U.S. Environmental Protection Agency
Office of Resource Conservation and Recovery

Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM)

Organic Materials Chapters

February 2016

Prepared by ICF International
For the U.S. Environmental Protection Agency
Office of Resource Conservation and Recovery

THIS PAGE IS INTENTIONALLY LEFT BLANK

Table of Contents

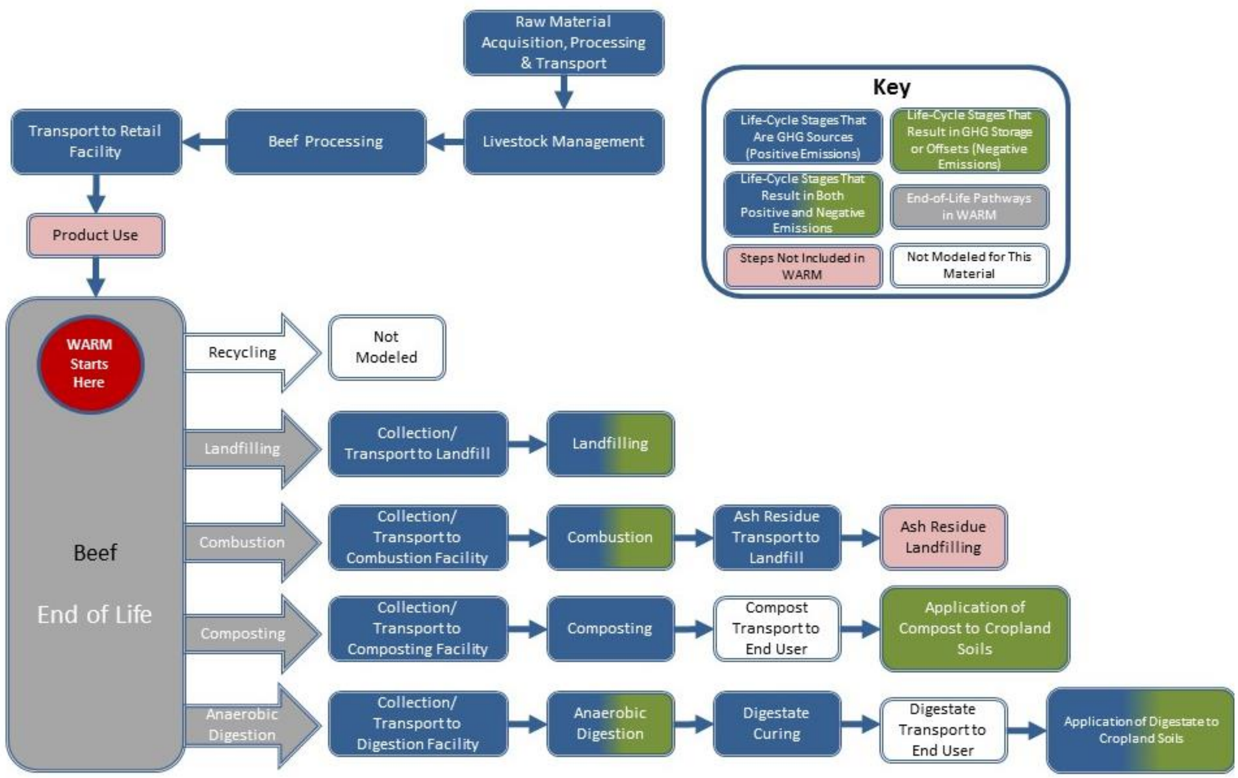
1 FOOD WASTE

1.1 INTRODUCTION TO WARM AND FOOD WASTE

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for food waste—including beef, poultry, grains, bread, fruits and vegetables, and dairy products—beginning at the point of waste generation.[1] The WARM GHG emission factors are used to compare the net emissions associated with these six organic material types in the following five materials management options: source reduction, composting, landfilling, combustion, and anaerobic digestion.

Exhibit 1-1, Exhibit 1-2, Exhibit 1-3, Exhibit 1-4, Exhibit 1-5, and Exhibit 1-6 illustrate the general life cycles and materials management pathways modeled in WARM for beef, poultry, grains, bread, fruits and vegetables, and dairy products, respectively. In each life-cycle diagram, the end-of-life pathways are the same for each material, with only the upstream raw material and production stages differing across food waste types. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Source Reduction, Composting, Landfilling, Combustion, and Anaerobic Digestion see the chapters devoted to those processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

Exhibit 1-1: Life Cycle of Beef in WARM



[1] Source reduction factors for grains, bread, fruits and vegetables, and dairy products were incorporated into WARM version 13 in June 2014; source reduction factors for beef and poultry were added as part of an update to WARM version 13 in March 2015.

Exhibit 1-2: Life Cycle of Poultry in WARM

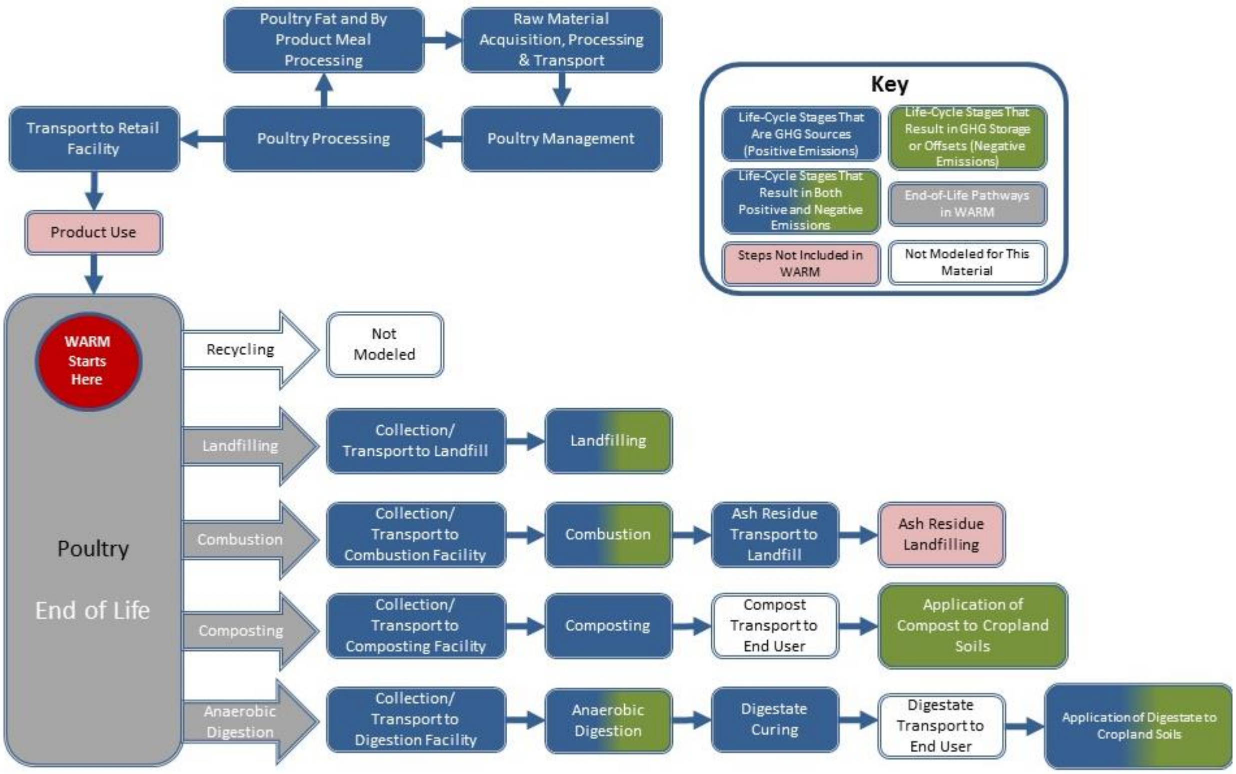


Exhibit 1-3: Life Cycle of Grains in WARM

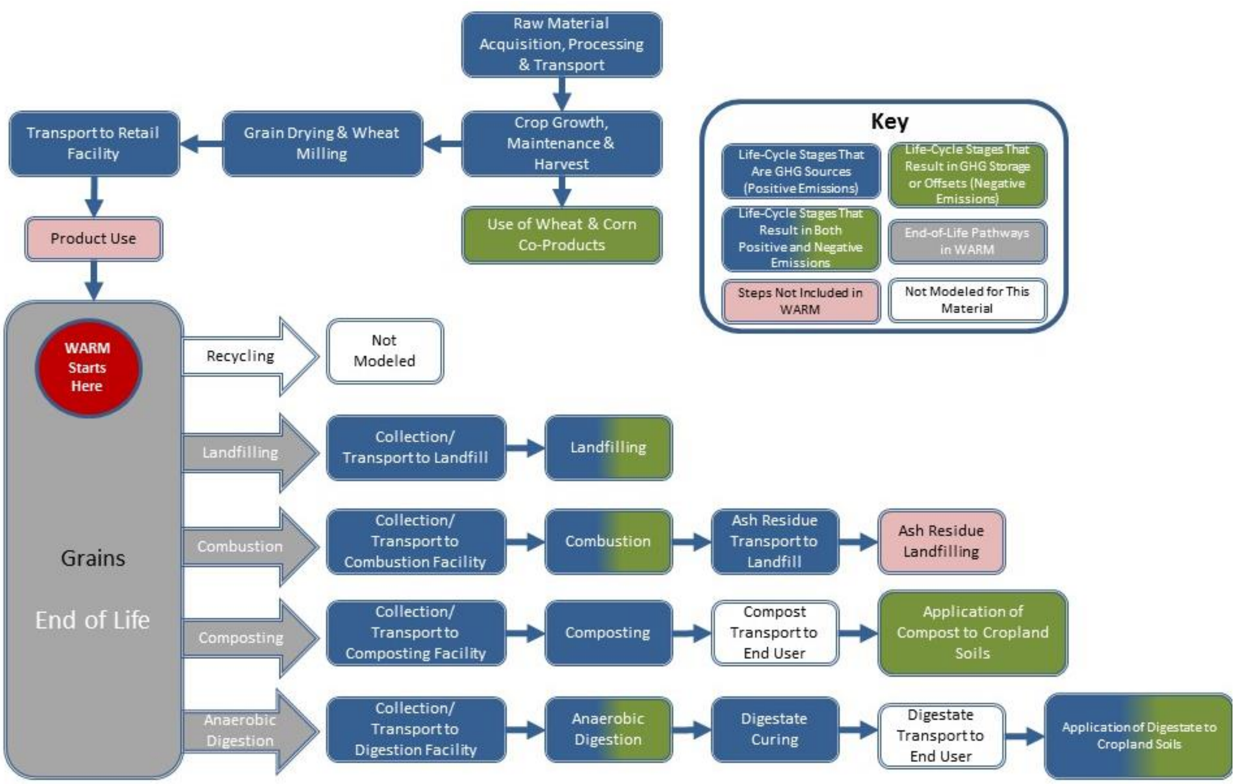


Exhibit 1-4: Life Cycle of Bread in WARM

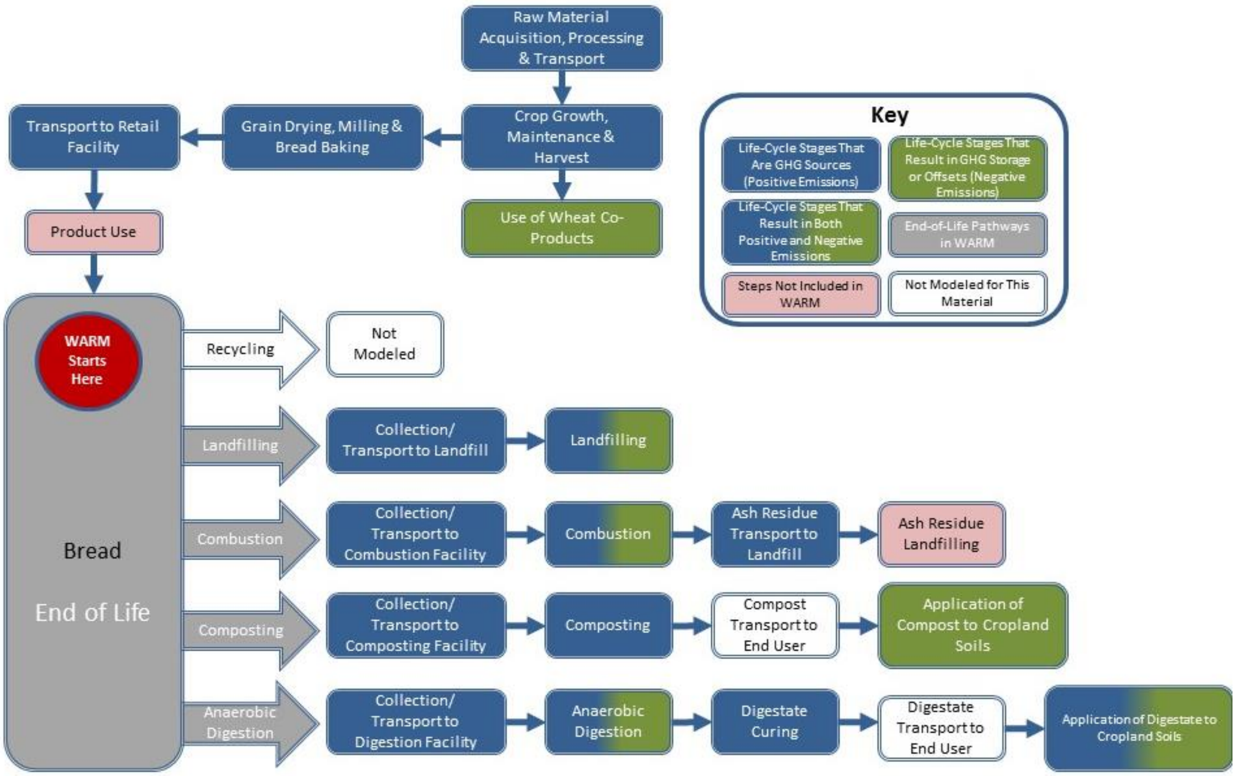


Exhibit 1-5: Life Cycle of Fruits and Vegetables in WARM

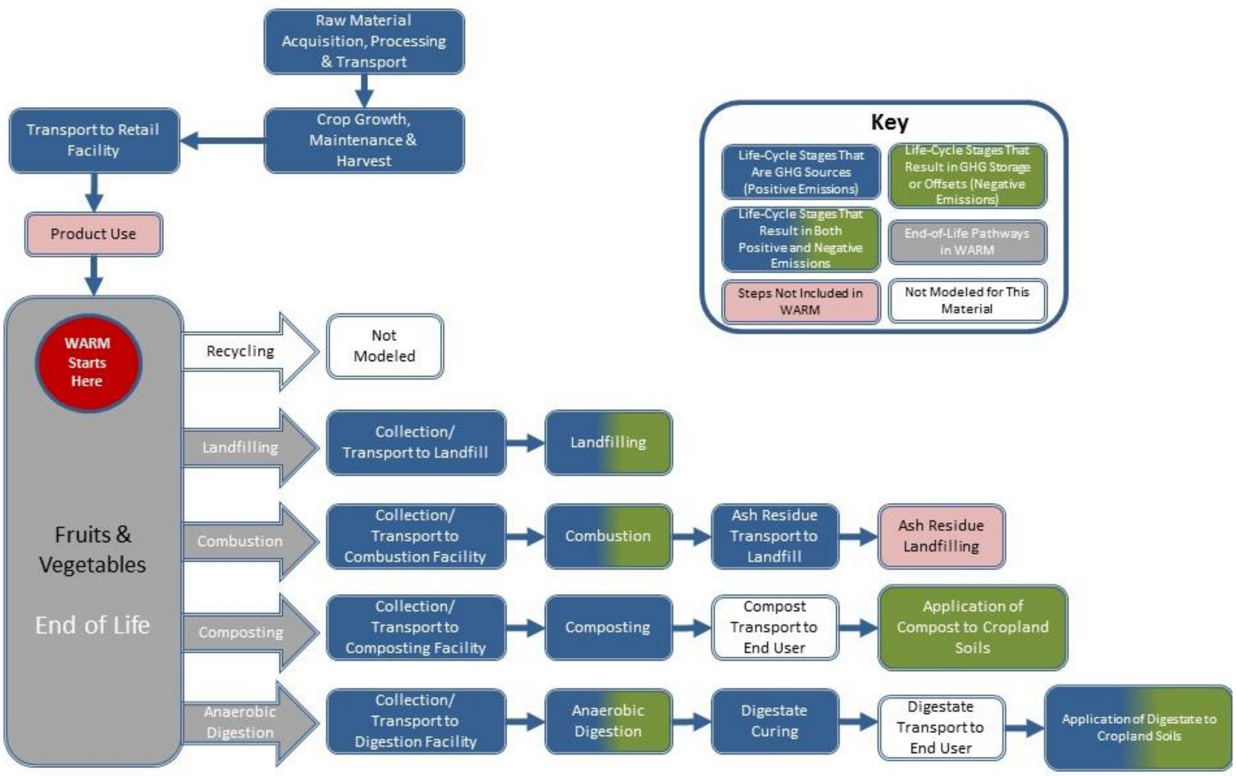
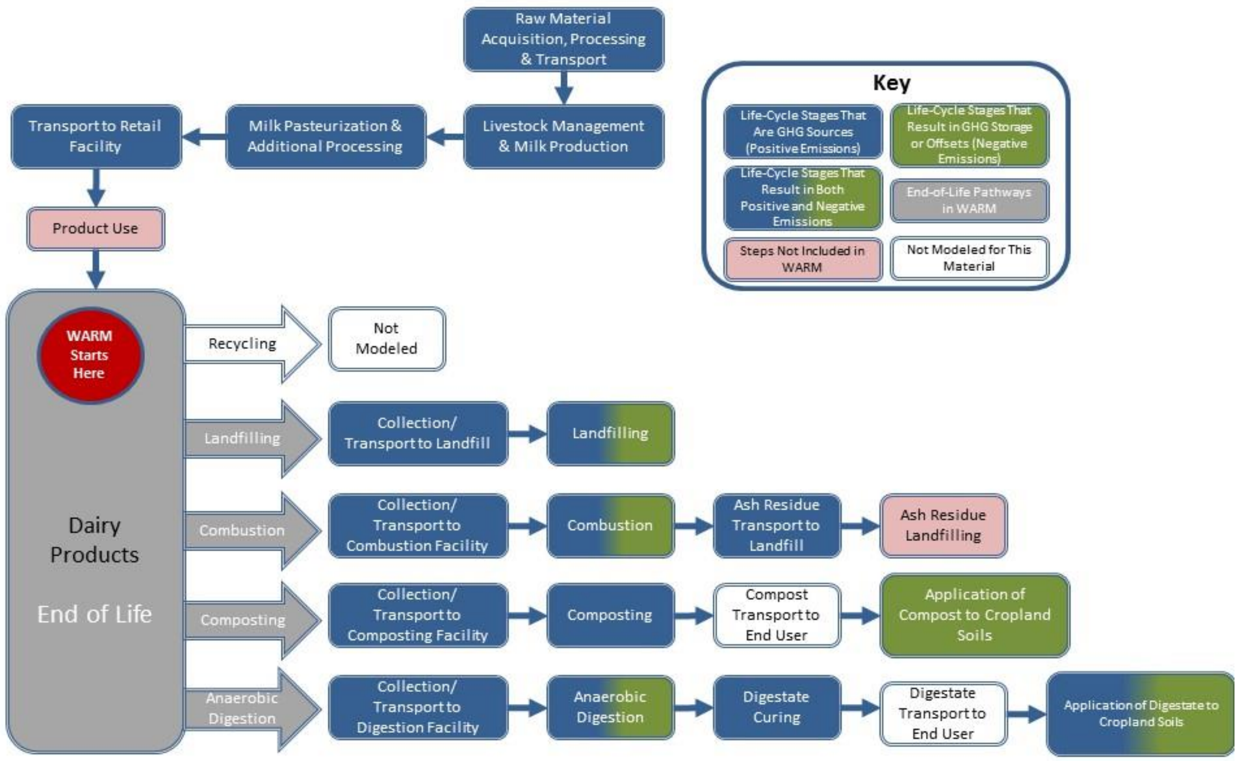


Exhibit 1-6: Life Cycle of Dairy Products in WARM



Food waste falls under the category of "organics" in WARM. Although paper, wood products and plastics are organic materials in the chemical sense, these categories of materials have very different life-cycle and end-of-life characteristics than food waste and are treated separately in the municipal solid waste (MSW) stream. Beef, poultry, grains, bread, fruits and vegetables, and dairy products include uneaten and prepared food from residences, commercial and non-commercial establishments, and industrial sources (USDA 2012b).

WARM also calculates emission factors for four mixed waste categories that include food waste. These mixed waste categories are provided to represent different types of common food wastes and to estimate emissions from a range of organic materials in wastes modeled by WARM users. Mixed food waste is also likely to include individual food waste components not currently modeled in WARM (e.g., meat types like pork). For more information on "proxies" that can be used to represent other food types not included in WARM, see the guidance document "Using WARM Emission Factors for Materials and Pathways Not in WARM." The mixed waste categories that include food waste are:

- "Food waste", which is a weighted average of the five main food type emission factors developed for WARM: beef, poultry, grains, fruits and vegetables, and dairy products.[2] The weighting is based on the relative shares of these five categories in the U.S. food waste stream, according to the U.S. Department of Agriculture (USDA) Economic Research Service (ERS) *Food Availability (per Capita) Data System - 2010,* and as shown in column (c) of Exhibit 1-7.
- "Food waste (meat only)", which is a weighted average of the two meat food type emission factors developed for WARM: beef and poultry. The weighting is based on the relative shares of

[2] Bread is an extension of the grains emission factor and represents wheat flour that is processed into bread; therefore, it is not included as a separate component in the weighted average food waste categories in WARM.

these two categories in the U.S. food waste stream according to USDA (2012b) and therefore not meant to be representative of emissions from other types of meat.

