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ABSTRACT

Cornell University Farm Services collects recyclable organics from various locations around the University including the dining halls and other food service establishments, the veterinary hospital, satellite dairy cattle, horse and chicken farms, cropping operations, and greenhouses. In 2013, they diverted approximately 6714 metric tons of organic residuals to the compost facility. A questionnaire was developed to get information from the facility in order to calculate greenhouse gas emissions for each step in this process including savings from carbon sequestration through compost use. It was found that in 2013, Cornell's compost facility emitted 104.6 metric tons carbon equivalent (MTCE) and saved 201.4 MTCE through compost use for a total carbon footprint savings of 96.7 MTCE/year (carbon negative). This equates to 0.0154 MTCE/tonne feedstock emitted and 0.03 MTCE saved through compost use for a total carbon footprint savings of 0.0146 MTCE/tonne fresh matter. These values are specific to this facility, but the questionnaire and calculations can be used by compost facilities to calculate the carbon footprint of composting.

Introduction

A carbon footprint is a measure of the impact of human activities on the environment in terms of the amount of greenhouse gases (GHGs) produced, less the amount of carbon (C) stored by the particular activity. Greenhouse gases are gases in the atmosphere that trap infrared radiation (heat) as it reflects off the surface of the earth and radiate it back into outer space, causing the "greenhouse effect." This absorption and radiation are what makes the earth warm enough for life to be sustained. Greenhouse gases include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Carbon dioxide is a gas used by plants during photosynthesis to make the substances they need for growth. The plants then return oxygen to the atmosphere and are eaten by animals, which in turn return CO_2 to the air when they breathe. Methane is a gas produced by microorganisms during the decay process of organic material. It is also generated in the guts of humans and other animals, especially ruminants, such as cattle, goats, and deer. Nitrous oxide is a gas that is produced by microorganisms in both the soil and ocean during the nitrogen (N) cycle which converts atmospheric N to a form more readily available to plants. The gases produced by living organisms or biological processes (biogenically) are a natural part of the carbon cycle on earth. According to the United States Environmental Protection Agency (USEPA) (2011) and the International Panel on Climate Change (IPCC) (2001), GHGs produced biogenically (produced by living organisms or biological processes) are not a concern as those are the ones that allow life on earth. It is the compounds that are produced in excess of the normal carbon cycle, those that are produced anthropogenically, that are causing concern.

Most important human activities emit GHGs (UNFCC 2000). Carbon dioxide, methane, and nitrous oxide are the most common GHGs that result from human activities. Human sources of CO_2 come primarily from the burning of fossil fuels such as coal, oil, and natural gas, and deforestation. Methane is emitted by agriculture, livestock production, digesters, landfills, and energy exploration and N_2O is produced by various agricultural and industrial practices, including the

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use of N fertilizer and the burning of organic material and fossil fuels. Measurement of the effect that these gases have on the environment is done based on global warming potential (GWP). According to the IPCC (2001), GWP is an index that describes the radiative characteristics of well-mixed greenhouse gases, which represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere, relative to that of CO_2. Accordingly, CO_2 has a GWP of 1, whereas N_2O and CH_4 have stronger GWPs (296 and 23, respectively). The USEPA (2011) inventoried GHG emissions and sinks in the United States between 1990 and 2009 and found that waste management activities generated 2.3% of total United States GHG emissions in 2009. Landfills accounted for approximately 17% of total United States CH_4 emissions in 2009. Methane is primarily produced through anaerobic decomposition of organic matter.

Organic waste, including food waste, leaf, and yard and other green waste, food-soiled paper, and other paper products comprise approximately 60% of the waste stream (USEPA 2014). Therefore, diversion of organic materials from landfills to alternative waste management options such as composting is a popular topic of discussion. However, GHGs are also released from compost facilities and must be taken into account when calculating the carbon footprint of composting. The purpose of this paper is to calculate GHG emissions and the carbon footprint of Cornell University's composting operations and provide information about data and processes that may then be used by other compost facilities to calculate their own.

Materials and Methods

System

System Description

Data from the Cornell Farm Services Compost Facility were used to calculate the carbon footprint. Farm Services compost facility started composting manure and bedding from the University's animal hospital and crop and greenhouse cleanout in 1992. The compost site was engineered by the Department of Biological and Environmental Engineering at Cornell as a 1.4 acre cloth and gravel pad with a leachate collection pond. A berm built from topsoil that was cleared from the site to install the pad, surrounds the pad and diverts water from the slope above the site off the pad and out of the leachate collection system. The liquids from the leachate ponds are used to irrigate surrounding hay crop fields at appropriate times of the year. Liquids are also used to incorporate water into the windrows when needed. The solids are scooped out of the pond each fall and are either put back in active compost windrows or used to strengthen the berms. In 1999, Farm Services started collecting food scraps from the five dining halls on campus. In 2000, plant material and soils from Cornell greenhouses, Plant Breeding, the Section of Soil and Crop Sciences and Cornell Plantations were brought to the site to be composted.

Until 2003, Cornell's compost was used to supplement nutrients on field crops and generally improve the soil as well as for research in compost quality and use. A decision was made to use more compost on campus and to sell some locally. In order to produce stable, mature compost, the pad was enlarged to the current size of 4.0 acres and a second leachate collection pond was built to accommodate the additional acreage in 2003. As of 2013, there are 20 dining establishments on campus that have their organics picked up by Farm Services for composting. Cornell is composting approximately 760 metric tons (MT) of pre- and post-consumer food scraps and compostables, 5500 MT of animal manure and bedding and 460 MT of plant material and soil. Two recipes are used for the compost windrows (Table 1). The food waste and veterinary hospital manure are composted together as recipe 1 and used on Cornell's agricultural fields. Recipe 2 consists of 88% dairy cattle and horse manure, along with their associated bedding and the rest is other animal manures, greenhouse waste, plant

Table 1. Average compost mixture composition.

Windrow recipe	Feedstock	Percentage (based on weight)
(1) Dining Hall and Veterinary Hospital	Food waste and compostables	53.0
	Veterinary manure and bedding	47.0
(2) Non-veterinary manure and bedding and plant and soil material	Dairy manure and bedding	63.0
	Horse manure and bedding	25.0
	Chicken manure and litter	1.0
	Other manure and bedding	3.0
	Greenhouse waste	3.0
	Plant material and soil	5.0

material, and soil. Recipe 2 is managed for sale and used in research.

