Part 1

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From Farm to Kitchen:
The Environmental Impacts of U.S. Food Waste

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Executive Summary

Over one-third of the food produced in the United States is never eaten, wasting the resources used to produce it and creating a myriad of environmental impacts. Food waste is the single most common material landfilled and incinerated in the United States, comprising 24 and 22 percent of landfilled and combusted municipal solid waste, respectively. This wasted food presents opportunities to increase food security, foster productivity and economic efficiency, promote resource and energy conservation, and address climate change.

As the United States strives to meet the Paris Agreement targets to limit the increase in global temperature to 1.5 degrees above pre-industrial levels, changes to the food system are essential. Even if fossil fuel emissions were halted, current trends in the food system would prevent the achievement of this goal. Globally, food loss and waste represent 8 percent of anthropogenic greenhouse gas emissions (4.4 gigatons CO_2e annually), offering an opportunity for meaningful reductions.

Reducing food waste can also help feed the world's growing population more sustainably. The United Nations (UN) predicts that the world population will reach 9.3 billion by 2050. This population increase will require a more than 50 percent increase in food production from 2010 levels. Decreasing food waste can lessen the need for new food production, shrinking projected deforestation, biodiversity loss, greenhouse gas emissions, water pollution, and water scarcity.

In 2015, the United States announced a goal to halve U.S. food loss and waste by 2030, but the nation has not yet made significant progress. The U.S. Environmental Protection Agency (EPA) prepared this report to inform domestic policymakers, researchers, and the public about (1) the environmental footprint of food loss and waste (FLW) in the U.S. and (2) the environmental benefits that can be achieved by reducing U.S. FLW. The report examines the farm-to-kitchen (cradle-to-consumer) impacts of FLW, excluding the impacts of managing FLW (e.g., methane emissions from landfills), which will be covered in a separate companion report (*The Environmental Impacts of U.S. Food Waste: Part 2*).

Given the size and dynamic complexity of the U.S. food system, no single agreed-upon comprehensive estimate of the total amount of U.S. FLW exists. Instead, the literature includes multiple credible estimates, which differ in scope and methodology, that together provide insights into the magnitude and distribution of U.S. FLW. Estimates that include food lost or wasted during all stages of the food supply chain (from primary production to consumption) range from 73 to 152 million metric tons (161 to 335 billion pounds) per year, or 223 to 468 kg (492 to 1,032 pounds) per person per year, equal to approximately 35 percent of the U.S. food supply. Roughly half of this food is wasted during the consumption stage (households and food service), and fruits and vegetables and dairy and eggs are the most frequently wasted foods.

This uneaten food results in a "waste" of resources—including agricultural land, water, pesticides, fertilizers, and energy—and the generation of environmental impacts—including greenhouse gas emissions and climate change, consumption and degradation of freshwater resources, loss of biodiversity and ecosystem services, and degradation of soil quality and air quality. Each year, U.S. FLW embodies:

- 560,000 km^2 (140 million acres) agricultural land – an area the size of California and New York combined;
- 22 trillion L (5.9 trillion gallons) blue water – equal to annual water use of 50 million American homes;
- 350 million kg (778 million pounds) pesticides;
- 6,350 million kg (14 billion pounds) fertilizer – enough to grow all the plant-based foods produced each year in the United States for domestic consumption;
- 2,400 million GJ (664 billion kWh) energy – enough to power more than 50 million U.S. homes for a year; and
- 170 million $MTCO_2$e GHG emissions (excluding landfill emissions) – equal to the annual CO_2 emissions of 42 coal-fired power plants.

This uneaten food also contains enough calories to feed more than 150 million people each year, far more than the 35 million estimated food insecure Americans. To estimate the environmental impact of FLW, researchers consider the amount of food lost or wasted as well as the type of food lost or wasted and supply chain stage at which it was lost or wasted. Food wasted further along the supply chain carries more impacts than food lost or wasted earlier, since the impacts are cumulative. For example, food lost during primary production embodies the resources used to grow the food, whereas food wasted during the consumption stage embodies the resources used to grow, process, package, store, and distribute the food up to the point the food reaches the consumer.

Given the substantial environmental impacts of FLW, halving FLW – as the U.S. aims to do – could meaningfully reduce the resource use and environmental impacts of the U.S. food system. Researchers estimate that halving U.S. FLW could reduce the environmental footprint of the current cradle-to-consumer food supply chain by:

- More than 300,000 square km^2 (75 million acres) agricultural land – an area greater than Arizona;
- 12 trillion L (3.2 trillion gallons) blue water – equal to the annual water use of 29 million American homes;
- Nearly 290,000 metric tons (640 million pounds) of bioavailable nitrogen from agricultural fertilizer with the potential to reach a body of water, cause algal blooms and deteriorate water quality;
- 940 million GJ (262 billion kWh) energy – enough to power 21.5 million U.S. homes for a year; and
- 92 million $MTCO_2e$ GHG – equal to the annual CO_2 emissions from 23 coal-fired power plants.