- "Food waste (non-meat)", which is a weighted average of the three non-meat food type emission factors developed for WARM: grains, fruits and vegetables, and dairy products. The weighting is based on the relative shares of these three categories in the U.S. food waste stream according to USDA (2012b).
- The "mixed organics category", which is a weighted average of the food waste and yard trimmings emission factors. The weighting is based on the relative shares of these two categories in the waste stream, according to the latest version of EPA's annual report, *Advancing Sustainable Materials Management: Facts and Figures*, and as shown in column (c) of Exhibit 1-8.[3] For the mixed organics category, WARM models the waste management pathways relevant to both food waste and yard trimmings (i.e., landfilling, combustion, anaerobic digestion and composting).

Exhibit 1-7: Relative Shares of Categories of Food Waste Modeled in WARM in the Waste Stream in 2010

(a) Material		(b) % of Total Food Waste Generation	(c) Weighted Percentage in WARM
Modeled in WARM	Beef	5.5%	9.3%
	Poultry	6.5%	11.0%
	Grains	7.8%	13.1%
	Fruits and Vegetables	29.3%	49.1%
	Dairy Products	10.3%	17.7%
	Total Modeled in WARM	*59.4%*	*100%*
Other Types	Other meats[a]	4.2%	NA
	Other poultry[b]	1.1%	
	Other grains	0.3%	
	Other fruits and vegetables	19.9%	
	Other dairy products	0.3%	
	Other foods[c]	14.8%	
All Foods	*Total*	*100%*	

[a] Includes veal, pork, and lamb.
[b] Includes turkey.
[c] Includes eggs, fish, shellfish, peanuts, tree nuts, coconut, caloric sweeteners, added fats and oils, and dairy fats.
Source: USDA 2012b.

Exhibit 1-8: Relative Shares of Yard Trimmings and Food Waste in the Waste Stream in 2013

(a) Material	(b) Generation (Short Tons)	(c) % of Total Organics Generation	(d) Recovery (Short Tons)	(e) Recovery Rate
Food Waste	37,060,000	52%	1,840,000	5.0%
Yard Trimmings	33,960,000	48%	20,600,000	60.2%

Source: EPA 2015b.

[3] Note that, unlike for other materials in WARM, the "food waste" and "mixed organics" categories are based on relative shares among materials *generated* rather than *recovered*. For food waste, this is because detailed data on the types of foods recovered in the United States are currently unavailable. For mixed organics, WARM assumes that users interested in composting would be dealing with a food waste and mixed organics category that is closer to the current rate of generation, rather than the current rate of recovery. Since the fraction of recovered food waste is so low, if the shares of yard trimmings and food waste recovered were used, the mixed organics factor would be essentially the same as the yard trimmings factor, rather than a mix of organic materials.

1.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The streamlined life-cycle GHG analysis in WARM focuses on the waste generation point, or the moment a material is discarded, as the reference point and only considers upstream GHG emissions when the production of new materials is affected by materials management decisions.[4] Recycling and source reduction are the two materials management options that impact the upstream production of materials, and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

As Exhibit 1-9 illustrates, all of the GHG sources relevant to food waste in this analysis fall under the raw materials acquisition and manufacturing and end-of-life sections of the life cycle. WARM does not include recycling as a management option for food waste, as food waste cannot be recycled in the traditional sense.

Exhibit 1-9: Food Waste GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Organics	GHG Sources and Sinks Relevant to Food Waste		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End of Life**
Source Reduction	**Offsets** • Transport of raw materials and products • Raw material acquisition • Production energy • Production process non-energy • Transport of food productions to retail	NA	NA
Recycling	Not applicable since food waste cannot be recycled		
Composting	NA	**Offsets** • Increase in soil carbon storage	**Emissions** • Transport to compost facility • Compost machinery
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Combustion-related nitrous oxide **Offsets** • Avoided utility emissions
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery • Landfill methane **Offsets** • Avoided utility emissions due to landfill gas combustion • Landfill carbon storage

[4] The analysis is streamlined in the sense that it examines GHG emissions only and is not a comprehensive environmental analysis of all emissions from materials management.

Materials Management Strategies for Organics	GHG Sources and Sinks Relevant to Food Waste		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Anaerobic Digestion	NA	**Offsets** • Increase in soil carbon storage from application of digestate to soils	**Emissions** • Transport to anaerobic digester • Equipment use and biogas leakage at anaerobic digester • CH_4 and N_2O emissions during digestate curing • N_2O emissions from land application of digestate **Offsets** • Avoided utility emissions due to biogas to energy Avoided synthetic fertilizer use due to land application of digestate

NA = Not applicable

WARM analyzes all of the GHG sources and sinks outlined in

Exhibit 1-9 to calculate net GHG emissions per short ton of food waste materials generated. GHG emissions arising from the consumer's use of any product are not considered in WARM's life-cycle boundaries. Exhibit 1-10 presents the net GHG emission factors for each materials management strategy calculated in WARM for food waste. Note that while a detailed analysis of food type-specific upstream GHG emissions has been conducted in WARM, EPA has not yet analyzed differences in GHG emissions by food type in the composting, combustion landfilling, and anaerobic digestion pathways. Therefore, the emission factors for those pathways are the same for each food waste type.

Additional discussion on the detailed methodology used to develop these emission factors may be found in Section 1.4.

Exhibit 1-10: Net Emissions for Food Waste and Mixed Organics under Each Materials Management Option (MTCO2E/Short Ton)

Material	Net Source Reduction Emissions	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions[a]
Food Waste	-3.66	NA	-0.18	-0.14	0.54	-0.05
Food Waste (non-meat)	-0.76	NA	-0.18	-0.14	0.54	-0.05
Food Waste (meat only)	-15.10	NA	-0.18	-0.14	0.54	-0.05
Beef	-30.05	NA	-0.18	-0.14	0.54	-0.05
Poultry	-2.47	NA	-0.18	-0.14	0.54	-0.05
Grains	-0.62	NA	-0.18	-0.14	0.54	-0.05
Bread	-0.67	NA	-0.18	-0.14	0.54	-0.05
Fruits and Vegetables	-0.44	NA	-0.18	-0.14	0.54	-0.05
Dairy Products	-1.74	NA	-0.18	-0.14	0.54	-0.05
Mixed Organics	NA	NA	-0.16	-0.16	0.20	-0.07

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
NA = Not applicable.
[a] Emission factors for dry digestion with curing of digestate before land application

1.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

For food waste, the GHG emissions associated with raw materials acquisition and manufacturing (RMAM) are (1) GHG emissions from energy used during the acquisition and food production processes, (2) GHG emissions from energy used to transport materials, (3) non-energy GHG emissions resulting from production processes, and (4) non-energy GHG emissions resulting from refrigerated transportation and storage. Process non-energy GHG emissions occur during the manufacture and application of agricultural fertilizers, from the management of livestock manure, and from enteric fermentation resulting from livestock. Transportation and storage non-energy emissions result from the fugitive emission of refrigerants.

The RMAM calculation in WARM also incorporates "retail transportation," which includes the average truck, rail, water, and other-modes transportation emissions required to transport food products from the production or processing facility to the retail/distribution point. Transportation emissions for the retail point to the consumer are not included. The energy and GHG emissions from retail transportation for each food waste type are presented in Section 1.4.1 describing the source reduction methodology for each food waste type.

EPA excluded emissions from food product packaging production, processing, and disposal from the food RMAM estimates because (1) food wastes and packaging wastes are frequently managed using different waste management pathways and (2) emission factors for many common packaging materials are already separately available in WARM.

The net emissions factors for source reduction of food waste include RMAM "upstream emissions" and are shown in the section on source reduction.

1.3.1 Beef

The emission factor for beef includes the energy and emissions associated with producing beef for retail sale, including the upstream impacts of producing livestock feed, cattle raising, enteric fermentation from cattle, and processing of the beef to prepare it for retail sale. In addition, the emission factor includes the energy and GHG emissions associated with the transport of beef products from production to retail sale. According to the USDA ERS loss-adjusted food availability data, beef constituted approximately 9 percent of food waste in 2010, as shown in Exhibit 1-7. Unlike some other food waste categories in WARM, the beef emission factor is a category solely represented by beef rather than a mix of individual food components, as shown in Exhibit 1-11.

Exhibit 1-11: Beef in the U.S. Food Waste Stream in 2010

Material Modeled in WARM	Loss Rate (Millions of pounds per year)	Percent of Category	Weighted Percentage in WARM
Beef	12,777	100%	100%

Source: USDA 2012b.

In order to develop national average estimates of the RMAM GHG emissions associated with production of beef, several key assumptions were made:

- Due to the large variety of potential products and coproducts from beef cattle (e.g., different beef cuts, inedible portions of the cattle, further-processed beef products) EPA has not separately modeled the impacts associated with the varied end-products derived from one animal. Instead, the EPA used LCI data in this analysis to estimate the energy and GHG emissions from a functional unit of one short ton of boneless, edible beef (Battagliese et al. 2013).
- EPA used LCI data for the production of conventional beef and did not model the production of organic beef or veal. The LCI data for the beef RMAM included on-farm data for a U.S. research farm combined with post-farm data aggregated across the U.S. beef industry. The on-farm data is assumed to be representative of farm production of cattle throughout the entire United States (Battagliese et al. 2013).

- EPA estimated energy use and GHG emissions for upstream grain production for cattle feed using data from Battagliese et al. (2013) rather than the grain production emission factor in WARM (See Section 1.3.3). This approach was used because LCI data did not allow for disaggregation of energy and emissions from feed production from the other RMAM inputs for beef.

1.3.2 Poultry

RMAM data for poultry include the upstream impacts of producing broiler chicken (i.e., domesticated chickens raised specifically for meat production) which represents 85.6 percent of poultry products in the U.S. waste stream according to the USDA ERS loss-adjusted food availability data from 2010, as shown in Exhibit 1-12. Turkey, the other component of poultry waste in the ERS loss-adjusted food availability data, was not included due to limitations acquiring RMAM data for its production and because it comprises a small share of the overall waste stream.

The poultry RMAM data includes the upstream energy and GHG emissions of all poultry production processes prior to retail storage and consumer use. For poultry, this includes three upstream stages: production of poultry feed, poultry production on a broiler farm (including energy use and emissions for milling feed and housing poultry), and poultry processing. Each stage accounts for transportation processes, from bringing feed ingredients to the broiler farm up to and including transportation of final broiler poultry products to retail. Transportation includes energy use and emissions from refrigeration.

Exhibit 1-12: Poultry in the U.S. Food Waste Stream in 2010

Material		Loss Rate (Millions of pounds per year)	Percent of Category	Weighted Percentage in WARM
Modeled in WARM	Chicken	15,134	85.6%	100%
Other Types	Turkey	2,545	14.4%	NA
All Poultry	*Total*	*17,680*	*100%*	

Source: USDA 2012b.

In order to develop national average estimates of the RMAM GHG emissions associated with production of poultry, several key assumptions were made:

- Due to the large variety of potential products and coproducts from broiler poultry (e.g., different poultry cuts, inedible portions of the chicken, further-processed poultry products) EPA has not separately modeled the impacts associated with the varied end-products derived from one animal. Instead, EPA used LCI data in this analysis to estimate the energy and GHG emissions from a functional unit of one short ton of processed broiler poultry.
- The mix of poultry feed inputs in the LCI data used by EPA included 2.5 percent poultry fat and 2.5 percent poultry by-product meal. Because WARM assumes that the functional unit consists of processed broiler poultry, EPA has not allocated upstream production emissions to poultry fat and by-product meal. This differs from the approach in the primary sources of LCI data used by EPA (Pelletier 2008, Pelletier 2010) but it allows a more consistent methodology with other food factors in WARM and most closely represents the poultry waste managed by WARM users.
- EPA used LCI data for the production of conventional poultry and did not model the production of organic poultry. The LCI data for the emission factor are representative of current, national average practices in the United States. The sources for the LCI data used by EPA (Pelletier 2008, Pelletier 2010) represent U.S. average figures using information from the U.S. poultry industry, academic studies, and peer-reviewed literature.

1.3.3 Grains and Bread

The emission factor for grains includes the upstream impacts of producing wheat flour, corn, and rice, which together constitute over 96 percent of grains in the U.S. waste stream. The USDA Economic Research Service (ERS) loss-adjusted food availability data from 2010 was used to determine the relative shares of various fruits and vegetables within the U.S. waste stream, as shown in Exhibit 1-13. Furthermore, the bread emission factor supplements the grain emission factor by including the additional energy used to manufacture wheat flour into bread, which is the predominant use for wheat flour (USDA 2012a). The other grain categories in the ERS loss-adjusted food availability data were not included either due to limitations acquiring RMAM data for their production and because they comprised such a small share of the overall waste stream. Furthermore, estimates of end-product manufacturing energy for corn and rice were not made due to lack of data availability.

Exhibit 1-13: Relative Shares of Grains in the U.S. Food Waste Stream in 2010

Material		Loss Rate (Millions of pounds per year)	Percent of Category	Weighted Percentage in WARM
Modeled in WARM	Wheat Flour	12,309	65.6%	68.3%
	Corn	3,025	16.1%	16.8%
	Rice	2,689	14.3%	14.9%
	Total Modeled in WARM	*18,023*	*96.1%*	*100%*
Other Types	Oats	609	3.2%	NA
	Other grains	130	0.7%	
All Grains	*Total*	*18,761*	*100%*	

Source: USDA 2012b.

In order to develop national average estimates of the RMAM GHG emissions associated with production of grains and bread, several key assumptions were made:

- EPA assumed that all grains modeled would be farmed in the United States using conventional (i.e., non-organic) farming practices. Production of winter wheat in Kansas, corn in Iowa and Illinois, and rice in Arkansas was assumed to be representative of national production due to those states' large share of domestic production for each respective grain.
- The LCI data for the production of grains were insufficient to characterize the full scope of energy and emissions associated with the production and processing of grains into a finished form. For this reason, the crop production data for all three grain products was supplemented with additional processing data for grain drying from the Ecoinvent database (Nemecek and Kagi, 2007). As the majority of wheat products use wheat flour, the wheat LCI data was further supplemented with the energy demand associated with wheat milling (Espinoza-Orias 2011).
- The grains emission factor includes milling of wheat into flour but assumes that wheat flour, corn, and rice can be purchased as dried grains without further processing or cooking. The bread emission factor assumes baking of wheat flour into bread. The emission factor for grains may understate the upstream emissions associated with corn and rice products that have undergone further processing.

1.3.4 Fruits and Vegetables

The broad category of fruits and vegetables includes a wide variety of cultivars produced worldwide, all with widely varying inputs, processing stages, and transportation distances. The fruit and vegetable energy and emission factors consist of a weighted average mix of materials that reflects the relative contribution of different fruits and vegetables to the total U.S. waste stream. The USDA Economic Research Service (ERS) loss-adjusted food availability data from 2010 was used to determine the relative shares of various fruits and vegetables within the U.S. waste stream, as shown below in

Exhibit 1-14. The ERS loss-adjusted food availability data include several more food categories than were included in the final emission factor; however, these were not included either due to limitations acquiring RMAM data for their production, or because they comprised such a small share of the overall waste stream. The remaining fruits and vegetables included within the emission factor together comprise 59.6 percent of the fruits and vegetables discarded within the United States in 2010, totaling nearly 68 million pounds annually.

Exhibit 1-14: Relative Shares of Fruits and Vegetables in the U.S. Food Waste Stream in 2010

Material		**Loss Rate (Millions of pounds per year)**	**Percent of Category**	**Weighted Percentage in WARM**
Modeled in WARM	Potatoes	18,294	16.4%	27.5%
	Tomatoes	18,650	16.1%	27.0%
	Citrus	14,200	12.5%	21.0%
	Melons	6,313	5.6%	9.3%
	Apples	5,575	4.9%	8.2%
	Bananas	4,705	4.1%	6.9%
	Total Modeled in WARM	*67,737*	*59.6%*	*100%*
Other Types	Other vegetables	16,815	14.8%	NA
	Other non-citrus fruit	10,428	9.2%	
	Corn	5,723	5.0%	
	Lettuce, spinach, and other greens	5,219	4.6%	
	Onions	4,116	3.6%	
	Legumes	2,005	1.8%	
	Berries	1,667	1.5%	
All Fruits and Vegetables	*Total*	*113,734*	*100%*	

Source: USDA 2012b.

In order to develop national average estimates of the RMAM GHG emissions associated with production of fruits and vegetables, several key assumptions were made:

- EPA assumed that all of the fruits and vegetables modeled would be farmed in the United States, with the exception of bananas, using conventional (i.e., non-organic) farming practices. Foreign-grown bananas were included within this assessment because they are one of the largest sources of fruit and vegetable waste within the U.S. waste stream. They were assumed to be produced in Central America using conventional farming practices due to the lack of suitable climate for their cultivation on a large scale within the United States.
- The differences in production impacts across different breeds of fruits and vegetables were not considered in the analysis. For example, energy and emissions associated with the production of Fuji apples were assumed to be representative of all apple production in the United States. Likewise, RMAM data for the farming of oranges was assumed to be representative of all citrus production due to lack of data for production of other citrus fruits and food consumption data showing that oranges comprise 65 percent of citrus fruits consumed in the United States in 2012 (Boriss, 2013).
- Because all of the components included in the fruits and vegetable factors can be consumed as fresh fruits and vegetables and due to the lack of data on fruit and vegetable processing, EPA has assumed that all fruits and vegetables enter the waste stream as fresh fruits and vegetables. Processed fruits and vegetables are likely to have a longer shelf life and therefore may comprise a smaller share of the food waste stream than fresh fruits and vegetables. As a result, the source reduction factors for fruits and vegetables exclude any potential impacts from freezing, canning,

pickling, or other processing steps. However, the fruits and vegetable factors should be considered an acceptable proxy for processed fruits and vegetable products.

1.3.5 Dairy Products

The production of dairy products includes the production of upstream animal feed for livestock, livestock handling, and the processing of milk into other dairy products. Dairy products within the U.S. waste stream include multiple varieties of milk, cheese, yogurt and frozen products. The weighted emission factor for dairy products in WARM includes 97 percent of the dairy products in the waste stream, as illustrated in Exhibit 1-15. The remaining products were not included due to both data limitations and because they constituted such a small share of dairy food waste.

Exhibit 1-15: Relative Shares of Dairy Products in the U.S. Food Waste Stream in 2010

Material		Per Capita Loss Rate (Lbs/Year)	Percent of Category	Weighted Percentage in WARM
Modeled in WARM	1% Milk	6.96	8.8%	9.0%
	2% Milk	17.83	22.5%	23.2%
	Skim Milk	7.93	10.0%	10.3%
	Whole Milk	13.69	17.3%	17.8%
	Ice Cream and Frozen Dairy	7.18	9.1%	9.3%
	Non-Fat and Dry Milk	1.55	2.0%	2.0%
	Generic Milk	8.45	10.7%	11.0%
	Cheddar	4.73	6.0%	6.1%
	Mozzarella	4.53	5.7%	5.9%
	Yogurt	4.12	5.2%	5.4%
	Total Modeled in WARM	*76.97*	*97.3%*	*100%*
Other Types	Evaporated Condensed Milk	1.77	2.3%	NA
	Eggnog	0.41	0.5%	
All Dairy	*Total*	*79.1*	*100%*	

Source: USDA 2012b.

In order to develop national average estimates of the RMAM GHG emissions associated with production of dairy products, several key assumptions were made:

- EPA used a regional average of milk production from five regions to model “generic milk” as a stand-in for specialty products such as chocolate milk and buttermilk. Similarly, unflavored “ice cream” is assumed to be representative of a variety of flavors in the marketplace.
- EPA used fruit yogurt as a proxy for general yogurt production, as it was the only variant of yogurt available within the dairy products production dataset, whereas ice cream served as a proxy for all frozen dairy products.
- “Cheddar” and “mozzarella” cheeses were assumed to be representative of the entire cheese production process due to their high share of the waste stream.
- GHG emissions for the production of grains used as cattle feed are based on data specific to dairy production and therefore do not use the same data sources used to develop the grains and bread emission factors in WARM.

1.4 MATERIALS MANAGEMENT METHODOLOGIES

Source reduction, landfilling, composting, combustion, and anaerobic digestion are five management options used to manage food waste.

1.4.1 Source reduction

When a material is source reduced (i.e., less of the material is made), GHG emissions associated with making the material and managing the post-consumer waste are avoided. As discussed above, under the measurement convention used in this analysis, source reduction for food waste has negative RMAM GHG emissions (i.e., it avoids emissions attributable to production) and zero end-of-life management GHG emissions. For more information, please refer to the Source Reduction chapter.

Exhibit 1-16 presents the inputs to the source reduction emission factor for production of each food waste type included in WARM. Beef has the lowest net emission factor, implying greatest emissions savings due to source reduction, owing to the large amount of emissions released during RMAM of beef.

Exhibit 1-16: Source Reduction Emission Factors for Food Waste ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Sequestration for Current Mix of Inputs	Forest Carbon Sequestration for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Food Waste	-3.66	-3.66	NA	NA	-3.66	-3.66
Food Waste (non-meat)	-0.76	-0.76	NA	NA	-0.76	-0.76
Food Waste (meat only)	-15.10	-15.10	NA	NA	-15.10	-15.10
Beef	-30.05	-30.05	NA	NA	-30.05	-30.05
Poultry	-2.47	-2.47	NA	NA	-2.47	-2.47
Grains	-0.62	-0.62	NA	NA	-0.62	-0.62
Bread	-0.67	-0.67	NA	NA	-0.67	-0.67
Fruits and Vegetables	-0.44	-0.44	NA	NA	-0.44	-0.44
Dairy Products	-1.74	-1.74	NA	NA	-1.74	-1.74

NA = Not applicable.
Notes: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
All food waste materials are assumed to be produced using 100% virgin inputs. Consequently, the source reduction benefits of both the "current mix of inputs" and "100% virgin inputs" are the same.

