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)

Background Chapters

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1 WARM BACKGROUND AND OVERVIEW

During the last century, population and economic growth have caused increased consumption of materials such as minerals, wood products and food. Materials consumption continues to accelerate while simultaneously shifting away from renewable materials like agriculture and forestry products toward non-renewable products such as metals and fossil fuel-derived products (EPA, 2009b). Source reduction, reuse and recycling of materials are ways that we can manage materials more sustainably.

Extracting, harvesting, processing, transporting and disposing of these materials result in greenhouse gas (GHG) emissions, in part due to the large amounts of energy required for these life-cycle stages. The U.S. Environmental Protection Agency's (EPA) Waste Reduction Model (WARM), the focus of this documentation, is a tool designed to help managers and policy-makers understand and compare the life-cycle GHG, energy, and economic implications of materials management options (recycling, source reduction, landfilling, combustion with energy recovery, anaerobic digestion, and composting) for materials commonly found in the waste stream. By comparing a baseline scenario (e.g., landfilling) to an alternate scenario (e.g., recycling), WARM can assess the economic, energy, and GHG implications that would occur throughout the material life cycle.

1.1 MATERIALS MANAGEMENT CONTEXT

The United States and the international community are focusing increasingly on a life-cycle materials management paradigm that considers the environmental impacts of materials at all life-cycle stages. Recognition is growing that, since traditional environmental policies focus on controlling "end-of-pipe" emissions, they do not provide a means for systematically addressing environmental impacts associated with the movement of materials through the economy. While "end-of-pipe" policies are often effective in controlling direct pollution, they may result in some environmental impacts being overlooked or shifted from one area of the life cycle to another (EPA, 2009b).

Materials management refers to how we manage material resources as they flow through the economy, from extraction or harvest of materials and food (e.g., mining, forestry, and agriculture), production and transport of goods, use and reuse of materials, and, if necessary, disposal. The EPA 2020 Vision Workgroup defines materials management as "an approach to serving human needs by using/reusing resources most productively and sustainably throughout their life cycles, generally minimizing the amount of materials involved and all the associated environmental impacts" (EPA, 2009b).

The EPA Office of Land and Emergency Management (OLEM) (formerly the Office of Solid Waste and Emergency Response) found that 42 percent of U.S. 2006 GHG emissions were associated with the manufacturing, use and disposal of materials and products (EPA, 2009a). As a result, changing materials management patterns is an important strategy to help reduce or avoid GHG emissions. Reducing the amount of materials used to make products, extending product life spans, and maximizing recycling rates are examples of possible materials management strategies that can significantly reduce GHG emissions (EPA, 2009b).

Private and public entities globally are moving toward life-cycle materials management. For example, the Organisation for Economic Cooperation and Development (OECD) and the Kobe 3R Action Plan (a plan issued by the Group of Eight) have recommended that member countries pay increased attention to life-cycle approaches to material flows. Companies in the metals, cement, agribusiness, food and retail industries are also formulating approaches to increase efficiency and reduce environmental impacts by taking a life-cycle view of materials and processes (EPA, 2009b).

1.2 GENESIS AND APPLICATIONS OF WARM

1.2.1 History of WARM Development

Recognizing the potential for source reduction and recycling of municipal solid waste (MSW) to reduce GHG emissions, EPA included a source reduction and recycling initiative in the original 1994 U.S. *Climate Change Action Plan.* EPA set an emission reduction goal based on a preliminary analysis of the potential benefits of these activities. It was clear that a rigorous analysis would be needed to gauge more accurately the total GHG emission reductions achievable through source reduction and recycling.

That *all* of the options for managing MSW should be considered also became clear. By addressing a broader set of MSW management options, EPA could gain a more comprehensive picture of the GHG benefits of voluntary actions in the waste sector and assess the relative GHG impacts of various waste management approaches. To this end, EPA launched a major research effort, which resulted in the development of life-cycle GHG and energy factors for materials across several categories (e.g., plastics, metals, wood products), the online GHG and energy calculation tool WARM applying these factors, and accompanying documentation. The first documentation report, entitled *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*, was published in 1998, the second edition in 2002 (retitled *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*) and the third edition in 2006 (EPA, 1998, 2002, 2006).

In 2010, EPA reorganized the WARM documentation into chapters by material and by process and included more in-depth descriptions of the WARM emission factors. Whereas the previous documentation reports were structured only around process chapters (i.e., source reduction, recycling, composting, combustion, landfilling), this materials-based structure allowed EPA to provide WARM users with more detailed information about the specific materials analyzed in WARM, which had not been included to a large extent in previous versions of the report, as well as more detailed information about of the calculations behind specific material emission factors.

The Recent Updates in WARM chapter describes the revisions made to different model versions and the documentation. Each year, EPA has updated the model itself to reflect updated statistics on national average electricity generation fuel mix, transmission and distribution losses, coal weighting for electricity generation, electricity generation per fuel type, the carbon content of fuels, landfill methane generation distribution (by type of landfill), landfill gas recovery and flaring rates, and waste generation and recovery rates. In addition, annual updates have often included new material emission factors and other improvements to the analysis (Exhibit 1-1 provides the dates when materials were added to WARM).

In WARM Version 15 (released in May 2019), the updates and improvements include new economic impact reports, detailed electronic material factors, and revisions to emission factors based on new reports and databases. Changes to other recent versions include addition of the anaerobic digestion pathway for managing organic wastes, including food waste, yard trimmings, and mixed organics; the addition of either updated or new emission factors for food waste, construction and demolition (C&D) materials, plastics, aluminum cans and ingot, PLA, and carpet; the addition of component-specific decay rates; and increased specificity in WARM with region-specific electricity grid factors and an updated method for estimating landfill gas collection efficiency.

1.2.2 WARM Audience and Related Efforts

The primary application of WARM is to support materials-related decision-making in the context of climate change. By quantifying the climate impacts of materials management decisions, the factors in this report and the tool enable municipalities, companies and other waste- and program-management decision-makers to measure the benefits of their actions. Other EPA decision-support tools such Individual WARM (iWARM) rely on WARM energy and emission factors to help users make a wide range of decisions. For example, the iWARM tool uses life-cycle information from WARM to quantify energy benefits of recycling small quantities of common waste materials by calculating the “run time” of a variety a household appliances (e.g., clothes washer, hairdryer, etc.) using electricity savings from recycling materials. Other applications have included quantifying the GHG reductions from voluntary programs aimed at source reduction and recycling, such as EPA’s WasteWise and Pay-As-You-Throw programs.

The international community has shown considerable interest in using the emission factors—or adapted versions—to develop GHG emission estimates for non-U.S. materials management.[1] For example, Environment Canada and Natural Resources Canada employed EPA’s life-cycle methodology and components of its analysis to develop a set of Canada-specific GHG emission factors to support analysis of waste-related mitigation opportunities (Environment Canada, 2005).

Global Warming Potentials

CO_2, CH_4, N_2O and perfluorocarbons (PFCs) are very different gases in terms of their heat-trapping potential. The Intergovernmental Panel on Climate Change (IPCC) has established CO_2 as the reference gas for measurement of heat-trapping potential (also known as global warming potential or GWP). By definition, the GWP of one kilogram (kg) of CO_2 is one. The GWPs of other common GHGs from materials management activities are as follows:

- CH_4 has a GWP of 25, which means that one kg of CH_4 has the same heat-trapping potential as 25 kg of CO_2.
- N_2O has a GWP of 298.
- PFCs are the most potent GHG included in this analysis; GWPs are 7,390 for CF_4 and 12,200 for C_2F_6.

WARM expresses comparative GHG emissions in metric tons of CO_2 equivalents ($MTCO_2E$), which uses the tool of GWP to allow all emissions to be compared on equal terms.

WARM uses GWPs from IPCC(2007).

1.2.3 Estimating and Comparing Net GHG Emissions

WARM compares the emissions and offsets resulting from a material in a baseline and an alternative management pathway in order to provide decision-makers with comparative emission results. For example, WARM could be used to calculate the GHG implications of landfilling 10 tons of office paper versus recycling the same amount of office paper.

The general formula for net GHG emissions for each scenario modeled in WARM is as follows:

Net GHG emissions = Gross manufacturing GHG emissions - (Increase in carbon stocks + Avoided utility GHG emissions)

This equation should only be considered in the context of comparing two alternative materials management scenarios in order to identify the lowest net GHG emissions. The following circumstances influence the net GHG emissions of a material:

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[1] Note that waste composition and product life cycles vary significantly among countries. This report may assist other countries by providing a methodological framework and benchmark data for developing GHG emission estimates for their solid waste streams.

- Through *source reduction* (for example, “lightweighting” a beverage can—using less aluminum for the same function), GHG emissions throughout the life cycle are avoided. In addition, when paper products are source reduced, additional carbon is sequestered in forests, through reduced tree harvesting.
- Through *recycling*, the GHG emissions from making an equivalent amount of material from virgin inputs are avoided. In most cases, recycling reduces GHG emissions because manufacturing a product from recycled inputs requires less energy than making the product from virgin inputs.
- *Composting* with application of compost to soils results in carbon storage and small amounts of CH_4 and N_2O emissions from decomposition.
- The *anaerobic digestion* captures biogas from the digestion of organic materials. The biogas is assumed to be combusted to produce energy, offsetting emissions from fossil fuel consumption. Additionally, the digestate resulting from the digestion process is applied to agricultural lands, resulting in soil carbon storage, avoided use of synthetic fertilizers, and trace CH_4 and N_2O emissions during digestate curing and after land application.
- *Landfilling* results in both CH_4 emissions from biodegradation and biogenic carbon storage. If captured, the CH_4 may be flared, which simply reduces CH_4 emissions (since the CO_2 produced by flaring is biogenic in origin, it is not accounted for in this assessment of anthropogenic emissions). If captured CH_4 is burned to produce energy, it offsets emissions from fossil fuel consumption.
- *Combustion* of waste may result in an electricity utility emissions offset if the waste is burned in a waste-to-energy facility, which displaces fossil-fuel-derived electricity.

1.2.4 Materials Considered in WARM

To measure the GHG impacts of materials management, EPA first decided which materials and products to analyze. EPA surveyed the universe of materials and products found in the solid waste stream and identified those that are most likely to have the greatest impact on GHGs. These determinations were initially based on (1) the quantity generated; (2) the differences in energy use for manufacturing a product from virgin versus recycled inputs; and (3) the potential contribution of materials to CH_4 generation in landfills. Since the initial assessment, many materials have been added. Materials that EPA selects for inclusion in WARM are generally selected based on the three principles above, with the additional criterion that enough data be available to create defensible emission factors. WARM Version 15, released in May 2019, includes 60 materials, products and mixed categories, as listed by category type in Exhibit 1-1 . Exhibit 1-1 also shows the main sources of virgin and recycled production energy data for each material, the vintage of those data, the year each material was first added to WARM, the percentage each material constitutes of total MSW generated in the United States (to the extent information is available), and whether the recycling process is modeled as open- or closed-loop in WARM (more information on the recycling process is presented in the Recycling chapter). EPA is in the process of gathering and reviewing new life-cycle inventory (LCI) data for several material types to develop updated and new emission factors for WARM. The definitions of the each of the WARM materials included in Exhibit 1-1 are presented in Exhibit 1-2.

Exhibit 1-1: Current Materials and Products in WARM, Historical Inclusion, and Source of Data

Material/Product	Year First Added to WARM (updated year if applicable)	Source of Main Process Energy Data	Approximate Year(s) of Current Energy Data[a]	% of MSW Generation by Weight[b]	Open- or Closed-Loop Recycling?[c]
Metals and Glass					
Aluminum Cans	1998 (2012)	PE Americas (2010)	2006	0.5%	Closed
Aluminum Ingot	2012	PE Americas (2010)	2006	NE	Closed
Steel Cans	1998	FAL (1998b)	1990	0.7%	Closed
Copper Wire	2005	Battelle (1975); Kusik and Kenahan (1978); FAL (2002b)	1973–2000	NE	Open
Glass	1998	RTI (2004)	Late 1990s	4.4%	Closed
Plastics					
HDPE (high-density polyethylene)	1998 (2012)	FAL (2011)	2000s	2.3%	Closed
LDPE (low-density polyethylene)	1998 (2012)	FAL (2011)	2000s	3.0%	Closed
PET (polyethylene terephthalate)	1998 (2012)	FAL (2011)	2000s	1.9%	Closed
LLDPE	2012	FAL (2011)	2000s	NE	Closed
PP	2012	FAL (2011)	2000s	NE	Closed
PS	2012	FAL (2011)	2000s	NE	Closed
PVC	2012	FAL (2011)	2000s	NE	Closed
Paper and Wood					
Corrugated Containers	1998	RTI (2004)	Late 1990s	11.9%	Both
Magazines/Third-Class Mail	2001	RTI (2004)	Late 1990s	2.0%	Closed
Newspaper	1998	RTI (2004)	Late 1990s	2.6%	Closed
Office Paper	1998	RTI (2004)	Late 1990s	1.7%	Closed
Phone Books	2001	RTI (2004)	Late 1990s	NE	Closed
Textbooks	2001	RTI (2004)	Late 1990s	NE	Closed
Dimensional Lumber	1998	FAL (1998c)	Mid 1990s	3.8%	Closed
Medium-Density Fiberboard	1998	FAL (1998c)	Mid 1990s	NE	Closed
Organics					
Food Waste	2014	NA	NA	15.1%	NA
Food Waste (meat only)	2015	NA	NA	IE	NA
Food Waste (non-meat)	2014	NA	NA	IE	NA
Beef	2015	Battagliese et al. (2013)	2011	IE	NA
Poultry	2015	Pelletier (2008, 2010)	Late 2000s	IE	NA
Grains	2014	LCA Digital Commons (2012)	2000s	IE	NA
Bread	2014	Espinoza-Orias (2011)	2011	IE	NA
Dairy Products	2014	Thoma et al. (2010)	2008	IE	NA
Fruits and Vegetables	2014	Luske (2010) UC Davis (multiple)	Late 2000s	IE	NA
Yard Trimmings	1998	NA	NA	13.3%	NA
Grass	2001	NA	NA	IE	NA
Leaves	2001	NA	NA	IE	NA
Branches	2001	NA	NA	IE	NA

Material/Product	Year First Added to WARM (updated year if applicable)	Source of Main Process Energy Data	Approximate Year(s) of Current Energy Data[a]	% of MSW Generation by Weight[b]	Open- or Closed-Loop Recycling?[c]
PLA	2012	NatureWorks, LLC (2010)	2009	NE	NA
Mixed Categories					
Mixed Paper (general)	1998	Virgin: FAL (1998a), RPTA (2003) Recycled: RPTA (2003)	Virgin: 1996; Recycled: early 2000s	NE	Open
Mixed Paper (primarily residential)	1998	FAL (1998a)	1996	NE	Open
Mixed Paper (primarily from offices)	1998	FAL (1998a)	1996	NE	Open
Mixed Metals	2002	NA	NA	9.1%	NA
Mixed Plastics	2001	NA	NA	13.1%	NA
Mixed Recyclables	1998	NA	NA	NE	NA
Mixed Organics	2001	NA	NA	NE	NA
Mixed MSW	2001	NA	NA	NE	NA
Composite Products					
Carpet[d]	2004 (2012)	FAL (2002a); Realff (2011)	2000s	1.4%	Open
Desktop CPUs[d]	2019	Various	2011-2019	NE	Open
Portable Electronic Devices[d]	2019	Various	2011-2019	NE	Open
Flat-panel Displays[d]	2019	Various	2011-2019	NE	Open
CRT Displays[d]	2019	Various	2011-2019	NE	Open
Electronic Peripherals[d]	2019	Various	2011-2019	NE	Open
Hard-copy Devices [d]	2019	Various	2011-2019	NE	Open
Mixed Electronics[d]	2019	NA	2011-2019	1.2%	Open
Construction and Demolition (C&D)					
Clay Bricks	2004	Athena Sustainable Materials Institute (1998)	Mid-late 1990s	NA	NA
Concrete[d]	2004	U.S. Census Bureau (1997),Wilburn and Goonan (1998)	1997	NA	Open
Fly Ash	2004	IPCC (1996), PCA (2003), Nisbet et al. (2000)	Early 2000s	NA	Open
Tires[d]	2006	Athena Sustainable Materials Institute (2000), Atech Group (2001), EIA (2009), Corti and Lombardi (2004)	Early 2000s	2.2%	Open
Asphalt Concrete[d]	2010	U.S. Census Bureau (1997), Athena Sustainable	Early 2000s	NA	Closed

Material/Product	Year First Added to WARM (updated year if applicable)	Source of Main Process Energy Data	Approximate Year(s) of Current Energy Data[a]	% of MSW Generation by Weight[b]	Open- or Closed-Loop Recycling?[c]
		Materials Institute (2001), U.S. Census Bureau (2001), Environment Canada (2005), Levis (2008), NREL (2009)			
Asphalt Shingles[d]	2010	Athena Sustainable Materials Institute (2000), Cochran (2006), CMRA (2007)	Early 1990s	NA	Open
Drywall[d]	2010	Venta (1997); recycling data from WRAP (2008)	Virgin: 1997; Recycled: 2008	NA	Both
Fiberglass Insulation	2010	Lippiatt (2007), Enviros Consulting (2003) for glass cullet production	Mid 2000s	NA	NA
Vinyl Flooring[d]	2010	ECOBILAN (2001), FAL (2007), Lippiatt (2007), Ecoinvent Centre (2008)	2007	NA	NA
Wood Flooring[e]	2010	Bergman and Bowe (2008), Hubbard and Bowe (2008), Bergman (2010)	Late 2000s	NA	NA

NA = Not applicable.
NE = Not estimated.
IE = Included elsewhere.