Note that these estimates are conservative in comparison with other published studies presented in this report, and that these savings can only be achieved through prevention (i.e., source reduction) of FLW. Recycling of food waste cannot achieve these benefits since a substantial fraction of the impacts occur during the primary production of food.

Modeling in the scientific literature also offer insights into how to maximize the environmental benefits of FLW reduction programs and policies, which the report summarizes into three key points:

1. The greatest environmental benefits can be achieved through prevention rather than recycling.
2. The largest energy and greenhouse gas emissions benefits can be obtained by reducing FLW from households and restaurants.
3. Focusing on reducing FLW of the most resource-intensive foods, such as animal products and fruits and vegetables, can yield the greatest environmental benefits.

The report also examines U.S. FLW in global context to evaluate the U.S. contribution to this global issue and to highlight key similarities and differences among regions and countries. Currently the United States wastes more food and more food per person than most any other country in the world. Also, the environmental impact of each unit of U.S. food loss and waste is greater than that of most other countries, as the U.S. wastes more food downstream and more animal products than the global average. Fortunately, positive examples of progress are emerging in similar countries. Over the last decade, countries such as the United Kingdom and Japan have substantially reduced food waste, contributing to the global effort under the UN Sustainable Development Goals.

As global populations and incomes rise, and the environment faces pressures from increased food production, reductions in the per person environmental footprint of agriculture will be essential to the sustainability of the planet. Limited options are available to sustainably increase the global food supply to meet growing demand. Closing yield gaps and increasing productivity alone will likely be insufficient to prevent further deforestation and environmental degradation. Even under the most promising scenarios of yield increases, up to 20 percent more land will be needed by 2050. Thus demand-side measures, such as reducing FLW or dietary shifts, will also be needed to sustainably increase the food supply. A recent study projects halving global FLW could result in a 24 percent reduction in cumulative global food system greenhouse gas emissions between 2020 and 2100 (331 Gt CO_2e), compared to a business-as-usual scenario. Significant reductions (6 to 16 percent) could also be achieved in the amounts of agricultural land, water, and fertilizer used in 2050 (compared to business-as-usual scenario) by halving global food loss and waste.

Key research needed to help the United States meet its goal to halve food loss and waste includes:

- Enhancing the data on U.S. FLW by improving precision and addressing data gaps.
- Increasing frequency at which the United States can track progress in reducing FLW.
- Quantifying the environmental impacts associated with U.S. waste of imported foods.
- Strengthening understanding of the interaction among food system supply chain stages with regard to FLW.
- Evaluating the life cycle impacts of proposed FLW prevention strategies.
- Exploring how trends in the U.S. food system will affect FLW and its environmental footprint in the future.
- Deepening our understanding of drivers of FLW unique to the United States.

Table of Contents

Chapter 1. Introduction 1
1.1 Purpose 1
1.2 Background 2
1.3 Scope and Definition of Terms 3
1.4 Report Overview 3
1.5 Methods 4

Chapter 2. Environmental Footprint of the U.S. Food Supply Chain 5
2.1 U.S. Food Supply Chain 5
2.2 Environmental Footprint 6
2.3 Inputs and Environmental Impacts 7
2.4 Imports 11
2.5 Other Factors 13

Chapter 3. Characterization of U.S. Food Loss and Waste 14
3.1 U.S. Food Surplus 14
3.2 Total U.S. FLW 16
3.3 U.S. FLW Over Time 19
3.4 Edibility of U.S. FLW 20
3.5 U.S. FLW, by Supply Chain Stage 22
3.6 U.S. FLW, by Food Category 25
3.7 Measurement Methodologies 28

Chapter 4. Environmental Footprint of U.S. Food Loss and Waste 31
4.1 Methodologies 31
4.2 Agricultural Land Use 34
4.3 Water Use 37
4.4 Pesticide and Fertilizer Application 40
4.5 Energy Use 44
4.6 Greenhouse Gas Emissions 47
4.7 Summary of Environmental Footprint 52

Chapter 5. Environmental Benefits of Reducing U.S. Food Loss and Waste 56
5.1 Environmental Benefits, Relative to Current Footprint 56
5.2 Environmental Benefits, Relative to Future Footprint 59
5.3 Summary of Environmental Benefits 61
5.4 Environmental Benefits, By Food Category and Supply Chain Stage 62

Chapter 6. U.S. Food Loss and Waste in Global Context 63
6.1 U.S. Share of Global FLW 63
6.2 Share of Food Supply Lost or Wasted 64
6.3 Characterization of FLW 65
6.4 Per Person FLW 67
6.5 Progress Towards Reducing Per Person FLW 70
6.6 Global Environmental Footprint of FLW 70
6.7 Environmental Benefits of Halving Global FLW 74