Post-consumer emissions are the emissions associated with materials management pathways that could occur at end of life. When source reducing food waste, there are no post-consumer emissions because production of the material is avoided in the first place, and the avoided food never becomes post-consumer. Forest carbon storage is not applicable to food waste, and thus does not contribute to the source reduction emission factor.

1.4.1.1 Developing the Emission Factor for Source Reduction of Beef

To produce beef, energy is directly used for livestock management, beef processing, and retail transport. Additionally, during the RMAM phase of the product life-cycle, upstream energy is used to produce cattle feed and other raw material inputs. In general, the majority of the energy for the production of these materials is derived from fossil fuels, either through the electricity grid or during on-site combustion of fuel during the farming process. Combustion of fossil fuels results primarily in CO_2 emissions, with small amounts of N_2O also emitted. Producing beef also results in process non-energy emissions of CO_2, CH_4 and N_2O, as described below. These process non-energy emissions primarily come from enteric fermentation by cattle, as well as the upstream impacts of fertilizer production and application to produce the grains fed to cattle. Exhibit 1-17 shows the results for each component and the total GHG emission factors for source reduction of beef.

Exhibit 1-17: Raw Material Acquisition and Manufacturing Emission Factor for Production of Beef ($MTCO_2E$/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e = b + c + d) Net Emissions
Beef	3.85	0.12	26.09	30.05

Beef production. The data for beef production used for developing the beef emission factor was provided by the National Cattlemen's Beef Association (NCBA), an industry group. The data used in WARM were derived from the same data used to produce a 2013 study prepared for NCBA by BASF Corporation, "More Sustainable Beef Optimization Project: Phase 1 Final Report" (Battagliese et al. 2013). The study provides a cradle-to-grave assessment of beef production in 2007 and 2011 and measures the environmental impacts and consumer benefits of beef products in multiple categories, including GHG emissions.

To align the data in Battagliese et al. (2013) with the scope of the source reduction emission factors in WARM, EPA separated the cumulative upstream energy demand and process non-energy emissions from beef production from energy and emissions that are outside the scope of source reduction emission factors in WARM (i.e., retail storage, consumer transport, and retail packaging). The sorted data set included the upstream cumulative energy demand by energy source and the aggregated process non-energy emissions sorted by gas. In the study, some impacts of beef production were allocated to by-products on an economic basis based on their value relative to the beef produced in the value chain. The by-products allocated economically include products from both feed and beef production, such as dried distillers' grains, beef tallow, and offal.

EPA calculated the emissions associated with beef production in two separate stages: first, process energy emissions were calculated by determining the cumulative energy demand for producing one short ton of beef. Secondly, process non-energy emissions from producing one short ton of beef were estimated separately and added to the process energy emissions. Initially, the energy (in units of million Btu) for beef production was sorted between renewable bio-energy embedded in crops and demand for energy from fossil fuel combustion and the electricity grid. GHG emissions from bio-energy are treated as biogenic emissions that do not contribute to the GHG emission factor. The energy and electricity demand estimated in the data from the Battagliese et al. (2013) report factored in both efficiency losses in the grid and upstream conversion losses from energy extraction. The process energy used to produce beef and the resulting emissions are shown in Exhibit 1-18. The beef source reduction factor is meant to model all beef waste that occurs during consumers use, including losses during preparation and inedible portions.

Exhibit 1-18: Process Energy GHG Emissions Calculations for Production of Beef

Material	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Beef	62.25	3.85

The process non-energy emissions from beef production are dominated by CH_4 and N_2O emissions primarily resulting from enteric fermentation and fertilizer use for feed production, respectively. Methane comprises approximately 63 percent of non-energy GHG emissions from beef production, whereas N_2O comprises 37 percent. Collectively, the process non-energy emissions exceed the process energy emissions associated with beef production. Exhibit 1-19 shows the components for estimating process non-energy GHG emissions for beef.

Exhibit 1-19: Process Non-Energy GHG Emissions Calculations for Production of Beef

Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Beef	<0.01	0.66	–	–	0.03	26.09

– = Zero emissions.

Retail Transport. The retail transport data for beef products was taken from the same dataset as the upstream production cumulative energy demand and process non-energy emissions (Battagliese et al. 2013). The energy demand from transportation, which was not disaggregated from the mix of fuels used for other process emissions, was assumed to be derived primarily from diesel fuel consumption during retail transport. This energy demand was scaled by a carbon coefficient for diesel combustion to estimate the retail transportation GHG emissions.

1.4.1.2 Developing the Emission Factor for Source Reduction of Poultry

To produce poultry, energy is directly used on-site at poultry farms, for poultry processing, and for retail transport. During the RMAM phase of the products' life-cycle, upstream energy is used to produce poultry feed. In general, the majority of the energy for the production of these materials is derived from fossil fuels, either through the electricity grid or via on-site combustion of fuel during the farming process. Combustion of fossil fuels results primarily in emissions of CO_2, as well as small amounts of N_2O. Additionally, poultry production results in process non-energy emissions of CO_2, CH_4 and N_2O, as described below. These process non-energy emissions primarily come from on-farm gaseous emissions by poultry, as well as the upstream impacts of fertilizer production and application in growing poultry feed inputs.

To represent poultry source reduction in WARM, EPA used a functional unit of one short ton of processed broiler poultry.[5] Processed broiler poultry refers to the broiler after it has gone through initial processing to remove trimmings[6] from the bird, leaving the bones and meat that are transported to retail and purchased by consumers. Exhibit 1-20 shows the results for each component and the total GHG emission factors for source reduction of poultry.

Exhibit 1-20: Raw Material Acquisition and Manufacturing Emission Factor for Production of Poultry ($MTCO_2E$/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e = b + c + d) Net Emissions
Poultry	1.34	0.27	0.87	2.47

EPA developed the energy and emission factors suitable for inclusion in WARM using the LCI data available from Pelletier (2008, 2010). First, energy and non-energy input assumptions, material processing assumptions, and LCI data were extracted for each source of energy use and GHG emissions. These sources were then assessed to identify gaps within Pelletier (2008, 2010) that were either outside of the scope of the studies but within the scope of WARM, or where assumptions and results were not

[5] Alternative functional units considered by EPA included one short ton of live weight broiler poultry (before processing) and one short ton of boneless broiler poultry meat. The functional unit of one short ton of processed boiler poultry was used because it is consistent with other food factors in WARM and most closely represents the waste generated from end-use of poultry products.

[6] Trimmings consist of poultry processing wastes, such as offal, blood, and feathers. When these waste products are separated from the broiler, they are processed into poultry fat and poultry by-product meal (BPM) that is used for animal feed, as described in Pelletier (2008, 2010).

provided in enough detail to be sufficiently modeled in WARM without supplementary data. EPA separated the raw data from broiler poultry production into three stages: production of poultry feed, poultry production on a broiler farm, and poultry processing. Inputs at each stage were separated into categories for energy-related inputs (i.e., fuel and electricity) and non-energy related inputs (e.g., materials). Process conversion assumptions—such as the share of each type of feed going into an average metric ton of poultry feed, or the conversion rate to turn poultry feed into live weight broiler poultry—were extracted from the scientific literature and used to develop unit process descriptions at each stage (Pelletier 2008, 2010).

Where data were not available in Pelletier (2008, 2010) to ensure consistency with WARM's life-cycle boundaries, EPA supplemented the LCI data from Pelletier (2008, 2010) with the following data sources:

- Corn production energy use and emissions from existing corn energy and emission factors in WARM, developed from data available in the U.S. Department of Agriculture (USDA) LCA Digital Commons database.[7]
- Fertilizer production energy use and emissions for corn, soy, and synthetic fertilizer offset by poultry litter (Ecoinvent Centre 2007).
- Transportation modes and distances of material inputs for soy production (Ecoinvent Centre 2007).
- Lime and salt production energy use, GHG emissions, and the transportation modes and distances of inputs raw material inputs (Ecoinvent Centre 2007).
- Transportation modes and distances to processing and retail from the Bureau of Transportation Statistics (BTS) Commodity Flow Survey (BTS 2013).
- The share of live-weight broiler poultry that is diverted to waste products (Ockerman 2000).
- Fuel carbon coefficients from the U.S. Greenhouse Gas Inventory (EPA 2014).

EPA used the LCI data obtained from the LCA Digital Commons database, the Swiss Ecoinvent version 2 database, and the BTS Commodity Flow Survey to estimate energy demand and GHG emissions associated with poultry production.

In order to convert embedded emissions from poultry feed into live weight broiler poultry, EPA used a conversion factor of 1.9 kilogram of poultry feed per kilogram of live weight broiler produced (Pelletier 2008). Exhibit 1-21 shows the mix of poultry feed inputs as modeled in WARM based on assumptions in Pelletier (2008, 2010).

Exhibit 1-21: Mix of Poultry Feed Inputs Assumed for Source Reduction Factor (%)

Corn	Soy	Fishmeal	Chicken Fat	Chicken By-Product Meal	Salt and Limestone
70%	20%	2.5%	2.5%	2.5%	2.5%

Corn was assumed to make up 70 percent of poultry feed. Since corn production is already included in WARM as part of the source reduction factor for grains, EPA used process energy emissions

[7] Where possible, EPA has also been consistent with other food factors in WARM. For instance, corn is assumed to make up a 70 percent of poultry feed. Since EPA had already estimated upstream production emissions for corn during the development of the grain source reduction factor in WARM, the corn LCI data used in the grains factor was incorporated into the poultry factor.

assumptions from on-farm corn production for consistency. See Section 1.4.1.3 for a detailed description on development of emissions estimates for corn production. Soy production was assumed to make up 20 percent of poultry feed. EPA calculated process energy emissions from soy production based on the fuel input mix provided in Pelletier (2010), including petrol, diesel, liquid petroleum gas (LPG), and grid electricity. To estimate the energy emissions associated with producing fertilizers used to produce soy, EPA calculated the cumulative energy demand required to produce the mix of fertilizers needed to grow one kilogram of soybeans based on data available in the Ecoinvent database (Ecoinvent Centre 2007). EPA then determined the share that each fuel type contributed to total energy demand. Each energy source's contribution to the total energy demand was then multiplied by the fuel-specific carbon coefficients used in WARM to determine the total process energy emissions associated with the production of fertilizers used in soy production.

Poultry feed was assumed to consist of 2.5 percent fishmeal and 2.5 percent salt and limestone (Pelletier 2010). Total energy use and greenhouse gas emissions per kilogram of fishmeal were obtained from Pelletier (2010). To estimate a fuel breakdown for energy use, EPA assumed that the mix of fuel inputs into fishmeal was the same as for the other broiler poultry feed inputs due to the similar feed ingredients used in producing both fishmeal and poultry—including poultry waste by-product feed, fishmeal, corn, and soy (Pelletier 2010). For salt and limestone, energy use and GHG emissions are based on data sets from the Ecoinvent version 2 database (Ecoinvent Centre 2007). Although the datasets are representative of European production, EPA used data sets that had been converted using U.S. electricity grid mix assumptions that provide a more representative accounting of energy use and GHG emissions in the United States.

Poultry feed was assumed to consist of 2.5 percent poultry fat and 2.5 percent poultry by-product meal (BPM) (Pelletier 2010). EPA chose not to allocate energy use or GHG emissions to the poultry fat or BPM removed at the processing stage. In doing so, EPA's approach allocates all energy use and emissions from producing live weight broiler poultry to poultry meat and bone products. EPA chose this approach because it reflects the type of poultry products likely to enter the municipal solid waste stream[8], the remaining trimmings are a waste product that would not have been produced otherwise, and because poultry fat and BPM is recirculated back into poultry feed as a closed loop. Waste products account for 28 percent of live-weight broiler poultry, while the remaining share is poultry meat and bone (Ockerman 2000). Since EPA's approach did not allocate any emissions to poultry fat or BPM, emissions from the production of these inputs were already included in the source reduction factor and only the additional energy from processing poultry fat and BPM into poultry feed was added to the source reduction factor.

Some energy and GHG emissions are avoided when poultry litter is applied as a fertilizer, offsetting the use of synthetic fertilizers. Pelletier (2008, 2010) provided estimates of the amount of synthetic fertilizers that are avoided through application of poultry litter.[9] Using a similar approach as used for fertilizers for soy production, EPA determined the cumulative energy demand and mix of fuels for the production of synthetic fertilizers avoided by application of poultry litter using data available in the Ecoinvent database (Ecoinvent Centre 2007). Avoided emissions were calculated as described for soy fertilizers by applying fuel-specific carbon coefficients. The total process energy used to produce poultry and the resulting emissions are shown in Exhibit 1-22.

[8] Compared to other meat products, poultry bones are more likely to be included in products available to consumers and therefore enter the municipal solid waste stream. Therefore, poultry bones are included in the functional unit used in WARM.
[9] Avoided synthetic fertilizers are provided in kilograms of active ingredients nitrogen (30 kg), phosphorous (30 kg), and potassium (20 kg) avoided per metric ton of poultry litter.

Exhibit 1-22: Process Energy GHG Emissions Calculations for Production of Poultry

Material	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Poultry	22.80	1.34

Process non-energy emissions were estimated by EPA for production and application of fertilizers used in poultry feed production, emissions from poultry litter application as a fertilizer, and emissions avoided by replacing synthetic fertilizers with poultry litter. Non-energy emissions from poultry production are generated from fertilizer production—which includes a variety of chemical processes that release non-fossil fuel carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) into the atmosphere—and N_2O emissions from the application of synthetic fertilizer and poultry litter to soils. To capture these emissions, EPA isolated the portion of energy-related GHG emissions and subtracted this from total GHG emissions from fertilizer production, leaving only process non-energy emissions.

To estimate emissions from the application of fertilizer, to agricultural soils, EPA followed IPCC (2006b) guidelines using the active ingredients given from Pelletier (2008). EPA used process non-energy emissions assumptions from on-farm corn production for consistency; see Section 1.4.1.3 for a detailed description on development of emissions estimates for corn production. To estimate process non-energy emissions from soy production, EPA calculated the emissions from the application of the nitrogen-based fertilizer to agricultural soils using IPCC 2006 guidelines (IPCC 2006b). To estimate process non-energy emissions from the application of poultry litter and the avoided non-energy emissions from the resulting displaced fertilizer, EPA's methodology followed IPCC (2006b) guidelines, and applied assumptions on the nitrogen content and the percent of nitrogen emitted from fertilizer application obtained from Pelletier (2008).

Exhibit 1-23: Process Non-Energy Emissions Calculations for Production of Poultry

Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Poultry	0.05	<0.01	–	–	<0.01	0.86

– = Zero emissions.

Retail Transport. For this analysis, distribution of poultry products to their final point of sale was assumed to have two components: the energy and GHG emissions associated with diesel consumed during vehicle operation and the GHG impact of fugitive refrigerants emitted from refrigerated vehicles. Fugitive emissions of refrigerants consisted of a mix of 1,1,1,2-Tetrafluoroethane (R-134a), Chlorodifluoromethane (HCFC-22), Monochloropentafluoroethane (R-155), and 1,1-Difluoroethane (HFC-152a). Due to lack of data for poultry-specific transportation, the fugitive emissions associated with refrigerated vehicle transport were assumed to be the same as for refrigerated dairy delivery via a medium-sized truck (Thoma et al. 2010). In the Thoma et al. 2010 study, estimates of fugitive emissions of refrigerants during the transport phase were estimated via a sales-based approach, which equated purchases of refrigerants for the truck fleet to fugitive refrigerants released via leakage.

EPA estimated the retail transport ton-miles per shipment of poultry based on the Bureau of Transportation Statistics (BTS) 2012 Commodity Flow Survey (BTS 2013). The process energy and non-energy emissions for the transportation of poultry to retail are shown in Exhibit 1-24 and Exhibit 1-25, respectively.

Exhibit 1-24: Process Energy GHG Emissions Calculations for Transportation of Poultry

Material	Transportation Energy per Short Ton (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Poultry	3.68	0.26

Exhibit 1-25: Non-Energy Emissions Calculations for Transportation of Poultry

Material	CO_2 Emissions (MT/Short Ton)[a]	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Poultry	0.01	–	–	–	0.00	0.01

– = Zero emissions.

[a] The estimate of non-energy CO_2 emissions includes a mixture of various refrigerants, predominantly HFC 143a, HFC 134a, HFC-125, and HCFC-22, released during refrigerated transport.

1.4.1.3 Developing the Emission Factor for Source Reduction of Grains and Bread

To produce both grains and bread, energy is used during the RMAM phase of the products' life cycles. In general, the majority of the energy for the production of these materials is derived from fossil fuels, either through the electricity grid or during on-site combustion of fuel during the farming process. Combustion of fossil fuels results primarily in emissions of CO_2, as well as small amounts of N_2O. Additionally, producing grains results in process non-energy emissions of CO_2, CH_4 and N_2O, as described below. The production of winter wheat, corn and rice all require different material and energy inputs, and a weighted average of the three grain types was used to create a single emission factor for grains. The upstream energy and emissions for wheat flour were combined with the energy used to prepare bread to develop a second emission factor for bread. Exhibit 1-26 shows the results for each component and the total GHG emission factors for source reduction of both grains and wheat-based bread.

Exhibit 1-26: Raw Material Acquisition and Manufacturing Emission Factor for Production of Grains and Bread ($MTCO_2E$/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Grains	0.31	0.02	0.28	0.62
Bread	0.35	0.01	0.30	0.67

To calculate the production emissions, EPA obtained life-cycle inventory (LCI) data for the three grain products—wheat, corn, and rice—available in the USDA National Agricultural Library's LCA Digital Commons database. The Digital Commons database is intended to provide LCI data for use in life-cycle assessment (LCA) of food, biofuels, and a variety of other biological products. Primary unit process input and output data have been developed by researchers at the University of Washington Design for Environment Laboratory under the direction of Dr. Joyce Cooper using USDA National Agricultural Statistics Service and ERS datasets. Data on bread production was derived from Espinoza-Orias et al. 2011, which contained data characterizing the energy use associated with producing both white bread and wholemeal bread.

The LCI data from the Digital Commons datasets only provide material inputs, outputs and, processes in units of magnitude per unit of agricultural product produced without any estimates of the energy or GHG impacts associated with production. For example, the LCI data include estimates of the amount of fertilizers needed for grain production but do not include data on the energy needed for fertilizer production or the direct GHG emissions from fertilizer application. In order to translate these values into the actual energy demand and emissions associated with agricultural production, EPA identified matching unit processes and corresponding LCI data for those materials and processes within the life-cycle software, SimaPro. The unit processes within the database are taken from the Swiss Ecoinvent version 2 database and the U.S. LCI Database.

Grains. Several steps were needed to develop energy and emission factors suitable for inclusion in WARM using the LCI data available from the Digital Commons and other secondary sources. Translating the upstream LCI data provided by Digital Commons into the SimaPro format required linking materials and processes in the LCI dataset to existing Ecoinvent or U.S. LCI Database upstream processes within the software, albeit at the risk of increasing uncertainty. In the process of matching material and process flows from the Digital Commons LCI files to unit processes in SimaPro, the magnitude of each process or material contribution (e.g., the amount of combine harvesting needed to produce 1 short ton of wheat) from the LCI dataset was preserved. At the end of this stage, each year of grain data included a unit process output (1 short ton of grains) and a series of linked material inputs and processes, each with their respective GHG emissions and energy demands contributing to the total impact of producing that unit of grain.

The emissions were calculated in two separate stages: first, energy-derived emissions were calculated by determining the cumulative energy demand for producing one short ton of each grain. Secondly, non-energy emissions were estimated and added to the fossil fuel-derived emissions.

To estimate the energy-derived emissions, EPA calculated the cumulative energy demand for each dataset within SimaPro through an energy demand impact assessment method in the software. This method calculated the total life-cycle energy in million Btu required to produce one unit of grain and then separated the total into several categories, including: petroleum, nuclear power, biomass, natural gas, coal, and renewables. Each energy source's contribution to the total energy demand was then multiplied by the fuel-specific carbon coefficients used in WARM for all materials to determine the total energy-derived emissions associated with the production of one unit of grain. For wheat, additional energy demand from milling was included due to the fact that over 90 percent of wheat grain used for food is converted to flour prior to use (USDA 2012a). The estimate for milling energy expenditure was taken from Espinoza-Orias 2011 and was assumed to be taken from the national average electricity grid. The process energy used to produce the each individual grain product, the weighted average of grains and the resulting emissions are shown in Exhibit 1-27.

Exhibit 1-27: Process Energy GHG Emissions Calculations for Production of Grains

Material	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Wheat Flour	4.02	0.23
Corn	6.98	0.41
Rice	9.66	0.58
Grains	5.35	0.31

The non-energy emissions came from two components of the grains' life cycle: fertilizer production and fertilizer application. Fertilizer production includes a variety of chemical processes that release non-fossil fuel CO_2, CH_4, and N_2O into the atmosphere. To capture these emissions, EPA ran an impact assessment method within SimaPro on the grains' upstream processes that only considered non-fossil emissions of these gases to isolate the process emissions from fertilizer production.

To estimate the GHG emissions associated with fertilizer application, EPA assessed the total amount of nitrogen fertilizer applied to each grain, and then used stoichiometry to identify the share of nitrogen applied in each dataset. From there, EPA utilized the IPCC Tier 1 method for managed soils to calculate the total amount of N_2O and CO_2 released from fertilizer application, run-off, volatilization, and leaching (IPCC 2006b). The IPCC Tier 1 approach was chosen to maintain consistency with other agricultural LCAs and the International EPD System's Product Category Rules (PCR) for arable crops (International EPD System 2013). Exhibit 1-28 shows the components for estimating process non-energy GHG emissions for each type of grain and the weighted average.