Organic material is managed using a turned windrow system. The compost windrows are approximately 350 feet long, 6 feet tall, and 15 feet wide. Monday through Friday, a Cornell Farm Services staff member picks up organics from dining facilities. Food scraps and compostables are added daily to existing windrows consisting of veterinary manure and bedding using a front end loader. A trench is created in the windrow and the organics are put into that trench and covered with additional carbon material. The other feedstocks (non-hospital manure and plant and soil material) are piled at the end of a separate windrow being built and incorporated by the windrow turner when the windrow reaches the desired length. Windrows are turned, using a 400 HP self-propelled straddle turner, based on the internal temperature. Turning is done regularly from April until November, but not generally in the winter months.

The entire composting process occurs in approximately six to nine months after which recipe 1 is used on Cornell farm fields and in campus construction projects while recipe 2 is moved to a curing area for maturation and sale. Testing for compost parameters is done periodically. Results have shown that compost quality has remained consistent over the years.

Goal of the Study

The goal of this study was to establish baseline information on GHG emissions for a large-scale composting operation and create equations/worksheets for compost facility managers to use as a template. The information garnered is a carbon footprint (i.e., GHG only, no other emissions at this time). The information gained from calculating the carbon footprint can also be used to revise processes or make management decisions that could decrease the carbon footprint of a facility.

Functional Unit

The functional unit is used as the reference to calculate all the inputs and outputs of the system based on the function or service provided by the product. Amlinger, Peyr, and Cuhls (2008) suggest all emission factors should be recorded in kg or g per metric ton fresh matter (kg/Mg FM) input material for general comparison of treatment systems and processes. All calculations were based on the total amount of organic waste processed from January through December 2013 and are presented as MT of carbon dioxide (CO_2) equivalent per Mg of fresh matter feedstock processed (MTCE/Mg FM). MTCE for methane and nitrous oxide were calculated using IPCC's Third Assessment Report values of 23 and 296, respectively (USEPA 2011). During this time, Cornell Farm Services Compost Facility received and processed 6714 MT of organic waste into 17 windrows of 2 different recipes, resulting in the production of 1452 MT of compost, which constitutes an average for the 2 recipes of 21.6% of the initial feedstock weight being transformed into the final compost product.

System Boundaries

The system boundaries were the composting process (i.e., receiving, pre-processing, pile building, composting, turning, curing, storage, and pumping of retention ponds), and compost use. Figure 1 shows the flow of a composting facility and defines the system boundaries used in this project. GHG emissions were calculated for each of the steps listed that occur at Cornell Farm Services Compost Facility.

Data and Calculations

Data Collection

A questionnaire was developed and filled out by the manager of Cornell Farm Services Compost Facility (Appendix A in Supplemental Material). The questionnaire divided the composting process into six categories: (1) raw materials acquisition, (2) pre-processing of materials, (3) windrow building, (4) composting, (5) curing, and (6) product use. These answers were used to determine feedstock physical and chemical characteristics, collection quantities and distances, compost recipe, number and dimension of windrows, number of turnings, fuel consumption, and the amount of compost produced and how it was used.

Fuel consumption emissions, based on the above answers, were modeled after information gathered from several sources. Emissions due to the decomposition process were calculated using equations derived from an extensive literature review. Avoided emissions in the use phase were also calculated from an extensive literature review on emission reductions due to increased soil C storage. All of these are described in detail below.

Fuel Consumption

Emissions from gasoline or diesel fuel used were gathered from several sources. Kilograms of CO_2 emitted

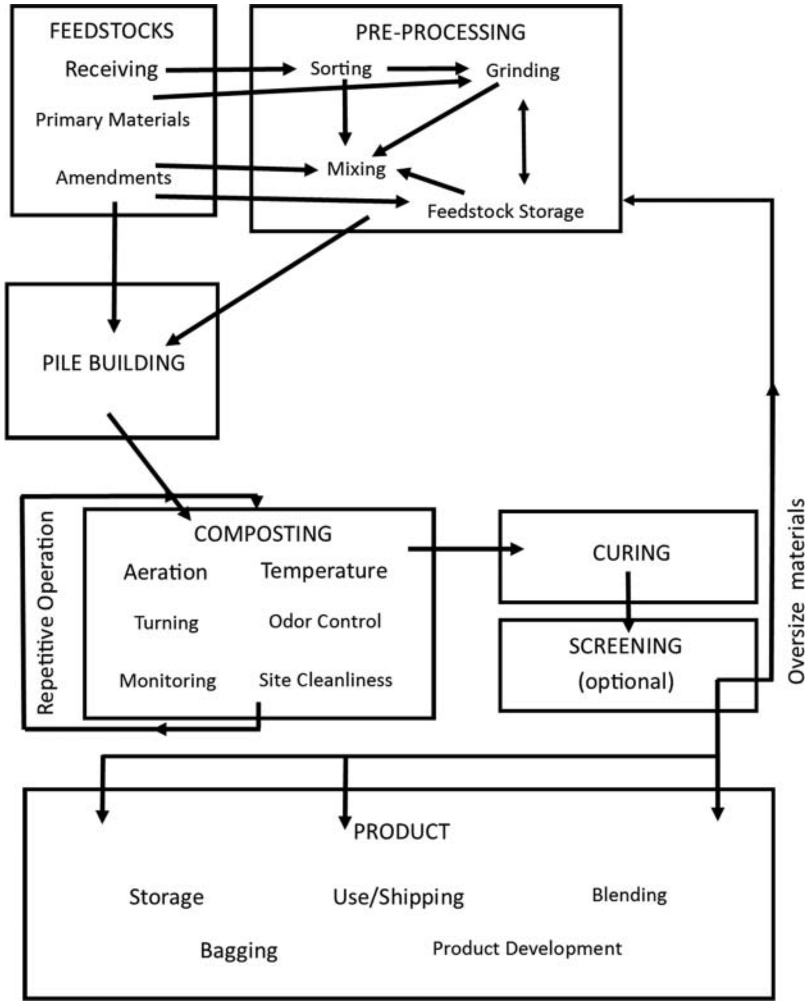

Figure 1. Flow of a composting facility used to define system boundaries.

per unit of fuel are available from the US Energy Information Administration (US EIA) (2011) in a table titled "Carbon Dioxide Emission Factors for Transportation Fuels." This same source, in a table titled "Methane and Nitrous Oxide Emissions Factors for Highway Vehicles," also supplies grams (g) nitrous oxide (N_2O) and g methane (CH_4) per mile or km driven based on type of vehicle and model year. The missing values, kg CO_2 per mile driven and g N_2O and CH_4 per unit of fuel used, were calculated from these aforementioned tables, using the average miles/gallon (mpg) of fuel for vehicle type given in CO_2 emission factors for United States by vehicle distance (Greenhouse Gas Protocol 2012). Table 2 shows these values by vehicle type as defined by the USEPA (TransportPolicy 2013).