Chapter 7. Conclusions and Research Gaps 79
7.1 Conclusions 79
7.2 Strategies to Maximize the Environmental Benefits of Halving U.S. FLW 81
7.3 Research Gaps 82

References 84

Appendix A: Inputs and Environmental Impacts 94

Appendix B: USDA and FAO FLW Data 101

Appendix C: Literature Search Methodology 103

CHAPTER 1.
Introduction

Over one-third of the food produced in the United States is never eaten, wasting the resources used to produce it and creating a myriad of environmental impacts (FAO, 2019b; CEC, 2017). Food waste is the single most common material landfilled and incinerated in the United States, comprising 24 and 22 percent of landfilled and combusted municipal solid waste, respectively (U.S. EPA, 2020f). This wasted food presents opportunities to increase food security, foster productivity and economic efficiency, promote resource and energy conservation, and address climate change.

As the United States strives to meet the Paris Agreement targets to limit the increase in global temperature to 1.5 degrees above pre-industrial levels, changes to the food system are essential. Even if fossil fuel emissions were halted, current trends in the food system would prevent the achievement of this goal (Clark et al., 2020). Globally, food loss and waste represents 8 percent of anthropogenic greenhouse gas emissions (4.4 gigatons CO_2e annually) (FAO, 2015b), offering an opportunity for meaningful reductions.

Reducing food waste can also help feed the world's growing population more sustainably. The United Nations (UN) predicts that the world population will reach 9.3 billion by 2050. This population increase will require a more than 50 percent increase in food production from 2010 levels (UN, 2020a; Searchinger et al., 2019). Decreasing food waste can lessen the need for new food production, shrinking projected deforestation, biodiversity loss, greenhouse gas emissions, water pollution, and water scarcity (Springmann et al., 2018; Jalava et al., 2016; Bajželj et al., 2014; Kummu et al., 2012).

In 2015, the United States announced a goal to halve U.S. food loss and waste by 2030, but the nation has not yet made significant progress. Currently the United States wastes more food per person than most any other country in the world[1] (Chen et al., 2020). Over the last decade, countries such as the United Kingdom (UK) and Japan have substantially reduced food waste, contributing to the global effort under the UN (WRAP, 2020; Parry et al., 2015). Halving U.S. FLW can help tackle climate change, feed those in need, and protect water availability, water quality, air quality, and biodiversity and ecosystem services.

1.1 Purpose

The U.S. Environmental Protection Agency (EPA) prepared this report to inform domestic policymakers, researchers, and the public about (1) the environmental footprint of food loss and waste (FLW) in the U.S. and (2) the environmental benefits that can be achieved by reducing U.S. FLW.

This report provides estimates of the environmental footprint of current levels of FLW to assist stakeholders in (a) clearly communicating the significance of FLW; (b) decision-making among competing environmental priorities, including FLW; and (c) designing tailored FLW reduction strategies that maximize environmental benefits. The report also identifies key knowledge gaps where new research could improve our understanding of U.S. FLW and help shape successful strategies to reduce its environmental impact.

As shown in Figure 1-1, this report (*The Environmental Impacts of U.S. Food Waste: Part 1*) examines the environmental burden of the "cradle-to-consumer" (i.e., "farm-to-kitchen") segments of the U.S. food supply chain – beginning with primary agricultural production and continuing through distribution, processing, and retail, ending with the consumption (or waste) of food at home or away from home, such as at restaurants and cafeterias. A companion report (*The Environmental Impacts of U.S. Food Waste: Part 2*) will examine the environmental footprint of the pathways for food once it becomes "waste" (i.e., is not consumed), such as landfilling, combustion, composting, and anaerobic digestion. Together these two reports encompass the net environmental footprint of U.S. FLW.

[1] The U.S. wastes more food per person per day (measured in calories) than any other country and wastes the third largest amount of food per person per day (measured in grams) behind New Zealand and Ireland (Chen et al., 2020).