Exhibit 1-28: Process Non-Energy Emissions Calculations for Production of Grains

Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Wheat Flour	0.04	<0.01	–	–	<0.01	0.30
Corn	0.03	<0.01	–	–	<0.01	0.18
Rice	0.04	<0.01	–	–	<0.01	0.31
Grains	0.04	<0.01	–	–	<0.01	0.28

– = Zero emissions.

The Digital Commons LCI data assumes that the production of each of the three grains included in WARM leads to the production of one or more co-products. These co-products include corn silage, corn stover, wheat straw, and rice straw. In keeping with ISO 14044 standards, EPA allocated impacts to co-products in proportion to the economic value of the products. Using data from the USDA ERS Commodity Costs and Returns database, EPA determined the economic value per acre of production for corn, corn silage, rice, wheat, and wheat straw for each of the LCI data years (USDA 2013). This provided enough data to determine economic allocation percentages for wheat and wheat straw. Supplementary data from a 2009 study by van der Voet et al. provided prices for corn stover, allowing EPA to estimate the allocation percentages for corn, corn silage, and corn stover. However, EPA was unable to find a reliable source for the economic value of rice straw. An anecdotal article cited rice straw's value at approximately $10 to $20 per acre, which would translate to allocation of 1 to 3 percent of rice production energy and emissions to rice straw (Smith 2004).

Bread. Bread production was estimated by taking an estimate of bread production energy intensity from Espinoza-Orias et al. 2011, which contained LCI data characterizing the energy use associated with producing bread. For the purposes of this analysis, white bread was chosen as it is more common than wheat bread. The study found that wheat milling and baking, respectively, had energy demands of 0.059 kWh and 0.600 kWh per loaf of bread, which was assumed to be 0.8 kg. This equated to 2.55 million Btu of cumulative energy demand to prepare one ton of bread, of which the entirety was assumed to be taken from the national average electricity grid. To estimate the total farm-to-retail energy associated with bread, EPA summed the bread production energy emissions with those for wheat flour, but did not include corn or rice. Corn and rice were excluded from this process because the energy use data for milling and baking were based on wheat bread production and because wheat-based bread is the predominant bread category in the United States (USDA 2012a). The process energy used to produce bread and the resulting emissions are shown in Exhibit 1-29.

Exhibit 1-29: Process Energy GHG Emissions Calculations for Production of Bread

Material	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Wheat Flour	4.02	0.23
Bread Baking	2.32	0.12
Bread	6.34	0.35

Retail Transport: Retail transport energy and emissions for both bread and grains were estimated with the Bureau of Transportation Statistics 2012 Commodity Flow Survey, consistent with other materials in WARM, and are equal across the three types of grains. The average miles traveled to retail per shipment are derived from the study and converted into transportation energy, which then is used to estimate GHG emissions from retail transport. The calculations for estimating the transportation energy emission factor for grains and bread are shown in Exhibit 1-30.

Exhibit 1-30: Transportation Energy Emissions Calculations for Production of Bread and Grains

Material	Average Miles per Shipment	Retail Transportation Energy (Million Btu per Short Ton of Product)	Retail Transportation Emission Factors ($MTCO_2E$ per Short Ton of Product)
Grains	265	0.29	0.02
Bread	169	0.18	0.01

Source: BTS 2013.

1.4.1.4 Developing the Emission Factor for Source Reduction of Fruits and Vegetables

To produce fruit and vegetable products, energy is used both in the acquisition of raw materials and in the food production process itself. In general, the majority of energy used for these activities is derived from fossil fuels. Combustion of fossil fuels results in emissions of CO_2. In addition, producing and transporting fruits and vegetables also results in process non-energy emissions of CH_4, N_2O, and refrigerants, as described in detail below. Hence, the RMAM component of the fruits and vegetables source reduction emission factor consists of process energy, process non-energy emissions in the acquisition of raw materials, process non-energy emissions in the transport of fruits and vegetables to retail, and non-energy emissions during transport.

Exhibit 1-31 shows the results for each component and the total GHG emission factors for source reduction of fruits and vegetables. The process energy used to produce the each individual fruit and vegetable, the weighted average for the fruits and vegetables category, and the resulting emissions are shown in Exhibit 1-32. Finally, Exhibit 1-33 shows the components for estimating process non-energy GHG emissions for each type of grain and the weighted average. The methodology used to calculated these emissions estimates is described below.

Exhibit 1-31: Raw Material Acquisition and Manufacturing Emission Factor for Production of Fruits and Vegetables ($MTCO_2E$/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e = b + c + d) Net Emissions
Fruits and Vegetables	0.20	0.17	0.07	0.44

Exhibit 1-32: Process Energy GHG Emissions Calculations for Production of Fruits and Vegetables

Material	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Potatoes	1.73	0.10
Tomatoes	3.77	0.25
Citrus	4.60	0.31
Melons	1.80	0.12
Apples	4.58	0.30
Bananas	2.45	0.14
Fruits and Vegetables (weighted average)	*3.17*	*0.20*

Exhibit 1-33: Process Non-Energy Emissions Calculations for Production of Fruits and Vegetables

Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Potatoes	0.01	–	–	–	<0.00	0.05
Tomatoes	<0.00	<0.00	–	–	<0.00	0.07
Citrus	0.01	<0.00	–	–	<0.00	0.05
Melons	<0.00	<0.00	–	–	<0.00	0.04
Apples	–	<0.00	–	–	<0.00	0.01
Bananas	0.03	<0.00	–	–	<0.00	0.10
Fruits and Vegetables (weighted average)	*0.01*	*<0.00*	–	–	*<0.00*	*0.06*

– = Zero emissions.

Data used to develop the source reduction emission factor for fresh fruits and vegetables in WARM came primarily from three sources. Data for the production of apples, melons, tomatoes, and oranges came from the University of California Cooperative Extension's (UCCE) sample cost production studies (Fake et al. 2009, O'Connell et al 2009, Stoddard et al. 2007, Wunderlich et al. 2007). These studies are intended as hypothetical guides for farmers to produce crops, and include yield projections and sample requirements for fuel, fertilizers, irrigation, and plant protection products.[10] Data for the production of bananas was acquired from a 2010 life-cycle assessment (LCA) conducted by Soil and More International, on request of the Dole Food Company (Luske 2010). The banana LCA study characterizes the cradle-to-retail GHG emissions associated with banana production in Costa Rica and retail in Western Europe. In developing the source reduction emission factor, EPA used supplementary data to model international shipping and retail transport to the United States. Lastly, the data for potato production was acquired from the Ecoinvent 2.0 database, available within the SimaPro LCA Software.

The primary fruit and vegetable production datasets were supplemented with data from a variety of sources. Retail transport for domestically-produced fruits and vegetables was informed by the Bureau of Transportation Statistics (BTS) 2012 Commodity Flow Survey (BTS 2013). Loss rates for the transport of fresh fruits and vegetables from production to retail were derived from USDA Economic Research Service (ERS) loss-adjusted food availability data (USDA 2012b). In order to evaluate the impacts from retail transport of bananas produced in Central America to the United States, Luske 2010 was supplemented by disaggregated data for the ocean transport of bananas to various ports in the United States (Bernatz 2009). The cumulative energy demand and non-energy GHG emissions from upstream materials and processes, such as harvesting and fertilizer production, were informed by unit processes from the Ecoinvent 2.0 database, available within SimaPro.

Apples, Oranges, Melons, and Tomatoes. Production of apples, oranges, melons, and tomatoes were all characterized in the UCCE's Cost and Return datasets in terms of expected yields and recommended inputs. In order to translate the material and process inputs estimated by the UCCE, EPA extracted the expected yields and material and process inputs from each study and normalized them by the expected yield of the plot of land to provide inputs in a functional unit per unit of fruits and vegetables (e.g., short tons of urea fertilizer per short ton of apples produced). Next, EPA linked each input to a unit process from either the Ecoinvent 2.0 or the U.S. LCI database within SimaPro. For example, each liter of diesel or short ton of fertilizer required per acre of apple cultivation was

[10] Practices described in the production studies are based on real-world production practices considered typical for the crop and area, but may not apply to every situation. The sample cost of production studies for a variety of commodities are available from the University of California-Davis, at: http://coststudies.ucdavis.edu/.

translated into liters of diesel or short tons of fertilizer per short ton of fruits and vegetables in the U.S. LCI database. At the end of this stage, each fruit or vegetable dataset within SimaPro included a unit process output (1 short ton of a given fruit or vegetable) and a series of material inputs and processes, each linked to its GHG emissions and energy demands, which collectively contribute to the total impact of producing that unit of fruit or vegetable.

The emissions were calculated in two separate stages: first, energy-derived emissions were calculated by determining the cumulative energy demand for producing one short ton of each type of fruit or vegetable. Secondly, non-energy emissions were estimated and added to the fossil fuel-derived emissions.

To estimate the energy-derived emissions, EPA calculated the cumulative energy demand for each of the assembled datasets within SimaPro through an energy demand impact assessment method in the software. This method calculated the total life-cycle energy in mega joules (MJ) required to produce one unit of fruit or vegetable and then determined the share of each fuel type contributed to total energy demand, including: petroleum, nuclear power, biomass, natural gas, coal, and renewables. Each energy source's contribution to the total energy demand was then multiplied by the fuel-specific carbon coefficients used in WARM for all materials to determine the total energy-derived emissions associated with the production of one unit of fruit or vegetable.

The non-energy emissions came from two components of the fruit and vegetable life cycle: fertilizer production and fertilizer application. Fertilizer production includes a variety of chemical processes that release non-fossil fuel carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) into the atmosphere. To capture these emissions, EPA ran an impact assessment method within SimaPro on the fruits and vegetables' upstream processes that only considered non-fossil emissions of these gases to isolate the process emissions from fertilizer production.

To estimate the GHG emissions associated with fertilizer application, EPA assessed the total amount of nitrogen fertilizer applied to each crop, and then used stoichiometry to identify the share of nitrogen applied in each dataset. From there, EPA utilized the IPCC Tier 1 method for managed soils to calculate the total amount of N_2O and CO_2 released from fertilizer application, run-off, volatilization, and leaching (IPCC 2006b). The IPCC Tier 1 approach was chosen to maintain consistency with other agricultural LCAs and the International EPD System's Product Category Rules (PCR) for arable crops (International EPD System 2012).

Refrigerated road transport is also assumed for apples, oranges, melons, and tomatoes transported to retail in the United States (see "Retail Transport" sub-section below).

Bananas. The source reduction emission factor for bananas was developed using a similar process to the emission factors developed from the UCCE's datasets, utilizing a 2010 LCA of banana production in Costa Rica (Luske 2010). EPA compiled the material and process inputs for banana production and normalized them by the expected yield of bananas to provide inputs in a functional unit per unit of fruit (e.g., short tons of urea fertilizer per short ton of bananas). The normalized inputs were then translated into unit processes within SimaPro for cumulative energy demand and non-energy emissions analysis. Fertilizer emissions were estimated using the IPCC Tier 1 approach using the fertilizer inputs provided by Luske 2010. See the above sub-section (Apples, Oranges, Melons, and Tomatoes) for more information on this process.

Unlike the other components of the fruit and vegetable energy and emission factors, bananas are shipped internationally in specially-made, refrigerated cargo containers to prevent over-ripening prior to sale. The average transportation distance to the United States was multiplied by a separate factor for emissions per ton-kilometer of refrigerated ocean cargo transport (BSR 2012). Additionally, due to the role of refrigeration in the ocean transport of bananas, EPA incorporated the estimate of fugitive refrigerant emissions during processing and transport in Luske 2010, summarized in Exhibit 1-34. In addition to refrigerated ocean transport, refrigerated road transport is also assumed for bananas transported domestically after they are imported into the United States (see “Retail Transport” sub-section below).

Exhibit 1-34: Fugitive Refrigerant Emissions for International Transport of Bananas

Refrigerant	Percent of Total	Global Warming Potential (GWP)[a]	Emissions ($MTCO_2e$/Short Ton of Bananas)
Pentafluoroethane (HFC-125a)	44%	2,800	7.81E-03
1,1,1-Trifluoroethane (HFC-143a)	52%	3,800	9.23E-03
1,1,1,2-Tetrafluoroethane (HFC-134a)	4%	1,300	7.10E-04
Total	100%	3,260	1.77E-02

Source: Luske 2010.

[a] GWP values are based on the IPCC Second Assessment Report (IPCC SAR).

Potatoes. Unlike the emission factors for bananas and the fruits and vegetables characterized by the UCCE, a unit process for potatoes was already available within the SimaPro life-cycle software as part of the Ecoinvent 2.0 database. The unit process included a co-product of potato leaves; however, in the dataset, it was allocated at 0.0 percent due to its low economic value. Consequently, it was not included in this analysis.

As described in the “Apples, Oranges, Melons and Tomatoes” sub-section above, EPA conducted a cumulative energy demand and non-energy emissions assessment in order to export the data in a format suitable for import into WARM.

As with the other components of the fruits and vegetables source reduction emission factors, EPA estimated the GHG emissions associated with fertilizer application. EPA extracted the amounts of nitrogen fertilizer and liming materials applied to the potato crops from the Ecoinvent unit process data and utilized the IPCC Tier 1 method for managed soils to calculate the total amount of N_2O and CO_2 released from fertilizer application, run-off, volatilization, and leaching.

Retail Transport. For this analysis, distribution of fruits and vegetables to their final point of sale was assumed to have two components: the energy and GHG emissions associated with fossil fuel combustion from vehicle operation and the GHG impact of fugitive refrigerants emitted from refrigerated vehicles. The GHG emissions from vehicle operation were a product of diesel fuel combustion. Fugitive emissions of refrigerants consisted of a mix of 1,1,1,2-Tetrafluoroethane (R-134a), Chlorodifluoromethane (HCFC-22), Monochloropentafluoroethane (R-155), and 1,1-Difluoroethane (HFC-152a). Due to lack of data for fruit and vegetable-specific transportation, the fugitive emissions associated with refrigerated vehicle transport were assumed to be the same as for refrigerated dairy delivery via a medium-sized truck (Thoma et al. 2010). In the Thoma et al. 2010 study, estimates of fugitive emissions of refrigerants during the transport phase were estimated via a sales-based approach, which equated purchases of refrigerants for the truck fleet to fugitive refrigerants released via leakage.

Retail transport ton-miles per shipment for all fruits and vegetables were informed by the Bureau of Transportation Statistics (BTS) 2012 Commodity Flow Survey (BTS 2013). Bananas were assumed to have land-based domestic transport in addition to refrigerated ocean transport, as described in the “Bananas” sub-section above. The process energy and non-energy emissions for the transportation of fruits and vegetables to retail are shown in Exhibit 1-35 and Exhibit 1-36, respectively.

Exhibit 1-35: Process Energy GHG Emissions Calculations for Transportation of Fruits and Vegetables

Material	Transportation Energy per Short Ton (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Fruits and Vegetables	2.28	0.17

Exhibit 1-36: Non-Energy Emissions Calculations for Transportation of Fruits and Vegetables

Material	CO_2 Emissions (MT/Short Ton)[a]	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Fruits and Vegetables	0.01	–	–	–	–	0.01

– = Zero emissions.

[a] The estimate of non-energy CO_2 emissions includes a mixture of various refrigerants, predominantly HFC 143a, HFC 134a, HFC-125, and HCFC-22, released during refrigerated transport.

Retail transport of perishables such as fruits and vegetables also results in losses due to spoilage and physical damage to the produce that would render it unfit for sale. Loss rates for the transport of fresh fruits and vegetables from production to retail were derived from USDA Economic Research Service (ERS) loss-adjusted food availability data (USDA 2012b). Loss rates for each fruit and vegetable in the analysis were compiled from USDA (2012b) and then re-weighted based on each product's share of the waste stream. An overview of the individual and weighted loss rates for fruit and vegetable transport to retail is presented in Exhibit 1-37. The loss rates were specific to losses incurred strictly during the transport of fresh fruits and vegetables instead of a weighted mix of fresh and processed fruits and vegetables in order to maintain consistency with the scope and methodology used to develop the food waste source reduction emission factors in WARM. The calculated weighted loss rate of 7.1 percent (shown in the final row in Exhibit 1-37) was applied to both production and transportation emissions of all fruits and vegetables modeled in WARM, indicating that for every 1,000 short tons of fruits and vegetables sold at retail, 1,076 short tons had left the production site (indicating a loss of 7.1 percent of the original amount). This factor increased GHG emissions from production and transport by approximately 7.6 percent.

Exhibit 1-37: Loss Rates for Transport of Fruits and Vegetables from Production to Retail

Fruit and Vegetable Category	Total Losses (Millions of Pounds)	Percent of Category	Individual Loss Rate	Weighted Loss Rate
Potatoes	18,650	27.5%	4.0%	1.1%
Tomatoes	18,294	27.0%	15.0%	4.1%
Citrus	14,200	21.0%	3.7%	0.8%
Melons	6,313	9.3%	9.2%	0.9%
Apples	5,575	8.2%	4.0%	0.3%
Bananas	4,705	6.9%	0.0%	0.0%
Fruits and Vegetables (weighted average)	67,737	100%	NA	7.1%

Source: USDA 2012b.

1.4.1.5 Developing the Emission Factor for Source Reduction of Dairy Products

To produce dairy products, energy is used during the acquisition of raw materials and manufacturing (RMAM) phase of the products' life cycle. In general, the majority of the energy for the production of these materials is derived from fossil fuels, either through the electricity grid or during on-site combustion of fuel during the farming process. Combustion of fossil fuels results primarily in emissions of CO_2, as well as small amounts of N_2O. Additionally, dairy production results in in process non-energy emissions of CO_2, CH_4 and N_2O, as described below. Dairy products have a high share of non-energy process emissions of CH_4 from enteric fermentation by dairy cattle. Refrigerated transport of dairy products to retail also results in small amounts of high-global warming potential (GWP) refrigerant emissions. The broad category of dairy foods includes a wide variety of products with differing inputs and processing stages. While dairy products can have differing upstream energy and emissions impacts, the emission factor described in this section considers a weighted average of dairy products commonly found in U.S. municipal waste. Exhibit 1-38 shows the results for each component and the total GHG emission factors for source reduction of dairy products.

Exhibit 1-38: Raw Material Acquisition and Manufacturing Emission Factor for Production of Dairy Products ($MTCO_2E$/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e = b + c + d) Net Emissions
Dairy Products	0.80	0.05	0.89	1.74

The LCI data for dairy production used for developing the dairy products emission factor was provided by the Innovation Center for U.S. Dairy, an industry group. The Innovation Center conducted its own LCA for dairy production (Thoma et al. 2010). The Innovation Center's LCA's scope is larger than the scope used to develop the WARM energy and emission factors, covering the cradle-to-grave life-cycle of dairy products including retail storage, consumer use, and disposal. Dairy production is linked to several other systems that produce products outside the scope of this specific LCA, including feed co-products (e.g., dried distillers' grains) and beef. In the data set from the Innovation Center, impacts for most co-products are allocated economically. However, causal allocation is used for both beef based on feed nutrient content and for corn silage based on crop nitrogen requirements determined from reported yield.[11] Causal mass balance is used for different fat-content milks during production (Thoma et al. 2010). Because the Innovation Center's data set already allocated impacts to co-products, EPA did not further modify the data to account for impacts from products outside the scope used in WARM.

Dairy Products. To align the dairy production LCI data with WARM, the LCI data had to be made consistent with the scope of the food waste factors in WARM. This involved removing portions of the unit processes in SimaPro that were outside the scope of the analysis, such as retail storage, consumer transport, packaging, and consumer use (e.g., cooking and consumer food loss). Through this process, EPA created a series of unit processes for specific dairy products (e.g., skim milk, ice cream) that only included the material inputs and process flows prior to retail stocking and sales. For consistency with other energy and emission factors in WARM, EPA also used LCI data for product transportation from production to retail, as described below.

The emissions were calculated in two separate stages: first, energy-derived emissions were calculated by determining the cumulative energy demand for producing one short ton of the weighted average dairy total. Secondly, non-energy emissions were estimated and added to the fossil fuel-derived emissions.

To estimate the energy-derived emissions, EPA calculated the cumulative energy demand for the weighted dairy average using the cumulative energy demand impact assessment method in SimaPro. This method resulted in an estimate of the total life-cycle energy in million Btu required to produce one short ton of weighted average dairy products. EPA then separated the total energy consumption into the fuel categories used for generating the energy, including petroleum, nuclear power, biomass, natural gas, coal, and renewables. EPA then multiplied each energy source's contribution to the total energy demand by the fuel-specific carbon coefficients used in WARM for all

[11] Within the framework of the ISO 14040 standard for life-cycle assessment, causal allocation refers to the allocation of environmental impacts based on the physical relationships between materials and their environmental burdens. In this instance, it refers to isolating the energy flows to the cattle system that go towards milk production from those directed towards meat production.

materials to determine the total energy-derived emissions associated with the production of one short ton of dairy product. The process energy used to produce dairy products and the resulting emissions are shown in Exhibit 1-39.

Exhibit 1-39: Process Energy GHG Emissions Calculations for Production of Dairy Products

Material	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Dairy Products	13.61	0.80

The bulk of the non-energy production emissions came from three components of the dairy life cycle: enteric fermentation, fertilizer production, and fertilizer application. To capture these emissions, EPA ran an impact assessment method within SimaPro on the upstream dairy production processes that only considered non-fossil emissions of these gases in order to avoid double-counting process emissions from the energy-derived emissions, which are separately calculated within WARM. Exhibit 1-40 shows the components for estimating process non-energy GHG emissions for dairy products.