Many composting facilities use agricultural vehicles for tasks such as mixing and turning. As these vehicles are not being used on the road, fuel consumption is measured by the amount of fuel used during a specific time period. Downs and Hansen (1998) report the average fuel consumption (AFC) for year-round operation of diesel and gasoline tractors at 0.048 (0.182) and 0.068 (0.257) gallons (liters) per hour per power take-off horsepower (PTO-hp). Power take-off horsepower is approximately 80% of the horsepower of the tractor. If the number of hours it takes to perform each task was not available, total energy consumed was used to calculate GHG emissions.

Raw Materials Acquisition—Questions A.1, A.2.a, and A.2.b of the Questionnaire

GHGs emitted during raw materials acquisition for a composting facility come from the energy used (electricity, diesel, gasoline, natural gas, etc.) to acquire feedstocks and amendments. For each feedstock used by the composting facility, the operator was asked to record how it was transported (self-transport or pick-

Table 2. GHG emissions per liter of fuel used and per mile traveled.

Fuel type	Vehicle type/mpg[1]	mpg[1]	kg CO_2 per gallon[2]	kg CO_2 per mile[3]	g N_2O per gallon[4]	g N_2O per mile[5]	g CH_4 per gallon[4]	g CH_4 per mile[5]
Gasoline			8.74					
	Light duty truck	16.2		0.33	0.75	0.05	0.43	0.06
	Heavy duty truck, rigid	8.8		0.62	0.83	0.09	0.49	0.13
	Heavy duty truck, articulated	5.9		0.92	0.56	0.09	0.33	0.13
Diesel			10.14					
	Light duty truck	16.2		0.39	0.02	0.001	0.02	0.001
	Heavy duty truck, rigid	8.8		0.72	0.42	0.03	0.04	0.003
	Heavy duty truck, articulated	5.9		1.01	0.28	0.03	0.03	0.003

[1]Average mpg of fuel for each vehicle type calculated from individual values available on the Greenhouse Gas Protocol website, 2012.
[2]Values from US EIA 2011.
[3]Calculated value.
[4]Calculated value.
[5]Values from US EIA 2011.

up), the type of vehicle used (including brand, model, etc.), the horsepower, type of fuel, number of miles traveled for pick-up or delivery and number of times per week this happened. The questionnaire also asked for the weight (as received) of each feedstock and the total energy (e.g., gallons of diesel) used for raw materials acquisition for the calendar year. According to the Greenhouse Gas Protocol (2008) Mobile Combustion GHG Emissions Calculation Tool, fuel use data are most accurate for calculating CO_2 emissions, whereas distance traveled data are most accurate for calculating CH_4 and N_2O emissions. Therefore, emissions from raw materials acquisition were calculated based on the number of miles traveled per year by each vehicle transporting feedstocks for CH_4 and N_2O plus the amount of fuel used in transporting feedstocks for CO_2. Each vehicle listed was classified as light-duty (LDT), gasoline or diesel powered, or heavy-duty truck (HDT), gasoline or diesel powered, according to definitions by the USEPA (TransportPolicy 2013). Heavy duty trucks were further defined as rigid, designed to haul loads on well-maintained roads, or articulated, for the ability to drive over rough terrain and over-the-road. It was assumed that all of the trucks used at Cornell Farm Services Compost Facility are articulated. It was also assumed that the tractors used for hauling would have the same emissions as the diesel HDT articulated trucks because of their size and ability to be used in the same manner.

Pre-Processing—Questions B.1 and B.2 of the Questionnaire

GHGs during the pre-processing step in a composting facility come from the energy used to sort, grind, and mix the feedstocks prior to building a pile or windrow. Emissions could also come from stored feedstocks, although CO_2 emissions would not be counted as they are considered biogenic (see below in Composting). For each possible pre-processing step, if it was used, the questionnaire asked for type of equipment, horsepower, type of fuel and duration of the activity (hours per week), as well as the total energy used for pre-processing in a calendar year. As all pre-processing steps involve stationary combustion, GHG emissions were calculated based on the number of hours each piece of equipment was used in gallons per hour per PTO-hp as described above.

Windrow Building—Questions C.1, C.3, and C.4 of the Questionnaire

Emissions from this step in a composting facility come from the energy used while building a pile or windrow, or while loading an in-vessel composter. For each compost recipe used, the questionnaire asked for the number of windrows/piles or batches made in the calendar year, type of equipment used, its horsepower, fuel and length of time it takes, in hours, to create a windrow/pile or batch, as well as the total energy used for building windrows/piles or loading in the calendar year. Windrow building emissions were calculated the same way as pre-processing; based on the number of hours each piece of equipment was used in gallons per hour per PTO-hp as described above.

Composting—Questions C.1 through C.4, and D.1 Through D.4

Emissions from the composting process come from the energy used for turning the pile/windrow or in-vessel composter as well as N_2O and CH_4 emissions coming directly from the organic material as it composts. As per the recommendation of the IPCC, CO_2 emissions from the composting feedstocks were not included as CO_2 emissions from degradation of organic material are considered biogenic. There has been much debate on whether or not compost piles emit CH_4 during the process. The USEPA (2006) and ROU (2007) suggest that well-managed compost piles do not produce methane (as they should not be anaerobic) and even if they do produce some in the center of the pile it will be oxidized to CO_2 by the time it reaches the surface.

However, other researchers have measured emissions of CH_4 from compost piles and have made some conclusions as to which parts of the process of composting have the most effect on GHG emissions. Amlinger, Peyr, and Cuhls (2008) measured emissions from several different combinations of biosolids and green waste and found that the composition of the feedstocks along with process management issues such as aeration, mechanical agitation, moisture control, and temperature are important factors controlling CH_4 and N_2O emissions. Similarly, oxygen and moisture content of manure mixed with varying amounts of bulking materials had an effect on CH_4 and N_2O emissions (Luo et al. 2013; Maeda et al. 2013; Maulini-Duran et al. 2014; Sommer and Moller 2000; Zhu-Barker et al. 2017). Pattey, Trzcinski, and Desjardins (2005) found a positive correlation between rising temperatures and CH_4 emissions. Emission differences have been found between piles that are passively aerated versus those that are frequently turned (Hao et al. 2001; Fukumoto et al. 2003; Puyuelo, Gea, and Sanchez 2014) as well as forced air versus static piles in mortality composting (Szanto et al. 2007; Xu et al. 2007a, 2007b; Zhu et al. 2014). Researchers measuring emissions from food waste and green waste composting systems found differences in GHG emissions due to number of times feedstocks were turned, length of time composting occurred, ratio of wet to dry materials and dimensions of the piles/windrows or in-vessel composters (Ahn et al. 2011; Andersen et al. 2010a, 2010b; Chowdhury, de Neergaard, and Jensen 2014a, 2014b; Greenwaste Project 2013; Yamulki 2006; Yang et al. 2013). Compost covers and biofilters have also played a role in GHG emissions (Hellmann et al. 1997; Luo et al. 2014; Morris et al. 2011) as well as timing and frequency of turning (Mulbry and Ahn 2014).

