type	ANDOC (MT C/t waste)	C_Methane (MT C/t waste)	Total Bio CO2 (MT CO ₂ /t waste)
Food Waste	0.117	0.012	0.385
Yard Trimmings	0.063	0.006	0.209
Mixed Organics	0.101	0.010	0.334

5.2 Biogenic Emissions from Composted Organic Waste

While landfilling subjects waste to an anaerobic environment, composting is designed to break down organic waste in a primarily aerobic environment. Degradable organic carbon decomposes primarily into biogenic CO₂, with trace amounts of carbon emitted as CH₄.⁹ Similar to landfills, the total carbon released as CO₂ during composting is dependent on the properties of the waste. Carbon that is not released remains in the compost, some of which will further decay after finished compost has been applied to soils.

There are three main types of carbon in finished composts with regard to carbon decay kinetics: fast, slow and passive. The fast and slow carbon, otherwise known as active carbon, degrades due to bacterial and fungal use of carbon compounds in the soil. The passive carbon content is made of humic substances, large organic macromolecules formed during the thermophilic stage of the composting process.⁴ Passive carbon decays extremely slowly, if at all. In this method, a study that quantified the soil carbon storage separately for the active and passive carbon was used.¹⁴

For this method, the biogenic *emissions* from composting were estimated by assuming that the entirety of the degradable organic carbon content of the waste is emitted as CO₂, either during the composting phase or after compost application, *with the exception* of the carbon that is stored in soils longer than 30 years as quantified in the previous version of this study.⁵⁸ The waste characteristics for the 'mixed organics' category of waste (which is a combination of food waste and yard trimmings) were used for input into the biogenic CO₂ calculation.

$$\text{Bio_CO2c} = \text{Bio_Cc} \times (44/12) \quad (10)$$

$$\text{Bio_Cc} = \text{DOC} - \text{CS} \quad (11)$$

where,

- Bio_CO2c** = Estimated biogenic emissions from composted organic waste, including downstream emissions after application to soils *(MT CO₂E/ton of feedstock)*
- Bio_Cc** = Estimated biogenic emissions of carbon from composted organic waste including downstream emissions after application to soils *(MT C/ton of feedstock)*
- DOC** = Degradable organic carbon content of waste *(MT C/ton of feedstock)*
- CS** = Estimated carbon stored in soils 30 years after application of compost, as calculated above *(MT C/ton feedstock)*

5.3 Biogenic Emissions Results

Table 16. Biogenic emissions results.

Waste Type	Bio_CO2 _{LF} (MT CO ₂ /ton waste input)	Bio_CO2 _c (MT CO ₂ /ton waste input)
Mixed Organics	0.33	0.39

From the results of this estimation shown in Table 16, biogenic emission of CO₂ would not be expected to vary significantly for a mixed organics waste stream when the waste is diverted from landfill to composting. Although the composting process leaves a considerable fraction of carbon in the finished compost, much of this carbon will decay into CO₂ following application of the compost to soil. This result suggests that the total amount of carbon that remains in the soil after 30 years is comparable to the total amount of carbon that would be stored in the landfill long term from a mixed organic waste stream.

6. NOTES AND REFERENCES

1. USEPA (2013) *Inventory of U.S. greenhouse gas emissions and sinks: 1990-2011*, United States Environmental Protection Agency.
2. USEPA (1994) *Composting yard trimmings and municipal solid waste*, United States Environmental Protection Agency, EPA530-R-94-003.
3. ROU (2007) *Life cycle inventory and life cycle assessment for windrow composting systems*, Recycled Organics Units, The University of New South Wales.
4. Barker AV (1997) Composition and uses of compost, In: *Agricultural Uses of By-Products and Wastes*, Rechcigl JE and MacKinnon HC (eds), American Chemical Society Symposium Series 668, Washington D.C.
5. Khaleel R, Reddy KR, Overcash MR (1981) Changes in soil physical properties due to organic waste applications: a review *Journal of Environmental Quality*, **10(2)**, 133-141.
6. Cogger CG (2005) Potential compost benefits for restoration of soils disturbed by urban development *Compost Science and Utilization*, **13(4)**, 243-251.
7. Shiralipour A, McConnell DB, Smith WH (1992) Physical and chemical properties of soils as affected by municipal solid waste compost application *Biomass and Bioenergy*, **3(3-4)**, 261-266.
8. Zeman C, Depken D, Rich M (2002) Research on how the composting process impacts greenhouse gas emissions and global warming *Compost Science and Utilization*, **10(1)**, 72-86.
9. Boldrin A, Andersen JK, Moller J, Christensen TH, Favoino E (2009) Compost and compost utilization: accounting of greenhouse gases and global warming contributions *Waste Management and Research*, **27**, 800-812.
10. Favoino E and Hogg D (2008) The potential role of compost in reducing greenhouse gases *Waste Management and Research*, **26**, 61-69.
11. Mondini C, Cayuela ML, Sinicco T, Cordaro F, Roig A, Sanchez-Monedero MA (2007) Greenhouse gas emissions and carbon sink capacity of amended soils evaluated under laboratory conditions *Soil Biology and Biochemistry*, **39**, 1366-1374.
12. Lou XF and Nair J (2009) The impact of landfilling and composting on greenhouse gas emissions – a review *Bioresource Technology*, **100**, 3792-3798.
13. Please see *Proposed method for estimating greenhouse gas emission reductions from recycling*, for more discussion on the boundaries of the life cycle.
14. USEPA (2012) *Solid waste management and greenhouse gases: Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM)*.
15. San Joaquin Valley Air Pollution Control District (2013) *Greenwaste Compost Site Emissions Reductions from Solar-powered Aeration and Biofilter Layer, Report from the Contract Team.*
http://www.valleyair.org/Grant_Programs/TAP/documents/C-15636-ACP/C-15636_ACP_FinalReport.pdf