Exhibit 1-40: Process Non-Energy Emissions Calculations for Production of Dairy Products

Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Dairy Products	0.04	0.03	–	–	<0.01	0.88

Retail Transport: The Innovation Center dataset includes complete LCI data on the retail transportation process for dairy products including energy and emissions from onboard refrigeration equipment to prevent spoilage. Because these data were available in the Innovation Center dataset and because refrigeration is an essential part of the transport of these milk-based products, EPA used these data to develop the retail transport energy and emissions estimates for WARM. This approach differs from the methodology used for estimating retail transport for other materials currently in WARM, which rely on average commodity retail transportation distances provided by the U.S. Census Bureau data and, for materials other than fruits and vegetables, do not involve refrigerated transport. EPA estimated the energy-derived emissions from transport by calculating the cumulative energy demand within the software. Non-energy emissions, which were in the form of fugitive refrigerants, were evaluated with the non-fossil-derived GHG emissions impact assessment method within the software. The process energy and non-energy emissions for the transportation of dairy products to retail are shown in Exhibit 1-41 and Exhibit 1-42, respectively.

Exhibit 1-41: Process Energy GHG Emissions Calculations for Transportation of Dairy Products

Material	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Dairy Products	0.65	0.05

Exhibit 1-42: Non-Energy Emissions Calculations for Transportation of Dairy Products

Material	CO_2 Emissions (MT/Short Ton)[a]	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Dairy Products	0.01	–	–	–	–	0.01

– = Zero emissions.

[a] The estimate of non-energy CO_2 emissions includes a mixture of various refrigerants, predominantly HFC 143a, HFC 134a, HFC-125, and HCFC-22, released during refrigerated transport.

1.4.2 Recycling

Recycling, as modeled in WARM (i.e., producing new products using end-of-life materials), does not commonly occur with the food waste types modeled in WARM. Therefore, WARM does not consider GHG emissions or storage associated with the traditional recycling pathway for food waste. However, food waste can be converted to compost, a useful soil amendment, as described in section 1.4.3.

1.4.3 Composting

1.4.3.1 Developing the Emissions Factor for the Composting of Food Waste

Composting food waste results in increased carbon storage when compost is applied to soils. The net composting emission factor is calculated as the sum of emissions from transportation, processing of compost, the carbon storage resulting from compost application, and the fugitive emissions of methane (CH_4) and nitrous oxide (N_2O) produced during decomposition.[12] WARM currently assumes that carbon dioxide (CO_2) emissions that occur as a result of the composting process are biogenic and are not counted (for further explanation, see the text box on biogenic carbon in the Introduction and Background chapter). Exhibit 1-43 details these components for food waste and mixed organics. For additional information on composting in WARM, see the Composting chapter. The three emission sources and one emission sink resulting from the composting of organics are:

- *Nonbiogenic CO_2 emissions from collection and transportation*: Transportation of yard trimmings and food scraps to the central composting site results in nonbiogenic CO_2 emissions.[13] In addition, during the composting process the compost is mechanically turned, and the operation of this equipment also results in nonbiogenic CO_2 emissions.
- *Carbon Storage*: When compost is applied to the soil, some of the carbon contained in the compost does not decompose for many years and therefore acts as a carbon sink.
- *Fugitive CH_4 and N_2O emissions*: microbial activity during composting decomposes waste into a variety of compounds, which generates small amounts of CH_4 and N_2O gas, a net contributor to the GHG emissions associated with the composting pathway.

Exhibit 1-43: Components of the Composting Net Emission Factor for Food Waste and Mixed Organics

Composting of Post-Consumer Material (GHG Emissions in $MTCO_2E$/Short Ton)						
Material Type	**Raw Material Acquisition and Manufacturing (Current Mix of Inputs)**	**Transportation to Composting**	**Compost CO_2**	**Compost CH_4 and N_2O**	**Soil Carbon Storage**	**Net Emissions (Post-Consumer)**
Food Waste	NA	0.02	–	0.05	-0.24	-0.18
Mixed Organics	NA	0.02	–	0.07	-0.24	-0.16

NA = Not applicable.
[a] Yard trimmings are a 50%, 25%, 25% weighted average of grass, leaves, and branches, based on U.S. generation data from EPA (2015b).

Transportation energy emissions occur when fossil fuels are used to collect and transport yard trimmings and food scraps to a composting facility, and then to operate the composting equipment that turns the compost. To calculate these emissions, WARM relies on assumptions from FAL (1994), which are detailed in Exhibit 1-44.

[12] These fugitive emission sources were added in June 2014 to WARM Version 13.
[13] Transportation emissions from delivery of finished compost from the composting facility to its final destination were not counted.

Exhibit 1-44: Emissions Associated with Transporting and Turning Compost

	Diesel Fuel Required to Collect and Transport One Ton (Million Btu)[a]	Diesel Fuel Required to Turn the Compost Piles (Million Btu)[a]	Total Energy Required for Composting (Million Btu)	Total CO_2 Emissions from Composting ($MTCO_2E$)
All Material Types	0.04	0.22	0.26	0.02

[a] Based on estimates found on Table I-17 on page I-32 of FAL 1994.

WARM currently assumes that carbon from compost remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils (the "soil carbon restoration" effect)[14] and carbon stored in non-reactive humus compounds (the "increased humus formation" effect)[15]. The carbon values from the soil carbon restoration effect are scaled according to the percentage of compost that is passive, or non-reactive, which is assumed to be 52 percent (Cole, 2000). The weighted soil restoration value is then added to the increased humus formation effect in order to estimate the total sequestration value associated with composting. The inputs to the calculation are shown in Exhibit 1-45.

Exhibit 1-45: Soil Carbon Effects as Modeled in Century Scenarios ($MTCO_2E$/Short Ton of Organics)

Scenario	Soil Carbon Restoration			Increased Humus Formation	Net Carbon Flux[a]
	Unweighted	Proportion of C that is Not Passive	Weighted estimate		
Annual application of 32 tons of compost per acre	-0.04	48%	-0.07	-0.17	-0.20

[a] The net carbon flux sums each of the carbon effects together and represents the net effect of composting a short ton of yard trimmings in $MTCO_2E$.

The nonbiogenic CO_2 emissions from transportation, collection and compost turning are added to the compost carbon sink in order to calculate the net composting GHG emission factors for each organics type. As Exhibit 1-43 illustrates, WARM estimates that the net composting GHG factor for all organics types is the same for all sources of compost.

1.4.4 Combustion

1.4.4.1 Developing the Emissions Factor for the Combustion of Food Waste

Combusting food waste results in a net emissions offset (negative emissions) due to the avoided utility emissions associated with energy recovery from waste combustion. The combustion net emission factor is calculated as the sum of emissions from transportation of waste to the combustion facility, nitrous oxide (N_2O) emissions from combustion, and the avoided CO_2 emissions from energy recovery in a waste-to-energy (WTE) plant. Although combustion also releases the carbon contained in food waste in the form of CO_2, these emissions are considered biogenic and are not included in the WARM net emission factor. Exhibit 1-46 presents these components of the net combustion emission factor for food waste and mixed organics. WARM assumes the same emission factors for all food waste types. For

[14] EPA evaluated the soil carbon restoration effect using Century, a plant-soil ecosystems model that simulates long-term dynamics of carbon, nitrogen, phosphorous and sulfur in soils. For more information, see the Composting chapter.

[15] EPA evaluated the increased humus formation effect based on experimental data compiled by Dr. Michael Cole of the University of Illinois. These estimates accounted for both the fraction of carbon in the compost that is considered passive and the rate at which passive carbon is degraded into CO_2. For more information, see the Composting chapter.

additional information on combustion in WARM, see the Combustion chapter. The two emissions sources and one emissions offset that result from the combusting of food waste are:

- *CO_2 emissions from transportation of waste.* Transporting waste to the combustion facility and transporting ash from the combustion facility to a landfill both result in transportation CO_2 emissions.
- *Nitrous oxide emissions from combustion.* Waste combustion results in measurable emissions of nitrous oxide (N_2O), a GHG with a high global warming potential (EPA, 2015a).
- *Avoided utility CO_2 emissions*. Combustion of MSW with energy recovery in a WTE plant also results in *avoided* CO_2 emissions at utilities.

Exhibit 1-46: Components of the Combustion Net Emission Factor for Food Waste and Mixed Organics ($MTCO_2E$/Short Ton)

	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Food Waste	NA	0.01	–	0.04	-0.19	–	-0.14
Mixed Organics	NA	0.01	–	0.04	-0.20	–	-0.16

NA = Not applicable

For the CO_2 emissions from transporting waste to the combustion facility, and ash from the combustion facility to a landfill, EPA used an estimate of 60 lbs CO_2 per ton of MSW for transportation of mixed MSW developed by FAL (1994). EPA then converted the Franklin Associates estimate from pounds of CO_2 per ton of mixed MSW to $MTCO_2E$ per ton of mixed MSW and applied it to estimate CO_2 emissions from transporting one short ton of mixed MSW and the resulting ash. WARM assumes that transportation of food waste uses the same amount of energy as transportation of mixed MSW.

Studies compiled by the Intergovernmental Panel on Climate Change (IPCC) show that MSW combustion results in measurable emissions of N_2O, a GHG with a high global warming potential (IPCC, 2006a). The IPCC compiled reported ranges of N_2O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. WARM averages the midpoints of each range and converts the units to $MTCO_2E$ of N_2O per ton of MSW. Because the IPCC did not report N_2O values for combustion of individual components of MSW, WARM uses the same value for food waste and mixed organics.

Most WTE plants in the United States produce electricity and only a few cogenerate electricity and steam (EPA, 2006). In this analysis, EPA assumes that the energy recovered with MSW combustion would be in the form of electricity, as shown in Exhibit 1-47. The exhibit shows emission factors for mass burn facilities (the most common type of WTE plant). EPA used three data elements to estimate the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy content of each waste material, (2) the combustion system efficiency in converting energy in MSW to delivered electricity, and (3) the electric utility CO_2 emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants.

Exhibit 1-47: Utility GHG Emissions Offset from Combustion of Food Waste

(a) Material	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity ($MTCO_2E$/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted ($MTCO_2E$/Short Ton) (e = b × c × d)
Food Waste	4.7	17.8%	0.22	0.19

To estimate the gross GHG emissions per ton of waste combusted, EPA sums emissions from combustion N_2O and transportation CO_2. These emissions were then added to the avoided utility emissions in order to calculate the net GHG emission factor, shown in Exhibit 1-46. WARM estimates that combustion of food wastes results in a net emission reduction.

1.4.5 Landfilling

1.4.5.1 Developing the Emissions Factor for the Landfilling of Food Waste

Landfilling food waste can result in either net carbon storage or net carbon emissions, depending on the specific properties of the waste material. The landfilling emissions factor is calculated as the sum of emissions from transportation of waste to the landfill and operation of landfill equipment, methane emissions from landfilling, and the carbon storage resulting from undecomposed carbon remaining in landfills. Exhibit 1-48 presents these components of the landfilling emission factor for food waste and mixed organics. WARM assumes the same emission factors for all food waste types. For additional information on landfilling in WARM, see the Landfilling chapter. The two emissions sources and one emissions sink that result from the landfilling of food waste are:

- *Transportation of food waste*. Transportation of food waste to landfill results in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes.
- *Methane emissions from landfilling*. When food waste is landfilled, anaerobic bacteria degrade the materials, producing CH_4 and CO_2, collectively referred to as landfill gas (LFG). Only the CH_4 portion of LFG is counted in WARM, because the CO_2 portion is considered of biogenic origin and therefore is assumed to be offset by CO_2 captured by regrowth of the plant sources of the material.
- *Landfill carbon storage.* Because food waste is not completely decomposed by anaerobic bacteria, some of the carbon in these materials remains stored in the landfill. This stored carbon constitutes a sink (i.e., negative emissions) in the net emission factor calculation.

Exhibit 1-48: Landfilling Emission Factors for Food Waste and Mixed Organics ($MTCO_2E$/Short Ton)

Material Type	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided CO_2 Emissions from Energy Recovery	Landfill Carbon Storage	Net Emissions (Post-Consumer)
Food Waste	–	0.02	0.67	-0.06	-0.09	0.54
Mixed Organics	–	0.02	0.53	-0.05	-0.30	0.20

Note: The emission factors for landfill CH_4 presented in this table assume that the methane management practices and decay rates at the landfill are an average of national practices.
Negative values denote GHG emission reductions or carbon storage.
NA = Not applicable; upstream raw material acquisition and manufacturing GHG emissions are not included in landfilling since the life-cycle boundaries in WARM start at the point of waste generation and landfilling does not affect upstream GHG emissions.

Transportation energy emissions occur when fossil fuels are used to collect and transport food waste to a landfill, and then to operate the landfill equipment. To calculate these emissions, WARM relies on assumptions from FAL (1994). EPA then converted the Franklin Associates estimate from pounds of CO_2 per ton of mixed MSW to $MTCO_2E$ per ton of mixed MSW and applied it to estimate CO_2 emissions from transporting one short ton of mixed MSW. WARM assumes that transportation of food waste uses the same amount of energy as transportation of mixed MSW.

WARM calculates CH_4 emission factors for landfilled materials based on the CH_4 collection system type installed at a given landfill. There are three categories of landfills modeled in WARM: (1) landfills that do not recover LFG, (2) landfills that collect the LFG and flare it without recovering the flare energy, and (3) landfills that collect LFG and combust it for energy recovery by generating electricity. The Excel version of WARM allows users to select component-specific decay rates based on different assumed moisture contents of the landfill and landfill gas collection efficiencies for a series of landfill management scenarios. The tables in this section show values using the national average moisture conditions, based on the national average precipitation at landfills in the United States and for landfill gas collect efficiency from "typical" landfill operations in the United States. The decay rate and management scenario assumed influences the landfill gas collection efficiency. For further explanation, see the Landfilling chapter.

Exhibit 1-49 depicts the emission factors for each LFG collection type based on the national average landfill moisture scenario and "typical" landfill management operations. Overall, landfills that do not collect LFG produce the most CH_4 emissions. Food waste readily degrades in landfills, and consequently emits the most CH_4 of all organic materials in landfills. The emissions generated per short ton of material drop by over half for food waste if the landfill recovers and flares CH_4 emissions. These emissions are even lower in landfills where LFG is recovered for electricity generation because LFG recovery offsets emissions from avoided electricity generation.[16]

Exhibit 1-49: Landfill CH4 Emissions for Three Different Methane Collection Systems, National Average Landfill Moisture Conditions, Typical Landfill Management Operations, and National Average Grid Mix ($MTCO_2E$/Wet Short Ton)

Material	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electric Generation
Food Waste	1.57	0.68	0.46

Note: Negative values denote GHG emission reductions or carbon storage.

A portion of the carbon contained in food waste does not decompose after disposal and remains stored in the stored in the landfill. Because this carbon storage would not normally occur under natural conditions (virtually (virtually all of the carbon in the organic material would be released as CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic carbon sink. The carbon storage associated with each material type depends on the initial carbon content, the extent to which that carbon carbon decomposes into CH_4 in landfills, and temperature and moisture conditions in the landfill. The background and details of the research underlying the landfill carbon storage factors are detailed in the Landfilling chapter.

Exhibit 1-50 shows the carbon storage factor calculations for landfilled food waste.

[16] These values include a utility offset credit for electricity generation that is avoided by capturing and recovering energy from landfill gas to produce electricity. The utility offset credit is calculated based on the non-baseload GHG emissions intensity of U.S. electricity generation, since it is non-baseload power plants that will adjust to changes in the supply of electricity from energy recovery at landfills.

Exhibit 1-50: Calculation of the Carbon Storage Factor for Landfilled Food Waste

(a) Material	(b) Ratio of Carbon Storage to Dry Weight (grams of Carbon Stored/dry gram of Material)[a]	(c) Ratio of Dry Weight to Wet Weight	(d) Ratio of Carbon Storage to Wet Weight (grams of Carbon/wet gram of Material) (d = b × c)	(e) Amount of Carbon Stored ($MTCO_2E$ per Wet Short Ton)
Food Waste	0.08	0.27	0.02	0.07

[a] Based on estimates developed by James W. Levis, Morton Barlaz, Joseph F. DeCarolis, and S. Ranji Ranjithan at North Carolina State University; see Levis et al. 2013.

The landfill CH_4 and transportation emissions sources are added to the landfill carbon sink in order to calculate the net GHG landfilling emission factors for food waste, shown in the final three columns of Exhibit 1-51 for landfills equipped with different LFG collection systems. The final net emission factors indicate that food waste results in net emissions, due to relatively high CH_4 emissions and low carbon storage in landfills.

Exhibit 1-51: Components of the Landfill Emission Factor for the Three Different Methane Collection Systems Typically Used In Landfills ($MTCO_2E$/Short Ton)

(a)	(b) Net GHG Emissions from CH_4 Generation			(c)	(d)	(e) Net GHG Emissions from Landfilling (e = b + c + d)		
Material	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electric Generation	Net Landfill Carbon Storage	GHG Emissions From Transpor-tation	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Food Waste	1.46	0.63	0.52	-0.09	0.02	1.39	0.56	0.45

Note: Negative values denote GHG emission reductions or carbon storage.

1.4.6 Anaerobic Digestion

1.4.6.1 Developing the Emissions Factor for the Anaerobic Digestion of Food Waste

The anaerobic digestion emissions factor is calculated as the sum of emissions from transportation of waste to the anaerobic digester and operation of anaerobic digester equipment, methane emissions from anaerobic digesting, the carbon storage resulting from applying the digestate to soil, the net electricity export to grid and fertilizer offsets. Both wet and dry digestion is applicable for food waste. Exhibit 1-52 presents these components of the dry anaerobic digestion emission factor for food waste with digestate curing and Exhibit 1-53 with digestate directly applied to land. Exhibit 1-54 contains the GHG sources and sinks for wet digestion with digestate curing and Exhibit 1-55 with digestate directly applied to land. For additional information on anaerobic digestion in WARM, see the Anaerobic Digestion chapter. The three emissions sources and three emissions sink that result from the anaerobically digesting food waste are:

- *Transportation Energy*. WARM includes emissions associated with transporting and anaerobic digestion of the material. Transportation energy emissions occur when fossil fuels are combusted to collect and transport material to the anaerobic digestion facility, to transport digestate for land application, and to operate on-site equipment for curing and spreading digestate.

- *Process Energy.* Preprocessing includes grinding, screening and mixing the feedstock before they are fed into the reactor. The emissions associated with electricity and diesel consumption during preprocessing and operation are assessed in WARM for both wet and dry digesters. WARM estimates the emissions associated with two scenarios for digestate beneficial use: curing the digestate and applying the resulting compost to agricultural lands, or directly applying digestate to agricultural lands without curing.
- *Avoided Utility Emissions.* Methane biogas is produced during the digestion process and collected for combustion. WARM models the recovery of biogas for electricity generation and assumes that this electricity offsets non-baseload electricity generation in the power sector.
- *Avoided Fertilizer Application.* The application of digestate to agricultural lands is able to offset a portion of the synthetic fertilizer application needed for agricultural lands due to its high nutrient content. WARM includes avoided fertilizer offsets for both nitrogen and phosphorous in synthetic fertilizers.
- *Process Non-Energy.* Fugitive emissions occur at the digester, during the curing process, and after land application.
- *Soil Carbon Storage.* Similar to carbon from compost applied to agricultural lands, EPA assumes that carbon from digestate applied to agricultural lands remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils and carbon stored in non-reactive humus compounds.

Exhibit 1-52: Dry Anaerobic Digestion Emission Factors for Food Waste with Digestate Curing ($MTCO_2E$/Short Ton)

Material	Process Energy	Avoided Utility Emissions	Avoided Fertilizer Application	Soil Carbon Storage	Process Non-Energy	Transportation Energy	Net Emissions (Post–Consumer)
Food Waste	0.02	-0.15	-0.01	-0.03	0.12	0.00	-0.05
Food Waste (meat only)	0.02	-0.15	-0.01	-0.03	0.12	0.00	-0.05
Food Waste (non-meat)	0.02	-0.15	-0.01	-0.03	0.12	0.00	-0.05
Beef	0.02	-0.15	-0.01	-0.03	0.12	0.00	-0.05
Poultry	0.02	-0.15	-0.01	-0.03	0.12	0.00	-0.05
Grains	0.02	-0.15	-0.01	-0.03	0.12	0.00	-0.05
Bread	0.02	-0.15	-0.01	-0.03	0.12	0.00	-0.05
Fruits and Vegetables	0.02	-0.15	-0.01	-0.03	0.12	0.00	-0.05
Dairy Products	0.02	-0.15	-0.01	-0.03	0.12	0.00	-0.05
Mixed Organics	0.02	-0.10	-0.01	-0.09	0.11	0.00	-0.07

Negative values denote GHG emission reductions or carbon storage.