In short, the feedstocks used, moisture, C and N content, and the carbon to nitrogen (C:N) ratio of the initial composting mixture can have an effect on GHG emissions during the compost process. The type and size of the system, how often it is turned, and length of the composting phase can also play a part in GHG emissions. Therefore, the questionnaire asked for compost process, recipes (including percentages of each feedstock by weight), and percent moisture, C, N, and the C:N ratio. For each recipe, it asked for the number of windrows/piles or batches made per year, information on the equipment used to make one, the length of time it takes and the dimensions. Emissions reported in the literature were analyzed using JMP 10.0.2 software (SAS Institute, Inc., Cary, NC 2012) to create regression equations for N_2O and CH_4 emissions based on the parameters given in the literature. Twenty-seven studies using a total of 111 compost piles/windrows or in-vessel systems were used in the statistical analysis. Feedstock information, type of system (e.g., windrow, in-vessel, etc.), whether or not the compost was turned, and duration of composting was given for all of the studies and Table 3 shows the number of data points for which the other parameters were given.

For emissions from the use of energy during the composting phase, the questionnaire asks for type of aeration, equipment used for turning, including horse power and type of fuel, how long it takes to turn as well as the approximate number of times each windrow/pile is turned throughout processing and how long the composting phase is in days. Other questions include the weight loss of feedstock at the end of the phase, whether or not water is added, site maintenance is done and the total amount of energy used during this phase. Mechanical process emissions were calculated based on the number of hours each piece of equipment was used for this step in gallons per hour per PTO-hp as described above.

Curing—Questions E.1 Through E.4

Emissions from curing come from the energy used to move the compost to a curing pad. They may also come directly from the curing piles, but there is very little literature available to accurately calculate these emissions, so these were not included. Questions asked to calculate emissions from curing included the type and horsepower of equipment used, as well as type of fuel and the time required to move each pile/windrow or batch. Total energy used in the calendar

Table 3. Parameters and number of values reported in the literature from which N_2O and CH_4 emissions were measured.

Parameter	No. of data points	Citation(s)
% Moisture	47	Ahn et al. 2011; Andersen et al. 2010b; Chowdhury, de Neergaard, and Jensen 2014 a and 2014b; Fukumoto et al. 2003; Hao et al. 2001; Hassouna et al. 2008; Maeda et al. 2013; Maulini-Duran et al. 2014; Mulbry and Ahn 2014
% Carbon	38	Ahn et al. 2011; Amlinger, Peyr, and Cuhls 2008; Amon et al. 2011; Andersen et al. 2010 a; Hao et al. 2001, Hassouna et al. 2008; Hellebrand 1998; Mulbry and Ahn 2014; Puyuelo, Gea, and Sanchez 2014; Xu et al. 2007 a; Zhu et al. 2014; Zhu-Barker et al. 2017
% Nitrogen	42	Ahn et al. 2011; Amlinger, Peyr, and Cuhls 2008; Amon et al. 2011; Andersen et al. 2010 a; Fukumoto et al. 2003; Hao et al. 2001, Hassouna et al. 2008; Hellebrand 1998; Maeda et al. 2013; Mulbry and Ahn 2014; Puyuelo, Gea, and Sanchez 2014; Xu et al. 2007 a; Zhu et al. 2014; Zhu-Barker et al. 2017
C:N ratio	62	Ahn et al. 2011; Amlinger, Peyr, and Cuhls 2008; Amon et al. 2011; Andersen et al. 2010 a; Chowdhury, de Neergaard, and Jensen 2014 a, 2014b; Hao et al. 2001, Hassouna et al. 2008; Hellebrand 1998; Mulbry and Ahn 2014; Puyuelo, Gea, and Sanchez 2014; Sommer and Moller 2000; Szanto et al. 2007; Xu et al. 2007a; Yamulki 2006; Zhong et al. 2013; Zhu et al. 2014; Zhu-Barker et al. 2017
Size (width, height, length)	56	Ahn et al. 2011; Amlinger, Peyr, and Cuhls 2008; Andersen et al. 2010 a, 2010b; Fukumoto et al. 2003; Greenwaste Project 2013; Hao et al. 2001; Luske 2010; Martinez-Blanco et al. 2010; Mulbry and Ahn 2014; Pattey, Trzcinski, and Desjardins 2005; Phong 2012; Sommer and Moller 2000; Szanto et al. 2007; Xu et al. 2007 a and 2007b; Yang et al. 2013; Zhong et al. 2013; Zhu et al. 2014
Turning frequency	111	Ahn et al. 2011; Amlinger, Peyr, and Cuhls 2008; Amon et al. 2011; Andersen et al. 2010 a; Chowdhury, de Neergaard, and Jensen 2014b; Fukumoto et al. 2003; Greenwaste Project 2013; Hao et al. 2001; Hassouna et al. 2008; Hellebrand 1998; Luo et al. 2014; Maeda et al. 2013; Martinez-Blanco et al. 2010; Maulini-Duran et al. 2014; Mulbry and Ahn 2014; Pattey, Trzcinski, and Desjardins 2005; Phong 2012; Puyuelo, Gea, and Sanchez 2014; Sommer and Moller 2000; Szanto et al. 2007; Xu et al. 2007 a and 2007b; Yamulki 2006; Yang et al. 2013; Zhong et al. 2013; Zhu et al. 2014; Zhu-Barker et al. 2017

year for curing was the final question in this section. Emissions from curing were calculated based on the number of hours each piece of equipment was used for this step.

Product Processes and Product Use—Questions F.1 through F.4

Depending on the facility, the cured product could be screened and/or bagged, processes which would use energy and therefore emit GHGs. In addition, storage of finished compost could happen in a different place than the curing and thus take energy to move, or could be under cover or in a building in which electricity or other forms of energy are used. The energy used to deliver or spread/incorporate (if used on-site) the finished product should also be taken into account. Fuel emissions from customer pick-up were estimated based on average distances traveled within Tompkins County for landscapers and homeowners and vehicles used were assumed to be gasoline powered $^1/_2$, $^3/_4$ or 1-ton light duty pick-up trucks. Emissions from product processes were calculated based on the number of hours each piece of equipment was used for this step in gallons per hour per PTO-hp as described above and on the number of miles traveled for pick-up/delivery of compost.