[a] Note that years are approximate because each source draws on a variety of data sources from different years.

[b] Source for percent generation data is EPA (2018).

[c] Closed-loop recycling indicates a recycling process where end-of-life products are recycled into the same product. Open-loop recycling indicates that the products of the recycling process (secondary product) are not the same as the inputs (primary material).

[d] Indicates composite product.

[e] Wood flooring also falls under the Paper and Wood category.

The material types listed in Exhibit 1-1 generally fall into two overarching waste categories – municipal solid waste (MSW) and construction and demolition (C&D). MSW generally includes metals and glass, plastics, paper and wood, organics, mixed categories and composite products. These materials are household, commercial, institutional and light industrial waste collected and managed by a municipality. C&D materials are materials that are produced during construction, renovation or demolition of structures and include clay bricks, concrete, fly ash, tires, asphalt concrete, asphalt shingles, drywall, fiberglass insulation, vinyl flooring and wood flooring. EPA's interest in C&D materials is the result of a growing interest in environmentally friendly or "green" building practices, including reusing and recycling the impressive quantities of C&D debris that are generated each year. In 2008, 143.5 million tons of C&D waste were generated (Waste Business Journal, 2009). One major difference between waste management for C&D materials versus MSW materials is that C&D materials are typically disposed of in landfills created specifically for C&D waste that do not accept MSW waste. C&D and MSW landfills differ in several ways, including in the design and operation requirements of the landfills. From the GHG perspective, the most significant difference between the two landfill types is that C&D landfills generally do not have the landfill methane capture systems that are common at MSW landfills. Thus, the methane that is produced in C&D landfills is eventually released directly to the atmosphere.

As shown in the fifth column of Exhibit 1-1, the listed MSW materials constitute more than 75 percent, by weight, of MSW. Several materials, including most C&D materials, were not included in the waste characterization report cited here (EPA 2018a), so the utility of this percent estimate is limited.[2]

Exhibit 1-2: WARM Material Definitions

WARM Material	WARM Data Source Definition
Aluminum Cans	Aluminum cans represent cans produced out of sheet-rolled aluminum ingot.
Aluminum Ingot	Aluminum ingot is processed from molten aluminum in the form of a sheet ingot suitable for rolling, extruding, or shape casting. Thus, it serves as a pre-cursor to manufacture of aluminum products such as aluminum cans. It can serve as a proxy for certain aluminum materials such as electrical transmission and distribution wires, other electrical conductors, some extruded aluminum products, aluminum product cuttings, joinings and weldings, and consumer durable products such as home appliances, computers, and electronics.
Steel Cans	Steel cans represent three-piece welded cans produced from sheet steel that is made in a blast furnace and basic oxygen furnace (for virgin cans) or electric arc furnace (for recycled cans).
Copper Wire	Copper wire is used in various applications, including power transmission and generation lines, building wiring, telecommunication, and electrical and electronic products.
Glass	Glass represents glass containers (e.g., soft drink bottles and wine bottles).
HDPE	HDPE (high-density polyethylene) is usually labeled plastic code #2 on the bottom of the container, and refers to a plastic often used to make bottles for milk, juice, water and laundry products. It is also used to make plastic grocery bags.
LDPE	LDPE (Low-density polyethylene), usually labeled plastic code #4, is often used to manufacture plastic dry cleaning bags. LDPE is also used to manufacture some flexible lids and bottles.
PET	PET (Polyethylene terephthalate) is typically labeled plastic code #1 on the bottom of the container. PET is often used for soft drink and disposable water bottles, but can also include other containers or packaging.
LLDPE	LLDPE (linear low-density polyethylene) is used in high-strength film applications. Compared to LDPE, LLDPE's chemical structure contains branches that are much straighter and closely aligned, providing it with a higher tensile strength and making it more resistant to puncturing or shearing
PP	PP (Polypropylene) is used in packaging, automotive parts, or made into synthetic fibres. It can be extruded for use in pipe, conduit, wire, and cable applications. PP's advantages are a high impact strength, high softening point, low density, and resistance to scratching and stress cracking. A drawback is its brittleness at low temperatures
PS	GPPS (General Purpose Polystyrene) has applications in a range of products, primarily domestic appliances, construction, electronics, toys, and food packaging such as containers, produce baskets, and fast food containers.
PVC	PVC (Polyvinyl Chloride) is produced as both rigid and flexible resins. Rigid PVC is used for pipe, conduit, and roofing tiles, whereas flexible PVC has applications in wire and cable coating, flooring, coated fabrics, and shower curtains
PLA	Polylactic acid or PLA is a thermoplastic biopolymer constructed entirely from annually renewable agricultural products, e.g., corn, and used in manufacturing fresh food packaging and food service ware such as rigid packaging, food containers, disposable plastic cups, cutlery, and

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[2] Note that these data are based on national averages. The composition of solid waste varies locally and regionally.

WARM Material		WARM Data Source Definition
		plates
Corrugated Containers		Corrugated container boxes made from containerboard (liner and corrugating medium) used in packaging applications.
Magazines/Third-Class Mail		Third Class Mail is now called Standard Mail by the U.S. Postal Service and includes catalogs and other direct bulk mailings such as magazines, which are made of coated, shiny paper. This category represents coated paper produced from mechanical pulp.
Newspaper		Newspaper represents uncoated paper made from 70% mechanical pulp and 30% chemical pulp. For the carbon sequestration portion of the factor, it was assumed that the paper was all mechanical pulp.
Office Paper		Office paper represents paper made from uncoated bleached chemical pulp.
Phone Books		Phone books represent telephone books that are made from paper produced from mechanical pulp.
Textbooks		Textbooks represent books made from paper produced from chemical pulp.
Dimensional Lumber		Lumber includes wood used for containers, packaging, and building and includes crates, pallets, furniture and dimensional lumber like two-by-fours.
Medium-Density Fiberboard		Fiberboard is a panel product that consists of wood chips pressed and bonded with a resin. Fiberboard is used primarily to make furniture.
Food Waste		Food waste consists of uneaten food and wasted prepared food from residences, commercial establishments such as grocery stores and restaurants, institutional sources such as school cafeterias, and industrial sources such as factory lunchrooms. This emission factor contains a weighted average of the largest food waste components in the waste stream, including beef, poultry, grains, dairy products, fruits and vegetables.
Food Waste (meat only)		"Food waste (meat only)" is a weighted average of the two meat food type emission factors in WARM: beef and poultry. The weighting is based on the relative shares of these two categories in the U.S. food waste stream
Food Waste (non-meat)		"Food waste (non-meat)" is a weighted average of the three non-meat food type emission factors developed in 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
Beef		Beef represents the upstream emissions and energy associated with the production of beef cattle in the United States, including the upstream energy and emissions associated with feed production.
Poultry		Poultry describes the upstream emissions and energy associated with the production of broiler chicken (i.e., domesticated chickens raised specifically for meat production), including the upstream energy and emissions associated with feed production.
Grains		Grains consists of a weighted average of the relative amounts of grain products in the municipal waste stream, consisting of wheat flour, corn and rice.
Bread		Bread consists of the upstream emissions and energy associated with wheat flour production, as well as the additional energy used to bake it into bread.
Dairy Products		Dairy Products consists of a weighted average of the emissions associated with nearly the entire dairy product waste stream, including milk, cheese, ice cream, and yogurt.
Fruits and Vegetables		Fruits and Vegetables represents the average fresh fruits and vegetable components of food waste, consists of a weighted average of the six most common fruits and vegetables in the municipal waste stream, including apples, bananas, melons, oranges, potatoes, and tomatoes.
Yard Trimmings		Yard trimmings are assumed to be 50% grass, 25% leaves, and 25% tree and brush trimmings (EPA, 2015, p. 56) from residential, institutional and commercial sources.
Mixed Paper	General Definition	Mixed paper is assumed to be 24% newspaper, 48% corrugated cardboard, 8% magazines, and 20% office paper (Barlaz, 1998).
	Residential Definition	Residential mixed paper is assumed to be 23% newspaper, 53% corrugated cardboard, 10% magazines and 14% office paper (Barlaz, 1998).
	Office Definition	Office mixed paper is assumed to be 21% newspaper, 5% corrugated cardboard, 36% magazines and 38% office paper (Barlaz, 1998).
Mixed Metals		Mixed metals are made up of a weighted average of 35% aluminum cans and 65% steel cans.
Mixed Plastics		Mixed plastics are made up of a weighted average of 40% HDPE and 60% PET plastic.
Mixed Recyclables		Mixed recyclables are made up of a weighted average of approximately 1% aluminum cans, 2% steel cans, 6% glass, 1% HDPE, 2% PET, 57% corrugated cardboard, 7% magazines/third-class

WARM Material	WARM Data Source Definition
	mail, 10% newspaper, 8% office papers, <1% phonebooks, <1% textbooks, and 5% dimensional lumber. See those definitions for details.
Mixed Organics	Mixed organics are made up of a weighted average based on 53% food waste and 47% yard trimmings. See those definitions for details.
Mixed MSW	Mixed MSW (municipal solid waste) comprises the waste materials typically discarded by households and collected by curbside collection vehicles; it does not include white goods (e.g., refrigerators, toasters) or industrial waste.
Carpet	Carpet represents nylon broadloom residential carpet containing face fiber, primary and secondary backing, and latex used for attaching the backings.
Desktop CPUs	Desktop CPUs include the stand-alone processing unit for a desktop computer and does not include the monitor or any peripherals (e.g., mice, keyboards).
Portable Electronic Devices	Portable electronic devices include laptops, e-readers, tablets, smart phones, and basic mobile phones.
Flat-panel Displays	Flat-panel displays include LED and liquid crystal display (LCD) televisions, plasma televisions, and LED and LCD computer monitors.
CRT Displays	CRT displays include CRT televisions and CRT computer monitors. While CRT displays are no longer manufactured, many are still entering the waste stream in the U.S.
Electronic Peripherals	Electronic peripherals consist of electronic devices used in conjunction with other products and include keyboards and mice.
Hard-copy Devices	Hard-copy devices include electronic devices used for preparing hard-copy documents, including printers and multi-function devices.
Mixed Electronics	Mixed recyclables are made up of a weighted average of approximately 11% desktop CPUs, 5% portable electronic devices, 23% flat-panel displays, 44% CRT displays, 2% electronic peripherals, and 15% hard-copy devices. See those definitions for details.
Clay Bricks	Bricks are produced by firing materials such as clay, kaolin, fire clay, bentonite, or common clay and shale. The majority of the bricks produced in the United States are clay. In WARM, clay brick source reduction is considered to be the reuse of full bricks rather than the grinding and reusing of broken or damaged brick.
Concrete	Concrete is a high-volume building material produced by mixing cement, water, and coarse and fine aggregates. In WARM, concrete is assumed to be recycled into aggregate, so the GHG benefits are associated with the avoided emissions from mining and processing aggregate.
Fly Ash	Fly ash is a byproduct of coal combustion that is used as a cement replacement in concrete.
Tires	Scrap tires are tires that have been disposed of by consumers and have several end uses in the U.S. market, including as a fuel, in civil engineering, and in various ground rubber applications such as running tracks and molded products.
Asphalt Concrete	Asphalt concrete is composed primarily of aggregate, which consists of hard, graduated fragments of sand, gravel, crushed stone, slag, rock dust or powder.
Asphalt Shingles	Asphalt shingles are typically made of a felt mat saturated with asphalt. Fiberglass shingles are composed of asphalt cement (22% by weight), a mineral stabilizer like limestone or dolomite (25%), and sand-sized mineral granules/aggregate (38%), in addition to the fiberglass felt backing (15%) (CMRA, 2007).
Drywall	Drywall, also known as wallboard, gypsum board or plaster board, is manufactured from gypsum plaster and a paper covering.
Fiberglass Insulation	Fiberglass insulation is produced from a blend of sand, limestone, soda ash and recycled glass cullet, which accounts for about 40% of the raw material inputs.
Vinyl Flooring	All vinyl flooring is composed of polyvinyl chloride (PVC) resin, along with additives such as plasticizers, stabilizers, pigments and fillers.
Wood Flooring	Virgin hardwood flooring is produced from lumber. Coatings and sealants can be applied to wood flooring in “pre-finishing” that occurs at the manufacturing facility, or onsite.

1.3 INTRODUCTION TO WARM METHODOLOGY

1.3.1 A Streamlined Life-Cycle Inventory

Source reduction, recycling, composting, anaerobic digestion, combustion and landfilling are all materials management options that provide opportunities for reducing GHG emissions, depending on individual circumstances. Although source reduction and recycling are often the most advantageous practices from a GHG perspective, a material-specific comparison of all available materials management options clarifies where the greatest GHG benefits can be obtained for particular materials. A material-specific comparison can help waste managers and policy-makers identify the best options for GHG reductions through materials management.

EPA determined that the best way to conduct such a comparative analysis is a streamlined application of a life-cycle assessment (LCA). A full LCA is an analytical framework for understanding the material inputs, energy inputs and environmental releases associated with manufacturing, using, transporting and disposing of a given material. A full LCA generally consists of four parts: (1) goal definition and scoping; (2) an inventory of the materials and energy used during all stages in the life of a product or process, and an inventory of environmental releases throughout the product life cycle; (3) an impact assessment that examines potential and actual human health effects related to the use of resources and environmental releases; and (4) an assessment of the change that is needed to bring about environmental improvements in the product or processes.

WARM does not provide a full LCA, as EPA wanted the tool to be transparent, easy to access and use, and focused on providing decision-makers with information on climate change impacts, namely GHG and energy implications. WARM's streamlined LCA is limited to an inventory of GHG emissions and sinks and energy impacts. This study did not assess human health impacts, or air, water or other environmental impacts that do not have a direct bearing on climate change. WARM also simplifies the calculation of emissions from points in the life cycle that occur before a material reaches end of life.

1.3.2 Assessing GHG Flux Associated with Material Life-Cycle Stages

The streamlined LCA used in WARM depends on accurately assessing the GHG and energy implications of relevant life-cycle stages. The GHG implications associated with materials differ depending on raw material extraction requirements and how the materials are manufactured and disposed of at end of life. WARM evaluates the GHG emissions associated with materials management based on analysis of three main factors: (1) GHG emissions throughout the life cycle of the material (including the chosen end-of-life management option); (2) the extent to which carbon sinks are affected by manufacturing, recycling and disposing of the material; and (3) the extent to which the management option recovers energy that can be used to replace electric utility energy, thus reducing electric utility emissions.

The life cycle of a material or product includes the following primary life-cycle stages: (1) extraction and processing of raw materials; (2) manufacture of products; (3) transportation of materials and products to markets; (4) use by consumers; and (5) end-of-life management. GHGs are emitted from (1) the pre-consumer stages of raw materials acquisition and manufacturing, and (2) the post-consumer stage of end-of-life management.

WARM does not include emissions from the use phase of a product's life, since use does not have an effect on the waste management emissions of a product. Since the design and results of WARM include the difference between the baseline and the alternative waste management scenarios that show the GHG savings from different treatment options, emissions from the use phase are the same in both the baseline and alternative scenarios; therefore, emissions from the use phase are excluded and all tables and analyses in this report use a “waste generation” reference point.

Materials management decisions can reduce GHGs by affecting one or more of the following:

- *Energy consumption* (specifically combustion of fossil fuels) and the resulting GHG emissions associated with material extraction, manufacturing, transporting, using, and end-of-life management of the material or product.[3]
- *Non-energy-related manufacturing emissions*, such as the carbon dioxide (CO_2) released when limestone used in steel manufacturing is converted to lime, or the perfluorocarbons (PFCs) generated during the aluminum smelting process.
- *Methane (CH_4) emissions from decomposition* of organic materials in landfills.
- *CO_2 and nitrous oxide (N_2O) emissions* from waste combustion.
- *Carbon sequestration and storage*, which refer to natural or manmade processes that remove carbon from the atmosphere and store it for long periods or permanently.