16. Blengini GA (2008) Using LCA to evaluate impacts and resources conservation potential of composting: a case study of the Asti District in Italy *Resources, Conservation and Recycling*, **52**, 1373-1381.
17. USEPA (2013) 40 CFR *Part 98 - Mandatory Greenhouse Gas Reporting, Table C-1*.
18. CalRecycle (2010) Third Assessment of California's Compost- and Mulch-Producing Infrastructure, *California Department of Resources Recycling and Recovery*.
19. Amlinger F, Peyr S, Cuhls C (2008) Greenhouse gas emissions from composting and mechanical biological treatment *Waste Management and Research*, **26**, 47-60.
20. Personal Communication, Robert Horowitz, CalRecycle staff.
21. CARB (2008) *Appendix G: Emissions Inventory ~ Methodology and Results*, Material to support the Statewide Truck and Bus Regulations, California Air Resources Board.
22. Beck-Friis B, Pell M, Sonesson U, Jonsson H, Kirchmann H (2000) Formation and emission of N₂O and CH₄ from compost heaps of organic household waste *Environmental Monitoring and Assessment*, **62**, 317-331.
23. IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Chapter 2, Table 2.14.
24. Pattey E, Tzcinski MK, Desjardins RL (2005) Quantifying the reduction of greenhouse gas emissions as a result of composting dairy and beef cattle manure *Nutrient Cycling in Agroecosystems*, **72**, 173-187.
25. Hao X, Chang C, Larney FJ, Travis GR (2001) Greenhouse gas emissions during feedlot manure composting *Journal of Environmental Quality*, **30**, 376-386.
26. Czepiel P, Douglas E, Harriss R, Crill P (1996) Measurements of N₂O from composted organic wastes *Environmental Science and Technology*, **30**, 2519-2525.
27. South Coast Air Quality Management District (2001) Ammonia and Volatile Organic Compound (VOC) Emissions from a Greenwaste Composting Operation, *Source Test Report 01-171*.
http://www.arb.ca.gov/cc/compost/documents/inlandempire1_source.pdf
28. Hellmann B, Zelles L, Palojarvi A, Bai Q (1997) Emission of climate-relevant trace gases and succession of microbial communities during open-windrow composting *Applied and Environmental Microbiology*, **63(3)**, 1011-1018.
29. South Coast Air Quality Management District (2001) Remote Sensing Tests for Ammonia and Volatile Organic Compound (VOC) Emissions from Greenwaste Composting Operation, *Source Test Report 01-176*.
http://www.arb.ca.gov/cc/compost/documents/inlandempire2_source.pdf
30. McConnell DB, Shiralipour A, Smith WH (1993) Compost application improves soil properties *Biocycle*, April, 61-63.