The benefits of compost use are well known (USCC 2001). Compost is an excellent soil conditioner. Application adds organic matter, improves soil structure, reduces fertilizer requirements, and reduces soil erosion. In addition, applying compost adds C, in the form of organic matter, to the soil, a viable strategy to sequester C from the atmosphere (Brown and Cotton 2011; Franzluebbers and Doraiswamy 2007; Rahman 2013). Although there is research indicating fertilizer savings from compost use (Blengini 2008; Brown, Kruger, and Subler 2008; Chan et al. 2011; Flavel and Murphy 2006), reduced water use and decreased soil erosion as well as avoiding the impacts of mining and transporting peat (Saer et al. 2013; Schlesinger 2000), this study used only C sequestration to calculate emission savings through the use of compost. The emissions savings from applying compost are reported in the literature either as MTCE per Mg FM used to create the compost, per Mg of compost applied, or based on the amount of carbon in the compost. Table 3 shows these studies and the values derived from them. Carbon sequestration from the use of Farm Services Compost was calculated by taking an average of all of the calculations shown in table 4.

Results and Discussion

Total GHG emissions in 2013 from the operation of Cornell Farm Services Compost Facility were 104.6 MTCE/year or 0.0154 MTCE/Mg FM processed (Table 5). When emissions savings from C sequestration due to compost use are added to the emissions

Table 4. Values derived for C sequestration from the literature.

Author	MTCE	Units	Basis
Brown et al. 2010	−0.25	Per MT compost (dry weight) applied	Based on values obtained in two PhD theses concerning application of biosolids to agricultural, roadside, and mining land.
USEPA 2012	−0.24	Per short ton (wet weight) compost applied	This is the value used by EPA's WARM model for carbon sequestration from compost application. This value was derived from simulations of 30 scenarios of compost application using CENTURY.
Tian et al. 2009	$y = 0.064x - 0.11$, where y is the annual net soil C sequestration x is the annual compost application (dry weight)	Per MT compost applied per year (dry weight). This value then needs to be multiplied by 44/12 to convert C to CO_2	Results of a study indicating that soil C sequestration was significantly correlated with biosolids application rate.
Yoshida, Gale, and Park et al. 2012	0.0677	Per MT FM	This was estimated using the EASEWASTE model and values from leaf and yard waste composting in Madison, WI
Blengini 2008	0.048	Per ton FM	Composting of 1;ton of bio-waste is thought to have a carbon dioxide sequestration potential of 48;kg.
Boldrin et al. 2009	$CO_{2,bind} = C_{input} \times C_{bind} \times \frac{44}{12}$ where C_{input} is the C content of compost, C_{bind} is the Fraction of C which is "stable"	Total amount of carbon dioxide bound from an application of compost	The carbon still bound to the soil after 100 years has been estimated to be 2–14% of the input carbon in compost. Wet weight basis.
Smith et al. 2001	$CO_2 = C_{input} \times 8.2\% \times \frac{44}{12}$ where C_{input} is the C content of compost	Total amount of carbon dioxide bound from an application of compost	This study looked at several other studies to estimate the life time of carbon in the soil organic matter pool and estimated carbon storage to be 8.2% of the input of carbon in the compost. Wet Weight basis.

from the process, Cornell Farm Services Compost Facility shows a savings of 96.73 MTCE/year (0.0146 MTCE/Mg FM). These results indicate that composting at Cornell University is carbon negative. The following sections detail the specifics for calculation of GHG emissions at each step.

Raw Materials Acquisition

According to the questionnaire (Appendix A in Supplemental Material), manure and bedding from the animal hospital and other Cornell owned dairy and horse barns, plant material, and soil from the greenhouses and food waste, compostable service ware, and food-soiled paper products are picked up by Farm Services and delivered to the compost site using one or more heavy duty articulated diesel powered trucks or tractors. Chicken manure and bedding from the poultry facilities is transported by the poultry facility in a light-duty gasoline powered truck and plant matter and plot material from field trials are transported by farm enterprises with a diesel powered tractor. A total of 6695 miles was driven to acquire 6714 MT of feedstock for composting in the 2013 calendar year.

Equation 1 was used to calculate GHG emissions for feedstock acquisition. Fuel use data was used for calculating CO_2 emissions and distance traveled

Table 5. GHG emissions in MTCE/year and MTCE/Mg FM from each step in the operation of Cornell Farm Services Compost Facility from January through December 2013.

Step	MTCE /year	MTCE/Mg FM
Feedstock acquisition	26.32	0.0039
Pre-processing	3.13	0.0005
Pile building	2.56	0.0004
Turning	43.45	0.0063
Composting	22.28	0.0033
Curing	0.58	0.0001
Retention pond pumping	2.34	0.0003
Product pick-up and land application	3.98	0.0006
Total emissions from processes	104.62	0.0154
Carbon storage	(201.35)	(0.0299)
Carbon Footprint of Cornell Farm Services Compost Facility	(96.73)	(0.0146)

data was used for calculating CH_4 and N_2O emissions, converted to MTCE using the IPCC's third assessment review values of 296 and 23, respectively, and summed. Emissions per mile traveled using the individual values for each feedstock (*i* to *n)* and the emission factors for N_2O and CH_4 for each vehicle type found in table 2 above were added to CO_2 emissions from the use of 2563 gallons of diesel fuel and 25 gallons of gasoline reported by Farm Services. Acquisition of raw materials for composting at Cornell emitted 26.3 MTCE GHG in 2013; or 0.0039 MTCE/Mg FM (26.3 MTCE/6,714 MT).

Pre-Processing

Of the pre-processing steps listed in the questionnaire, Cornell Farm Services Compost Facility did not sort or grind, they only mixed. Nor did they dispose of any contaminants in the pre-processing step. In 2013, mixing was done 2 hours per week using a 75 horsepower (hp) diesel powered John Deere 344G Loader. Equation 2 was used to calculate GHGs from stationary combustion of fuel based on the number of hours used and the horsepower of the vehicle (*i* to *n*). Cornell Farm Services Compost Facility emitted 3.13 MTCE in 2013 or 0.0005 MTCE/Mg FM during pre-processing of compost feedstocks.