The first four mechanisms *add* GHGs to the atmosphere and contribute to climate change. The fifth—carbon storage—*reduces* GHG concentrations. Forest growth is one mechanism for sequestering carbon; if more biomass is grown than is removed (through harvest or decay), the amount of carbon stored in trees increases.

Each combination of material or product type and materials management option will have different implications for energy consumption, GHG emissions and carbon storage. This is because the upstream (raw materials acquisition, manufacturing and forest carbon sequestration) and downstream (recycling, composting, combustion, anaerobic digestion, and landfilling) characteristics of each material and product are different. Section 1.3.2 gives an overview of how WARM analyzes each of the upstream and downstream stages in the life cycle. The GHG emissions and carbon sinks are described in detail and quantified for each material in the material-specific chapters.

1.3.2.1 Waste Generation Reference Point

One important difference between WARM and other life-cycle analyses is that WARM calculates emission impacts from a waste generation reference point, rather than a raw materials extraction reference point. Raw materials extraction is the point at which production of the material begins, which is why many life-cycle analyses choose this reference point. However, WARM uses the waste generation point (the moment that a material is discarded) because in WARM, the GHG benefits measured result from the choice of one waste management path relative to another. WARM does capture upstream emissions and sinks, but only when at least one of the practices being compared is recycling or source reduction, as these are the only instances where the choice of a materials management practice will affect upstream emissions.

To apply the GHG emission factors developed in this report, one must compare a baseline scenario with an alternate scenario. For example, one could compare a baseline scenario, where 10 tons of office paper are landfilled, to an alternate scenario, where 10 tons of office paper are recycled.

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[3] Depending on the material/product type; however, the use phase is not included in WARM, as discussed in the previous paragraph.

1.3.3 Emissions Sources and Sinks in WARM

As discussed above, EPA focused on aspects of the life cycle that have the potential to emit GHGs as materials are converted from raw resources to products and then to waste. Exhibit 1-3 describes the steps in the material life cycle modeled in WARM at which GHGs are emitted, carbon sequestration is affected, and electric utility energy is displaced. As shown, EPA examined the potential for these effects at the following points in a material's life cycle:

- Raw material acquisition and manufacturing (fossil fuel energy and other emissions, and changes in forest carbon sequestration);
- Carbon sinks in forests and soils (forest carbon storage associated with reduced tree harvest from source reduction and recycling, soil carbon storage associated with application of compost); and
- End-of-life management (CO_2, CH_4, and N_2O emissions associated with composting and anaerobic digestion, nonbiogenic CO_2 and N_2O emissions from combustion, and CH_4 emissions from landfills); these emissions are offset to some degree by carbon storage in soil and landfills, as well as by avoided utility emissions from energy recovery at combustors, anaerobic digesters, and landfills.
- At each point in the material life cycle, EPA also considered transportation-related energy emissions.

Estimates of GHG emissions associated with electricity used in the raw materials acquisition and manufacturing steps are based on the nation's current mix of energy sources, including fossil fuels, hydropower and nuclear power. However, when estimating GHG emission reductions attributable to electric utility emissions avoided from landfill gas capture, anaerobic digesters, or waste-to-energy at combustion facilities, the electricity use displaced by waste management practices is assumed to be from non-baseload power plants to represent the marginal electricity emissions offset. EPA did not analyze the GHG emissions typically associated with consumer use of products because the purpose of the analysis is to evaluate one materials management option relative to another. EPA assumed that the energy consumed during use would be approximately the same whether the product was made from virgin or recycled inputs. In addition, energy use at this life-cycle stage is small (or zero) for all materials studied except electronics.

Exhibit 1-3 shows how GHG sources and sinks are affected by each waste management strategy. For example, the top row of the exhibit shows that source reduction (1) reduces GHG emissions from raw materials acquisition and manufacturing; (2) results in an increase in forest carbon sequestration for certain materials; and (3) does not result in GHG emissions from waste management .[4] The sum of emissions (and sinks) across all steps in the life cycle represents net emissions for each material management strategy.

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[4] The source reduction techniques the EPA researchers analyzed involve using less of a given product—e.g., by making aluminum cans with less aluminum ("lightweighting"); double-sided rather than single-sided photocopying; or reuse of a product. EPA did not analyze source reduction through material substitution (except in the special case of fly ash)—e.g., substituting plastic boxes for corrugated paper boxes. For a discussion of source reduction with material substitution, see the Source Reduction chapter.

Exhibit 1-3: Components of Net Emissions for Various Materials Management Strategies

Materials Management Strategies	**GHG Sources and Sinks Modeled in WARM**		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End of Life**
Source Reduction	**Offsets** • Decrease in GHG emissions, relative to the baseline of manufacturing with the current industry average mix of virgin and recycled inputs	**Offsets** • Increase in forest carbon sequestration (for paper and wood products) due to avoided harvesting	NA
Recycling	**Emissions** • Transport of recycled materials • Recycled manufacture process energy and non-energy **Offsets** • Transport of raw materials and products • Virgin manufacture process energy and non-energy		**Emissions** • Transport to recycling facility and sorting of recycled materials at material recovery facility (MRF)
Composting	**Emissions**[a] • Baseline process and transportation emissions due to manufacture with the current mix of virgin and recycled inputs	**Offsets** • Increase in soil carbon storage from application of compost to soils	**Emissions** • Transport to compost facility • Equipment use at compost facility • CH_4 and N_2O emissions during composting
Combustion	**Emissions** • Baseline process and transportation emissions due to manufacture with the current mix of virgin and recycled inputs	NA	**Emissions** • Transport to WTE facility • Combustion-related non-biogenic CO_2 and N_2O **Offsets** • Avoided electric utility emissions due to WTE • Avoided steel manufacture from steel recovery at WTE for combusted materials including steel cans, mixed metals, mixed recyclables, electronics, tires and mixed MSW
Landfilling	**Emissions** • Baseline process and transportation emissions due to manufacture with the current mix of virgin and recycled inputs	NA	**Emissions** • Transport to landfill • Equipment use at landfill • Landfill methane **Offsets** • Avoided utility emissions due to landfill gas to energy • Landfill carbon storage
Anaerobic Digestion	**Emissions**[a] • Baseline process and transportation emissions due to manufacture with the current mix of virgin and recycled inputs	**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

Materials Management Strategies	GHG Sources and Sinks Modeled in WARM		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
			• Avoided synthetic fertilizer use due to land application of digestate

NA = Not Applicable.

[a] Manufacturing and transportation GHG emissions are considered for composting and anaerobic digestion for only food waste and PLA (composting only) because yard trimmings are not considered to be manufactured.

CO_2 Emissions from Biogenic Sources

The United States and all other parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to develop inventories of GHGs for purposes of (1) developing mitigation strategies and (2) monitoring the progress of those strategies. In 2006, the Intergovernmental Panel on Climate change (IPCC) updated a set of inventory methods that it had first developed in 1996 to be used as the international standard (IPCC (1996); IPCC (2006)). The methodologies used in this report to evaluate emissions and sinks of GHGs are consistent with the IPCC guidance.

One of the elements of the IPCC guidance that deserves special mention is the approach used to address CO_2 emissions from biogenic sources. For many countries, the treatment of CO_2 flux from biogenic sources is most important when addressing releases from energy derived from biomass (e.g., burning wood), but this element is also important when evaluating waste management emissions (for example, the decomposition or combustion of grass clippings or paper). The carbon in paper and grass trimmings was originally removed from the atmosphere by photosynthesis and, under natural conditions, it would cycle back to the atmosphere eventually as CO_2 due to degradation processes. The quantity of carbon that these natural processes cycle through the Earth's atmosphere, waters, soils and biota is much greater than the quantity added by anthropogenic GHG sources. But the focus of the UNFCCC is on anthropogenic emissions—those resulting from human activities and subject to human control. Those emissions have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle and altering the atmosphere's heat-trapping ability.

For processes with CO_2 emissions, if the emissions are from biogenic materials and the materials are grown on a sustainable basis, then those emissions are considered simply to close the loop in the natural carbon cycle. They return to the atmosphere CO_2 that was originally removed by photosynthesis. In this case, the CO_2 emissions are *not* counted. (For purposes of this analysis, biogenic materials are paper and wood products, yard trimmings and food discards.) On the other hand, CO_2 emissions from burning fossil fuels *are* counted because these emissions would not enter the cycle were it not for human activity. Likewise, CH_4 emissions from landfills *are* counted. Even though the source of carbon is primarily biogenic, CH_4 would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH_4 formation.

Note that this approach does not distinguish between the timing of CO_2 emissions, provided that they occur in a reasonably short time scale relative to the speed of the processes that affect global climate change. In other words, as long as the biogenic carbon would eventually be released as CO_2, whether it is released virtually instantaneously (e.g., from combustion) or over a period of a few decades (e.g., decomposition on the forest floor) is inconsequential.

1.4 SUMMARY OF THE LIFE CYCLE STAGES MODELED IN WARM

1.4.1 GHG Emissions and Carbon Sinks Associated with Raw Materials Acquisition and Manufacturing

Raw inputs are needed to make various materials, including ore for manufacturing metal products, trees for making paper products, and petroleum or natural gas for producing plastic products. Fuel energy also is required to obtain or extract these material inputs.

The inputs for *manufacturing* considered in this analysis are (1) energy and (2) either virgin raw materials or recycled materials.[5]

When a material is source reduced, GHG emissions associated with raw material acquisition, producing the material and/or manufacturing the product and managing the post-consumer waste are avoided. Since many materials are manufactured from a mix of virgin and recycled inputs, the quantity of virgin material production that is avoided is not always equal to the quantity of material source reduced. To estimate GHG emissions associated with source reduction, WARM uses a mix of virgin and recycled inputs (referred to throughout the documentation as “the current mix”), based on the national average for that material. For example, in source reducing 100 tons of aluminum cans, WARM models that only 32 tons of virgin aluminum manufacture are avoided, because the current mix for aluminum is 32 percent virgin inputs and 68 percent recycled inputs. WARM also assumes that source reduction of paper and wood products increases the amount of carbon stored in forests by reducing the amount of wood harvested. See the Source Reduction process chapter for further information on calculation of offsets resulting from source reduction.

The GHG emissions associated with raw materials acquisition and manufacturing are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport materials, and (3) non-energy GHG emissions resulting from manufacturing processes.[6] Each of these emission sources is described below. Changes in carbon sequestration in forests also are associated with raw materials acquisition for paper and wood products. For more information on forest carbon sequestration associated with source reduction of paper and wood products, see the Forest Carbon Storage chapter.

1.4.1.1 Process Energy GHG Emissions

Process energy GHG emissions consist primarily of CO_2 emissions from the combustion of fuels used in raw materials acquisition and manufacturing. CO_2 emissions from combustion of biomass are not counted as GHG emissions. (See “CO_2 Emissions from Biogenic Sources” text box in section 1.3.3.)

The majority of process energy CO_2 emissions result from the direct combustion of fuels, e.g., to operate ore mining equipment or to fuel a blast furnace. Fuel also is needed to extract the oil or mine the coal that is ultimately used to produce energy and transport fuels to the place where they are used. Thus, indirect CO_2 emissions from “precombustion energy” are counted in this category as well. When electricity generated by combustion of fossil fuels is used in manufacturing, the resulting CO_2 emissions are also counted.

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[5] Water is also often a key input to manufacturing processes, but is not considered here because it does not have direct GHG implications.

[6] For some materials (plastics, magazines/third-class mail, office paper, phone books, and textbooks), the transportation data EPA received were included in the process energy data. For these materials, EPA reports *total* GHG emissions associated with process and transportation in the “process energy” estimate. The transportation energy estimate therefore only includes emissions from transport from the point of manufacture to a retail facility.

To estimate process energy GHG emissions, EPA first obtained estimates of both the total amount of process energy used per ton of product (measured in British thermal units or Btu) and the fuel mix (e.g., diesel oil, natural gas, fuel oil). Next, emission factors for each type of fuel were used to convert fuel consumption to GHG emissions based on fuel combustion carbon coefficients per fuel type (EPA, 2018b). As noted earlier, making a material from recycled inputs generally requires less process energy (and uses a different fuel mix) than making the material from virgin inputs.

The fuel mixes used in these calculations reflect the material-specific industry average U.S. fuel mixes for each manufacturing process. However, it is worth noting that U.S. consumer products (which eventually become MSW) increasingly come from overseas, where the fuel mixes may differ. For example, China relies heavily on coal and generally uses energy less efficiently than does the United States. Consequently the GHG emissions associated with the manufacture of a material in China may be higher than they would be for the same material made in this country. In addition, greater energy is likely to be expended on transportation to China than on transportation associated with domestic recycling. However, such analysis is beyond the scope of this model, which focuses only on domestic production, transportation, consumption and disposal.

1.4.1.2 Process Non-Energy GHG Emissions

Some GHG emissions occur during the manufacture of certain materials and are not associated with energy consumption. In this analysis, these emissions are referred to as *process non-energy emissions*. For example, the production of steel or aluminum requires lime (calcium oxide, or CaO), which is produced from limestone (calcium carbonate, or $CaCO_3$), and the manufacture of lime results in CO_2 emissions. In some cases, process non-energy GHG emissions are associated only with production using virgin inputs; in other cases, these emissions result when either virgin or recycled inputs are used.

1.4.1.3 Transportation Energy GHG Emissions

Transportation energy GHG emissions consist of CO_2 emissions from the combustion of fossil fuels used to (1) transport raw materials and intermediate products during the manufacturing stage and (2) transport the finished products from the manufacturing facilities to the retail/distribution point.

The estimates of transportation energy emissions for transportation of raw materials to the manufacturing or fabrication facility are based on: (1) the amounts of raw material inputs and intermediate products used in manufacturing one short ton of each material; (2) the average distance that each raw material input or intermediate product is transported; and (3) the transportation modes and fuels used. For the amounts of fuel used, the study used data on the average fuel consumption per ton-mile for each mode of transportation as represented in the industry average life-cycle inventory data.

The estimates of GHG emissions from transporting manufactured products or materials from the manufacturing point to the retail/distribution point are calculated using information from the U.S. Census Bureau, along with the Bureau of Transportation Statistics. These agencies conducted a Commodity Flow Survey that determined the average distance typical commodities were shipped in the United States, and the percentage of each of the various transportation modes that was used to ship these commodities (BTS, 2013). However, there is large variability in the shipping distance and modes used, and so transportation emission estimates given here are somewhat uncertain.

The final step of the analysis applies fuel combustion carbon coefficients for each fuel type from the U.S. Inventory in order to convert fuel consumption to GHG emissions (EPA, 2018b).

1.4.1.4 Carbon Storage, Carbon Sequestration and Carbon Stocks

This analysis includes carbon sequestration and storage when relevant to materials management practices. Carbon storage is the prevention of the release of carbon to the atmosphere. In the context of WARM, this storage can occur in living trees, in undecomposed biogenic organic matter (wood, paper, yard trimmings, food waste) in landfills, or in undecomposed biogenic organic matter in soils due to compost or digestate amendment.

Carbon sequestration is the transfer of carbon from the atmosphere to a carbon pool, where it can be stored if it is not rereleased to the atmosphere through decay or burning. Carbon sequestration occurs when trees or other plants undergo photosynthesis, converting CO_2 in the atmosphere to carbon in their biomass. As forests grow, they absorb atmospheric CO_2 and store it. When the rate of uptake exceeds the rate of release, carbon is said to be sequestered. In this analysis, EPA considered the impact of waste management on forest carbon storage. The amount of carbon stored in forest trees is referred to as a forest's carbon stock. WARM models carbon storage, sequestration and stocks at several points in the life-cycle analysis, as detailed below:

- Forest carbon storage *increases* as a result of source reduction or recycling of paper products because both source reduction and recycling cause annual tree harvests to drop below otherwise anticipated levels (resulting in additional accumulation of carbon in forests). Consequently, source reduction and recycling "get credit" for increasing the forest carbon stock, whereas other waste management options (combustion and landfilling) do not. See the Source Reduction and Recycling process chapters for more information on this modeling analysis.
- Although source reduction and recycling are associated with forest carbon storage, the application of compost to degraded soils enhances soil carbon storage. The Composting process chapter details the modeling approach used to estimate the magnitude of carbon storage associated with composting.
- Landfill carbon stocks increase over time because much of the organic matter placed in landfills does not decompose, especially if the landfill is located in an arid area. See the Landfilling process chapter for further information on carbon storage in landfills.