31. Bruun S, Hansen TL, Christensen TH, Magid J, Jensen LS (2006) Application of processed organic municipal solid waste on agricultural land – a scenario analysis *Environmental Modeling and Assessment*, **11**, 251-265.
32. Bresson LM, Koch C, Le Bissonnais Y, Barriuso E, Lecomte V (2001) Soil surface structure stabilization by municipal waste compost application *Soil Science Society of America Journal*, **65**, 1804-1811.
33. Giusquiani PL, Pagliai M, Gigliotti G, Businelli D, Benetti A (1995) Urban waste compost: effects on physical, chemical and biochemical soil properties *Journal of Environmental Quality*, **24**, 175-182.
34. Serra-Wittling C, Houot S, Barriuso E (1996) Modification of soil water retention and biological properties by municipal solid waste compost, *Compost Science and Utilization*, **4(1)**, 44-52.
35. Crohn DM (2010) *Compost Best Management Practices and Benefits*, Prepared for CalRecycle. Draft.
36. CARB (2008) *Recommended approaches for setting interim significance thresholds for greenhouse gases under the California Environmental Quality Act*, Preliminary Draft Staff Proposal, California Air Resources Board.
37. CARB (2008) Climate change scoping plan: a framework for change, California Air Resources Board.
38. Faucette LB, Risse LM, Nearing MA, Gaskin JW, West LT (2004) Runoff, erosion, and nutrient losses from compost and mulch blankets under simulated rainfall *Soil and Water Conservation*, **59(4)**, 154-160.
39. Mays DA, Terman GL, Duggan JC (1973) Municipal compost: effects of crop yields and soil properties *Journal of Environmental Quality*, **2(1)**, 89-92.
40. Duggan JC and Wiles CC (1976) Effects of municipal compost and nitrogen fertilizer on selected soils and plants *Compost Science*, **17(5)**, 24-31.
41. Movahedi Naeini SAR and Cook HF (2000) Influence of municipal compost on temperature, water, nutrient status and the yield of maize in a temperate soil, *Soil Use and Management*, **16**, 215-221.
42. Smiciklas KD, Walker PM, Kelley TR (2008) Evaluation of compost for use as a soil amendment in corn and soybean production *Compost Science and Utilization*, **16(2)**, 183-191.
43. Montemurro F, Malorana M, Convertini G, Ferri D (2006) Compost organic amendments in fodder crops: effects on yield, nitrogen utilization and soil characteristics *Compost Science and Utilization*, **14(2)**, 114-123.
44. Personal Communication, Control Laboratory, Watsonville, California. Due to confidentiality concerns, the nutrient data was sent as a compilation of samples from the Southwest region (California, Hawaii, Arizona, New Mexico, Nevada, Utah, and Colorado). Of the ~1200 samples averaged, 80% of the samples were taken from within California.
45. Wood S and Cowie A (2004) *A review of greenhouse gas emission factors for fertilizer production*, for IEA Bioenergy Task 38.
46. Roe NE, Stoffella PJ, Bryan HH (1993) Municipal solid waste compost suppresses weeds in vegetable crop alleys *Hortscience*, **28(12)**, 1171-1172.
47. Brown MW and Tworkoski T (2004) Pest management benefits of compost mulch in apple orchards *Agriculture, Ecosystems, and Environment*, **103**, 465-472.

48. Geisler G, Hellweg S, Hofstetter TB, Hunderbuehler K (2005) Life-cycle assessment in pesticide product development: methods and case study on two plant-growth regulators from different product generations *Environmental Science and Technology*, **39**, 2406-2413.
49. Niggli U, Weibel FP, Gut W (1990) Weed control with organic mulch materials in orchards. Results from 8 year field experiments *Acta Horticulturae*, **285**, 97-102.
50. Ozores-Hampton M, Obreza TA, Stofella PJ (2001) Mulching with composted MSW for biological control of weeds in vegetable crops *Compost Science and Utilization*, **9(4)**, 352-361.
51. CARB (2010) *Local government operations protocol: for the quantification and reporting of greenhouse gas emissions inventories*, California Air Resources Board.
52. Breitenbeck G.A, Schellinger D (2004) Calculating the Reduction in Material Mass and Volume during Composting, *Composting Science and Utilization*, **12(4)**, 365-371.
53. IPCC (2006) *2006 IPCC guidelines for national greenhouse gas inventories*, Intergovernmental Panel on Climate Change, Volume 5, Chapter 4: Biological treatment of solid waste.
54. ICF Consulting (2005) Determination of the impact of waste management activities on greenhouse gas emissions: 2005 update, Submitted to Environment Canada and Natural Resources Canada, Final Report, Contract No. K2216-04-0006.
55. Singer JW, Malone RW, Tomer MD, Meade TG, Welch J (2006) Compost effect on water retention and native plant establishment on a construction embankment *Journal of Soil and Water Conservation*, **61(5)**, 268-273.
56. Konomi K, Savabi MR, Shinde D, Jayachandran K, Nkedi-Kizza P, Reed ST (2005) *Water and atrazine movement in a calcareous compost applied soil during simulated multiple storm events* *Water, Air and Soil Pollution*, **165**, 365-377.
57. Celik I, Ortas I, Kilic S (2004) Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert soil, *Soil & Tillage Research*, **78**, 59-67.
58. ARB (2011). Method for Estimating Greenhouse Gas Emission Reductions from Compost from Commercial Organic Waste. Available at: http://www.arb.ca.gov/cc/protocols/localgov/pubs/compost_method.pdf
59. ARB (2009). Initial Statement of Reasons for the Proposed Regulation to Reduce Methane Emissions from Municipal Solid Waste Landfills. <http://www.arb.ca.gov/regact/2009/landfills09/isor.pdf>
60. ARB (2014). California's 2000-2012 Greenhouse Gas Emissions Inventory Technical Support Document. http://www.arb.ca.gov/cc/inventory/doc/methods_00-12/ghg_inventory_00-12_technical_support_document.pdf
61. Assumes 58% grass/leaves, 42% prunings/trimmings (branches)
62. Assumes 71% food waste, 17% grass/leaves, and 12% prunings/trimmings (branches)
63. Modeled with two different values for oxidation factor representing reasonable bounds.