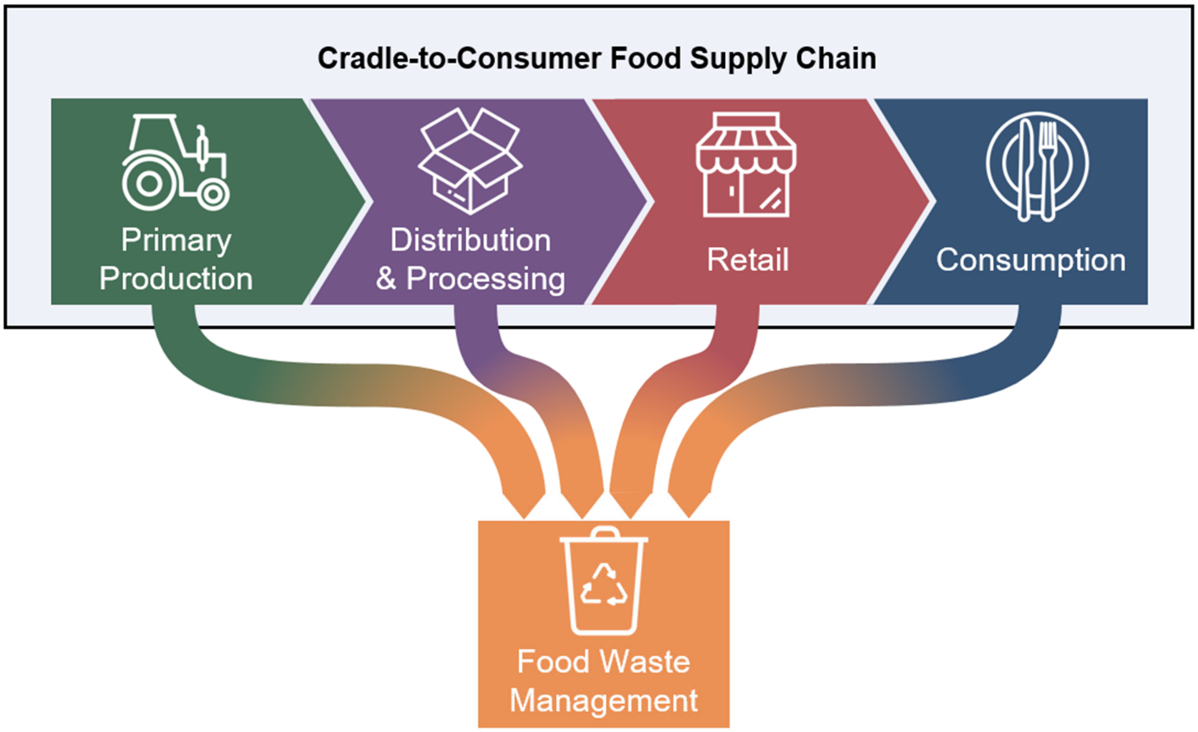

FIGURE 1-1. STAGES OF THE U.S. FOOD SUPPLY CHAIN

1.2 Background

Recognizing the critical importance of reducing food waste, in September 2015, the United States announced the U.S. *2030 Food Loss and Waste Reduction Goal* to halve per person food waste at the retail and consumer level by the year 2030 (U.S. EPA, 2020d). This goal aligns with Sustainable Development Goal (SDG) Target 12.3 of the 2030 Agenda for Sustainable Development, a wide-ranging resolution adopted by the UN General Assembly in October 2015 (UN, 2015). National governments representing roughly half the world's population have adopted comparable food waste reduction goals (Flanagan et al., 2019). SDG Target 12.3 also includes the goal of reducing food losses during production, though a quantitative target was not set.

Achieving this goal is ambitious. Fortunately, many U.S. states, municipalities, institutions, and private sector businesses have established food waste reduction goals or initiated programs to reduce food waste in recent years. Laws and executive orders in at least three states (New Jersey, Oregon, and Washington) have established goals to reduce food waste by half by 2030 (NCSL, 2020; State of Oregon, 2020; State of New Jersey, 2017). At least seven states (California, Connecticut, Maryland, Massachusetts, New York, Rhode Island, and Vermont) have enacted organic waste recycling laws, most of which apply to waste by large commercial sources (Maryland DOE, 2021; ReFED, 2021b; Heller, 2019). On July 1, 2020, Vermont became the first state to institute a statewide ban on sending residential food scraps to landfills. Cities such as Baltimore and Denver have developed food waste reduction and recovery strategies, and a growing number of cities, including Austin, Boulder, Minneapolis, New York City, San Francisco, and Seattle, have organic waste bans or organics recycling programs in place (ReFED, 2021b; Heller, 2019). Two-thirds of the world's 50 largest food companies have set a FLW reduction target consistent with SDG Target 12.3 (Flanagan et al., 2019); and 34 businesses and organizations have publicly committed to halve FLW in their U.S. operations by 2030 as part of EPA's *Food Loss and Waste 2030 Champions* group (U.S. EPA, 2020d).