1.4.2 GHG Emissions and Carbon Sinks Associated with Materials Management

As shown in Exhibit 1-3, depending on the material, WARM models up to five post-consumer materials management options, including recycling, composting, combustion, anaerobic digestion, and landfilling. WARM also models source reduction as an alternative materials management option. This section describes the GHG emissions and carbon sinks associated with each option.

1.4.2.1 Recycling

When a material is recycled, this analysis assumes that the recycled material replaces the use of virgin inputs in the manufacturing process. This approach is based on the assumption that demand for new materials/products and demand for recycled materials remains constant. In other words, increased recycling does not cause more (or less) material to be manufactured than would have otherwise been produced. In WARM, each ton of recycled material would displace the virgin material that would have been produced in the absence of recycling. EPA recognized that, in reality, there may be a relationship between recycling and demand for products with recycled content since these products may become cheaper as the supply of recycled materials increases. However, for the purpose of simplicity in WARM, EPA assumed that increased recycling does not change overall demand for products.

The avoided GHG emissions from remanufacture using recycled inputs is calculated as the difference between (1) the GHG emissions from manufacturing a material with 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material (accounting for loss rates associated with curbside collection losses and remanufacturing losses) with 100 percent virgin inputs. The GHG emissions associated with manufacturing a material with 100 percent recycled inputs includes the process of collecting and transporting the recyclables used in remanufacture. EPA did not consider GHG emissions at the MSW management stage because the recycled material is diverted from waste management facilities (i.e., landfills or combustion facilities).[7] If the product made from the recycled material is later composted, combusted or landfilled, the GHG emissions at that point would be attributed to the product that was made from the recycled material. The Recycling chapter discusses the process in further detail.

Recycling processes can be broadly classified into two different categories: open-loop and closed-loop recycling. Most of the materials in WARM are modeled in a closed-loop recycling process where end-of-life products are recycled back into the same product (e.g., a recycled aluminum can becomes a new aluminum can). Decisions about whether to model materials in an open-loop or closed-loop process are based on how the material is most often recycled and the availability of data. For materials recycled in an open loop, the products of the recycling process differ from the inputs. In open-loop emission factors, the GHG benefits of material recycling result from the avoided emissions associated with the virgin manufacture of the *secondary* products into which the material is recycled.

The materials modeled as open-loop recycling processes in WARM are: mixed paper, corrugated containers (partial open-loop) copper wire, carpet, electronics, concrete, tires, fly ash, asphalt shingles and drywall (partial open-loop).[8, 9] For more detail on the recycling pathways for particular materials or products, see the material-specific chapter. For more information on recycling, see the Recycling process chapter.

1.4.2.2 Source Reduction

In this analysis, source reduction is measured by the amount of material that would otherwise be produced but is not generated due to a program promoting waste minimization or source reduction. Source Reduction refers to any change in the design, manufacture, purchase or use of materials or products (including packaging) that reduces the amount of material entering the waste collection and disposal system. Source reduction conserves resources and reduces GHG emissions. The avoided GHG emissions are based on raw material acquisition and manufacturing processes for the industry average current mix of virgin and recycled inputs for materials in the marketplace.[10] There are no emissions from end-of-life management because it is assumed that a certain amount of material or product was never produced in the first place.

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[7] The EPA researchers did not include GHG emissions from managing residues (e.g., wastewater treatment sludges) from the manufacturing process for either virgin or recycled inputs.

[8] Note that corrugated is modeled using a partial open-loop recycling process. Roughly 70 percent of the recycled corrugated is closed-loop (i.e., replaces virgin corrugated) and 30 percent is open-loop (i.e., replaces boxboard).

[9] Most recycled drywall is used for a variety of agricultural purposes, but can also be recycled back into new drywall. Approximately 20 percent of recycled drywall is closed-loop (i.e., replaces virgin drywall) and 80 percent is open-loop (i.e., used for agricultural purposes).

[10] Changes in the mix of production (i.e., higher proportions of either virgin or recycled inputs) result in incremental emissions (or reductions) with respect to this reference point.

1.4.2.3 Composting

WARM models composting as resulting in both carbon storage and minimal CO_2 emissions from transportation and mechanical turning of the compost piles. Composting also results in CO_2 emissions from the decomposition of source materials, which include leaves, brush, grass, food waste and newspaper. However, as described in the text box on "CO_2 Emissions from Biogenic Sources," the biogenic CO_2 emitted from these materials during composting is not counted toward GHG emissions. Composting also produces small amounts of CH_4 and N_2O (due to anaerobic decomposition during composting), which vary depending on the carbon and nitrogen ratios of the waste being composted. Because recent literature indicated that these fugitive emissions occurred even in well-managed compost piles, these emissions were added into WARM version 13. Composting does result in increased soil carbon storage due to the effects of compost application on soil carbon restoration and humus formation. For more information on GHG flux resulting from composting, see the Composting process chapter.

1.4.2.4 Combustion

When materials are combusted at waste-to-energy facilities, GHGs in the form of CO_2 and N_2O are emitted. Nonbiogenic CO_2 emitted during combustion (i.e., CO_2 from plastics) is counted toward the GHG emissions associated with combustion, but biogenic CO_2 (i.e., CO_2 from paper products) is not. WARM assumes that the combustion pathway involves only waste-to-energy facilities that produce electricity. This electricity substitutes for utility-generated electricity and therefore the net GHG emissions are calculated by subtracting the electric utility GHG emissions avoided from the gross GHG emissions. GHG emissions from combustion are described further in the Combustion chapter.

1.4.2.5 Anaerobic Digestion

During anaerobic digestion, degradable materials, such as yard trimmings and food waste, are digested in a reactor in the absence of oxygen to produce biogas that is between 50-70% CH_4. This biogas is then typically burned on-site for electricity generation. WARM includes anaerobic digestion as a materials management option for yard trimmings, food waste, and mixed organics. As modeled in WARM, anaerobic digestion results in CO_2 emissions from transportation, preprocessing and digester operations, carbon storage (associated with application of digestate to agricultural soils), nitrogen and phosphorous fertilizer offsets, net electricity offsets, and where applicable, digestate curing. Emissions estimates also include fugitive emissions of CH_4 and N_2O produced during digestate decomposition.

1.4.2.6 Landfilling

When organic matter is landfilled, some of this matter decomposes anaerobically and releases CH_4. Some of the organic matter never decomposes at all; instead, the carbon becomes stored in the landfill. Landfilling of metals and plastics does not result in CH_4 emissions or carbon storage.

At some landfills, virtually all of the CH_4 produced is released to the atmosphere. At others, CH_4 is captured for flaring or combustion with energy recovery (e.g., electricity production). Almost all of the captured CH_4 is converted to CO_2, but is not counted in this study as a GHG because it is biogenic. With combustion of CH_4 for energy recovery, emission factors reflect the electric utility GHG emissions avoided. Regardless of the fate of the CH_4, the landfill carbon storage associated with landfilling of some organic materials is accounted for. GHG emissions and carbon sinks from landfilling are described in the Landfilling chapter.

1.4.2.7 Forest Carbon Storage

See section 1.4.1.4 for discussion.

1.4.2.8 Avoided Electric Utility GHG Emissions Related to Waste

Waste that is used to generate electricity (either through waste combustion, biogas capture at an anaerobic digester, or recovery and burning of CH_4 from landfills) displaces fossil fuels that utilities would otherwise use to produce electricity. Fossil fuel combustion is the single largest source of GHG emissions in the United States. When waste is substituted for fossil fuels to generate electricity, the GHG emissions from burning the waste are offset by the avoided electric utility GHG emissions. When gas generated from decomposing waste at a landfill is combusted for energy, GHG emissions are reduced from the landfill itself, and from avoided fossil fuel use for energy.

1.4.3 Temporal Aspects of Emission Factors in WARM

The emission factors used by WARM represent the full life-cycle changes in GHG emissions resulting from an alternative end-of-life management practice relative to the current, or baseline practice. Certain components of these life-cycle GHG emission factors, however, do not occur immediately following end-of-life management of a material, but over a longer period of time. For example, for paper, yard waste and food waste materials, not all of the GHG reductions occur within the same year of recycling: a portion of the reduction in GHG emissions results from avoided methane emissions from landfills and increased carbon storage in soils and forests. These emission reductions, resulting from the avoided degradation of organic materials into methane in landfills and the accumulation of carbon in forests, can occur over a timeframe of years to decades.

Consequently, WARM correctly accounts for the full range of GHG emission benefits from alternative waste management practices, but it does not explicitly model the timing of GHG reductions from these practices. Therefore, since WARM is a tool that describes the full life-cycle benefits of alternative waste management pathways, it is not appropriate to directly compare the benefits of alternative waste management as modeled through WARM with traditional GHG Inventory reports, which quantify GHG emissions from different sectors on an annual basis. This section explains the temporal components of WARM's emission factors, and explains how WARM considers these timing issues.

1.4.3.1 Temporal Components of WARM

The GHG emissions that occur throughout a materials management pathway can be released instantaneously or over a period of time. For example, while combustion instantaneously releases GHGs, the energy used to transport materials releases GHGs over the course of the trip, and materials decomposing in landfills may release methane for decades. Four main parts of the life-cycle GHG emissions and sinks calculated by WARM occur over time: (1) landfill methane emissions, (2) landfill carbon storage, (3) forest carbon sequestration and storage, and (4) soil carbon storage from compost. All four temporal components are relevant to management of organic materials such as paper and other wood products, food waste and yard trimmings.

- <u>Landfill Methane Emissions:</u> When placed into a landfill, a fraction of the carbon within organic materials degrades into methane emissions. The quantity and timing of methane emissions released from the landfill depends upon at least four factors: (1) how much of the original material decays into methane (varies from material to material), (2) how readily the material decays, (3) landfill moisture conditions (wetter leading to faster decay), and (4) landfill gas collection practices. Food waste and yard trimmings degrade within 20 to 30 years; materials with slower decay rates, such as paper and wood products, release a sizable fraction of their ultimate methane emissions after 30 years.

- Landfill Carbon Storage: The fraction of carbon in organic materials that does not degrade into landfill gas is permanently stored in the landfill. Consequently, the amount of carbon stored in the landfill over time is affected by how much of the original material decays into landfill gas, and the speed (or rate) at which the material decays.
- Forest Carbon Sequestration and Storage: Recycling or “source reducing” wood products offsets the demand for virgin wood. Trees that would otherwise be harvested are left standing in forests. In the short term, this reduction in harvest increases carbon storage in forests; over the longer-term, some of this additional carbon storage decreases as forest managers adjust by planting fewer new trees in managed forests. Results from USDA Forest Service models suggest that the forest carbon storage benefit is long-term, lasting at least for several decades (EPA, 2006, p. 41). WARM’s life-cycle perspective includes several timing issues involving complex economic relationships that affect the market for wood products (e.g., change in demand for virgin wood, adjustment in harvest practices and change in forest management in response to tree harvesting) relevant to carbon storage and release.
- Soil Carbon Storage: The stock of carbon in soils is the result of a balance between inputs (usually plant matter) and outputs (primarily CO_2 flux during decomposition of organic matter). When compost or digestate is applied to soils, a portion of the carbon in the compost remains un-decomposed for many years and acts as a carbon sink. While research into the mechanisms and magnitude of carbon storage is ongoing by EPA, WARM currently assumes that carbon from compost and digestate remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils and carbon stored in non-reactive humus compounds. Although the carbon storage rate declines with time after initial application, the life-cycle perspective in WARM assumes that the carbon stored in compost and digestate after a 10-year period is stable in the long term.

Evaluating the timing of GHG emissions from waste management practices involves a high level of uncertainty. For example, the timing of methane emissions from and carbon storage in landfills depends upon uncertain and variable parameters such as the ultimate methane yield and rate of decay in landfills; evaluating forest carbon storage involves complex economic relationships that affect the market for wood products and the management of sustainably harvested forests. In addition to the four components described above, timing issues may also apply to process energy and non-energy emissions from raw material acquisition and manufacturing, transportation and other activities. Timing issues for these components could depend upon factors such as how quickly markets respond to changes in demand for virgin materials given increases in recycling.

EPA designed WARM as a tool for waste managers to use to compare the full, life-cycle GHG benefits of alternative waste management pathways. Its strength as a tool is due to the relatively simple framework that distills complicated analyses of the life-cycle energy and GHG emissions implications of managing materials into a user-friendly spreadsheet model. The purpose of WARM, therefore, is to capture the full life-cycle benefits of alternative waste management practices rather than model the timing of GHG emissions or reductions.

This is fundamentally different from GHG inventories that quantify GHG emissions from different sectors on an annual basis. GHG inventories, in contrast, are used to establish baselines, track GHG emissions and measure reductions over time. The annual perspective of inventories, however, changes depending upon the timeframe used to evaluate GHG emissions, offering a narrow—and sometimes incomplete—picture of the full life-cycle benefits of materials management options. In contrast, the life-cycle view is exactly the perspective that WARM is designed to communicate. As a result, WARM's emission factors cannot be applied to evaluate reductions from annual GHG inventories because they do not necessarily represent annual reductions in emissions (i.e., emission reductions that occur within the same calendar year).

1.5 LIMITATIONS

When conducting this analysis, EPA used a number of analytical approaches and numerous data sources, each with its own limitations. In addition, EPA made and applied assumptions throughout the analysis. Although these limitations would be troublesome if used in the context of a regulatory framework, EPA believes that the results are sufficiently accurate to support their use in decision-making and voluntary programs. Some of the major limitations include the following:

- The manufacturing GHG analysis is based on estimated industry averages for energy usage, and in some cases the estimates are based on limited data. In addition, EPA used values for the average GHG emissions per ton of material produced, not the marginal emission rates per incremental ton produced. In some cases, the marginal emission rates may be significantly different.
- The forest carbon sequestration analysis deals with a very complicated set of interrelated ecological and economic processes. Although the models used represent the state-of-the-art in forest resource planning, their geographic scope is limited. Because of the global market for forest products, the actual effects of paper recycling would occur not only in the U.S. but in Canada and other countries. Other important limitations include: (1) the model assumed that no forested lands will be converted to non-forest uses as a result of increased paper recycling; and (2) EPA used a point estimate for forest carbon sequestration, whereas the system of models predicts changing net sequestration over time. Forest carbon sequestration is discussed further in the Forest Carbon Storage chapter.
- The composting analysis considered a small sampling of feedstocks and a single compost application (i.e., agricultural soil). The analysis did not consider the full range of soil conservation and management practices that could be used in combination with compost and their impacts on carbon storage.
- The combustion analysis used national average values for several parameters; variability from site to site is not reflected in the estimate.
- The landfill analysis: (1) incorporated some uncertainty on CH_4 generation and carbon sequestration for each material type, due to limited data availability; and (2) used estimated CH_4 recovery levels for the year 2013 as a baseline.
- Every effort has been made to tailor WARM to the conditions found in the U.S., including, where possible, production processes, fuel mixes and other underlying factors. Therefore, the results can only be considered applicable to the U.S., and caution should be used in applying or extrapolating them to other countries.

EPA cautions that the emission factors in WARM should be evaluated and applied with an appreciation for the limitations in the data and methods, as described further at the end of each chapter.

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2 WARM DEFINITIONS AND ACRONYMS

2.1 DEFINITIONS

Aerobic	Occurring in the presence of free oxygen.
Anaerobic	Occurring in the absence of free oxygen.
Anthropogenic	Derived from human activities.
Baseload electricity	An estimate of the electricity produced from plants that are devoted to the production of baseload electricity supply. Baseload plants are the production facilities used to meet continuous energy demand, and produce energy at a constant rate. Plants that run at over 80% capacity are considered "baseload" generation; a share of generation from plants that run between 80% and 20% capacity is also included based on a "linear relationship."
Biogas	A gas produced during the breakdown of organic matter in the absence of oxygen and comprised of a mixture of different gases.
Biogenic	Of non-fossil, biological origin.
C&D landfill	A landfill designed for and accepting only construction and demolition materials.
Carbon offset	Emission savings or storage that can be considered to cancel out emissions that would otherwise have occurred. For example, electricity produced from burning landfill gas is considered to replace electricity from the grid, leading to a carbon offset because landfill gas production and combustion results in lower GHG emissions than grid electricity production from fossil fuels.
Carbon sequestration	The removal of carbon (usually in the form of carbon dioxide) from the atmosphere, by plants or by technological means.
Carbon storage	Prevention of the release of carbon to the atmosphere by its storage in living plants (e.g., trees) and undecayed and unburned dead plant material (e.g., wood products, biogenic materials in landfills).
Cellulose	A polysaccharide that is the chief constituent of all plant tissues and fibers.
Closed-loop recycling	A *recycling* process in which the primary product type is remanufactured into the same product type. (e.g., Aluminum cans recycled into aluminum cans.)
Combustion	A waste management strategy in which the waste material is burned. Waste-to-energy combustion facilities are set up to produce useful heat and/or electricity.