Exhibit 1-53: Dry Anaerobic Digestion Emission Factors for Food Waste with Direct Land Application ($MTCO_2E$/Short Ton)

Material	Process Energy	Avoided Utility Emissions	Avoided Fertilizer Application	Soil Carbon Storage	Process Non-Energy	Transportation Energy	Net Emissions (Post–Consumer)
Food Waste	0.02	-0.15	-0.02	-0.08	0.12	0.00	-0.11
Food Waste (meat only)	0.02	-0.15	-0.02	-0.08	0.12	0.00	-0.11
Food Waste (non-meat)	0.02	-0.15	-0.02	-0.08	0.12	0.00	-0.11
Beef	0.02	-0.15	-0.02	-0.08	0.12	0.00	-0.11
Poultry	0.02	-0.15	-0.02	-0.08	0.12	0.00	-0.11
Grains	0.02	-0.15	-0.02	-0.08	0.12	0.00	-0.11

Material	Process Energy	Avoided Utility Emissions	Avoided Fertilizer Application	Soil Carbon Storage	Process Non-Energy	Transportation Energy	Net Emissions (Post–Consumer)
Bread	0.02	-0.15	-0.02	-0.08	0.12	0.00	-0.11
Fruits and Vegetables	0.02	-0.15	-0.02	-0.08	0.12	0.00	-0.11
Dairy Products	0.02	-0.15	-0.02	-0.08	0.12	0.00	-0.11
Mixed Organics	0.02	-0.10	-0.01	-0.22	0.09	0.00	-0.22

Exhibit 1-54: Wet Anaerobic Digestion Emission Factors for Food Waste with Digestate Curing ($MTCO_2E$/Short Ton)

Material	Process Energy	Avoided Utility Emissions	Avoided Fertilizer Application	Soil Carbon Storage	Process Non-Energy	Transportation Energy	Net Emissions (Post–Consumer)
Food Waste	0.01	-0.12	-0.02	-0.03	0.10	0.00	-0.06
Food Waste (meat only)	0.01	-0.12	-0.02	-0.03	0.10	0.00	-0.06
Food Waste (non-meat)	0.01	-0.12	-0.02	-0.03	0.10	0.00	-0.06
Beef	0.01	-0.12	-0.02	-0.03	0.10	0.00	-0.06
Poultry	0.01	-0.12	-0.02	-0.03	0.10	0.00	-0.06
Grains	0.01	-0.12	-0.02	-0.03	0.10	0.00	-0.06
Bread	0.01	-0.12	-0.02	-0.03	0.10	0.00	-0.06
Fruits and Vegetables	0.01	-0.12	-0.02	-0.03	0.10	0.00	-0.06
Dairy Products	0.01	-0.12	-0.02	-0.03	0.10	0.00	-0.06
Mixed Organics	NA	NA	NA	NA	NA	NA	NA

Exhibit 1-55: Wet Anaerobic Digestion Emission Factors for Food Waste with Direct Land Application ($MTCO_2E$/Short Ton)

Material	Process Energy	Avoided Utility Emissions	Avoided Fertilizer Application	Soil Carbon Storage	Process Non-Energy	Transportation Energy	Net Emissions (Post–Consumer)
Food Waste	0.01	-0.13	-0.03	-0.08	0.08	0.00	-0.14
Food Waste (meat only)	0.01	-0.13	-0.03	-0.08	0.08	0.00	-0.14
Food Waste (non-meat)	0.01	-0.13	-0.03	-0.08	0.08	0.00	-0.14
Beef	0.01	-0.13	-0.03	-0.08	0.08	0.00	-0.14
Poultry	0.01	-0.13	-0.03	-0.08	0.08	0.00	-0.14
Grains	0.01	-0.13	-0.03	-0.08	0.08	0.00	-0.14
Bread	0.01	-0.13	-0.03	-0.08	0.08	0.00	-0.14
Fruits and Vegetables	0.01	-0.13	-0.03	-0.08	0.08	0.00	-0.14
Dairy Products	0.01	-0.13	-0.03	-0.08	0.08	0.00	-0.14
Mixed Organics	NA	NA	NA	NA	NA	NA	NA

WARM accounts for the GHG emissions resulting from fossil fuels used in vehicles collecting and transporting waste to the anaerobic digestion facility. Diesel is used for transporting the feedstock and solids to the anaerobic digester. To calculate the emissions, WARM relies on assumptions NREL's US Life Cycle Inventory Database (USLCI) (NREL 2015). The NREL emission factor assumes a diesel, short-haul truck.

The recovery of heat and electricity from the combusted biogas offsets the combustion of other fossil fuel inputs. WARM assumes that the combusted biogas produces electricity that offsets non-baseload electricity generation. Electricity generation from combustion of biogas is assumed to be unavailable for 15% of operation time and the process is assumed to be 29% efficient (EPA, 2013). Exhibit 1-56 and Exhibit 1-56 show the amount of methane generated and the net electricity exported to the grid.

Exhibit 1-56: Methane Generation, Treatment and Use by Material Type for Dry Digestion

Material	Mass of Methane Generated (kg/ton)	Mass of Methane Leaked (kg/ton)	Mass of Methane Flared (kg/ton)	Mass of Methane Combusted for Energy (kg/ton)	Energy from Combusted Methane (MMBtu/ton)	Electricity Generation (kWh/ton)	Net Electricity to the Grid (kWh/ton)
Food Waste	60.0	1.18	8.80	50.0	2.37	201.4	183
Mixed Organics	41.1	0.81	6.03	34.3	1.62	138	120

Exhibit 1-57: Methane Generation, Treatment and Use by Material Type for Wet Digestion

Material	Mass of Methane Generated (kg/ton)	Mass of Methane Leaked (kg/ton)	Mass of Methane Flared (kg/ton)	Mass of Methane Combusted for Energy (kg/ton)	Energy from Combusted Methane (MMBtu/ ton)	Electricity Generation (kWh/ton)	Energy Available to Heat Digester (MMBtu/ ton)	Energy Required to Heat Reactor (MMBtu/ ton)
Food Waste	60.0	1.18	8.80	50.0	2.37	201.4	1.26	0.14

If the digestate is cured before land application, the solids are aerobically cured in turned windrows. The resulting compost is then screened, transported to agriculture lands, and used in place of a portion of the conventional nitrogen and phosphorus fertilizer that would be needed for the same agricultural lands. Diesel fuel is consumed during this process. If the digestate is not cured, it is directly applied to agricultural lands.

EPA assumes that digestate applied to agricultural land allows for some synthetic fertilizer use to be avoided. WARM includes avoided fertilizer offsets for land application of the digestate generated from anaerobic digestion but not for compost generated from composting due to the difference in feedstocks used for each material management pathway, shown in Exhibit 1-58. Further information can be found in Anaerobic Digestion chapter.

Exhibit 1-58: Nitrogen and Phosphorous Fertilizer Offset by Material Type

Material	Nitrogen Fertilizer Offset (kg N/ton)	Phosphorous Fertilizer Offset (kg P/ton)	Nitrogen Fertilizer Offset ($MTCO_2e$/ton)	Phosphorous Fertilizer Offset ($MTCO_2e$/ton)
Food Waste	1.084	1.286	-0.009	-0.002
Mixed Organics	0.873	1.074	-0.007	-0.002

WARM calculates the carbon storage impact of direct storage of carbon in depleted soils and carbon stored in non-reactive humus compounds separately and then sums them to estimate the carbon storage factor associated with each short ton of organics composted. For more information on carbon storage calculations, see the Composting chapter, which includes information on the Century model framework and simulations.

To estimate the gross GHG emissions per ton of waste combusted, EPA sums emissions from transportation, processing and operations, and fugitive emissions. These emissions were then added to the avoided utility emissions, avoided fertilizer application and soil carbon storage in order to calculate the net GHG emission factor, shown in Exhibit 1-52, Exhibit 1-53, Exhibit 1-54, and Exhibit 1-55**Exhibit**

2-14: Dry Anaerobic Digestion Emission Factors for Yard Trimmings with Digestate Curing ($MTCO_2E$/Short Ton). WARM estimates that anaerobic digestion of yard trimmings results in a net emission reduction for both the curing and non-curing scenarios.

1.5 LIMITATIONS

The results of the analysis presented in this chapter are limited by the reliability of the various data elements used. This section details limitations, caveats and areas of current and future research.

1.5.1 Source Reduction

EPA will conduct follow-on research to continue to refine and improve the accuracy of the food waste emission factors.

- The food waste factors assume conventional production practices and therefore do not capture any potential differences in life-cycle impacts from organic production practices.
- The LCI data used to model beef production is based on on-farm data from the largest research farm in the U.S. combined with post-farm data for the entire U.S. beef industry (Battagliese et al. 2013). The study authors intend to expand the next phase of the research effort to reflect regional differences in beef production throughout the United States, though the overall impact of these regional differences on the final findings is uncertain.
- For poultry production, GHG emissions have been allocated to both poultry meat and bones. EPA has chosen this allocation method to be consistent with other WARM food waste factors and to represent the waste materials that users of WARM are most likely to generate. However, there are other allocation methods not represented here, including allocating emissions only to boneless poultry meat or to the entire live weight mass of the broiler, resulting in emissions also being allocated to poultry fat and BPM products that are reprocessed into poultry feed.
- EPA's peer review process for the poultry source reduction factors brought to EPA's attention the growing use of distiller's grains as a potential input to poultry feed. Distiller's grains have not been included at this point because these were not included as a feed input in the underlying LCI data used to develop the poultry source reduction. EPA will evaluate information on the use of distiller's grains as it becomes available in future updates to the poultry factors.
- For grain production, upstream energy demand and emissions associated with fertilizer production for nitrogen-based fertilizers are determined from a unit process for a weighted production mix of nitrogen fertilizers used in the United States. In the future, EPA may break this out into impacts by each specific type of nitrogen fertilizer and incorporate more recent LCI data for fertilizer production.
- Fertilizer-related soil emissions were estimated for poultry, grains, fruits and vegetables using the IPCC Tier 1 Method. In the future, EPA will investigate how use of the IPCC Tier 1 method may differ from the current methodology for estimating emissions from soils from fertilizer use in the U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks report.
- Impacts from co-products of fruit and vegetable products were not included in this analysis due to data limitations. For apples, oranges, melons, and tomatoes, the primary RMAM datasets did not include any information about co-products. However, differences between the amount of fruits and vegetables harvested in these scenarios and the final amount available for sale indicates that a portion of the production was unsalable. Due to a lack of data on the pathways

for these fruits and vegetables and their assumed value, EPA determined that the impacts from any possible co-products are outside the scope of this effort.

- Luske 2010 determined that approximately 10 percent (by mass) of the bananas produced within the scope of its assessment were unsuitable for international sale and sold to a separate distributor for a much lower price for local distribution. Relative to the price of the bananas destined for international sale, these bananas had approximately 0.3 percent of the value of the entire yield. Because of the low value and lack of distribution to the United States, EPA deemed that impacts from this co-product were outside of the scope of analysis.
- Though Luske 2010 reported its own estimate for the life-cycle emissions for banana production, EPA supplemented the data and applied a different methodology to maintain consistency with the other fruits and vegetables within the weighted emission factor and with the scope of WARM. First, to narrow the scope of the data to cradle-to-retail, EPA did not assess the impacts of retail storage at the destination country. Second, to make the dataset more relevant to bananas sold within the United States, EPA did not utilize the ocean transport data for bananas shipped to Belgium and Germany from the study. Instead, EPA assumed an average transportation distance from Central American banana plantations to U.S. ports, acquired from a separate study on fruit transportation distances (Bernatz 2009). On average, the port-to-port shipment distance to the United States from Guatemala and Costa Rica, the two largest suppliers of bananas, was approximately 3,094 kilometers per shipment.
- Food products that are discarded at any point from primary production through retail transport could generate GHG impacts through decomposition during landfilling or composting. However, this potential source of GHG emissions is not included in the WARM fruits and vegetables source reduction emission factor for various reasons. First, the fruits and vegetables that are lost or otherwise discarded at the point of production may simply be left on the field and are accounted for in the soil emissions calculations described above. Secondly, USDA (2012b) does not distinguish between the food loss rates at primary production versus those during transportation, and therefore it is unclear what share of the food waste loss occurs during retail transport itself. In its 2010 tomato packaging sustainable materials management study, EPA also found that information on losses at farm and in distribution was limited and in some cases conflicting (EPA 2010). EPA assumes that the share of food waste loss during retail transport is small and that the corresponding GHG impact of its disposal would not have a large impact on the final emission factor.
- Due to lack of available data, emissions from the release of fugitive refrigerants during refrigerated transportation of poultry and fruits and vegetables were estimated based on data developed specific to dairy products (Thoma et al. 2010). However, the emissions burden from fugitive refrigerants likely varies across the different food types modeled in WARM. EPA will evaluate incorporating refrigerated transport data and assumptions specific to different food types modeled in future updates, if available.

1.5.2 Composting

- Due to data and resource constraints, the analysis considers a small sampling of feedstocks and a single compost application (cropland soil). EPA analyzed two types of compost feedstocks—yard trimmings and food scraps—although sewage sludge, animal manure and several other compost feedstocks also may have significant GHG implications. Similarly, it was assumed that compost was applied to degraded agricultural soils growing corn, despite widespread use of compost in specialty crops, land reclamation, silviculture, horticulture and landscaping.

- This analysis did not consider the full range of soil conservation and management practices that could be used in combination with application of compost, and the impacts of those practices on carbon storage. Research indicates that adding compost to agricultural soils in conjunction with various conservation practices enhances the generation of soil organic matter to a much greater degree than applying compost alone. Examples of these conservation practices include conservation tillage, no-till, residue management, crop rotation, wintering and summer fallow elimination.
- In addition to the carbon storage benefits of adding compost to agricultural soils, composting may lead to improved soil quality, improved plant productivity, improved soil water retention and cost savings. As discussed earlier, nutrients in compost tend to foster soil fertility (Brady and Weil, 1999). In fact, composts have been used to establish plant growth on land previously unable to support vegetation. In addition to these biological improvements, compost also may lead to cost savings associated with avoided waste disposal, particularly for feedstocks such as sewage sludge and animal manure.
- This analysis did not consider the differences in compost emissions resulting from composting different food waste types. A future improvement may involve research into developing food type-specific composting factors for WARM.

1.5.3 Landfilling

- WARM currently assumes that 82 percent of MSW landfill CH_4 is generated at landfills with LFG recovery systems (EPA, 2015a). The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate, so the application of landfill gas collection systems at landfills will have an effect on lowering the emission factors presented here over time. WARM is updated annually to account for changes in the percent of MSW landfill CH_4 that is collected at U.S. landfills.
- This analysis did not consider the differences in landfill emissions resulting from landfilling different food waste types. A future improvement may involve research into developing food type-specific landfilling factors for WARM.

1.5.4 Combustion

- Opportunities exist for the combustion system efficiency of WTE plants to improve over time. As efficiency improves, more electricity can be generated per ton of waste combusted (assuming no change in utility emissions per kWh), resulting in a larger utility offset, and the net GHG emissions benefit from combustion of MSW will increase.
- The reported ranges for N_2O emissions from combustion of organics were broad. In some cases, the high end of the range was 10 times the low end of the range. Research has indicated that N_2O emissions vary with the type of waste burned. In the absence of better data on the composition and N_2O emissions from food waste combustion on a national scale in the United States , the average value used for food waste should be interpreted as an approximate value.
- This analysis used the non-baseload mix of electricity generation facilities as the proxy for calculating the GHG emissions intensity of electricity production that is displaced at the margin from energy recovery at WTE plants and LFG collection systems. Actual avoided utility GHG emissions will depend on the specific mix of power plants that adjust to an increase in the supply of electricity, and could be larger or smaller than estimated in these results.

- This analysis did not consider the differences in combustion emissions resulting from combusting different food waste types. A future improvement may involve research into developing food type-specific combustion factors for WARM.

1.5.5 Anaerobic Digestion

- WARM assumes that the biogas generated during anaerobic digestion is used in an internal combustion engine to generate electricity which is used to offset grid electricity. Multiple other uses have been identified for the biogas through EPA's review of literature and stakeholder engagement. These uses were not modeled here.
- WARM assumes that the digestate generated during anaerobically digesting organic waste is applied to agricultural land; however EPA's review of literature and stakeholder engagement identified other uses for digestate beyond land application. These have not been addressed within WARM.
- In discussions with stakeholders and in EPA's review of literature, it was indicated that there was little evidence that different anaerobic digestion reactor configurations have significantly different methane yields. However, the net GHG emissions from anaerobically digesting yard trimmings are sensitive to methane yield assumptions. EPA believes that the modeling approach used in WARM provides reasonable estimates of the GHG emissions to represent a wide range of anaerobic digestion configurations.

1.6 REFERENCES

Barlaz, M.A. (2008). Memorandum to Parties Interested in Carbon Sequestration from Municipal Solid Waste: "Corrections to Previously Published Carbon Storage Factors." February 27, 2008.

Barlaz, M.A. (2005). Letter to Randy Freed, ICF International: "Decomposition of Leaves." June 29, 2005.

Barlaz, M.A. (1998). Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills. *Global Biogeochem. Cycles*, 12 (2): 373–380.

Battagliese, T., Andrade, J., Schulze, I., Uhlman, B., and Barcan, C. (2013). More Sustainable Beef Optimization Project. Phase 1 Final Report, June 2013. Submitted by BASF Corporation.

Bernatz, G. (2009). *Apples, Bananas, and Oranges: Using GIS to Determine Distance Travelled, Energy Use, and Emissions from Imported Fruit*. Volume 11, Papers in Resource Analysis. 16 pp. Saint Mary's University of Minnesota Central Services Press. Winona, MN.

Bernatz, G. (2013). Personal email correspondence with Nikita Pavlenko, ICF. July 12th, 2013.

Boriss, H. (2013). "Citrus Profile." Agricultural Marketing Resource Center.

Brady, N., & R. Weil. (1999). *The Nature and Properties of Soils*. Upper Saddle River, NJ: Prentice Hall.

BSR. (2012). *Clean Cargo Working Group Global Trade Lane Emissions Factors*. Business for Social Responsibility (BSR). August 2012.

Bureau of Transportation Statistics. (2013). "2012 Commodity Flow Survey." Retrieved from: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/commodity_flow_survey/index.html.

Cole, M. (2000). Personal communication between Dr. Michael Cole, University of Illinois, and Randy Freed, ICF Consulting, July 3, 2000.

Ecoinvent Centre. (2007). *Ecoinvent data v2.0*. Ecoinvent reports No.1-25, Swiss Centre for Life Cycle Inventories, Dübendorf, 2007. Retrieved from: www.ecoinvent.org.

EIA. (2013). *Electric Power Annual 2011.* Retrieved from: http://www.eia.gov/electricity/annual/archive/2011/.

EPA. (2015a). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2013.* (EPA 430-R-15-004). Washington, DC: U.S. Government Printing Office. Retrieved from http://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf.

EPA. (2015b). *Advancing Sustainable Materials Management: Facts and Figures 2013.* (EPA530-R-15-002). Washington, DC: U.S. Government Printing Office. Retrieved from http://www.cta.tech/CorporateSite/media/environment/eCycle/2013_advncng_smm_rpt.pdf.

EPA. (2013). *The Landfill Methane Outreach Program (LMOP) LFGE Benefits Calculator.* Available online at: http://www.epa.gov/lmop/projects-candidates/lfge-calculator.html.

EPA. (2010). *Evaluating the Environmental Impacts of Packaging Fresh Tomatoes Using Life-Cycle Thinking & Assessment: A Sustainable Materials Management Demonstration Project.* Final Report. Prepared for the U.S. Environmental Protection Agency. October 29.

EPA. (2006). *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. Washington, DC: U.S. Environmental Protection Agency.

EPA. (1998). *AP-42 Emission Factors for Municipal Solid Waste Landfills – Supplement E.* Washington, DC: U.S. Environmental Protection Agency.

Espinoza-Orias, N., H. Stichnothe, and A. Azapagic. (2011). "The Carbon Footprint of Bread". International Journal of Life Cycle Assessment, (2011) 16:351–365.

Fake, C., K.M. Klonsky, and R.L. De Moura. (2009). *Sample Costs to Produce Mixed Vegetables*. University of California Cooperative Extension. VM-IR-09. Retrieved from: http://coststudies.ucdavis.edu/files/MixedVegIR09.pdf.

FAL. (1994). *The Role of Recycling in Integrated Solid Waste Management to the Year 2000.* Franklin Associates Ltd. (Stamford, CT: Keep America Beautiful, Inc.), September.

Harrington, K. (1997). Personal communication between Karen Harrington, Minnesota Office of Environmental Assistance, and ICF Consulting, October 1997. Value reported by an RDF facility located in Newport, MN.

International EPD System. (2013). "Product Category Rules: Arable Crops (Multiple CPC-Codes)." June 12, 2013. Retrieved from: http://www.environdec.com/en/PCR/Detail/?Pcr=8804#.UrIW9NJDuSo.

International EPD System. (2012). *Product Category Rules—Fruits and Nuts*. Version 1.0. August 23rd, 2012. Retrieved from: http://www.environdec.com/en/PCR/Detail/?Pcr=8235.

IPCC. (2006a). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste*, Chapter 3: Solid Waste Disposal. Intergovernmental Panel on Climate Change. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html.

IPCC. (2006b). "IPCC Guidelines for National Greenhouse Gas Inventories: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application". Retrieved from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf.

ISO. (2006). International Standard 14044: Environmental management – Life Cycle Assessment – Requirements and guidelines. International Organization for Standardization. First edition. July 7, 2006.

Kim, D., G. Thoma, D. Nutter, F. Milani, R. Ulrich, and G. Norris. (2013). "Life cycle assessment of cheese and whey protein in the USA." International Journal of Life Cycle Assessment; 18:1019-1035.

Levis, J. W., Barlaz, M. A., DeCarolis, J. F., Ranjithan, S. R. (2013). What is the optimal way for a suburban U.S. city to sustainably manage future solid waste? Perspectives from a Solid Waste Optimization Life-cycle Framework (SWOLF). Environ. Sci. Technol., submitted.

Luske, B. (2010). Comprehensive Carbon Footprint Assessment Dole Bananas. Soil and More International. Retrieved from: http://dolecrs.com/uploads/2012/06/Soil-More-Carbon-Footprint-Assessment.pdf.

Miller, D. and Y. Wang, eds. (2013). "Carbon and Water Footprint of U.S. Milk, From Farm to Table." International Dairy Journal; 31 (Supplement 1): S1-S100.

National Agriculture Statistics Service (NASS). (2013). "NASS Quick Stats: Grain Yield and Production by State". Retrieved from: http://www.nass.usda.gov/Quick_Stats/.

Nemecek, T., and Kagi, T. (2007). *Life Cycle Inventories of Agricultural Production Systems*. Ecoinvent Report No. 15. Retrieved from: http://db.ecoinvent.org/reports/15_Agriculture.pdf .

O'Connell, N.V., C.E. Kallsen, K.M. Klonsky, and R.L. De Moura. (2009). *Sample Costs to Establish an Orange Orchard and Produce Oranges*. University of California Cooperative Extension. OR-VS-09. Retrieved from: http://coststudies.ucdavis.edu/files/orangevs2009.pdf.