The annual market value of U.S. FLW is estimated to be $408 billion (ReFED, 2021a). While actions to prevent FLW typically carry some cost (i.e., time or money), reducing FLW can lead to financial savings for households and businesses (Champions 12.3, 2017a; WRAP, 2013). For example, an investment in a food waste education campaign of 26 million British pounds (GBP) over five years in the UK resulted in an estimated savings of 6.5 billion GBP—and 3.4 million metric tons of carbon dioxide equivalent (million $MTCO_2e$) in annual avoided emissions—from households wasting less food (Champions 12.3, 2017a). A recent analysis by ReFED, a multi-stakeholder nonprofit organization, projects the United States could achieve net financial benefits from a wide variety of food waste prevention strategies, including enhancements to demand planning, packaging, surplus and imperfect produce channels, inventory management, date labeling, donation infrastructure, and education campaigns (ReFED, 2021a). A study sponsored by Champions 12.3 (a coalition of senior executives from business, government, international organizations, and research institutions) examined food waste reduction efforts in 700 companies (1,200 sites) across 17 countries including the United States. The study found that more than 99 percent of the sites had a net positive financial return from their investment in food waste reductions and that the median benefit-cost ratio was 14 to 1 (Champions 12.3, 2017a). In addition, by reducing FLW, the substantial cost of disposing of FLW could be reduced. A recent Commission on Environmental Cooperation (CEC) report indicates FLW accounts for $1.3 billion in tipping fees (charges for waste disposal) in the United States (CEC, 2017).

While some FLW is necessary for food system resilience (i.e., intentional redundancy to prevent shortages or price shocks with unexpected weather or natural disasters), and some may be unavoidable, broad consensus is forming around the ability and need to halve FLW (ReFED, 2021a; Bajželj et al., 2020; FAO, 2020).

1.3 Scope and Definition of Terms

This report focuses on the environmental impacts of producing food that is ultimately wasted. Food waste also has important and far-reaching social and economic impacts. Although these impacts are outside the scope of this report, they are discussed briefly when they intersect with environmental issues or to provide relevant context.

In this report, the term "food loss and waste" (FLW) is defined as food intended for human consumption that is not ultimately consumed by humans. Information about food grown for other purposes, such as biofuels or feed for animals not raised for human consumption, is excluded. However, when estimating the environmental footprint of producing livestock and farmed seafood, data on animal feed is included when possible. Food donated to food banks or upcycled into new food products is considered "surplus" or "excess" food and not FLW. Food that is recycled or disposed is considered FLW.

The terms "food loss and waste," "food waste," and "wasted food" are used interchangeably to describe food loss and waste in the report. Generally, studies on FLW define "food loss" as food that is not consumed due to unintentional limitations in production or supply. For example, food might be left unharvested or unutilized due to weather, low market demand, or failures in storage, transportation, or processing. The term "food waste" generally refers to food that is not consumed due to inefficiency or choice at the retail and consumption stage. In this report the term "consumption" (or the "consumption" stage of the food supply chain) is used to denote the receipt of food by consumers for use at home or away from home. This term is used regardless of whether the food is ultimately eaten (i.e., it is not used to mean the biological ingestion of food).

1.4 Report Overview

The report begins by examining the resource requirements and environmental impacts of the U.S. food system (Chapter 2) and characterizing the amount, type, and timing (i.e., at which stages of the supply chain) of FLW currently in the U.S. (Chapter 3). Chapter 4 marries these data to estimate the cradle-to-consumer environmental footprint of U.S. FLW. Chapter 5 summarizes the potential environmental benefits of halving FLW in the U.S., and Chapter 6 provides global context, highlighting key similarities and differences between the U.S. and global averages and the U.S. and other developed nations. Chapter 7 summarizes the findings of this report and identifies key research needed to help the U.S. achieve its *2030 Food Loss and Waste Reduction Goal* with maximum environmental benefits.

1.5 Methods

Preparation of this report began with a systematic literature search to identify and collect relevant peer-reviewed publications, book chapters, and other publicly available information pertinent to FLW. The literature search included references from 2010 through 2020, with priority given to publications from 2014 or later. Additional, more recent sources were added during the review process. Appendix B provides further details about the literature search methods, including key words, literature databases, and screening methods.

Most of the sources cited in this report are peer-reviewed publications. This report also references a number of government and intergovernmental reports and data sources, which may or may not have been peer reviewed. Examples include food supply and demand data from the U.S. Department of Agriculture (USDA) and the Centers for Disease Control and Prevention (CDC); food loss and waste estimates from EPA, USDA, and CEC; and information about global food loss and waste from the Food and Agriculture Organization (FAO) of the UN. Additional gray literature from non-governmental organizations is referenced to provide context, such as the commonly cited food loss and waste estimates from ReFED and the Natural Resources Defense Council (NRDC) and additional information from the World Resources Institute (WRI) and the UK Waste and Resources Action Programme (WRAP).

CHAPTER 2.

Environmental Footprint of the U.S. Food Supply Chain

The U.S. food system requires heavy use of the nation's land, water, and other finite resources, the use of which directly and indirectly affects environmental quality . This chapter provides an overview of the environmental footprint of the U.S. food supply chain, from cradle to consumer, as a foundation for understanding the environmental footprint of U.S. FLW presented in Chapter 4.