Combustion emissions	Emissions from combustion adjusted based on regional avoided utility emission factors.
Composting	A waste management strategy in which aerobic microbial decomposition transforms biogenic material such as food scraps and yard trimmings into a stable, humus-like material (compost).
Curing	The aerobic drying of digestate after it has been dewatered.
Demanufacturing	Disassembly and recycling of obsolete consumer products such as computers, electronic appliances, and carpet into their constituents in order to recover the metal, glass, plastic, other materials, and reusable parts.
Digestate	The material remaining after anaerobically digesting biogenic matter. Digestate can be in liquid or solid form and can either be cured before land application or directly applied.
Downstream emissions	Emissions that occur at life-cycle stages after use: e.g., waste management.
Dry Digestion	The process of breaking down organic waste into useful biogas and compost in an environment with little or no oxygen. This process accepts all organic matter and operates at high total solids levels (20->40% total solids).
Embedded energy	The energy contained within the raw materials used to manufacture a product. For example, the embedded energy of plastics is due to their being made from petroleum. Because petroleum has an inherent energy value, the amount of energy that is saved through plastic recycling and source reduction is directly related to the energy that could have been produced if the petroleum had been used as an energy source rather than as a raw material input.
Emission factor	Greenhouse gas emission in metric tons of carbon dioxide equivalent per short ton of material managed.
End-of-life pathways	The end-of-life management strategies available in WARM: recycling, composting, combustion, and landfilling. Sometimes source reduction is included in this phrase, although source reduction does not occur at end of life.
Energy content	The inherent energy of a material. For example, the amount of energy in a plastic potentially available for release during combustion.
Fertilizer offset	WARM calculates fertilizer offsets by assuming that the application of compost or digestate avoids the GHG emissions associated with the production and application of some portion of the fertilizer required for arable land.

Forest carbon sequestration	As forests grow, they absorb atmospheric CO_2 and store it. When the rate of uptake exceeds the rate of release, carbon is said to be sequestered. See also carbon sequestration and carbon storage.
Fugitive Emissions	During the composting process, microbial activity decomposes waste into a variety of compounds, whose composition depends on many factors, including the original nutrient balance and composition of the waste, the temperature and moisture conditions of the compost, and the amount of oxygen present in the pile. In WARM, this process is refers to the generation of small amounts of CH_4 and N_2O.
Hemicellulose	Constituent of plant materials that is a polysaccharide, easily hydrated, and easily decomposed by microbes.
Inorganic	1. Not referring to or derived from living organisms. 2. In chemistry, any compound not containing carbon (with a few exceptions).
Landfill carbon storage	Biogenic materials in a landfill are not completely decomposed by anaerobic bacteria, and some of the carbon in these materials is stored. Because this carbon storage would not normally occur under natural conditions (virtually all of the organic material would degrade to CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic sink. However, carbon in plastic that remains in the landfill is not counted as stored carbon, because it is of fossil origin.
Landfilling	A waste management strategy involving the anaerobic decomposition of organic substrates producing CH_4 and CO_2.
Leachate	Liquid that percolates through waste material in a landfill picking up contaminants from the waste material. Landfill leachate must be collected and properly disposed of to avoid transferring the contaminants to groundwater
Life-cycle assessment	An accounting method that evaluates and reports the full life-cycle inputs and outputs (including GHG emissions) associated with the raw materials extraction, manufacturing or processing, transportation, use, and end-of-life management of a good or service.
Loss rate	The amount of recovered material that is lost during the recycling process, relative to the total amount of collected material. The inverse of the retention rate.
Materials (or waste) management strategy	One of the five strategies in WARM: source reduction, recycling, composting, combustion, and landfilling.
Methanogenic	Biologically producing methane.
MSW landfill	A landfill designed for and accepting only municipal solid waste.

Non-baseload electricity	An estimate of the marginal electricity produced from plants that are more likely to respond to incremental changes in electricity supply and demand based on their capacity factor. All power plants with capacity factors below 20% are considered "non-baseload". Plants that run at over 80% capacity are considered “baseload” generation and not considered the “non-baseload”; a share of generation from plants that run between 80% and 20% capacity is included based on a “linear relationship”.
Open-loop recycling	A *recycling* process in which the primary product is remanufactured into other products that are different from the original primary product. (e.g., carpet recycled into molded auto parts).
Organic	1. Referring to or derived from living organisms. 2. In chemistry, any compound containing carbon (with a few exceptions).
Partial-open-loop recycling	A *recycling* process in which a portion of the primary product type is remanufactured into the same product type, while the remaining portion is recycled into other product types. e.g., corrugated containers are recycled into both corrugated containers and paperboard.
Post-consumer emissions	Emissions that occur after a consumer has used a product or material: generally, waste management emissions.
Post-consumer recycling	Materials or finished products that have served their intended use and have been diverted or recovered from waste destined for disposal, having completed their lives as consumer items. In contrast, pre-consumer recycling is material (e.g., from within the manufacturing process) that is recycled before it reaches the consumer.
Pre-combustion emissions	The GHG emissions that are produced by extracting, transporting, and processing fuels that are in turn consumed in the manufacture of products and materials.
Process energy emissions	Emissions from energy consumption during the acquisition and manufacturing processes
Process non-energy emissions	Emissions occurring during manufacture that are not associated with energy consumption, e.g., perfluorocarbons (PFCs) are emitted during the production of aluminum.
Recovery	The collection of used materials for recycling. Generally recovered materials are taken from the point of use to a materials recovery facility (MRF).
Recycled input credit	WARM calculates the recycled input credit by assuming that the recycled material avoids—or offsets—the GHG emissions associated with producing the same amount of material from virgin inputs.

Recycling	Recovering and reprocessing usable products that might otherwise become waste.
Retail transport emissions	The typical emissions from truck, rail, water, and other-modes of transportation required to transport materials or products from the manufacturing facility to the retail/distribution point.
Retention rate	The amount of recovered material that is transformed into a recycled product, relative to the total amount of collected material. The inverse of the loss rate.
Source reduction	Any change in the design, manufacture, purchase, or use of materials or products that reduces or delays the amount or toxicity of material entering waste collection and disposal. These practices include lightweighting, double-sided copying, and material reuse. It is also possible to source reduce one type of material by substituting another material.
Transportation emissions	Emissions from energy used to transport materials, including transport of manufactured product to retail/distribution point.
Upstream emissions	Emissions that occur at life-cycle stages prior to use: e.g., raw materials acquisition, manufacturing, and transportation.
Waste-to-energy facility	Municipal solid waste incinerator that converts heat from combustion into steam or electricity
Wet digestion	The process of breaking down organic waste into useful biogas and compost in an environment with little or no oxygen. This process accepts only food waste and operates at low total solids levels (<10-20% total solids). Water is added during the digestion process.

2.2 ACRONYMS

AF&PA	American Forest and Paper Association
BBP	benzyl butyl phthalate
Btu	British thermal unit
C	carbon
C_2F_6	hexafluoroethane
$CaCO_3$	limestone
CaO	lime
CF_4	tetrafluoromethane
CH_4	Methane
CO_2	carbon dioxide
CPU	central processing unit
CRT	cathode ray tube

DINP	diisononyl phthalate
EF	emission factor
eGRID	U.S. EPA's Emissions & Generation Resource Integrated Database
EPA	U.S. Environmental Protection Agency
FAL	Franklin Associates, Ltd.
FC	forest carbon
FRA	Forest Resources Association
GHG	greenhouse gas
GWP	global warming potential
HDPE	high-density polyethylene
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kWh	kilowatt-hour
lb	pound
LCA	life cycle assessment
LCD	liquid crystal display
LCI	life cycle inventory
LDPE	low-density polyethylene
LED	light-emitting diode
LFG	landfill gas
MDF	medium-density fiberboard
MRT	mean residence time
MSW	municipal solid waste
MTCE	metric tons carbon equivalent
MTCO2E	metric tons carbon dioxide equivalent
N	nitrogen
N_2O	nitrous oxide
NAPAP	North American Pulp and Paper
NREL	National Renewable Energy Laboratory
PCB	printed circuit board
PET	polyethylene terephthalate
PRC	paper recovery
PVC	polyvinyl chloride
PWH	pulpwood harvest
RDF	refuse-derived fuel
RMAM	raw materials acquisition and manufacturing
TS	total solids
USDA	U.S. Department of Agriculture
USDA-FS	U.S. Department of Agriculture, Forest Service
VCT	vinyl composition tile
VOC	volatile organic compound
WARM	Waste Reduction Model
WTE	waste-to-energy

3 RECENT UPDATES IN WARM

Since the release in 2006 of the 3rd edition of the *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks* Report*,* EPA has restructured the life-cycle emission factor documentation previously published as a single report. As of 2010, the resulting WARM documentation consists of individual chapters for each material type and waste management practice that EPA has analyzed. This approach is more suited to the model structure and allows for easier updating in the future than the previous hard-copy report structure. This Recent Updates document is designed to communicate the structure of updates to recent versions of WARM.

With each new version of WARM, the model documentation is updated to reflect the regular annual updates made to WARM, as well as other changes and improvements made to the model, as described below. It should be noted that changes listed in “Annual Changes” and “Changes Made for WARM Version 15” have not been implemented in other EPA tools including iWARM.

3.1 ANNUAL CHANGES

Certain updates to underlying WARM data are made annually, and have been implemented in WARM Version 15. These include:

- Assumptions about landfill methane generation are updated based on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.
- MSW generation and recovery rates are updated based on the latest *Advancing Sustainable Materials Management: Facts and Figures 2015. Assessing Trends in Material Generation, Recycling and Disposal in the United States* report.
- The composition of yard trimmings is updated based on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.
- Various aspects of the U.S. average electricity mix are updated based on EIA’s *Annual Energy Review* and the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.
- State electricity grid emission factors are updated based on the eGRID database.
- GHG equivalencies are updated to match EPA's GHG Equivalency Calculator.

3.2 CHANGES MADE FOR WARM VERSION 15

In addition to the Annual Changes listed above, other updates made to WARM since Version 14 include:

- **Electronics –** EPA has replaced the previous life-cycle emission factors for Personal Computers with seven more detailed electronic materials. EPA developed separate materials management factors for Desktop CPUs, Portable Electronic Devices, Flat-panel Displays, CRT Displays, Electronic Peripherals, Hard-copy Devices, and Mixed Electronics.
- **Economic Impacts –** EPA expanded the impact assessment reports in WARM to include economic impacts from employment (labor hours), wages, and taxes. The economic impacts include direct impacts associated with the actual transformation of recyclable materials into the marketable products and indirect impacts including the collection, sorting and transportation of a material.

3.3 CHANGES MADE FOR WARM VERSION 14

In addition to the Annual Changes listed above, other updates made to WARM since Version 13 include adding Anaerobic Digestion as a new management pathway:

- **Anaerobic Digestion –** WARM now includes anaerobic digestion as a materials management option for yard trimmings, food waste, and mixed organics.
    - EPA developed separate estimates of emissions for wet anaerobic digestion and dry anaerobic digestion. Wet digestion and dry digestion are possible pathways for food waste while yard trimmings are only able to be processed in a dry digester.
    - EPA included two scenarios for handling digestate: the direct application of digestate to land and the curing of digestate before land application.
- **Transportation –** EPA updated the emission factor used for post-consumer transportation for the combustion, composting, landfilling and anaerobic digestion. The updated emission factor was also included in the user-defined transportation distances.
- **Landfilling –** EPA updated the material properties of organic matter, including the initial carbon content, proportion of carbon stored and the methane yield. These updates affect the amount of carbon stored during landfilling.

3.4 CHANGES MADE FOR WARM VERSION 13

Updates made for WARM Version 13 include the following:

- **Food Waste –** EPA added new emission factors to characterize the energy and GHG emissions associated with the source reduction of food waste.
    - These new emission factors include three separate weighted averages of food wastes available in the online version of WARM: Food Waste, Food Waste (meat only), and Food Waste (non-meat). EPA also added individual emission factors for beef, poultry, grains, bread, fruits and vegetables, and dairy products available in the Excel tool.
    - The scope of the new emission factors encompasses farm-to-retail and are informed by a variety of food production life-cycle inventories and peer-reviewed studies.
- **Landfilling –** EPA revised the landfill gas methodology in WARM to improve the estimates of gas collection system operating efficiency and align it with more recent scientific literature.
    - This analysis improves upon the landfill gas collection efficiency modeling in WARM and updates the methane oxidation rates.
    - EPA used a Monte Carlo analysis model developed by James Levis and Morton Barlaz to more accurately estimate the fraction of total produced landfill gas that is used beneficially, flared, and vented to the atmosphere at landfills that manage landfill gas.
    - The Excel version of WARM now allows users the option of selecting and reviewing results based on California regulatory gas collection scenario as one of four landfill gas collection scenarios, developed using a Monte Carlo analysis and informed by recent, peer-reviewed scientific literature.
- **Composting –** EPA updated the composting waste management pathway to include fugitive emissions of CH_4 and N_2O during composting.

  - These estimates were derived from a literature review of recent studies on composting.
  - “Green”, or predominantly nitrogenous organic wastes such as yard trimmings have differing fugitive emissions than “brown”, or predominantly carbon waste such as food waste. The Mixed Organics material type uses a weighted average of both types of waste.
- **Source Reduction**—EPA updated the source reduction management pathway to include source reduction emissions for several different mixed material categories, including: Mixed Paper, Mixed Metals, and Mixed Plastics.

3.5 CHANGES MADE FOR WARM VERSION 12

Updates made to WARM for Version 12 include the following:

- The Excel macro programming in WARM has been removed. The removal of macros does not affect the results or functionality of the tool. All of the energy and emissions (both $MTCO_2E$ and MTCE) results are displayed automatically (previously, the user could choose which to display).
- The emission factor for the broadloom carpet recycling pathway was updated to include two new plastic resin components. These were based on input and data from Dr. Matthew Realff of the Georgia Institute of Technology, which were informed by the 2009 Carpet America Recovery Effort (CARE) 2009 annual report.
- The energy content of broadloom carpet was updated to incorporate more recent data provided by Dr. Matthew Realff of Georgia Institute of Technology, which were informed by the 2009 Carpet America Recovery Effort (CARE) 2009 annual report.
- Revised the emission factors for three plastics: high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polyethylene terephthalate (PET).
- Developed emission and energy factors for four new plastics to add to the model: Linear low-density polyethylene (LLDPE), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC).
- The Mixed Recyclables and Mixed Plastics emission and energy factors were updated to remove the inclusion of LDPE as a recycled plastic type. Previously, these factor incorporated LDPE, but updated data for recycling LDPE plastic were unavailable.
- The Mixed Recyclables and Mixed Plastics emission and energy factors were updated to reflect revisions to the underlying numbers in the virgin and recycled HDPE and PET emission factors.
- The emission and energy factors for aluminum cans were updated based on life-cycle data from the Aluminum Association. In addition, new emission and energy factors for aluminum ingot were developed.
- The emission and energy factors for polylactide (PLA), a biopolymer, were developed using life-cycle data provided by NatureWorks.

3.6 CHANGES MADE BETWEEN THE 3RD EDITION OF THE REPORT AND WARM VERSION 11

The primary changes and improvements to the life-cycle analysis since the 3rd edition of the report include the following:

- **Overarching Changes**

  - New GHG equivalencies were added to show the change in emissions calculated by the user in terms of gallons of gasoline, cylinders of propane, railway cars of coal, as a percentage of the annual CO_2 emissions from the U.S. transportation sector, and as a percentage of the annual CO_2 emissions from the U.S. electricity sector. All the GHG equivalencies were updated to match EPA's GHG Equivalency Calculator.
  - EPA modified the interface to display results in metric tons of carbon dioxide equivalent ($MTCO_2E$) as the default unit for GHG emissions, but results are still available in units of metric tons of carbon equivalent (MTCE).
  - The 1605(b) functionality in the Excel version of WARM was removed because 1605(b) no longer supports the reporting of savings from waste reduction.
- **Changes affecting Material Types**
  - New emission factors were added for six construction and demolition (C&D) materials: asphalt concrete, asphalt shingles, drywall, fiberglass insulation, vinyl flooring, and wood flooring.
  - Emission factors for tires were updated: the tire recycling pathway now encompasses ground and shredded rubber applications and no longer includes retreading as a recycling application. This change has decreased the overall net benefit of recycling scrap tires.
  - The material type “corrugated cardboard” was renamed to “corrugated containers” to eliminate redundancy of the former naming convention.
- **Changes affecting Waste Management Options**
  - The Excel version of WARM now incorporates region-specific electricity grid factors to more accurately model emissions associated with avoided generation of electricity due to landfill gas recovery in the landfilling pathway and waste-to-energy in the combustion pathway. This change increases the flexibility of WARM and allows the user to generate more precise results for their scenario. This functionality is not available in the online version of WARM where the default national average electricity grid mix (i.e., national average) is implicit.
  - The Excel version of WARM includes an updated method for estimating the landfill gas collection efficiency, allowing the user to select between three landfill gas collection efficiency scenarios based on specific landfill recovery characteristics: typical operation, worst-case collection, and aggressive gas collection. This change increases the flexibility of WARM and allows the user to generate more precise results for their scenario. This functionality is not available in the online version of WARM where the default national average landfill gas collection scenario (i.e., typical operation) is implicit.
  - Component-specific decay rates were added to the Excel version of WARM for all organic materials to more accurately model the rate at which each material decays within a landfill under given landfill moisture conditions: dry, average, wet, or bioreactor. This change increases the flexibility of WARM and allows the user to generate more precise results for their scenario. This functionality is not available in the online version of WARM where the default national average landfill moisture conditions (i.e., average) scenario is implicit.