Ockerman, H.W., Hansen, C. L. 2000. Animal By-Product Processing and Utilization (Boca Raton: CRC Press, 2000). Retrieved from: http://books.google.co.in/books?id=1uhZQK_5jeIC&printsec=frontcover#v=onepage&q&f=false.

Pelletier, N. 2008. "Environmental performance in the US broiler poultry sector: Life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions," Agricultural Systems 98 (2008): 67-73.

Pelletier, N. 2010. What's at Steak? Ecological Economic Sustainability and the Ethical, Environmental, and Policy Implications for Global Livestock Production (Dalhousie University, 2010).

Piers Industry Blog. (2013). "U.S. Banana Imports Jump 12% in Q1 2013." Retrieved from: http://content.piers.com/blog/us-banana-imports-rise-sharply.

Smith, C. (2004). "New Market for Baled Rice Straw." American Agriculturist. Retrieved from: http://farmprogress.com/story-new-market-for-baled-rice-straw-9-2951.

Stoddard, C.S., M. LeStrange, B. Aegerter, K.M. Klonsky, and R.L. De Moura. (2007). *Sample Costs to Produce Fresh Market Tomatoes*. University of California Cooperative Extension. TM-SJ-07. Retrieved from: http://coststudies.ucdavis.edu/files/tomatofrmktsj07.pdf.

Thoma, G., et al. (2010). "Global Warming Potential of Fluid Milk Consumed in the US: A Life Cycle Assessment." Innovation Center for U.S. Dairy and University of Arkansas.

USDA. (2013). "Commodity Costs and Returns." U.S. Department of Agriculture Economic Research Service. Retrieved from: http://www.ers.usda.gov/data-products/commodity-costs-and-returns.aspx#.UqtabtJDuSp.

USDA. (2012a). "Estimating Wheat Supply and Food Use". U.S. Department of Agriculture Economic Research Service. Retrieved from: http://www.ers.usda.gov/topics/crops/wheat/estimating-wheat-supply-and-use.aspx#.U5HRAHJdX1Y.

USDA. (2012b). "Food Availability (per Capita) Data System – 2010". U.S. Department of Agriculture Economic Research Service. Retrieved from: http://www.ers.usda.gov/data-products/food-availability-(per-capita)-data-system.aspx#.UqoMEtJDvy4.

USDA LCA Digital Commons. Retrieved from: https://www.lcacommons.gov/.

Van der Voet, E., G. Huppes, and H.A. Udo de Haes. (2009). Allocation Issues in LCA Methodology: A Case Study of Corn Stover-Based Fuel Ethanol. International Journal of Life Cycle Assessment, 14, 529-539. Retrieved from: https://openaccess.leidenuniv.nl/bitstream/handle/1887/15394/chapter%202.pdf?sequence=14.

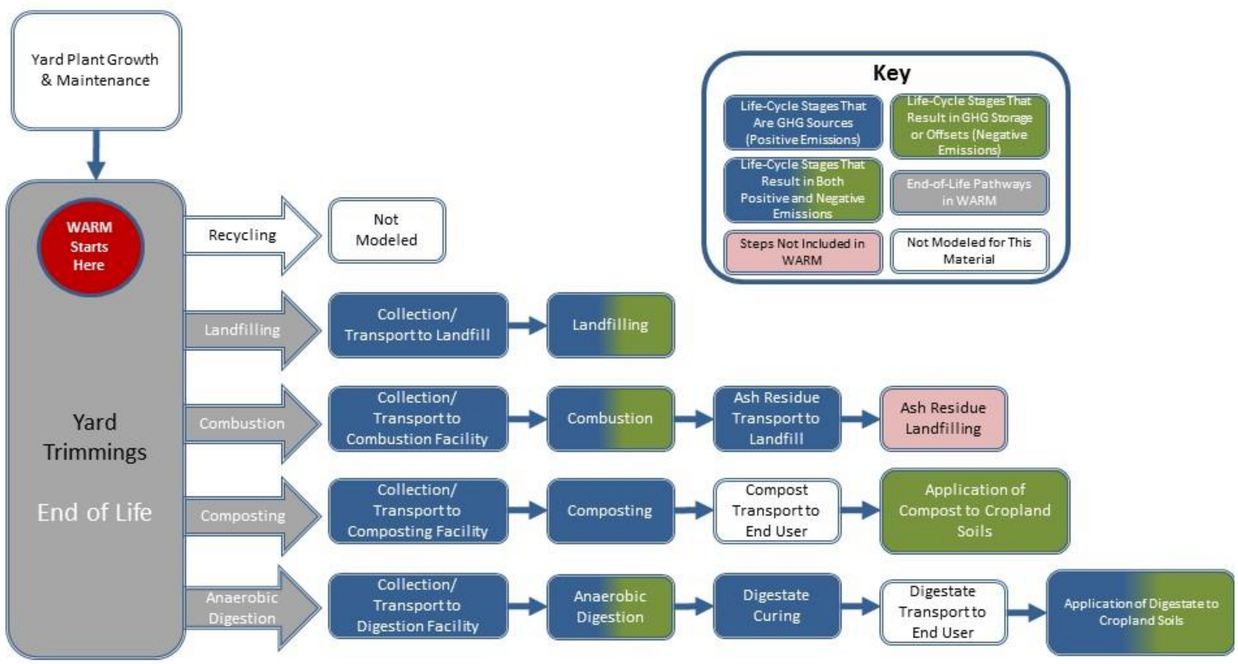
Wunderlich, L., K.M. Klonsky, and R.L. De Moura. (2007). *Sample Costs to Establish and Produce Apples.* University of California Cooperative Extension. AP-IR-07. Retrieved from: http://cecentralsierra.ucanr.edu/files/60510.pdf.

2 YARD TRIMMINGS

2.1 INTRODUCTION TO WARM AND YARD TRIMMINGS

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for yard trimmings beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated yard trimmings in the following four materials management options: composting, landfilling, combustion, and anaerobic digestion. Exhibit 2-1 shows the general outline of materials management pathways for these materials in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Composting, Landfilling, Combustion, and Anaerobic Digestion, see the chapters devoted to those processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

Exhibit 2-1: Life Cycle of Yard Trimmings in WARM



Yard trimmings fall under the category of "organics" in WARM. Although paper, wood products and plastics are organic materials in the chemical sense, these categories of materials have very different life-cycle and end-of-life characteristics than yard trimmings and are treated separately in the municipal solid waste (MSW) stream. Yard trimmings are grass clippings, leaves and branches. WARM also calculates emission factors for a mixed organics category, which is a weighted average of the food waste and yard trimmings emission factors for the waste management pathways relevant to both materials (i.e., landfilling, combustion, composting, and anaerobic digestion). For more information, see the Food Waste chapter. The weighting is based on the relative prevalence of these two categories in the waste stream, according to the latest (2015a) version of EPA's annual report, *Advancing Sustainable Materials Management: Facts and Figures,* and as shown in column (c) of Exhibit 2-2.[17]

[17] Note that, unlike for other materials in WARM, the "mixed" category is based on organics' relative prevalence among materials *generated* rather than *recovered*. This is because WARM assumes that users interested in

Exhibit 2-2: Relative Prevalence of Yard Trimmings and Food Waste in the Waste Stream in 2013

(a) Material	(b) Generation (Short Tons)	(c) % of Total Organics Generation	(d) Recovery (Short Tons)	(e) Recovery Rate
Food Waste	37,060,000	52%	1,840,000	5.0%
Yard Trimmings	33,960,000	48%	20,600,000	60.2%

Source: EPA (2015a).

2.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The streamlined life-cycle GHG analysis in WARM focuses on the waste generation point, or the moment a material is discarded, as the reference point and only considers upstream GHG emissions when the production of new materials is affected by materials management decisions.[18] Recycling and source reduction are the two materials management options that impact the upstream production of materials, and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

WARM does not include recycling or source reduction management options for yard trimmings. Yard trimmings cannot be recycled in the traditional sense and sufficient data are not currently available to model the material and energy inputs for trees and grass prior to becoming yard trimmings waste. As Exhibit 2-3 illustrates, most of the GHG sources relevant to yard trimmings in this analysis are contained in the waste management portion of the life cycle assessment, with the exception of increased soil carbon storage associated with composting of yard trimmings.

Exhibit 2-3: Yard Trimmings GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Yard Trimmings	GHG Sources and Sinks Relevant to Yard Trimmings		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	Not modeled in WARM due to data limitations		
Recycling	Not applicable since yard trimmings cannot be recycled		
Composting	Not applicable	**Offsets** • Increase in soil carbon storage	**Emissions** • Transport to compost facility • Compost machinery
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Combustion-related nitrous oxide **Offsets** • Avoided utility emissions

composting would be dealing with a mixed organics category that is closer to the current rate of generation, rather than the current rate of recovery. Since the fraction of recovered food waste is so low, if the shares of yard trimmings and food waste recovered were used, the mixed organics factor would be essentially the same as the yard trimmings factor, rather than a mix of organic materials.

[18] The analysis is streamlined in the sense that it examines GHG emissions only and is not a comprehensive environmental analysis of all emissions from materials management.

Materials Management Strategies for Yard Trimmings	GHG Sources and Sinks Relevant to Yard Trimmings		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery • Landfill methane **Offsets** • Avoided utility emissions due to landfill gas combustion • Landfill carbon storage
Anaerobic Digestion	NA	**Offsets** Increase in soil carbon storage from application of digestate to soils	**Emissions** • Transport to anaerobic digester • Equipment use and biogas leakage at anaerobic digester • CH_4 and N_2O emissions during digestate curing • N_2O emissions from land application of digestate **Offsets** • Avoided utility emissions due to biogas to energy • Avoided synthetic fertilizer use due to land application of digestate

NA = Not applicable

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 2-3 to calculate net GHG emissions per short ton of organic materials generated. GHG emissions arising from the consumer's use of any product are not considered in WARM's life-cycle boundaries. Exhibit 2-4 presents the net GHG emission factors for each materials management strategy calculated in WARM for organic materials.

Additional discussion on the detailed methodology used to develop these emission factors may be found in sections 2.4.1 through 2.4.6.

Exhibit 2-4: Net Emissions for Yard Trimmings and Mixed Organics under Each Materials Management Option ($MTCO_2E$/Short Ton)

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions[a]
Yard Trimmings	NA	NA	-0.15	-0.18	-0.18	-0.09
Grass	NA	NA	-0.15	-0.18	0.13	0.00
Leaves	NA	NA	-0.15	-0.18	-0.52	-0.14
Branches	NA	NA	-0.15	-0.18	-0.51	-0.23
Mixed Organics	NA	NA	-0.16	-0.16	0.20	-0.07

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
NA = Not applicable.
[a] Emission factors for dry digestion with curing of digestate before land application

2.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

WARM does not consider GHG emissions associated with raw materials acquisition or manufacturing for yard trimmings because this life-cycle stage is only applicable to the source reduction and recycling pathways, which are not modeled in WARM for yard trimmings, as explained previously.

2.4 MATERIALS MANAGEMENT METHODOLOGIES

Landfilling, composting, combustion, and anaerobic digestion are the four management options used to manage yard trimmings. Residential and commercial land management activities such as landscaping and gardening generate yard trimmings, which are typically either composted onsite, shredded with a mulching mower and used for landscaping onsite, or placed on the curb for transport to central facilities for either combustion, composting landfilling, or anaerobic digestion. Since 1990, many municipalities have implemented programs and policies designed to divert yard trimmings from landfills, and as a result, yard trimmings are increasingly composted or mulched onsite or collected for mulching and composting at a central facility (EPA, 2015a).

2.4.1 Source Reduction

Unlike food waste, yard trimmings do not generally require extensive material or fossil fuel energy inputs prior to becoming waste. While some material and energy inputs are used during the life of trees and grasses (i.e., fuel for lawn mowing, fertilizers), sufficient data needed to model raw material acquisition and production emissions or storage from yard trimmings are not currently available. Therefore, WARM does not consider GHG emissions or storage associated with source reduction of yard trimmings.

2.4.2 Recycling

Recycling, as modeled in WARM (i.e., producing new products using end-of-life materials), does not commonly occur with the yard trimmings materials modeled in WARM. Therefore, WARM does not consider GHG emissions or storage associated with the traditional recycling pathway for yard trimmings. However, yard trimmings can be converted to compost, a useful soil amendment, as described in section 2.4.3.

2.4.3 Composting

2.4.3.1 Developing the Emissions Factor for the Composting of Yard Trimmings

Composting yard trimmings results in increased carbon storage when compost is applied to soils. The net composting emission factor is calculated as the sum of emissions from transportation, processing of compost, the carbon storage resulting from compost application, and the fugitive emissions of methane (CH_4) and nitrous oxide (N_2O) produced during decomposition.[19] WARM currently assumes that carbon dioxide (CO_2) emissions that occur as a result of the composting process are biogenic and are not counted (for further explanation, see the text box on biogenic carbon in the Introduction and Background chapter). Exhibit 2-5 details these components for yard trimmings and mixed organics. For additional information on composting in WARM, see the Composting chapter. The two emission sources and one emission sink resulting from the composting of organics are:

- *Nonbiogenic CO_2 emissions from collection and transportation*: Transportation of yard trimmings to the central composting site results in nonbiogenic CO_2 emissions.[20] In addition, during the composting process the compost is mechanically turned, and the operation of this equipment also results in nonbiogenic CO_2 emissions.

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

[20] Transportation emissions from delivery of finished compost from the composting facility to its final destination were not counted.

- *Fugitive Emissions of CH_4 and N_2O:* Microbial activity during composting decomposes waste into a variety of compounds, which generates small amounts of CH_4 and N_2O gas, a net contributor to the GHG emissions associated with the composting pathway (for more information on fugitive emissions, please refer to the Composting chapter).
- *Carbon Storage*: When compost is applied to the soil, some of the carbon contained in the compost does not decompose for many years and therefore acts as a carbon sink.

Exhibit 2-5: Components of the Composting Net Emission Factor for Yard Trimmings and Mixed Organics

Composting of Post-Consumer Material (GHG Emissions in $MTCO_2E$/Short Ton)						
Material	**Raw Material Acquisition and Manufacturing (Current Mix of Inputs)**	**Transportation to Composting**	**Compost CO_2**	**Compost CH_4 and N_2O**	**Soil Carbon Storage**	**Net Emissions (Post-Consumer)**
Yard Trimmings[a]	NA	0.02	–	0.07	-0.24	-0.15
Grass	NA	0.02	–	0.07	-0.24	-0.15
Leaves	NA	0.02	–	0.07	-0.24	-0.15
Branches	NA	0.02	–	0.07	-0.24	-0.15
Mixed Organics	NA	0.02	–	0.07	-0.24	-0.16

NA = Not applicable.
[a] Yard trimmings are a 50%, 25%, 25% weighted average of grass, leaves, and branches, based on U.S. generation data from EPA (2015a).

Transportation energy emissions occur when fossil fuels are used to collect and transport yard trimmings to a composting facility, and then to operate the composting equipment that turns the compost. To calculate the emissions, WARM relies on assumptions from FAL (1994) for the equipment emissions and NREL's US Life Cycle Inventory Database (USLCI) (NREL 2015). The NREL emission factor assumes a diesel, short-haul truck. Exhibit 2-6 provides the emissions associated with transporting and turning compost.

Exhibit 2-6: Emissions Associated with Transporting and Turning Compost

Material	Diesel Fuel Required to Collect and Transport One Ton (million Btu)[a]	Diesel Fuel Required to Turn the Compost Piles (million Btu)[a]	Total Energy Required for Composting (million Btu)	Total CO_2 Emissions from Composting ($MTCO_2E$)
All Material Types	0.04	0.22	0.26	0.02

[a] Based on estimates found on Table I-17 on page I-32 of FAL (1994).

WARM currently assumes that carbon from compost remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils (the "soil carbon restoration" effect)[21] and carbon stored in non-reactive humus compounds (the "increased humus formation" effect)[22]. The carbon values from the soil carbon restoration effect are scaled according to the percentage of compost that is passive, or non-reactive, which is assumed to be 52 percent (Cole, 2000). The weighted soil restoration value is then added to the increased humus formation effect in order to estimate the total sequestration value associated with composting. The inputs to the calculation are shown in Exhibit 2-7.

[21] EPA evaluated the soil carbon restoration effect using Century, a plant-soil ecosystems model that simulates long-term dynamics of carbon, nitrogen, phosphorous and sulfur in soils. For more information, see the Composting chapter.

[22] EPA evaluated the increased humus formation effect based on experimental data compiled by Dr. Michael Cole of the University of Illinois. These estimates accounted for both the fraction of carbon in the compost that is considered passive and the rate at which passive carbon is degraded into CO_2. For more information, see the Composting chapter.

Exhibit 2-7: Soil Carbon Effects as Modeled in Century Scenarios ($MTCO_2E$/Short Ton of Organics)

Scenario	Soil Carbon Restoration			Increased Humus Formation	Net Carbon Flux[a]
	Unweighted	Proportion of C that is Not Passive	Weighted estimate		
Annual application of 32 tons of compost per acre	-0.04	48%	-0.07	-0.17	-0.24

[a] The net carbon flux sums each of the carbon effects together and represents the net effect of composting a short ton of yard trimmings in $MTCO_2E$.

The nonbiogenic CO_2 emissions from transportation, collection and compost turning are added to the compost carbon sink in order to calculate the net composting GHG emission factors for each organics type. As Exhibit 2-5 illustrates, WARM estimates that the net composting GHG factor for yard trimmings is the same for all sources of compost.

2.4.4 Combustion

2.4.4.1 Developing the Emissions Factor for the Combustion of Yard Trimmings

Combusting organics results in a net emissions offset (negative emissions) due to the avoided utility emissions associated with energy recovery from waste combustion. The combustion net emission factor is calculated as the sum of emissions from transportation of waste to the combustion facility, nitrous oxide emissions from combustion, and the avoided CO_2 emissions from energy recovery in a waste-to-energy (WTE) plant. Although combustion also releases the carbon contained in yard trimmings in the form of CO_2, these emissions are considered biogenic and are not included in the WARM net emission factor. Exhibit 2-8 presents these components of the net combustion emission factor for each organic material. For additional information on combustion in WARM, see the Combustion chapter. The two emissions sources and one emissions offset that result from the combusting of organics are:

- *CO_2 emissions from transportation of waste.* Transporting waste to the combustion facility and transporting ash from the combustion facility to a landfill both result in transportation CO_2 emissions.
- *Nitrous oxide emissions from combustion.* Waste combustion results in measurable emissions of nitrous oxide (N_2O), a GHG with a high global warming potential (EPA, 2015b).
- *Avoided utility CO_2 emissions*. Combustion of MSW with energy recovery in a WTE plant also results in *avoided* CO_2 emissions at utilities.

Exhibit 2-8: Components of the Combustion Net Emission Factor for Yard Trimmings and Mixed Organics ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Yard Trimmings	NA	0.01	–	0.04	-0.22	–	-0.18
Grass	NA	0.01	–	0.04	-0.22	–	-0.18
Leaves	NA	0.01	–	0.04	-0.22	–	-0.18
Branches	NA	0.01	–	0.04	-0.22	–	-0.18
Mixed Organics	NA	0.01	–	0.04	-0.20	–	-0.16

NA = Not applicable

For the CO_2 emissions from transporting waste to the combustion facility, and ash from the combustion facility to a landfill, EPA used an estimate of 60 lbs CO_2 per ton of MSW for transportation of mixed MSW developed by FAL (1994). EPA then converted the Franklin Associates estimate from pounds of CO_2 per ton of mixed MSW to $MTCO_2E$ per ton of mixed MSW and applied it to estimate CO_2 emissions from transporting one short ton of mixed MSW and the resulting ash. WARM assumes that transportation of yard trimmings and mixed organics uses the same amount of energy as transportation of mixed MSW.

Studies compiled by the Intergovernmental Panel on Climate Change (IPCC) show that MSW combustion results in measurable emissions of N_2O, a GHG with a high global warming potential (IPCC, 2006). The IPCC compiled reported ranges of N_2O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. WARM averages the midpoints of each range and converts the units to $MTCO_2E$ of N_2O per ton of MSW. Because the IPCC did not report N_2O values for combustion of individual components of MSW, WARM uses the same value for yard trimmings and mixed organics.

Most WTE plants in the United States produce electricity and only a few cogenerate electricity and steam (EPA, 2006). In this analysis, EPA assumes that the energy recovered with MSW combustion would be in the form of electricity, as shown in Exhibit 2-9. The exhibit shows emission factors for mass burn facilities (the most common type of WTE plant). EPA used three data elements to estimate the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy content of each waste material, (2) the combustion system efficiency in converting energy in MSW to delivered electricity, and (3) the electric utility CO_2 emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants.

Exhibit 2-9: Utility GHG Emissions Offset from Combustion of Yard Trimmings

(a) Material	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity ($MTCO_2E$/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted ($MTCO_2E$/Short Ton) ($e = b \times c \times d$)
Yard Trimmings	5.6	17.8%	0.22	0.22

To estimate the gross GHG emissions per ton of waste combusted, EPA sums emissions from combustion N_2O and transportation CO_2. These emissions were then added to the avoided utility emissions in order to calculate the net GHG emission factor, shown in Exhibit 2-9. WARM estimates that combustion of yard trimmings results in a net emission reduction.