Equation 1: GHG emissions from miles traveled and fuel used in feedstock acquisition
For each vehicle *i* to *n* and each "energy" type *j* to *n*

$$\frac{\text{MTCE}}{\text{year}} = \sum_{i}^{n}\left\{\left(\frac{\left(\left(\mathit{\#miles}_i \times \frac{\mathit{pickups}_i}{\mathit{week}} \times \frac{\mathit{weeks}}{\mathit{year}}\right) \times \frac{\text{N}_2\text{OEF}}{\mathit{mile}}\right)}{100} \times 296\right) + \left(\frac{\left(\left(\mathit{\#miles}_i \times \frac{\mathit{pickups}_i}{\mathit{week}} \times \frac{\mathit{weeks}}{\mathit{year}}\right) \times \frac{\text{CH}_4\text{EF}}{\mathit{mile}}\right)}{100} \times 23\right)\right\} + \sum_{j}^{n}\left\{\text{QE}_j \times \frac{\text{CO}_2\text{EF}}{\text{unit energy}}\right\} \tag{1}$$

where: miles = miles driven by each vehicle type;
pickups = number of times waste is picked up;
QE = quantity of energy used; and
EF = emission factor from table 2.

Equation 2: GHG emissions from stationary combustion
For each vehicle *i* to *n*

$$\frac{\mathit{MTCE}}{\mathit{year}} = \sum_{i}^{n}\left\{\left(\frac{\mathit{hours}_i}{\mathit{wk}} \times \frac{\mathit{wk}}{\mathit{yr}} \times \text{PTO} - \text{hp}_i \times \text{AFC}_i \times \frac{\text{CO}_2\text{EF}}{\text{unit energy}}\right) + \left(\left(\frac{\left(\frac{\mathit{hours}_i}{\mathit{wk}} \times \frac{\mathit{wk}}{\mathit{yr}} \times \text{PTO} - \text{hp}_i \times \text{AFC}_i \times \frac{\text{N}_2\text{OEF}}{\text{unit energy}}\right)}{100}\right) \times 296\right) + \left(\left(\frac{\left(\frac{\mathit{hours}_i}{\mathit{wk}} \times \frac{\mathit{wk}}{\mathit{yr}} \times \text{PTO} - \text{hp}_i \times \text{AFC}_i \times \frac{\text{CH}_4\text{EF}}{\text{unit energy}}\right)}{100}\right) \times 23\right)\right\} \tag{2}$$

where: hours = number of hours each vehicle operates
$\text{PTO-hp}_i = \text{hp}_i \times 0.8$;
AFC = Average fuel consumption per rated PTO-hp (0.048 for diesel fuel and 0.068 for gasoline);
EF = emission factor from table 2.

Pile Building

In 2013, Cornell Farm Services Compost Facility built 17 windrows. Windrows were built using a 75 hp diesel powered JD 344G Loader. Two different recipes were used in 2013. Nine windrows were created of recipe 1 as described in table 1 and eight windrows of recipe 2. The manager reported a total time of five hours (although occurring over a period of weeks) to create each windrow. As pile building involves stationary combustion, GHG emissions from this step were calculated based on the number of hours the loader was used (equation 2). In 2013, vehicle use for pile building emitted 2.6 MTCE (0.0009 MTCE/Mg FM).

Composting

Nitrous oxide emissions: Linear regression of N_2O by the variables reported in the literature (table 3) as having an effect on GHG emissions provided a significant fit model for N_2O emissions (p = 0.0264, r^2 = 0.9318). Linear regression showed that N_2O emissions were positively correlated with biosolids, food waste and yard waste composting, total carbon in the mix, forced air composting systems, height, length, and width-to-height ratio of the pile/windrow, and number of turns. They were negatively correlated with manure and mortality composting, total nitrogen and C:N ratio of the mix, passively aerated and windrow systems, width of the composting system, weeks of decomposition, and number of turns per week. Equation 3 is the prediction expression from linear regression.

Equation 3: Prediction equation for nitrous oxide emissions (g/year) from composting*

$$N_2O\left(\frac{g}{year}\right) = -1454.4 + \text{Main ingredient}\begin{pmatrix} \text{Biosolids } 493.7 \\ \text{Foodwaste } 167.5 \\ \text{Manure } -468.5 \\ \text{Mortality } -353.8 \\ \text{Yardwaste } 161.2 \\ \text{else } . \end{pmatrix} + (-3.8 \times \text{Total } N)$$
$$+ (-8.8 \times C:N \text{ ratio}) + (17.7 \times \text{Carbon}) + \text{System type}\begin{pmatrix} \text{Forced air } 26.1 \\ \text{Passively aerated} - 24.5 \\ \text{Windrow} - 1.6 \\ \text{else } . \end{pmatrix}$$
$$+ (-528.6 \times \text{Width}) + (1086.5 \times \text{Height}) + (2.2 \times \text{Length})$$
$$+ (786.3 \times \text{Width to height ratio})$$
$$+ (7.8 \times \text{Number of turns}) + (-3.0 \times \text{Weeks of composting})$$
$$+ (-62.0 \times \text{Turns per week}) \quad (3)$$

*a minus sign (−) in front of values for each of the parameters indicates negative correlation with N_2O emissions.

Nitrous oxide emissions from composting at Farm Services Compost Facility were 60.2 kg/year (17.82 MTCE/year) and 0.009 kg/Mg FM (2.66 MTCE/Mg FM, table 6). According to IPCC (2006), the estimated N_2O released during composting varies from less than 0.5–5% of the initial nitrogen content of the material. Emissions can be calculated as a product of an emission factor and the mass of organic waste composted. The emission factor was created by the IPCC (2006) based on peer-reviewed journal articles. The default emission factor for N_2O emissions is 0.3 g N_2O/kg organic waste processed (wet weight). This value assumes that the waste treated has 25–50% degradable organic carbon (DOC), 2% nitrogen (dry matter), and a moisture content of approximately 60%. Using the IPCC emission factor and default equation yields 0.39 MTCE from N_2O/year. This value is 45 times less than the value calculated using equation 3. The difference can be attributed to the fact that IPCC emission factor is based on the

Table 6. Estimated nitrous oxide and methane emissions from the composting process at Farm Services Compost Facility.