  - The waste-to-energy combustion pathway energy values (MMBTU) incorporate a revised methodology that considers the ratio of mass burn combustion facilities (17.8%) and the national average electric utility grid combustion efficiency (32%).
  - The recycling emission factors for the Mixed Paper material types were modified to include updated recycled boxboard data.

3.7 FUTURE UPDATES TO WARM

WARM is regularly updated to expand its coverage of materials and waste management pathways, to keep its methodology consistent with current research and literature, and to maintain the accuracy of its background data. Updates to WARM that may be implemented in the near future include the following:

- **Donations:** EPA is currently assessing the viability of adding donations as an alternative pathway for waste management, building off of the source reduction pathway and the reuse alternative described in the memo “Modeling Reuse in EPA's Waste Reduction Model” available through the WARM Documentation page.

4 FOREST CARBON STORAGE

This chapter describes the development of material-specific estimates of changes in forest carbon storage in WARM. It summarizes the approach used to estimate changes in forest carbon storage in managed forests resulting from source reduction and recycling of wood and paper products.

4.1 A SUMMARY OF THE GREENHOUSE GAS IMPLICATIONS OF FOREST CARBON STORAGE

Forests absorb (i.e., sequester) atmospheric carbon dioxide (CO_2) and store it in the form of cellulose and other materials. In the early stages of growth, trees store carbon rapidly; consequently, as tree growth slows, so does carbon sequestration. Trees naturally release carbon throughout their life cycle as they shed leaves, branches, nuts, fruit, and other materials, which then decay; carbon is also released when trees are cleared and processed or burned.

When paper and wood products are recycled or the production of these materials is avoided through source reduction, trees that otherwise would be harvested are left standing in forests. In the short term, this reduction in harvesting results in more carbon storage than would occur in the absence of the recycling or source reduction. Over the long term, when forest managers find they have more trees standing resulting from reduced harvesting, they will respond by planting fewer trees; therefore, while the carbon storage effect of source reduction and recycling is high in the short term, it is less pronounced in the long term.

WARM evaluates forest carbon storage implications for all wood and paper products, which include all of the paper types in WARM,[11] dimensional lumber, medium-density fiberboard (MDF), and hardwood flooring. Paper products are primarily nondurable goods, or goods that generally have a lifetime of less than three years (EPA, 2008, p. 76). Wood products such as dimensional lumber, MDF, and wood flooring are considered durable goods because they typically have a lifetime of much longer than three years (Skog, 2008). Because of the differences in harvesting practices, use, and service life of paper and wood products, EPA analyzed the forest carbon storage implications for paper products separately from wood products.

In the United States, uptake by forests has long exceeded release, a result of forest management activities and the reforestation of previously cleared areas. EPA estimated that the 2013 annual net carbon flux (i.e., the excess of uptake minus release) in U.S. forests was about 765.5 million metric tons of carbon dioxide equivalent ($MMTCO_2E$), which offset about 14 percent of U.S. energy-related CO_2 emissions. In addition, about 2,520 $MMTCO_2E$ was stored in wood products currently in use (e.g., wood in building structures and furniture, paper in books and periodicals) (EPA 2015). Considering the effect of forest carbon sequestration on U.S. net GHG emissions, the data clearly showed that a thorough examination was warranted for use in WARM.

This chapter summarizes the methodology, approach, and results of EPA's analysis of forest carbon storage. The next section outlines the overall methodology, including the key components in the assessment of changes in forest carbon storage. Sections 4.3 and 4.4 summarize forest carbon storage estimates for source reduction and recycling for paper and wood products. Section 4.5 outlines the limitations associated with EPA's analysis of forest carbon storage.

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[11] Corrugated containers, magazines/third-class mail, newspapers, office paper, phonebooks and textbooks.

4.2 FOREST CARBON STORAGE METHODOLOGY

WARM's Approach to Forest Carbon Storage

WARM adopts a waste management perspective that assumes life-cycle boundaries start at the point of waste generation (i.e., the moment a product such as paper or dimensional lumber reaches its end-of-life stage), and the methodology examines the resulting life-cycle GHG implications of alternative material management pathways relative to a baseline waste management scenario.

To evaluate forest carbon storage, WARM first assesses the amount of wood that would have been harvested from the forest with no efforts to increase source reduction or recycling. This establishes a "business-as-usual" baseline of wood harvests. Next, WARM examines how increased source reduction or recycling reduces the demand for wood harvests from the forest by avoiding the use of wood or by conserving paper and wood products relative to this business-as-usual baseline. The forest carbon storage is equal to the amount of carbon contained in wood that is not harvested as a result of increased recycling or source reduction.

In other words, rather than evaluating the entire stock and flows of carbon into and out of forests in the United States, WARM evaluates the difference, or *marginal* change, in forest carbon storage resulting from efforts to increase source reduction or recycling beyond the business-as-usual baseline. This approach is consistent with WARM's purpose of evaluating the benefits of alternative management practices relative to baseline activities.

On average in the United States, timber harvests are more than compensated by replanting; therefore, baseline forest carbon withdrawals need to be considered as part of the overall carbon stocks-and-flows cycle for forest and harvested wood products. This methodology is consistent with and supported by the Intergovernmental Panel on Climate Change (IPCC) Inventory Guidelines (IPCC, 2006) that distinguish between biogenic carbon that is harvested on a sustainable basis versus non-sustainable harvest, and the fact that land use change and forestry provide a large net sink for GHG emissions in EPA's U.S. GHG Inventory (2015).

EPA estimated the net change in forest carbon storage from source reduction or recycling of forest products by evaluating three components:

1. Changes in timber harvest (i.e., trees that have been cut from the forest) as a result of changes in demand for virgin wood.
2. Changes in forest stocks as a result of changes in harvest.
3. Changes in carbon storage in the in-use product pool (for durable wood products).

These three components taken together provide the net change in carbon storage resulting from recycling or source reduction of forest products. Exhibit 4-1 is a flow chart explaining the approach. First, for a forest product that is recycled or source reduced instead of being put in a landfill or combusted, WARM assumes that—if demand for forest products remains constant—recycling or reuse results in a reduction in the demand for virgin timber from forests. Second, this reduction in timber harvest results in a small increase in the stock of carbon that remains in U.S. forests. Third, durable wood products remain in use for many years,[12] and are themselves a significant source of carbon storage that is tracked in the U.S. GHG Inventory[13] (EPA, 2015). Since source reduction reduces the amount of virgin wood products that enter the market, and remanufacturing wood products into recycled products results in some loss of

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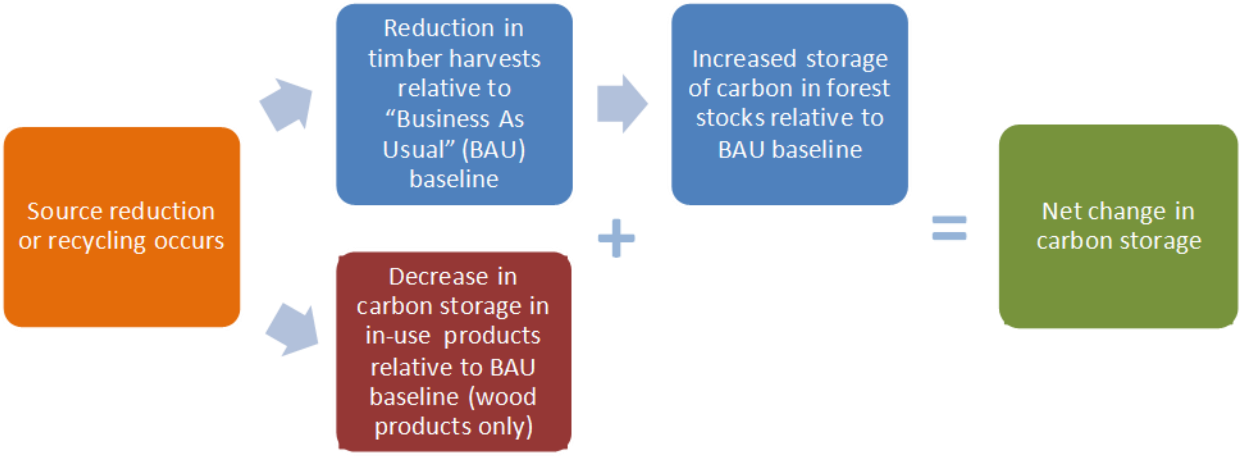
[12] For example, Skog (2008) estimates that the half-life of wood (i.e., the amount of time it takes for half of an initial amount of wood to reach the end-of-life stage) is 100 years in single-family housing and 30 years in other end uses.

[13] Durable wood products (also known as harvested wood products) accounted for 70.8 million metric tons of CO_2 of net carbon flux (equivalent to 19.3 million metric tons of carbon) in 2013. See Chapter 6 of the U.S. GHG Inventory (EPA, 2015).

material, increasing source reduction or recycling decreases the amount of carbon stored in in-use products.

Consequently, for durable wood products, recycling and source reduction increase the amount of carbon that is stored in U.S. forests, but simultaneously they decrease the amount of carbon from virgin products that would have been stored in durable wood products. Together, these two factors equal the net change in carbon storage resulting from increased source reduction or recycling. Note that the decrease in carbon storage in in-use products applies only to durable (wood) products; WARM does not consider changes in the in-use product carbon pool for nondurable (paper) goods because these products have shorter lifetimes, typically less than three years, and the carbon in these goods cycles out of the in-use pool over a relatively short period.

Exhibit 4-1: Forest Carbon Storage Methodology



4.3 FOREST CARBON STORAGE AND PAPER PRODUCTS

Paper products in WARM include corrugated containers, magazines/third-class mail, newspapers, office paper, phonebooks, and textbooks. These products are short-lived, nondurable goods that are harvested primarily from forests that are grown for making wood pulp for paper production. This section describes the methodology used to evaluate the two relevant components of forest carbon storage, outlined in Section 4.2, for paper products: changes in timber harvest and changes in forest stock.

Paper types fall into two broad categories, mechanical- and chemical-pulp papers. Mechanical pulping involves grinding logs into wood fibers and mixing with hot water to form a pulp suspension. Chemical pulping, also known as kraft pulping, involves removing the surrounding lignin in the wood raw material during a cooking process. (Verband Deutscher Papierfabrikin e.V., 2008) Of the paper types modeled in WARM, mechanical pulp papers include newspaper and textbooks. Office paper, corrugated containers, textbooks, and magazines/third-class mail are considered chemical-pulp paper types.[14]

4.3.1 Effect of Source Reduction and Recycling on Timber Harvests

Several U.S. Department of Agriculture Forest Service (USDA FS) efforts have analyzed the relationship between paper recovery (i.e., recycling) rates and pulpwood harvests (i.e., wood harvested

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[14] In general, shipping and packaging containers, paper bags, and printing and writing papers are manufactured from chemical pulp, while newspaper, specialty papers, tissue, toweling, paperboard, and wallboard are produced from mechanical pulp (AF&PA, 2010a).

for paper production) based on data compiled by the American Forest and Paper Association (AF&PA) and the Forest Resources Association (FRA). AF&PA collects information on the mass of recovered paper and wood pulp consumed (AF&PA, 2005) and paper and paperboard production (AF&PA, 2004). FRA publishes information on the annual amount of pulpwood received at pulp mills (FRA, 2004). Based on this information, along with assumptions about moisture content,[15] Dr. Peter Ince of USDA FS developed the following equation to relate paper recovery to pulpwood harvests (Ince and McKeever, 1995):

$$PWH = X \times \{PP - [PR \times (1 - EX) \times Y]\} \qquad \text{(Eqn. 1)}$$

Where,

PWH = Pulpwood harvests at 0 percent moisture content, i.e., ovendry (short tons)
PP = Paper production at 3 percent moisture content (short tons)
PR = Paper recovery at 15 percent moisture content (short tons)
EX = Percentage of recovered paper that is exported
X = Process efficiency of converting ovendry pulpwood to paper and paperboard at 3 percent moisture content, which is the ratio of finished paper to pulp, and accounts for the portion of paper and paperboard that is water and fillers
Y = Process efficiency of converting recovered paper at 15 percent moisture to paper and paperboard at 3 percent moisture, which is the ratio of recovered paper to finished paper, and accounts for the water in recovered paper

The values of *X* and *Y* are based on process efficiency estimates provided by John Klungness (Research Chemical Engineer, USDA FS) and Ken Skog (Project Leader, Timber Demand and Technology Assessment Research, USDA FS). The value for *EX*, the export rate, is based on AF&PA statistics on U.S. recovered paper exports. In 2008, approximately 40 percent of recovered paper was exported from the United States (AF&PA, 2010b).[16]

EPA used the relationship developed in Equation 1 to describe how a change in paper recovery affects pulpwood harvests. For example, if paper recovery increases by one short ton, by how much would pulpwood harvests be reduced to meet the same level of paper production in the United States?

Exhibit 4-2 column (f) shows that increasing paper recovery by one short ton would reduce (i.e., avoid) pulpwood harvests by 0.58 short tons for mechanical pulp papers and by 0.89 short tons for chemical pulp papers. This difference results from the lower ratio of pulp to finished paper for chemical-pulp papers because the chemical pulping process in paper manufacturing removes lignin from the raw wood material.

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[15] The moisture contents are pulpwood as harvested, 50 percent; paper and paperboard, 3 percent; wood pulp consumed, 10 percent; and recovered paper consumed, 15 percent. Knowing the moisture content is important to accurately gauge carbon contents of these materials.

[16] EPA included the export rate in the calculation of avoided pulpwood harvest per ton of paper recovered because the WARM analysis focuses on the United States; therefore, EPA assumed the avoided pulpwood harvest was affected only by recovered paper that stays in the United States. Recovered paper that is exported will produce a different offset for pulpwood harvests in other countries because forest management practices outside of the United States are likely to be different. The inclusion of the exported recovered paper as a factor in calculating avoided pulpwood harvest per ton of paper recovered is a conservative assumption because it results in a smaller reduction in pulpwood harvests from increased paper recovery.

Exhibit 4-2: Relationship Between Paper Recovery (i.e., Recycling) and Pulpwood Harvest (Values of Eqn. 1 Parameters)

(a)	(b) Ratio of Pulp to Finished Paper	(c) *X* = Process Efficiency (c = 1/b)	(d) *Y* = Ratio of Recovered Paper to Finished Paper	(e) EX (%)	(f) Avoided Short Tons PWH per Short Ton Paper Recovered (f = c × d × [1 – e])
Mechanical Pulp	0.900	1.11	0.875	40	0.58
Chemical Pulp	0.475	2.11	0.700	40	0.89

For source reduction, the change in pulpwood harvests from source reducing paper can be calculated directly from the process efficiency (X) of mechanical and chemical pulp production. This is because source reduction, by reducing consumption of paper, directly reduces paper production (PP in Equation 1) and, consequently, the amount of pulpwood harvested. Based on the process efficiency estimates in

Exhibit 4-2, WARM estimates that one short ton of source reduction avoids 1.1 short tons of pulpwood harvests for mechanical pulp, and 2.11 short tons of chemical pulp.

4.3.2 Effect of Changes in Timber Harvests on Forest Carbon Stocks

EPA based its analysis of carbon storage on model results provided by the USDA FS using its FORCARB II model of the U.S. forest sector. USDA FS models and data sets are the most thoroughly documented and peer-reviewed models available for characterizing and simulating the species composition, inventory, and growth of forests, and the Forest Service has used them to analyze GHG mitigation in support of a variety of policy analyses. FORCARB II is a USDA FS model that simulates the complex, dynamic nature of forest systems, including the interaction of various forest carbon pools, how carbon stocks in those pools change over time, and whether the response of forest carbon is linearly proportional to harvests. To explore these questions, USDA FS ran two enhanced recycling/source reduction pulpwood harvest scenarios in FORCARB II.