2.1 U.S. Food Supply Chain

The U.S. cradle-to-consumer food supply chain starts with agriculture and ends in the hands of consumers. While the definitions and organization of stages vary in the literature, the major stages of the U.S. cradle-to-consumer food supply chain typically include:

1. **Primary production:** Farming and harvesting of plants and animals, resulting in raw food materials.
2. **Distribution and processing:** Packaging, processing, manufacturing, transporting, distributing, and wholesale vending of food and food products.
3. **Retail:** Selling food and food products to the public at supermarkets or other stores.
4. **Consumption:** Receiving food at home or away from home, such as at restaurants, cafeterias, institutions, or other locations, regardless of whether the food is ultimately eaten or wasted.

The first two stages (primary production and distribution and processing) are often referred to as "upstream" in the supply chain, while the latter two stages (retail and consumption) are referred to as "downstream" from the earlier stages. As discussed in Chapter 1, while the management of FLW (e.g., via landfills, combustion, composting, or anaerobic digestion) is a part of the food system, it is not addressed in this report.

KEY FINDINGS

- *The U.S. cradle-to-consumer food supply chain includes four stages: (1) primary production, (2) distribution and processing, (3) retail, and (4) consumption (food service and households).*
- *Of the four stages, primary production accounts for most of the land, fertilizer, and pesticide use, plus the largest share of blue water withdrawals and GHG emissions. The consumption stage uses the largest share of energy.*
- *Among food categories, animal products require the most land, water, fertilizer, and energy and emit the most GHGs per unit of food.*
- *Approximately one-fifth of the U.S. food supply is imported; however, most studies assume all food is produced domestically and do not account for differences in the environmental footprint of production in different areas, including water scarcity, deforestation, and other factors that lead to biodiversity loss.*

2.2 Environmental Footprint

A wide variety of resources – including land, water, energy, and chemical inputs – are used by the U.S. cradle-to-consumer food supply chain. Figure 2-1 provides a snapshot of the environmental footprint based upon estimates from Canning et al. (2020)[2] and Crippa et al. (2021)[3]. The figure depicts a simplified model of five major inputs and greenhouse gas (GHG) emissions associated with each stage of the food supply chain and denotes percentage contributions, by supply chain stage.

As shown in Figure 2-1, primary production is responsible for the widest range of environmental inputs among the stages of the U.S. cradle-to-consumer food supply chain. The use of land and the application of pesticides and fertilizers occur chiefly during primary production, while the use of water and energy and the emissions of greenhouse gases occur all along the food supply chain (Crippa et al., 2021; Canning et al., 2020).