2.4.5 Landfilling

2.4.5.1 Developing the Emissions Factor for the Landfilling of Yard Trimmings

Landfilling organics can result in either net carbon storage or net carbon emissions, depending on the specific properties of the organic material. The landfilling emissions factor is calculated as the sum of emissions from transportation of waste to the landfill and operation of landfill equipment, methane emissions from landfilling, and the carbon storage resulting from undecomposed carbon remaining in landfills. Exhibit 2-10 presents the components of the landfilling emission factor for each yard trimmings material. For additional information on landfilling in WARM, see the Landfilling chapter. The two emissions sources and one emissions sink that result from the landfilling of organics are:

- *Transportation of organic waste*. Transportation of yard trimmings to landfill results in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes.
- *Methane emissions from landfilling*. When yard trimmings are landfilled, anaerobic bacteria degrade the materials, producing CH_4 and CO_2, collectively referred to as landfill gas (LFG). Only the CH_4 portion of LFG is counted in WARM, because the CO_2 portion is considered of biogenic origin and therefore is assumed to be offset by CO_2 captured by regrowth of the plant sources of the material.
- *Landfill carbon storage.* Because yard trimmings are not completely decomposed by anaerobic bacteria, some of the carbon in them remains stored in the landfill. This stored carbon constitutes a sink (i.e., negative emissions) in the net emission factor calculation.

Exhibit 2-10: Landfilling Emission Factors for Yard Trimmings and Mixed Organics ($MTCO_2E$/Short Ton)

Material Type	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided CO_2 Emissions from Energy Recovery	Landfill Carbon Storage	Net Emissions (Post-Consumer)
Yard Trimmings	–	0.02	0.36	-0.03	-0.54	-0.18
Grass	–	0.02	0.27	-0.02	-0.14	0.13
Leaves	–	0.02	0.28	-0.02	-0.79	-0.52
Branches	–	0.02	0.60	-0.06	-1.06	-0.51
Mixed Organics	–	0.02	0.53	-0.07	-0.30	0.20

Note: The emission factors for landfill CH_4 presented in this table assume that the methane management practices and decay rates at the landfill are an average of national practices.
Negative values denote GHG emission reductions or carbon storage.
NA = Not applicable; upstream raw material acquisition and manufacturing GHG emissions are not included in landfilling since the life-cycle boundaries in WARM start at the point of waste generation and landfilling does not affect upstream GHG emissions.

Transportation energy emissions occur when fossil fuels are used to collect and transport yard trimmings to a landfill, and then to operate the landfill equipment. To calculate the emissions, WARM relies on assumptions from FAL (1994) for the equipment emissions and NREL's US Life Cycle Inventory Database (USLCI) (NREL 2015). The NREL emission factor assumes a diesel, short-haul truck. EPA then converted the Franklin Associates estimate from pounds of CO_2 per ton of mixed MSW to $MTCO_2E$ per ton of mixed MSW and applied it to estimate CO_2 emissions from transporting one short ton of mixed MSW. WARM assumes that transportation of yard trimmings uses the same amount of energy as transportation of mixed MSW.

WARM calculates CH_4 emission factors for landfilled materials based on the CH_4 collection system type installed at a given landfill. There are three categories of landfills modeled in WARM: (1) landfills that do not recover LFG, (2) landfills that collect the LFG and flare it without recovering the flare energy, and (3) landfills that collect LFG and combust it for energy recovery by generating electricity. The Excel version of WARM allows users to select component-specific decay rates based on different assumed moisture contents of the landfill and landfill gas collection efficiencies for a series of landfill management scenarios. The tables in this section show values using the national average moisture conditions, based on the national average precipitation at landfills in the United States and for landfill gas collect efficiency from "typical" landfill operations in the United States. The decay rate and management scenario assumed influences the landfill gas collection efficiency. For further explanation, see the Landfilling chapter.

Exhibit 2-11 depicts the emission factors for each LFG collection type based on the national average landfill moisture scenario and "typical" landfill management operations. Overall, landfills that do not collect LFG produce the most CH_4 emissions. The emissions generated per short ton of material drop by approximately half for yard trimmings if the landfill recovers and flares CH_4 emissions. These emissions are even lower in landfills where LFG is recovered for electricity generation because LFG recovery offsets emissions from avoided electricity generation.[23]

Exhibit 2-11: Landfill CH_4 Emissions for Three Different Methane Collection Systems, National "Average" Landfill Moisture Conditions, Typical Landfill Management Operations, and National Average Grid Mix ($MTCO_2E$/Wet Short Ton)

Material	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electric Generation
Yard Trimmings	0.59	0.28	0.24
Grass	0.51	0.25	0.23
Leaves	0.59	0.26	0.22
Branches	0.77	0.38	0.26

Note: Negative values denote GHG emission reductions or carbon storage.

A portion of the carbon contained in yard trimmings does not decompose after disposal and remains stored in the landfill. Because this carbon storage would not normally occur under natural conditions (virtually all of the carbon in the organic material would be released as CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic carbon sink. The carbon storage associated with each material type depends on the initial carbon content, the extent to which that carbon decomposes into CH_4 in landfills, and temperature and moisture conditions in the landfill. The background and details of the research underlying the landfill carbon storage factors are detailed in the Landfilling chapter. As Exhibit 2-12 illustrates, branches and leaves result in the highest amount of carbon storage.

Exhibit 2-12: Calculation of the Carbon Storage Factor for Landfilled Yard Trimmings

(a) Material	(b) Ratio of Carbon Storage to Dry Weight (grams of Carbon Stored/dry gram of Material)[a]	(c) Ratio of Dry Weight to Wet Weight	(d) Ratio of Carbon Storage to Wet Weight (grams of Carbon/wet gram of Material) (d = b × c)	(e) Amount of Carbon Stored ($MTCO_2E$ per Wet Short Ton)
Yard Trimmings				0.54
Grass	0.24	0.18	0.04	0.14
Leaves	0.39	0.62	0.24	0.79
Branches	0.38	0.84	0.32	1.06

Note: Yard trimmings are calculated as a weighted average of grass, leaves and branches, currently based on an estimate in the *Facts and Figures* report for 2007 (EPA, 2008, p. 58). This information is not updated annually by EPA.
[a] Based on estimates developed by James W. Levis, Morton Barlaz, Joseph F. DeCarolis, and S. Ranji Ranjithan at North Carolina State University; see Levis et al. (2013).

The landfill CH_4 and transportation emissions sources are added to the landfill carbon sink in order to calculate the net GHG landfilling emission factors for each yard trimmings material, shown in the final three columns of

Exhibit 2-13 for landfills equipped with different LFG collection systems. The final net emission factors indicate that landfilling leaves and branches results in a net carbon sink. This negative net

[23] These values include a utility offset credit for electricity generation that is avoided by capturing and recovering energy from landfill gas to produce electricity. The utility offset credit is calculated based on the non-baseload GHG emissions intensity of U.S. electricity generation, since it is non-baseload power plants that will adjust to changes in the supply of electricity from energy recovery at landfills.

emission factor is due to the fact that these materials do not readily degrade in landfills and a substantial fraction of the carbon in these materials remains in the landfill permanently.

Exhibit 2-13: Components of the Landfill Emission Factor for the Three Different Methane Collection Systems Typically Used In Landfills ($MTCO_2E$/Short Ton)

(a)	(b) Net GHG Emissions from CH_4 Generation			(c)	(d)	(e) Net GHG Emissions from Landfilling (e = b + c + d)		
Material	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electric Generation	Net Landfill Carbon Storage	GHG Emissions From Transportation	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Yard Trimmings	0.73	0.35	0.29	-0.54	0.02	0.21	-0.17	-0.22
Grass	0.51	0.25	0.23	-0.14	0.02	0.39	0.12	0.10
Leaves	0.59	0.26	0.22	-0.79	0.02	-0.18	-0.51	-0.55
Branches	1.30	0.65	0.44	-1.06	0.02	0.26	-0.39	-0.61

Note: Negative values denote GHG emission reductions or carbon storage.

2.4.6 Anaerobic Digestion

2.4.6.1 Developing the Emissions Factor for the Anaerobic Digestion of Food Waste

The anaerobic digestion emissions factor is calculated as the sum of emissions from transportation of waste to the anaerobic digester and operation of anaerobic digester equipment, methane emissions from anaerobic digesting, the carbon storage resulting from applying the digestate to soil, the net electricity export to grid and fertilizer offsets. Due to the high amount of preprocessing that would be required, EPA assumes that wet digester operators do not use yard trimmings as a feedstock. Therefore dry digestion is the only digestion option for yard trimmings and mixed organics. Exhibit 2-14**: Dry Anaerobic Digestion Emission Factors for Yard Trimmings with Digestate Curing ($MTCO_2E$/Short Ton)** presents these components of the anaerobic digestion emission factor for yard trimmings and mixed organics with digestate curing and Exhibit 2-15 with digestate directly applied to land. For additional information on anaerobic digestion in WARM, see the Anaerobic Digestion chapter. The three emissions sources and three emissions sink that result from the anaerobically digesting food waste are:

- *Transportation Energy*. WARM includes emissions associated with transporting and anaerobic digestion of the material. Transportation energy emissions occur when fossil fuels are combusted to collect and transport material to the anaerobic digestion facility, to transport digestate for land application, and to operate on-site equipment for curing and spreading digestate.
- *Process Energy.* Preprocessing includes grinding, screening and mixing the feedstock before they are fed into the reactor. The emissions associated with electricity and diesel consumption during preprocessing and operation are assessed in WARM for dry digesters. WARM estimates the emissions associated with two scenarios for digestate beneficial use: curing the digestate and applying the resulting compost to agricultural lands, or directly applying digestate to agricultural lands without curing.

- *Avoided Utility Emissions.* Methane biogas is produced during the digestion process and collected for combustion. WARM models the recovery of biogas for electricity generation and assumes that this electricity offsets non-baseload electricity generation in the power sector.
- *Avoided Fertilizer Application.* The application of digestate to agricultural lands is able to offset a portion of the synthetic fertilizer application needed for agricultural lands due to its high nutrient content. WARM includes avoided fertilizer offsets for both nitrogen and phosphorous in synthetic fertilizers.
- *Process Non-Energy.* Fugitive emissions occur at the digester, during the curing process, and after land application.
- *Soil Carbon Storage.* Similar to carbon from compost applied to agricultural lands, EPA assumes that carbon from digestate applied to agricultural lands remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils and carbon stored in non-reactive humus compounds.

Exhibit 2-14: Dry Anaerobic Digestion Emission Factors for Yard Trimmings with Digestate Curing ($MTCO_2E$/Short Ton)

Material	Process Energy	Avoided Utility Emissions	Avoided Fertilizer Application	Soil Carbon Storage	Process Non-Energy	Transportation Energy	Net Emissions (Post–Consumer)
Yard Trimmings	0.02	-0.04	-0.01	-0.16	0.09	0.00	-0.09
Grass	0.02	-0.04	-0.01	-0.04	0.07	0.00	0.00
Leaves	0.02	-0.02	-0.01	-0.24	0.10	0.00	-0.14
Branches	0.02	-0.06	-0.01	-0.31	0.13	0.00	-0.23
Mixed Organics	0.02	-0.10	-0.01	-0.09	0.11	0.00	-0.07

Negative values denote GHG emission reductions or carbon storage.

Exhibit 2-15: Dry Anaerobic Digestion Emission Factors for Yard Trimmings with Direct Land Application ($MTCO_2E$/Short Ton)

Material	Process Energy	Avoided Utility Emissions	Avoided Fertilizer Application	Soil Carbon Storage	Process Non-Energy	Transportation Energy	Net Emissions (Post–Consumer)
Yard Trimmings	0.02	-0.04	-0.01	-0.38	0.06	0.00	-0.35
Grass	0.02	-0.04	-0.01	-0.10	0.06	0.00	-0.06
Leaves	0.02	-0.02	-0.01	-0.58	0.06	0.00	-0.53
Branches	0.02	-0.06	-0.01	-0.75	0.07	0.00	-0.73
Mixed Organics	0.02	-0.10	-0.01	-0.22	0.09	0.00	-0.22

WARM accounts for the GHG emissions resulting from fossil fuels used in vehicles collecting and transporting waste to the anaerobic digestion facility. Diesel is used for transporting the feedstock and solids to the anaerobic digester. To calculate the emissions, WARM relies on assumptions NREL's US Life Cycle Inventory Database (USLCI) (NREL 2015). The NREL emission factor assumes a diesel, short-haul truck.

The recovery of heat and electricity from the combusted biogas offsets the combustion of other fossil fuel inputs. WARM assumes that the combusted biogas produces electricity that offsets non-baseload electricity generation. Electricity generation from combustion of biogas is assumed to be unavailable for 15% of operation time and the process is assumed to be 29% efficient (EPA 2013). The methane generated and electricity exported to the grid is shown in Exhibit 2-16.

Exhibit 2-16: Methane Generation, Treatment and Use by Material Type for Dry Digestion

Material	Mass of Methane Generated (kg/ton)	Mass of Methane Leaked (kg/ton)	Mass of Methane Flared (kg/ton)	Mass of Methane Combusted for Energy (kg/ton)	Energy from Combusted Methane (MMBtu/ton)	Electricity Generation (kWh/ton)	Net Electricity to the Grid (kWh/ton)
Yard Trimmings	20.7	0.41	3.04	17.3	0.81	69.6	51.5
Grass	20.5	0.41	2.99	17.06	0.81	68.8	50.6
Leaves	13.1	0.26	1.91	10.9	0.52	44.0	25.9
Branches	28.9	0.58	4.26	24.1	1.14	97.1	78.9
Mixed Organics	41.1	0.81	6.03	34.3	1.62	138	120

If the digestate is cured before land application, the solids are aerobically cured in turned windrows. The resulting compost is then screened, transported to agriculture lands, and used in place of a portion of the conventional nitrogen and phosphorus fertilizer that would be needed for the same agricultural lands. Diesel fuel is consumed during this process. If the digestate is not cured, it is directly applied to agricultural lands.

EPA assumes that digestate applied to agricultural land allows for some synthetic fertilizer use to be avoided. WARM includes avoided fertilizer offsets for land application of the digestate generated from anaerobic digestion but not for compost generated from composting due to the difference in feedstocks used for each material management pathway, shown in Exhibit 2-17. Further information can be found in Anaerobic Digestion chapter.

Exhibit 2-17: Nitrogen and Phosphorous Fertilizer Offset by Material Type

Material	Nitrogen Fertilizer Offset (kg N/ton)	Phosphorous Fertilizer Offset (kg P/ton)	Nitrogen Fertilizer Offset ($MTCO_2e$/ton)	Phosphorous Fertilizer Offset ($MTCO_2e$/ton)
Yard Trimmings	0.643	0.844	-0.005	-0.001
Grass	0.628	0.323	-0.005	-0.001
Leaves	0.626	1.218	-0.005	-0.002
Branches	0.691	1.511	-0.006	-0.002
Mixed Organics	0.873	1.074	-0.007	-0.002

WARM calculates the carbon storage impact of direct storage of carbon in depleted soils and carbon stored in non-reactive humus compounds separately and then sums them to estimate the carbon storage factor associated with each short ton of organics composted. For more information on carbon storage calculations, see the Composting chapter, which includes information on the Century model framework and simulations.

To estimate the gross GHG emissions per ton of waste combusted, EPA sums emissions from transportation, processing and operations, and fugitive emissions. These emissions were then added to the avoided utility emissions, avoided fertilizer application and soil carbon storage in order to calculate the net GHG emission factor, shown in Exhibit 2-14**: Dry Anaerobic Digestion Emission Factors for Yard Trimmings with Digestate Curing ($MTCO_2E$/Short Ton)** and Exhibit 2-15. WARM estimates that anaerobic digestion of yard trimmings results in a net emission reduction for both the curing and non-curing scenarios.

2.5 LIMITATIONS

The results of the analysis presented in this chapter are limited by the reliability of the various data elements used. This section details limitations, caveats and areas of current and future research.

2.5.1 Composting

EPA is currently conducting research into process emissions from composting, carbon storage due to compost application, and other issues that are relevant to these calculations.

- As in the other chapters of this report, the GHG impacts of composting reported in this chapter evaluate emissions relative to other possible disposal options for yard trimmings (i.e., landfilling and combustion). This assumes that yard trimmings will be collected for end-of-life management by one of these alternative materials management practices. Yard trimmings, however, can also be simply left on the ground to decompose. This pathway is not modeled in WARM, since EPA would need to analyze the effect of decomposing yard trimmings in their home soil—and the associated soil carbon storage benefits—to develop absolute GHG emission factors for composting yard trimmings at a central facility relative to a baseline of leaving yard trimmings on the ground where they fall.
- Due to data and resource constraints, the analysis considers a small sampling of feedstocks and a single compost application (cropland soil). EPA analyzed two types of compost feedstocks—yard trimmings and food waste—although sewage sludge, animal manure and several other compost feedstocks also may have significant GHG implications. Similarly, it was assumed that compost was applied to degraded agricultural soils growing corn, despite widespread use of compost in specialty crops, land reclamation, silviculture, horticulture and landscaping.
- This analysis did not consider the full range of soil conservation and management practices that could be used in combination with application of compost, and the impacts of those practices on carbon storage. Research indicates that adding compost to agricultural soils in conjunction with various conservation practices enhances the generation of soil organic matter to a much greater degree than applying compost alone. Examples of these conservation practices include conservation tillage, no-till, residue management, crop rotation, wintering and summer fallow elimination.
- In addition to the carbon storage benefits of adding compost to agricultural soils, composting may lead to improved soil quality, improved plant productivity, improved soil water retention and cost savings. As discussed earlier, nutrients in compost tend to foster soil fertility (Brady and Weil, 1999). In fact, composts have been used to establish plant growth on land previously unable to support vegetation. In addition to these biological improvements, compost also may lead to cost savings associated with avoided waste disposal, particularly for feedstocks such as sewage sludge and animal manure.

2.5.2 Landfilling

- WARM currently assumes that 82 percent of MSW landfill CH_4 is generated at landfills with LFG recovery systems (EPA, 2015b). The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate, so the application of landfill gas collection systems at landfills will have an effect on lowering the emission factors presented here over time. WARM is updated annually to account for changes in the percent of MSW landfill CH_4 that is collected at U.S. landfills.

2.5.3 Combustion

- Opportunities exist for the combustion system efficiency of WTE plants to improve over time. As efficiency improves, more electricity can be generated per ton of waste combusted (assuming no change in utility emissions per kWh), resulting in a larger utility offset, and the net GHG emissions benefit from combustion of MSW will increase.
- The reported ranges for N_2O emissions from combustion of organics were broad. In some cases, the high end of the range was ten times the low end of the range. Research has indicated that N_2O emissions vary with the type of waste burned. In the absence of better data on the composition and N_2O emissions from organics combustion on a national scale in the United States , the average value used for yard trimmings should be interpreted as an approximate value.
- This analysis used the non-baseload mix of electricity generation facilities as the proxy for calculating the GHG emissions intensity of electricity production that is displaced at the margin from energy recovery at WTE plants and LFG collection systems. Actual avoided utility GHG emissions will depend on the specific mix of power plants that adjust to an increase in the supply of electricity, and could be larger or smaller than estimated in these results.

2.5.4 Anaerobic Digestion

- WARM assumes that the biogas generated during anaerobic digestion is used in an internal combustion engine to generate electricity which is used to offset grid electricity. Multiple other uses have been identified for the biogas through EPA's review of literature and stakeholder engagement. These uses were not modeled here.
- WARM assumes that the digestate generated during anaerobically digesting organic waste is applied to agricultural land; however EPA's review of literature and stakeholder engagement identified other uses for digestate beyond land application. These have not been addressed within WARM.
- In discussions with stakeholders and in EPA's review of literature, it was indicated that there was little evidence that different anaerobic digestion reactor configurations have significantly different methane yields. However, the net GHG emissions from anaerobically digesting yard trimmings are sensitive to methane yield assumptions. EPA believes that the modeling approach used in WARM provides reasonable estimates of the GHG emissions to represent a wide range of anaerobic digestion configurations.

2.6 REFERENCES

Barlaz, M.A. (2008). Memorandum to Parties Interested in Carbon Sequestration from Municipal Solid Waste: "Corrections to Previously Published Carbon Storage Factors." February 27, 2008.

Barlaz, M.A. (2005). Letter to Randy Freed, ICF International: "Decomposition of Leaves." June 29, 2005.

Barlaz, M.A. (1998). Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills. *Global Biogeochem. Cycles*, 12 (2): 373–380.

Brady, N., & R. Weil. (1999). *The Nature and Properties of Soils*. Upper Saddle River, NJ: Prentice Hall.

Cole, M. (2000). Personal communication between Dr. Michael Cole, University of Illinois, and Randy Freed, ICF Consulting, July 3, 2000.

EPA. (2015a). *Advancing Sustainable Materials Management: Facts and Figures 2013.* (EPA530-R-15-002). Washington, DC: U.S. Government Printing Office. Retrieved from http://www.cta.tech/CorporateSite/media/environment/eCycle/2013_advncng_smm_rpt.pdf.

EPA. (2015b). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2013. (EPA 430-R-15-004). Washington, DC: U.S. Government Printing Office. Retrieved from http://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf.

EPA. (2013). *The Landfill Methane Outreach Program (LMOP) LFGE Benefits Calculator.* Available online at: http://www.epa.gov/lmop/projects-candidates/lfge-calculator.html.

EPA. (2008). *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2007*. United States Environmental Protection Agency, Office of Solid Waste. EPA530-R-08-010. Retrieved from http://www.epa.gov/epawaste/nonhaz/municipal/pubs/msw07-rpt.pdf.

EPA. (2006). *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. Washington, DC: U.S. Environmental Protection Agency.

EPA. (1998). *AP-42 Emission Factors for Municipal Solid Waste Landfills – Supplement E.* Washington, DC: U.S. Environmental Protection Agency.

FAL. (1994). *The Role of Recycling in Integrated Solid Waste Management to the Year 2000.* Franklin Associates Ltd. (Stamford, CT: Keep America Beautiful, Inc.), September.

Harrington, K. (1997). Personal communication between Karen Harrington, Minnesota Office of Environmental Assistance, and ICF Consulting, October 1997. Value reported by an RDF facility located in Newport, MN.

IPCC. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste*, Chapter 3: Solid Waste Disposal. Intergovernmental Panel on Climate Change. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html