The base assumptions on pulpwood harvests are derived from the North American Pulp and Paper (NAPAP) model baseline projections developed for the Forest Service 2001 Resource Planning Act Timber Assessment. To investigate the effect of small and large changes in pulpwood harvests, the Forest Service modeled two reduced harvest scenarios, which involved decreasing pulpwood harvest by 6.7 million metric tons and 20.2 million metric tons for the period 2005 to 2009.[17] The Forest Service selected the values of 6.7 million and 20.2 million metric tons as representative low- and high-end reductions in pulpwood harvests based on the 50-percent paper recycling rate in 2005 (Freed et al., 2006). Harvests in all other periods were the same as the baseline.

The relative change in forest carbon storage per unit of reduced pulpwood harvest across the two decreased harvest scenarios is virtually identical (i.e., less than 1 percent), which suggests that the relationship between forest carbon storage and reduced pulpwood harvests is not affected by the size of the reduction in pulpwood harvests over the range investigated by the two scenarios.

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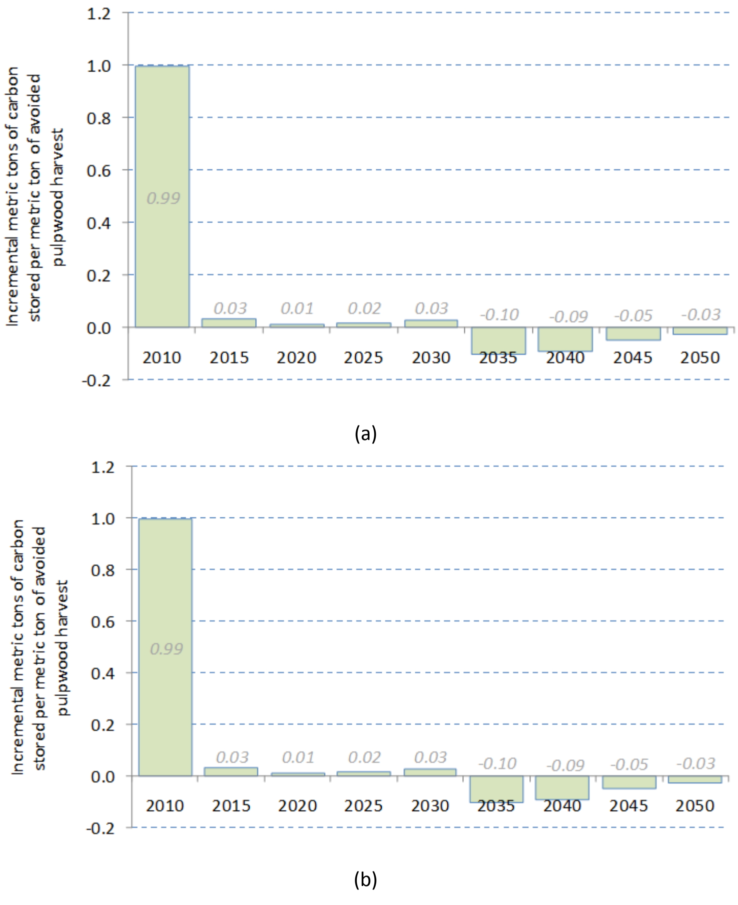
[17] EPA selected this timeframe because, at the time the EPA did the analysis, that period represented a short-term future time horizon over which reduced forest withdrawals could be evaluated against baseline projections.

For each scenario, the Forest Service calculated the change in carbon stocks compared with the base case; the change represents the carbon benefit of reduced harvests associated with recycling or source reduction. The change in metric tons of carbon equivalents (MTCE) is divided by the incremental metric tons of pulpwood harvested and multiplied by the weight ratio of CO_2 to carbon (44/12, or approximately 3.667) to yield results in units of $MTCO_2E$ per metric ton of pulpwood not harvested (i.e., the carbon storage rate). For more details, please refer to the conversions provided in Exhibit 4-4 and

Exhibit 4-5.

As shown in Exhibit 4-3, the cumulative carbon storage rate starts at about 0.99 MTCE per metric ton pulpwood in 2010, increases to about 1.08 MTCE per metric ton pulpwood in 2030, and declines with time to about 0.81 MTCE per metric ton pulpwood in 2050. According to EPA's detailed analysis of the FORCARB II results, the primary effect of reduced pulpwood harvests is to increase carbon stored in live trees that otherwise would have been harvested (shown by the sharp increase in carbon storage in 2010). This effect is offset to a small degree by a decrease in carbon storage in the amount of downed wood in the forest. Carbon storage in dead trees, the forest floor, and forest understory increases slightly; carbon stored in forest soils has no effect. Most of the changes in each of these pools of forest carbon peak in 2010 and moderate somewhat over the next 40 years, although the increase in carbon storage in the forest floor peaks over a longer time period in 2030. After 2030, the amount of carbon stored in live trees begins to decline, causing a reduction in forest carbon storage. This decline likely reflects the effect of market forces, which result in less planting of new managed forests in response to a lower level of demand for pulpwood harvests.

Exhibit 4-3: Change in Forest Carbon Storage Per Unit of Reduced Pulpwood Harvest for (a) Incremental Change in Forest Carbon Storage and (b) Cumulative Change in Forest Carbon Storage Per Unit of Reduced Pulpwood Harvest



Note: Colored bar for 2020 represents the value EPA selected to estimate the forest carbon storage benefit in WARM's GHG emission factors. EPA calculated the results by dividing the change in forest carbon storage in each year by 6.7 million metric tons of pulpwood harvests reduced over the period 2005 to 2009.

the major driver of the net carbon storage estimate appears to be the time it takes for the increase in carbon storage in live trees and the decrease in carbon storage in downed wood to begin to decline back toward baseline levels. Because the decrease in carbon storage in downed wood returns to baseline levels more quickly than the increase in carbon storage in live trees, the net change in carbon storage actually increases through 2030.

The FORCARB II results indicated that the effect of paper recycling or source reduction on carbon storage appears to be persistent (i.e., lasting at least for several decades). EPA chose to use the value for 2020 in the emission factors, or 1.04 MTCE per metric ton of pulpwood. The choice of 2020 represents a delay of about 5 to 15 years for the onset of incremental recycling, long enough to reflect the effects of the recycling program, but at a rate lower than the peak effect in 2030. As shown in Exhibit 4-3, the effect is relatively stable over time, so the choice of year does not have a significant effect.

For additional details on this methodology and a comparison of the FORCARB II results to those from other analyses, please see the *Revised Estimates of Effect of Paper Recycling on Forest Carbon* (Freed et al., 2006).

4.3.3 Changes in In-Use Product Carbon Pool

WARM does not consider changes in the in-use product carbon pool for nondurable goods because these products have shorter lifetimes, typically less than three years, and the carbon contained in these goods cycles out of the in-use pool over a relatively short period.

4.3.4 Net Change in Carbon Storage

To estimate the rate of forest carbon change per metric ton of paper recovery, multiply the rate of pulpwood of pulpwood harvest (*PWH*) per metric ton of paper recovery (*PRC*) (from Section 4.3.1) by the rate of forest forest carbon (*FC*) change per metric ton of pulpwood harvest (from Section 4.3.2), as shown in Exhibit 4-4. 4-4. Exhibit 4-4 shows the net change in carbon storage per unit of increased paper product recycling, while

Exhibit 4-5 shows the net change in carbon storage per unit of increased paper source reduction. The various paper grades fall into mechanical or chemical pulp categories as follows:

- Mechanical pulp papers: newspaper, telephone books.
- Chemical pulp papers: office paper, corrugated containers, textbooks, magazines/third class mail.

Note that the net change in carbon storage for recycling and source reduction of wood products (compared with paper products) is different, as discussed in Section 4.4.

Exhibit 4-4: Net Change in Carbon Storage per Unit of Increased Paper Product Recycling

(a)	(b)	(c)	(d)	(e)	(f)
Paper Product Recycled	**Reduction in Timber Harvest per Unit of Increased Recycling (Short Tons Timber/Short Ton of Wood) (from Section 4.3.1)**	**Change in Forest Carbon Storage per Unit of Reduced Timber Harvest (Metric Tons Forest Carbon/Metric Ton Timber) (from Section 4.3.2)**	**Change in Forest Carbon Storage per Unit of Reduced Timber Harvest ($MTCO_2e$/ Short Ton Timber) (d = c x 0.907 x 3.667)**	**Change in Carbon Storage in In-use Products per Unit of Increased Paper Product Recycling ($MTCO_2E$/Short Ton)**	**Net Change in Carbon Storage per Unit of Increased Paper Product Recycling ($MTCO_2E$/Short Ton) (e = b × d + e)**
Mechanical pulp	0.58	1.04	3.46	NA	2.02
Chemical pulp	0.89	1.04	3.46	NA	3.06

NA = Not applicable.

Exhibit 4-5: Forest Carbon Storage from Source Reduction of Paper Products

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Material	**Mechanical or Chemical Pulp**	**Reduction in Timber Harvest per Unit of Increased Source Reduction (Short Tons Timber/Short Ton of Wood) (from Section 4.3.1)**	**Change in Forest Carbon Storage per Unit of Reduced Timber Harvest (Metric Tons Forest Carbon/Metric Ton Timber) (from Section 4.3.2)**	**Change in Forest Carbon Storage per Unit of Reduced Timber Harvest ($MTCO_2e$/ Short Ton Timber) (e = d x 0.907 x 3.667)**	**Net Change in Carbon Storage per Unit of Increased Source Reduction, 100% Virgin Inputs ($MTCO_2E$ /Short Ton) (f = c × e)**	**Virgin Inputs in the Current Mix of Inputs[a] (%)**	**Net Change in Carbon Storage per Unit of Increased Source Reduction, Current Mix ($MTCO_2E$ /Short Ton) (h = f × g)**
Corrugated Containers	Chemical	2.11	1.04	3.46	7.26	65.1	4.73
Magazines/ Third-class Mail	Chemical	2.11	1.04	3.46	7.26	95.9	6.96
Newspapers	Mechanical	1.11	1.04	3.46	3.83	77.0	2.95
Office Paper	Chemical	2.11	1.04	3.46	7.26	95.9	6.96
Phonebooks	Mechanical	1.11	1.04	3.46	3.83	100.0	3.83
Textbooks	Chemical	2.11	1.04	3.46	7.26	95.9	6.96

[a] Source: FAL (2003).

The net forest carbon storage for source reduction of paper products is shown in Exhibit 4-5. The reduction in timber harvest per unit of increased source reduction (Exhibit 4-5, column (c)) is the process efficiency of converting pulpwood to finished paper (i.e., 1/ratio of pulp to finished paper), as described in Section 4.3.1. The net change in forest carbon storage depends on whether the source reduction of paper products is assumed to displace paper that would have been produced from 100-percent virgin inputs or the current industry-average mix of virgin and recycled inputs (FAL, 2003). For source source reduction that offsets paper produced from 100-percent virgin pulp, the net change in forest carbon carbon storage is shown in

Exhibit 4-5, column (e). For the case where source reduction offsets paper produced from the current mix of virgin and recycled inputs, however, WARM assumes that the net forest carbon effect is attributable only to the proportion of inputs that are virgin pulp, as shown in

Exhibit 4-5, column (g). WARM makes this assumption because displacing recycled inputs, which have already been harvested from the forest, are unlikely to have a direct effect on forest carbon storage.

4.4 FOREST CARBON STORAGE AND WOOD PRODUCTS

Wood products in WARM include dimensional lumber, MDF, and wood flooring. These products are long-lived, durable goods that are harvested from sustainably managed soft- and hardwood forests. This section describes the methodology EPA used to evaluate the three components of forest carbon storage, outlined in Section 4.2, for softwood products (i.e., dimensional lumber and MDF). The approach for evaluating forest carbon storage for hardwood flooring is similar and is provided in further detail in the Wood Flooring chapter.

4.4.1 Effect of Source Reduction and Recycling on Timber Harvests

To estimate the change in timber harvests that result from increased recycling and source reduction of softwood products, EPA used estimates provided by Dr. Skog for the system efficiencies (on a weight basis) of producing wood products from virgin inputs or recycled inputs. Assuming that overall demand for softwood products is constant, increases in recycling will reduce timber harvests according to the following ratio:[18]

$$TH = X/Y \qquad \text{(Eqn. 2)}$$

Where,

TH = Change in timber harvests resulting from increased recycling of wood products

X = Process efficiency of converting virgin roundwood into finished wood product

Y = Process efficiency of converting recycled wood into finished wood product

Based on the estimates provided by Dr. Skog, EPA assumed that one short ton of finished wood product requires 1.1 short tons of virgin roundwood[19] (i.e., harvested logs, with or without bark), on average, or 1.25 short tons of recycled wood. According to this relationship, each additional short ton of wood products recycled will reduce the demand for virgin roundwood from timber forests by a ratio of 1.1/1.25 = 0.88 short tons.

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[18] Unlike EPA's consideration of paper products, WARM does not consider exports of recycled wood outside of the United States. In contrast with recovered paper, which is exported to other countries for recycling, recovered wood typically is not directly exported for recycling. Instead, finished wood products or wood packaging materials (such as pallets, skids, containers, crates, boxes, cases, bins, reels, and drums) may be manufactured from recycled materials in the United States for export (Ince 1995; FAO 2005).

[19] Harvested logs, with or without bark; roundwood may be round, spilt, or roughly squared (FAO, 1997).

The effect of source reduction on timber harvests can be calculated from the process efficiency (*X*) of wood products production, assuming that one short ton of source reduction completely offsets virgin roundwood harvests that otherwise would be harvested to produce one short ton of wood products. Section 4.5 discusses the sensitivity of the forest carbon storage results to this assumption. Consequently, WARM estimates that one short ton of source reduction avoids 1.1 short tons of roundwood harvests for dimensional lumber and MDF wood products.

These values describe the change in timber harvests resulting from increased recycling and source reduction of softwood products. Together with the effects that changes in timber harvests have on forest carbon stocks (developed in Section 4.4.2), these two parameters describe how forest carbon storage changes as a result of increases in recycling and source reduction. The values developed in this section are also used to determine how source reduction and recycling affect carbon storage in in-use wood products, which is discussed in Section 4.4.3. The net changes in carbon storage from recycling and source reduction are calculated in Section 4.4.4, taking into account both changes in forest carbon storage and in-use product carbon storage.

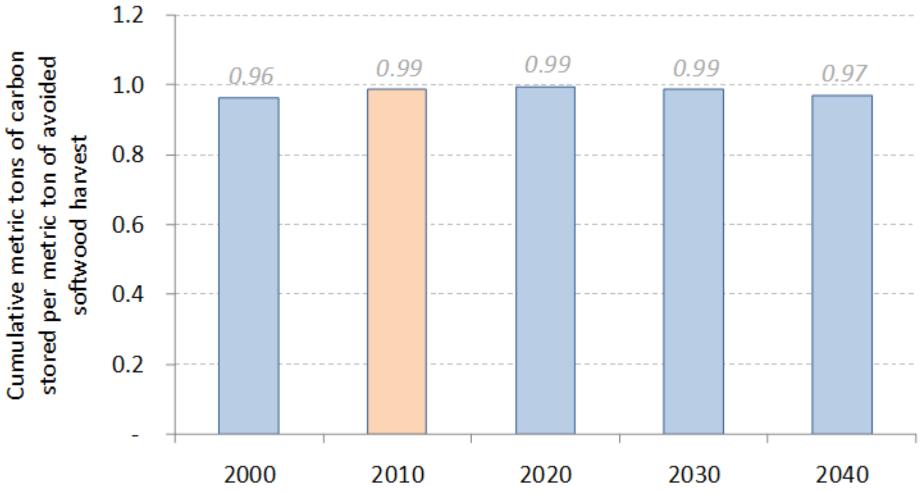
4.4.2 Effect of Changes in Timber Harvests on Forest Carbon Stocks

To investigate the change in forest carbon resulting from increased recycling and source reduction of wood products, EPA used estimates developed from the USDA FS's FORCARB II model. The method for wood products is similar to the approach for paper described in Section 4.3.2. First, EPA applied a harvest scenario developed in consultation with Dr. Skog and Dr. Linda Heath at USDA FS. EPA determined that the majority of wood products are derived from softwood and evaluated an increased wood recycling/source reduction scenario corresponding to a 1.7-percent reduction in softwood harvest. The 1.7-percent reduction is a representative estimate of the reduction in softwood harvests that could be achieved with a national increase in wood product recycling above current levels.

This reduction is distributed throughout the USDA FS regions in proportion to baseline harvest for the period 1998 to 2007. The cumulative reduction in softwood harvest from the 1.7-percent reduced harvest scenario is 26.4 million short tons over this period.