Variables[1]		kg/year		MTCE/year		kg/Mg FM		MTCE/Mg FM	
Recipe	No. windrows	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4
Manure/foodwaste[2]	9	35.98	120.10	10.65	2.76	0.005	0.018	1.59	0.41
Manure[3]	8	24.22	73.66	7.17	1.69	0.004	0.011	1.07	0.25
Total	17	60.20	193.76	17.82	4.46	0.009	0.029	2.66	0.66

[1]System type = windrow, width = 4.6 m, height = 1.8 m, length = 106.7 m, width-to-height ratio = 2.5, number of turns = 15, weeks of composting = 17.14, turns per week = 0.88 for both recipes.
[2]Total N = 3.1%, C:N = 46.8, Total C = 62.1%.
[3]Total N = 2.0%, C:N = 20.0, Total C = 39.5%.

characteristics of the waste alone and does not take into account the way the waste is processed rather it assumes that all composting systems are the same and seriously underestimates the amount of nitrous oxide emitted during the composting process. In addition, the characteristics of Cornell Farm Services waste was 62% carbon, 3% nitrogen, and 73% moisture for recipe #1 and 39% carbon, 2% nitrogen, and 57% moisture for recipe 2. The initial content of recipe #2 is similar to IPCC's assumptions, but recipe 1 is not.

Methane emissions: Linear regression of CH_4 by the variables reported in the literature (table 3) as having an effect on GHG emissions provided a significant fit model for CH_4 emissions ($p = 0.0057$, $r^2 = 0.9612$). Linear regression showed that CH_4 emissions were positively correlated with manure and mortality composting, the amount of carbon and nitrogen in the mix, forced air and windrow systems, the width, height, length, and width-to-height ratio of the systems, as well as to the number of turns. They were negatively correlated with composting of biosolids, food waste and yard waste, as well as the C:N ratio, passively aerated systems, weeks of decomposition, and number of turns per week. Equation 4 is the prediction expression from linear regression.

Equation 4: Prediction equation for methane emissions (g/year) from composting*

$$
\begin{aligned}
CH_4\left(\frac{g}{year}\right) = & -27,875.2 + \text{Main ingredient}\begin{pmatrix}\text{Biosolids} -4234.4 \\ \text{Foodwaste} -5877.1 \\ \text{Manure } 8209.7 \\ \text{Mortality } 7576.9 \\ \text{Yardwaste} -5675.0 \\ \text{else }.\end{pmatrix} + (191.1 \times \text{Total } N) \\
& + (-132.7 \times C:N \text{ ratio}) + (295.3 \times \text{Carbon}) + \text{System type}\begin{pmatrix}\text{Forced air } 1248.2 \\ \text{Passively aerated} -1318.0 \\ \text{Windrow} 69.9 \\ \text{else }.\end{pmatrix} \\
& + (169.3 \times \text{Width}) + (5970.2 \times \text{Height}) + (28.7 \times \text{Length}) \\
& + (3968.2 \times \text{Width}-\text{to}-\text{height ratio}) + (52.3 \times \text{Number of turns}) \\
& + (-11.5 \times \text{Weeks of composting}) + (-1787.4 \times \text{Turns per week})
\end{aligned} \tag{4}
$$

*a minus sign (−) in front of values for each of the parameters indicates negative correlation with CH_4 emissions.

Methane emissions from composting at Farm Services Compost Facility were 193.76 kg/year (4.46 MTCE/year) and 0.029 kg/Mg FM (0.66 MTCE/Mg FM, table 6). According to IPCC (2006), the estimated CH_4 released during composting varies from less than 1 percent to a few percent of the initial carbon content of the material. The default emission factor for CH_4 calculated by IPCC (2006) is 4 g CH_4/kg organic waste processed (wet weight) using the same assumptions on waste make-up as those used for N_2O emissions. The IPCC emission factor yields 26.9 MTCE from CH_4/year compared to 193.8 from linear regression. The value calculated from equation 4 is seven times the IPCC estimated value. Again, the difference can be attributed not only to the difference in waste make-up, but also to the fact that the IPCC method assumes that all composting will yield the same values, regardless of system and process variables.

Total GHG emissions from the composting process: Total GHG emissions (CH_4 and N_2O) from the composting process were calculated at 22.28 MTCE/yr or 0.0033 MTCE/Mg FM. This value is 16 times higher than GHG emissions using the IPCC method which yields 0.00015 MTCE/Mg FM. However, of all the literature reviewed in table 3, total GHG emissions from composting ranged between 0.0003 and 0.3289 MTCE/Mg FM with a mean of 0.1038 and a median of 0.0763 MTCE/Mg FM. Cornell Farm Services emissions from the composting process fall within that range, and in the lower 10% of the distribution.

Turning

In 2013, Cornell Farm Services Compost Facility turned each of their 17 windrows approximately 15 times. Turning was accomplished using a Frontier F18 Windrow Turner with a 425 horsepower engine fueled by diesel. The manager reported a total time of 30 hours spent turning windrows in 2013. GHG emissions from turning were calculated based on the number of hours the turner was used (equation 2). In 2013, vehicle use for turning emitted 43.5 MTCE (0.0064 MTCE/Mg FM) when calculated on stationary combustion.

Curing

Cornell Farm Services Compost Facility makes two different recipes for composting. The recipe that includes food scraps and veterinary hospital manure and bedding (recipe #1) does not get moved to a curing area as it is not sold. Instead, it is land applied directly from the composting windrow. The other eight windrows are loaded into a 105 hp diesel operated John Deere 6715 with dump trailer using a 75 hp diesel operated John Deere 344G loader and moved to the curing space on the facility site. The manager reported that it took eight hours and 55 gallons of diesel to move all of the windrows in 2013. GHG emissions from curing were calculated based on the number of hours the loader and tractor with dump was used (equation 2). In 2013, vehicle use for curing emitted 0.58 MTCE (0.0001 MTCE/Mg FM).

Product

Cornell Farm Services Compost Facility produced 1500 yards of compost from recipe #1 (manure and foodwaste) and 1800 yards of compost from recipe #2 (mixed manure). They do not bag or screen their product. Recipe #1 was land applied to University agricultural fields by Farm Services while recipe #2 was sold to landscapers, homeowners and the University. Farm Services loaded each of the nine recipe #1 windrows into an International dump truck using a 75 hp diesel operated John Deere 344G loader and hauled the material approximately 2.5 miles to the fields. It was then loaded into a John Deere 7710 155 hp spreader and land applied. It took approximately 1.5 hour to load and 1.5 hour to spread. GHG emissions for the application of recipe #1 was calculated using both equation 1 for miles traveled and adding it to equation 2 for hours of stationary combustion (0.42 MTCE/yr or 0.00006 MTCE/Mg FM).