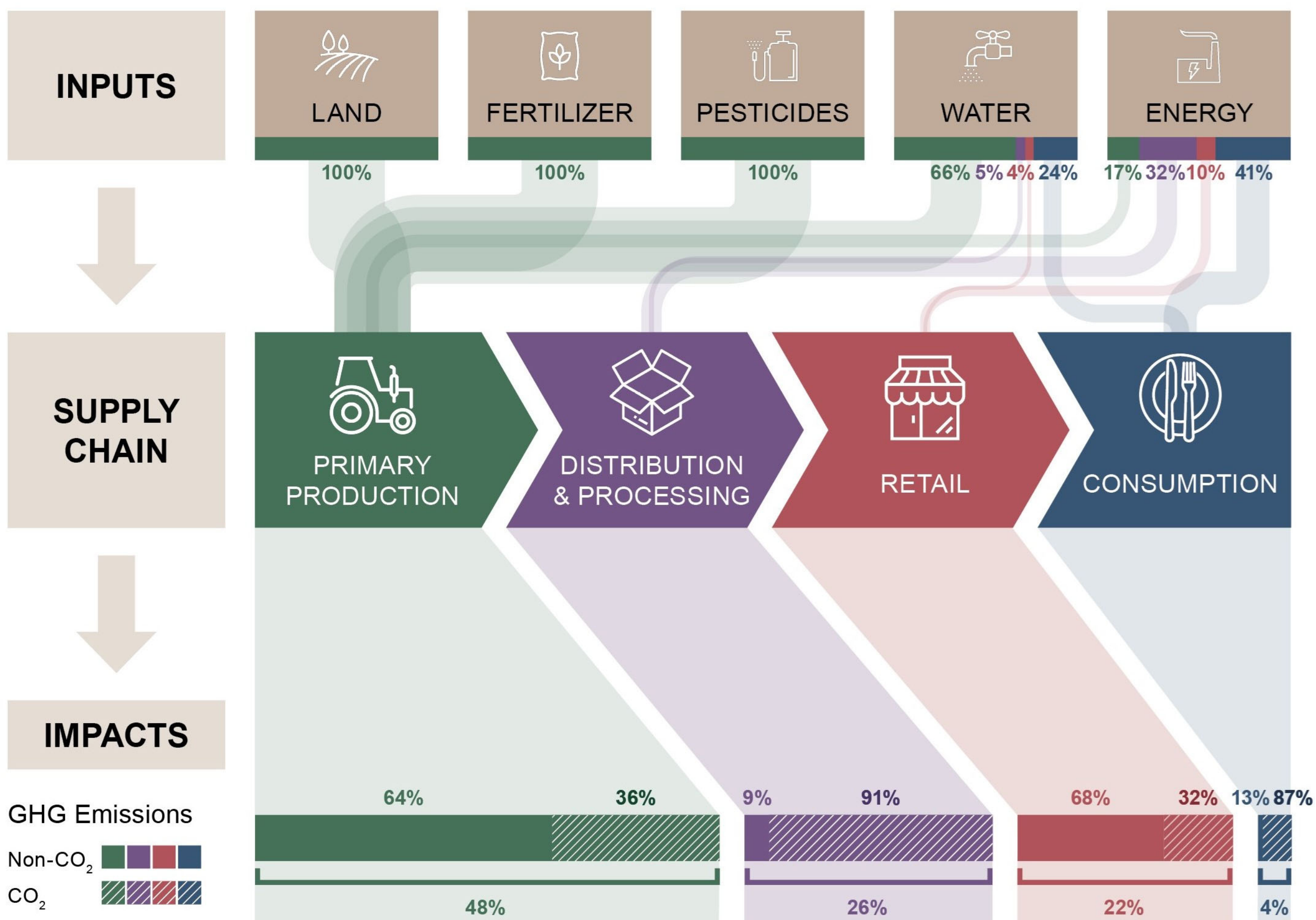

FIGURE 2-1. ENVIRONMENTAL FOOTPRINT OF THE U.S. CRADLE-TO-CONSUMER FOOD SUPPLY CHAIN

This figure portrays the use of five major inputs and the emission of greenhouse gases, by supply chain stage.
Data Source: Canning et al. (2020); Crippa et al. (2021)

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2 Canning et al. (2020) combined three models (a diet model, an environmentally extended input-output model of resource use in the food system, and a biophysical model of land use for crops and livestock) to estimate resource use. The study examines only domestic production, excluding resources used to produce exports and resources used in other countries to produce food imported into the United States.

3 Crippa et al. (2021) developed a database of global food emissions (EDGAR-FOOD), including emissions associated with land use and land-use changes, from the existing Emissions Database of Global Atmospheric Research (EDGAR). The database extends from 1990-2015 and covers all stages of the food chain for every country. With this data the authors analyzed global food-system emissions and trends and evaluated key contributors (by supply chain stage and country).

2.3 Inputs and Environmental Impacts

This report focuses primarily on five inputs to the U.S. cradle-to-consumer food supply chain—agricultural land use, water use, application of pesticides and fertilizers, and energy use—plus one environmental impact—greenhouse gas emissions. This section discusses these factors and describes their connection to the major environmental impacts of the cradle-to-consumer food supply chain, such as climate change and reductions in biodiversity and water quality and availability. Additional information on inputs and environmental impacts is provided in Appendix A via reference tables sorted by broad food category (plants, farm animals, and wild-caught and farmed seafood) and stage of the supply chain. These tables include information about inputs and environmental impacts beyond those detailed in the report, such as soil degradation, changes in air quality, and worker health.

Agricultural Land Use

Land is a limited resource integral to the production of food. This report focuses on the land used to produce food for human consumption, including land used to house livestock and produce feed (e.g., hay, feed grains, and oilseeds) for livestock and farmed seafood, where possible. Land used for non-food crops and biofuel feedstocks is excluded.

Over 25 percent of the United States' total land area is used to produce food, with annual per person estimates ranging from 3,399 to 10,800 m^2 (Canning et al., 2020; Birney et al., 2017; Peters et al., 2016). When land is used to produce food, it can alter soil, air, and water quality (Aneja et al., 2009; U.S. EPA, 2005; USDA, 1996a, b, c).

Of the land required for U.S. food production, 830,000 km^2 are used as cropland and more than 3 million km^2 are used as pasture (i.e., for grazing). While cropland represents a smaller share of total land use, it generally requires greater inputs (i.e., fertilizer, pesticides) and cultivation (e.g., tillage) than pasture, leading to greater environmental impacts. Of the cropland, approximately 530,000 km^2 (63 percent) are used to grow feed for livestock (Merrill and Leatherby, 2018). Due to feed and pasture requirements, animal products have a larger land footprint per kilogram than plant-based foods, with beef requiring significantly more land than other animal products (Bozeman et al., 2019; Eshel et al., 2014).