The effect of this reduction in harvest is to increase carbon sequestration in forests. To be consistent with the approach for paper recycling and source reduction, EPA analyzed effects only for tree and understory components (and excluded forest floor and soils). Exhibit 4-6 displays the results of the analysis for wood products. The results show that every metric ton of avoided timber harvest results in 0.96 to 0.99 metric tons of forest carbon storage. For consistency with the paper recycling/source reduction analysis, EPA selected the forest carbon storage benefit in 2010, representing a delay of 5 to 15 years from the onset of the simulated period of incremental recycling. This period is consistent with the 5 to 15 year timeframe used in the paper forest carbon analysis in Section 4.3. Consequently, EPA estimated that a one-metric-ton reduction in timber harvests increases forest carbon storage by 0.99 metric tons.

Exhibit 4-6: Cumulative Change in Forest Carbon Storage per Unit of Reduced Timber Harvest



Note: Colored bar for 2010 represents the value EPA selected to estimate the forest carbon storage benefit in WARM's GHG emission factors. EPA calculated the results by dividing the change in forest carbon storage in each year by 24 million metric tons of pulpwood harvests reduced over the period 1998 to 2007.

4.4.3 Changes in In-Use Product Carbon Pool

The final step involves estimating the effects of increased wood product recycling on carbon storage in in-use wood products.

For recycling, based on the estimates developed in Section 4.4.1, EPA assumed that 1.25 short tons of recycled wood are required to produce one short ton of finished wood product; in other words, every short ton of wood recycled yields 0.8 short tons of finished wood product (i.e., 1/1.25 = 0.8), and 0.2 short tons of wood are lost from in-use products. For wood products, EPA assumed a carbon density of 0.48 MTCE per short ton of wood, corresponding to softwoods in Southeast and South Central pine forests (Birdsey, 1992). Consequently, the carbon loss from the product pool is given by:

$$(1 \text{ short ton recycled} - 0.8 \text{ short tons retained}) \times 0.48 \text{ MTCE/short ton} \times 44/12 \text{ MTCO}_2\text{E/MTCE} = 0.35 \text{ MTCO}_2\text{E/short ton}$$

For source reduction of wood products, a short ton of wood offset by source reduction results in a decline in carbon that otherwise would have been stored in the in-use wood product.[20] This essentially represents a one-to-one relationship, where source reducing one short ton of wood avoids one short ton of wood that otherwise would have been manufactured into in-use products. Consequently, the change in the in-use product carbon pool from source reduction of one short ton of wood product is equal to the carbon density of the wood product, given by:

$$1 \text{ short ton source reduced} \times 0.48 \text{ MTCE/short ton} \times 44/12 \text{ MTCO}_2\text{E/MTCE} = 1.77 \text{ MTCO}_2\text{E/short ton}$$

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[20] Because dimensional lumber and MDF are not commonly manufactured from recycled inputs in the United States, WARM assumes that source reduction of wood products avoids virgin wood inputs only. This is a different approach than for source reduction for paper products, where the net change in forest carbon storage depends on whether the source reduction of paper products is assumed to displace paper that would have been produced from 100-percent virgin inputs, or the current industry-average mix of virgin and recycled inputs.

Both source reduction and recycling decrease the amount of carbon stored in in-use products; this decrease offsets some of the benefit of increasing storage in forests; see Section 2 for more details.

4.4.4 Net Change in Carbon Storage

Based on the estimates developed in the previous sections, Exhibit 4-7 shows the net change in forest carbon storage for recycling and source reduction of wood products. These results show that recycling and source reduction of one short ton of wood products corresponds to an increase in net carbon storage. In both cases, the increase in forest carbon storage is offset by a reduction in carbon storage in in-use products as a result of recycling or source reduction.

Exhibit 4-7: Net Change in Carbon Storage per Unit of Increased Wood Product Recycling

(a)	(b) Reduction in Timber Harvest per Unit of Increased Recycling or Source Reduction (Short Tons Timber/Short Ton of Wood) (from Section 4.4.1)	(c) Change in Forest Carbon Storage per Unit of Reduced Timber Harvest (Metric Tons Forest Carbon/Metric Ton Timber) (from Section 4.4.2)	(d) Change in Forest Carbon Storage per Unit of Reduced Timber Harvest ($MTCO_2e$/ Short Ton Timber) (d = c x 0.907 x 3.667)	(e) Change in Carbon Storage in In-use Products per Unit of Increased Wood Product Recycling ($MTCO_2E$/Short Ton) (from Section 4.4.3)	(f) Net Change in Carbon Storage per Unit of Increased Wood Product Recycling ($MTCO_2E$/Short Ton) (e = b × d + e)
Recycling	0.88	0.99	3.29	-0.35	2.53
Source Reduction	1.1	0.99	3.29	-1.77	1.84

Note: Positive values denote an increase in carbon storage; negative values denote a decrease in carbon storage.

4.5 LIMITATIONS

Several limitations are associated with the analysis. The forest product market is very complex, and EPA's simulation of some of the underlying economic relationships that affect the market simplifies some important interactions.

A general limitation of the analysis is that it does not account for any potential long-term changes in land use caused by a reduction in pulpwood or softwood demand, and landowners' choices to change land use from silviculture to other uses. If overall forest area is reduced, this would result in significant loss of carbon stocks. Hardie and Parks (1997) developed an area base model for use in Resource Planning Act assessments to help determine factors that influence land area change. They derived a model that estimated the elasticity of (a) forest land area change with respect to (b) pulpwood price change. They estimated the elasticity to be −0.10, but this was not significant at the 10-percent confidence level. This suggests that forest area change would be limited with a modest price change in pulpwood demand.

The following limitations relate to the estimate of forest carbon storage for paper products:

- Results are very sensitive to the assumption on paper exports (i.e., that paper exports comprise a constant proportion of total paper recovery). If all of the recovered paper is exported, none of the incremental recovery results in a corresponding reduction in U.S. pulpwood harvest. At the other extreme, if all of the incremental recovery results in a corresponding reduction in U.S. pulpwood harvest, the storage factor would be higher. The results are also sensitive to assumptions on the moisture content and the carbon content of pulpwood, pulp, and paper.
- This analysis does not consider the effect that decreases in pulpwood harvest may have on the supply curve for sawtimber, which could result in a potential increase in harvests of other wood products. This could result in a smaller reduction in harvest, offsetting some of

the carbon storage benefit estimated here. Prestamon and Wear (2000) investigated how pulpwood and sawtimber supply would change with changes in prices for each. They estimated that non-industrial private forest and industry may increase sawtimber supply when the price for pulpwood increases—and the change is perceived as temporary—although the estimate was not statistically significant. The sawtimber supply, however, may decrease when the pulpwood price increases—and the change is perceived as permanent—but, once again, the estimate was not statistically significant. Given that the relationship between the price change for pulpwood and supply of sawtimber was not consistent and was often statistically insignificant, there is not compelling evidence to indicate that the omission of this effect is a significant limitation to the analysis.

- A related issue is that if the domestic harvest of pulpwood decreases, it could result in a decrease in the cost of domestic production, which could shift the balance between domestic paper production and imports to meet demand.

The following limitations relate to the estimate of forest carbon storage for wood products:

- The estimated changes in timber harvests resulting from increased recycling and source reduction are based on process efficiency estimates that assume overall demand for softwood products remains constant. Increased recycling or source reduction of wood products could increase or decrease demand for new wood products to the extent that these changes influence factors such as virgin wood-product prices. EPA has not explicitly modeled this effect because of the complexity of virgin wood-product markets and the fact that the current assumption provides a first-order estimate of the change in timber harvests from recycling and source reduction.
- Similarly, in-use product carbon storage is modeled based on first-order reductions in carbon storage associated with losses from recycling wood products and avoided in-use product carbon storage from source reduction of wood products. This analysis provides an estimate of the direct, first-order effects on the in-use carbon pool associated with recycling or source reduction of wood products.

As shown in Exhibit 4-3 and Exhibit 4-6, estimates of forest carbon storage resulting from increased paper recycling vary over time. As noted earlier, WARM applies a single point estimate reflecting a time period that best balances the competing criteria of (1) capturing the long-term forest carbon sequestration effects, and (2) limiting the uncertainty inherent in projections made well into the future. The variation in forest carbon storage estimates over time and the limitations of the analysis discussed earlier indicate considerable uncertainty in the point estimate selected. In comparison to the estimates of other types of GHG emissions and sinks developed in other parts of WARM, the magnitude of forest carbon sequestration is relatively high. Based on these forest carbon storage estimates, source reduction and recycling of paper are found to have substantial net GHG reductions. Because paper products make up the largest share of municipal waste generation (and the largest volumes of waste managed through recycling, landfill use, and combustion), it is important to bear in mind the uncertainty in the forest carbon sequestration values when evaluating the results of this analysis.

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5 TRANSPORTATION ASSUMPTIONS

This chapter describes the development of waste and material transportation assumptions in WARM. It summarizes the approach used to estimate the greenhouse gas (GHG) and energy impacts from transportation stages in the materials management practices modeled in WARM.

5.1 SOURCE REDUCTION

When a material is source reduced, GHG emissions associated with producing the material and/or manufacturing the product and managing the post-consumer waste are avoided. The raw material acquisition and manufacturing (RMAM) calculation in WARM incorporates GHG emissions from energy used to transport materials, including “retail transportation,” which consists of the average truck, rail, water and other-modes transportation emissions required to get raw materials from the manufacturing facility to the retail/distribution point. Transportation emissions from the retail point to the consumer are not included. The transportation assumptions and data sources for source reduction modeling in WARM vary by material. For more information, reference individual material chapters of the WARM documentation.

5.2 RECYCLING

When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed of and managed as waste. Transportation-related impacts from recycling include collection and transportation to recycling center, transportation of recycled materials to remanufacturing, and avoided impacts from transport of raw materials and products for virgin material production.

5.2.1 Collection and Transportation to Recycling Center

The default distances and modes for collection and transportation of recycled materials to recycling center are included as part of the transportation of recycled materials to remanufacturing impacts, described under Section 5.2.2 and modeled on a material-specific basis. WARM assumes a default transportation distance to a recycling center of 20 miles but allows users the option of providing the distance needed for transportation to a recycling center for their operations. When modeling user-provided information on transportation to recycling center, EPA assumed that transportation by a diesel-powered short-haul truck using data from the National Renewable Energy Laboratory (NREL) U.S. Life Cycle Inventory Database (USLCI) (NREL, 2015) to quantify energy and emissions from transportation for each short ton of materials transported each mile (i.e., on a short ton-mile basis). EPA also used a pre-combustion scale-up factor for diesel fuel to account for fuel needed for crude oil extraction, refining, and transportation; the diesel heating value (FAL, 2011); and a diesel carbon coefficient from the U.S. EPA (2017). These assumptions and calculations are presented in Exhibit 5-1.

Exhibit 5-1: Emissions Associated with Transporting Waste to Recycling Centers

	(a) Combination Truck Diesel Fuel Use (Gallons/Short Ton-Mile)	(b) Diesel Fuel Pre-Combustion Scale-up Factor	(c) Diesel Fuel Heating Value (Btu/Gallon)	(d) Diesel Fuel Emission Factor ($MTCO_2E$/Million Btu)	(e) Recycling Center Transport Emission Factor ($MTCO_2E$/Short Ton-Mile) ($e = a \times b \times c \times d \div 10^6$)
Recycling	0.01	1.19	140,000	0.07	0.00016

Sources: NREL, 2015; FAL, 2011; EPA, 2017

Note: Totals in table may not sum due to independent rounding

5.2.2 Transportation of Recycled Materials to Remanufacturing

The assumptions and data sources for transport of recycled materials to remanufacturing in WARM vary by material. For more information, reference individual material chapters of the WARM documentation.

5.2.3 Avoided Impacts from Transportation of Raw Materials and Products for Virgin Material Production

The assumptions and data sources for avoided impacts from transportation of raw materials and products for virgin material production in WARM vary by material. For more information, reference individual material chapters of the WARM documentation.

5.3 ANAEROBIC DIGESTION

WARM accounts for the GHG emissions resulting from fossil fuels used in vehicles collecting and transporting waste to the anaerobic digestion facility. Exhibit 5-2 shows the diesel used for transporting the feedstock and solids to the anaerobic digester and the post-consumer transportation. To calculate the emissions, WARM relies on assumptions from the NREL USLCI (NREL, 2015). The NREL emission factor assumes a diesel, short-haul truck. WARM assumes a default transportation distance to an anaerobic digester of 20 miles but allows users the option of providing the distance needed for transportation to an anaerobic digestion for their operations using the transportation factor presented in Exhibit 5-1.

Exhibit 5-2: Diesel Use by Process and by Material Type for Dry Digestion

Material	Transportation and Spreading (Million Btu)	Post-Consumer Transportation (Million Btu)	Total Energy Required for Dry Anaerobic Digestion (Million Btu)	Total CO_2 Emissions from Dry Anaerobic Digestion ($MTCO_2E$)
Food Waste	0.25	0.04	0.33	0.02
Yard Trimmings	0.30	0.04	0.34	0.02
Grass	0.28	0.04	0.33	0.02
Leaves	0.31	0.04	0.36	0.02
Branches	0.32	0.04	0.37	0.02
Mixed Organics	0.29	0.04	0.34	0.02

5.4 COMPOSTING

WARM includes emissions associated with transporting and processing of the compost in aerated windrow piles. Transportation energy emissions occur when fossil fuels are combusted to collect and transport yard trimmings and food waste to the composting facility and then to operate composting equipment that turns the compost. EPA did not count transportation emissions from delivery of finished compost from the composting facility to its final destination. To calculate the emissions, WARM relies on assumptions from FAL (1994) for the equipment emissions and the NREL USLCI (NREL, 2015). The NREL emission factor assumes a diesel, short-haul truck. Exhibit 5-3 provides the transportation emission factor calculation. WARM assumes a default transportation distance to a composting facility of 20 miles but allows users the option of providing the distance needed for transportation to a composting facility for their operations using the transportation factor presented in Exhibit 5-1.

Exhibit 5-3: Emissions Associated with Transporting and Turning Compost

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

[a] Based on estimates from NREL (2015)

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

5.5 COMBUSTION

WARM includes emissions associated with transporting of waste and the subsequent transportation of the residual waste ash to the landfill. Transportation energy emissions occur when fossil fuels are combusted to collect and transport material to the combustion facility and then to operate on-site equipment. Transportation of any individual material in MSW is assumed to use the same amount of energy as transportation of mixed MSW. To calculate the emissions, WARM relies on assumptions from FAL (1994) for the equipment emissions and NREL USLIC (NREL, 2015). The NREL emission factor assumes a diesel, short-haul truck. Exhibit 5-4 provides the transportation emission factor calculation. WARM assumes a default transportation distance to a combustion facility of 20 miles but allows users the option of providing the distance needed for transportation to a combustion facility for their operations using the transportation factor presented in Exhibit 5-1.

Exhibit 5-4: Emissions Associated with Transporting Waste to Combustion Facilities and Ash Transportation

Material Type	Diesel Fuel Required to Collect and Transport One Short Ton of Waste (Million Btu)[a]	Diesel Fuel Required to Collect and Transport One Short Ton of Waste ($MTCO_2E$)[a]	Diesel Fuel Required for Ash Landfill Disposal from One Short Ton of Waste ($MTCO_2E$)[b]	Total CO_2 Emissions from Combustion ($MTCO_2E$)
Combustion	0.04	0.00	0.01	0.01

[a] Based on estimates from NREL (2015)

[b] Based on estimates in Table I-24 in FAL (1994)

5.6 LANDFILLING

WARM includes emissions associated with transportation and landfilling the material. Transportation energy emissions occur when fossil fuels are combusted to collect and transport material to the landfill facility and then to operate landfill operational equipment. To calculate the emissions, WARM relies on assumptions from FAL (1994) for the equipment emissions and NREL USLCI (NREL, 2015). The NREL emission factor assumes a diesel, short-haul truck. Exhibit 5-5 provides the transportation emission factor calculation. WARM assumes a default transportation distance to a combustion facility of 20 miles but allows users the option of providing the distance needed for transportation to a combustion facility for their operations using the transportation factor presented in Exhibit 5-1.

Exhibit 5-5: Landfilling Transportation and Equipment Energy and Emissions Assumptions and Calculation

Material Type	Diesel Fuel Required to Collect and Transport One Short Ton (Million Btu)[a]	Diesel Fuel Required for Landfilling Equipment (Million Btu)[b]	Total Energy Required for Composting (Million Btu)	Total CO_2 Emissions from Composting ($MTCO_2E$)
Landfilling	0.04	0.23	0.27	0.02

[a] Based on estimates from NREL (2015)

[b] Based on estimates in Table I-5 in FAL (1994)

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