64. The mixed organics category is modeled using a weighted average decay rate (k). This approach assumes that waste decay rates are dependent on each other, i.e. wood waste decay is enhanced due to the presence of food waste (and food waste decay is slowed by the presence of wood waste). This is the approach used to determine the decay rate for the 'mixed waste' category in the U.S. EPA WARM model. The alternative approach would be to separately model each waste type (food, grass, leaves, branches) independently (assuming no interaction), and take the weighted average of the result. According to the IPCC, there has been no research to identify the better of the two approaches, and the true answer probably lies in between each extreme. See 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 5, Ch.3, pg. 3.16.
65. CalRecycle (2009). California 2008 Statewide Waste Characterization Study.
66. (2013) EPA Proposed Amendments to Rule 40 CFR §98.343
67. Barlaz, M. A., Chanton, J. P., & Green, R. B. (2009). Controls on landfill gas collection efficiency: Instantaneous and lifetime performance. *Journal of the Air and Waste Management Association*, 59(12), 1399-1404.
68. ICF (2009). "WARM component-specific decay rate methods." Memorandum from ICF International to United States Environmental Protection Agency. October 30, 2009. (PDF, 16 pp, 192 KB)
69. Chanton, J.P., Spokas, K., and Bogner, J., Limits and dynamics of methane oxidation in landfill cover soils, *Waste Management* 31:823-832
70. Levis, J. W., & Barlaz, M. A. (2011). Is biodegradability a desirable attribute for discarded solid waste? Perspectives from a national landfill greenhouse gas inventory model. *Environmental Science and Technology*, 45(13), 5470-5476.
71. Kaplan, P. O., Decarolis, J., & Thorneloe, S. (2009). Is it better to burn or bury waste for clean electricity generation? *Environmental Science and Technology*, 43(6), 1711-1717.
72. Barlaz, M. A. (1998). Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills. *Global Biogeochemical Cycles*, 12(2), 373-380.
73. Wang, X., Nagpure, A. S., Decarolis, J. F., & Barlaz, M. A. (2013). Using observed data to improve estimated methane collection from select U.S. landfills. *Environmental Science and Technology*, 47(7), 3251-3257.
74. The phased gas collection scenario from Kaplan et al. is also used by Walker and Gin (2012), *CalRecycle Review of Waste to Energy and Avoided Landfill Methane Emissions*.
75. Chanton, J.P., Powelson, D. K., & Green, R. B. (2009). Methane oxidation in landfill soils, is a 10% default value reasonable? *Journal of Environmental Quality*, 38(2), 654-663.
76. Silver, W.L. et al. Climate Change Mitigation Potential of California's Rangeland Ecosystems: A Draft Report to the California Air Resources Board. (2013).
77. Maria Luz Cayuela, Miguel Angel Sánchez-Monedero, Asunción Roig, Tania Sinicco, Claudio Mondini, Biochemical changes and GHG emissions during composting of lignocellulosic residues with different N-rich by-products, *Chemosphere*, Volume 88, Issue 2, June 2012, Pages 196-203.

78. ARB (2012). Proposed Low Carbon Fuel Standard (LCFS) Pathway for the Production of Biomethane from High Solids Anaerobic Digestion (HSAD) of Organic (Food and Green) Wastes, *Staff Report*. http://www.arb.ca.gov/cc/protocols/localgov/pubs/compost_method.pdf
79. ROU (2006) Compost Use for Disease Suppression in NSW) Angus Campbell, project manager. Recycled Organics Unit, PO Box 6267, The University of New South Wales, Sydney Australia 1466
80. Rebecca Ryals, Whendee L. Silver (2013) Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands, *Ecological Applications*, 23 (1), 46-59
81. Marcia S. Delonge, Justine J. Owen, Whendee L. Silver (2014) Greenhouse Gas Mitigation Opportunities in California Agriculture: Review of California Rangeland Emissions and Mitigation Potential. NI GGMOCA R4. Durham, NC: Duke University

DRAFT