Landscapers purchased approximately 900 cubic yards of recipe #2. A search of the Ithaca area showed that local landscapers were located an average of 4.5 miles from the compost facility. It was assumed that landscapers would use a quarter or one-ton LDT gasoline powered truck with a capacity of 2 cubic yards. Therefore, it would take 450 loads at 4.5 miles for a total of 2025 miles traveled to pick-up the compost. It was also assumed that the 700 cubic yards of this recipe used by Cornell University would be picked-up with the same type of truck at an average distance of 3 miles for a total of 1050 miles. Homeowners purchased the rest of this recipe (200 cubic yards). Homeowners most likely used gasoline powered half-ton LDT pick-up trucks that can hold 1 cubic yard (200 loads). Farm Services Compost Facility is located in Tompkins County in NYS and the county lines surround the facility in approximately a 13 mile radius. This calculates to a total of 2600 miles driven to pick-up 200 cubic yards of compost. As there is no way to know how much gas or diesel fuel was used to pick-up and deliver the compost, GHG emissions for the pick-up of recipe #2 was calculated using equation 5 (3.56 MTCE/yr or 0.0005 MTCE/Mg FM). Emissions from on-site transportation/application of compost (recipe #1) and transportation for off-site use (recipe #2) totaled 3.98 MTCE/yr or 0.0006 MTCE/Mg FM.

on either the amount of compost applied, or on the amount of feedstock processed, resulting in an average GHG savings of 184.8 and 373.5 MTCE/year, respectively (0.0275 and 0.0556 MTCE/Mg FM). The third method used equation 6 and calculated carbon sequestration based on the amount of carbon applied to the soil from the compost. Farm services 3300 cubic yards of compost at a bulk density of 970 lbs/cubic yard and 10.7% carbon supplied 155.4 MT of carbon, resulting in GHG savings of 45.86 MTCE/year (0.0068 MTCE/MG FM). As little research has been done on the carbon sequestration potential of compost use, this study used an average of all of the methods described above resulting in GHG emissions savings of 201.4 MTCE/year (0.03 MTCE/MG FM).

Equation 5: GHG emissions from pick-up and delivery of finished compost
For each vehicle i to n

$$\frac{\text{MTCE}}{\text{year}} = \sum_i^n \left\{ \left(\left(\#miles_i \times \frac{capacity_i}{compost} \right) \times \frac{\text{CO}_2\text{EF}}{mile} \right) + \left(\left(\frac{\left(\#miles_i \times \frac{capacity_i}{compost} \times \frac{\text{N}_2\text{OEF}}{mile} \right)}{100} \right) \times 296 \right) + \left(\left(\frac{\left(\#miles_i \times \frac{capacity_i}{compost} \times \frac{CH_4EF}{mile} \right)}{100} \right) \times 23 \right) \right\} \quad (5)$$

where: miles = miles driven by each vehicle type;
capacity = amount picked up per load per vehicle;
compost = total amount of compost produced; and
EF = emission factor from table 2.

In addition to emissions from transportation and application, compost use is credited with storing carbon and therefore reducing the emissions of carbon dioxide. Three different methods have been used to calculate savings from compost use as described in table 4. The first two methods simply used an average of the published values for carbon sequestration based

Equation 6: Carbon sequestered based on the amount of carbon applied
For each recipe i to n

$$\frac{\text{MTCE}}{\text{year}} = \sum_i^n \frac{(Q_i \times C_i \times .082^1 \times 44/12) + (Q_i \times C_i \times .02^2 \times 44/12) + (Q_i \times C_i \times .08^2 \times 44/12) + (Q_i \times C_i \times .14^2 \times 44/12)}{4} \quad (6)$$

where Q = quantity of compost applied;
C = carbon content of compost (%);
[1]Smith et al. 2001 – 8.2% of carbon applied is bound.
[2]Boldrin et al. 2009 – 2% of carbon (low-end), 8% of carbon (average) and 14% of carbon (high-end) estimated to be bound.

Additional Information

The retention ponds are pumped annually with a Deutz powered irrigation pump that uses a total of 229 gallons of diesel fuel a year. As the number of hours it took to pump the ponds was not available, emissions from irrigation were calculated on the total amount of fuel used (equation 7). In 2013, use of the irrigation pump emitted 2.3 MTCE (0.0003 MTCE/Mg FM).

Equation 7: GHG emissions fuel used for pumping retention ponds

For each energy type i to n

$$\frac{\text{MTCE}}{\text{year}} = \sum_{i}^{n}\left\{\left(\frac{\text{QE}_i \times \frac{\text{N}_2\text{OEF}}{\text{unit energy}}}{100} \times 296\right) + \left(\frac{\left(\text{QE}_i \times \frac{\text{CH}_4\text{EF}}{\text{unit energy}}\right)}{100} \times 23\right) + \left(\text{QE}_i \times \frac{\text{CO}_2\text{EF}}{\text{unit energy}}\right)\right\} \quad (7)$$

where: QE = quantity of energy used;
EF = emission factor from table 2.

Total GHG Emissions

Total GHG emissions from the management of organic waste at Cornell Farm Services Compost Facility were 104.6 MTCE/year or 0.0154 MTCE/Mg FM. When reductions from the use of compost are added, Farm Services had a savings of 96.7 MTCE for 2013, or 0.0146 MTCE/Mg FM showing that composting of Cornell University's organic waste is carbon negative. Looking at emissions from each step (table 5), it is clear that the largest portion of GHG emissions comes from the combustion of fuel during the turning process (49.6%), followed by the transportation of feedstocks to the facility (30.7%). If turning were reduced, not only would less fuel be used, but GHG emissions from the compost itself would be reduced as number of turns was positively correlated with both N_2O and CH_4 emissions from the pile during composting. Sequestration of carbon from compost use offsets all of the emissions from the process. If fertilizer and water savings were taken into account as well, this facility's carbon footprint would be even lower.

The carbon footprint of Cornell University's Compost Facility was calculated for each step in the process from acquisition of feedstocks through use of the compost produced. Carbon dioxide, methane, and nitrous oxide emitted from energy and machinery use was calculated using values obtained from the USEIA (2011) and the Greenhouse Gas Protocol (2008). These values can be used by other compost facilities to calculate emissions when the energy type (electricity and fuel), type of vehicle, miles to transport and/or hours of stationary operation are known. A regression equation for emissions of N_2O and CH_4 from compost piles was generated from statistical analysis of published values as actual measurement of emission of these gases is not always possible. As new research is performed, these equations should be updated. The same is true for the emission savings garnered from the use of compost. This paper cites three different methods that calculate very different values. Regardless, by calculating the emissions involved in each step of the process, a compost facility can work on reducing those emissions through changes in management. The authors intend to have a calculator tool created from the calculations presented in this paper for other facilities to use.

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