While the amount of land used for agriculture in the United States has been fairly stable since before the 1960s (USDA, 2017), natural ecosystems are being converted to agricultural land in other countries (in some cases, to meet demand in the United States – see Section 2.4), and researchers project a need to further expand agricultural land to feed the growing global population (UN, 2020a; Searchinger et al., 2019). Expanding agricultural land use can lead to loss of biodiversity and ecosystem services (e.g., pollinators, soil fertility, water filtration) and release of greenhouse gas emissions, as well as affect hydrologic cycle and local climates (Chaudhary and Kastner, 2016; Power, 2010; Foley et al., 2005).

Water Use

The food system depends on freshwater for many functions, from irrigating crops to processing food products to preparing and cooking food. Like land, usable freshwater supplies are limited, and many parts of the United States have already reached a "water-stressed" state (Marston et al., 2021; Capel et al., 2018). As shown in Figure 2-1, primary production is a major user of freshwater. Producing plants, animals and farmed seafood for human consumption means there is less water available for other uses (Pfister et al., 2011; Rost et al., 2008).

Calculating the Environmental Footprint of Animal Products

When estimating the environmental footprint of producing meat and other animal products (e.g., dairy or farmed seafood), researchers should account for the inputs and impacts associated with feeding and housing the animals. For example, the environmental footprint of pork production includes not only the resources associated with housing the animal (e.g., land, water and electricity use for housing the animals and GHG emissions from manure management), but also the resources required for growing animal feed (e.g., the land, water, fertilizers, pesticides and energy required to grow corn, oats, soybeans and other animal feed and the GHG emissions associated with their production). Where possible, these comprehensive estimates of the inputs and impacts of animal products are included throughout the report.

In addition, water stress can affect aquatic organisms and groundwater-dependent terrestrial ecosystems (Pfister et al., 2011). With climate change altering hydrologic patterns, water scarcity will likely increase in the United States and globally (Distefano and Kelly, 2017).

In this report, water use is classified by its source and/or purpose:

1. Blue water – freshwater from surface water and groundwater;
2. Green water – rainwater that is soaked up by cropland or rangeland vegetation or soil; and
3. Grey water – freshwater that is needed to dilute pollutants to meet water quality standards (Mekonnen and Hoekstra, 2011; Rost et al., 2008).

This report focuses primarily on blue water, with green water data provided when available. Unless otherwise noted, the term water in this report refers to blue water. Gray water is not consumptive (in that plants, livestock or farmed seafood do not consume grey water like they do blue and green water), and it is difficult to measure (Mekonnen and Hoekstra, 2011), and thus is excluded from this report.

All stages of the U.S. cradle-to-consumer food supply chain require blue water. In total, the cradle-to-consumer food supply chain is responsible for approximately 30 percent of U.S. blue water withdrawals (approximately 34 trillion gallons annually) (Rehkamp and Canning, 2018). Primary production accounts for the largest volume of water withdrawals (Canning et al., 2020), principally for irrigation (63 percent) (USDA, 2021b). Aquaculture (i.e., farming of aquatic organisms) (2 percent) and livestock watering and hygiene (less than 1 percent) account for smaller shares of blue water withdrawals (Dieter et al., 2018). However, measuring freshwater withdrawals (i.e., how much water is withdrawn from surface or groundwater) during primary production may overestimate the amount of water agriculture consumes[4], as only approximately half of the water withdrawn is taken up by plants and the other half recharges groundwater or soils (Bhagwat, 2019). Much of the water used in aquaculture flows through the farm and is returned after use (USGS, 2019). To measure water consumption, models are used to determine crop requirements and irrigation efficiencies. For example, using these methods, it is estimated that 62 percent of irrigation water is consumed (Dieter et al., 2018). Of consumptive blue water use, Marston et al. (2018) estimates 56 percent is from groundwater, and 44 percent is from surface water sources. In this report "water withdrawal" or "water use" data and "water consumption" data are distinguished where possible.

During primary production, the amount of blue water required per kilogram of food produced varies widely by food category. About 80 percent of vegetable crops and 94 percent of orchard fruit and nut crops are irrigated in the United States (USDA, 2015b, 2013), however meat and other animal products can require a larger amount of blue water (per unit of food) once irrigation of animal feed is included (Bozeman et al., 2019; D'Odorico et al., 2018; Eshel et al., 2014).

Downstream from primary production, blue water is utilized during food processing (as a food ingredient and for processing operations, cleaning, and sanitation) and during the consumption stage (for food preparation and cooking) (Bhagwat, 2019). Not surprisingly, beverages account for the greatest blue water withdrawals during food processing, followed by processed foods and flavorings and livestock slaughtering and processing (Marston et al., 2018). However, total food processing blue water withdrawals account for a very small fraction of cradle-to-consumer food system water withdrawals, which are dominated by the primary production and consumption stages (Canning et al., 2020; Marston et al., 2018).

Green water is also critically important for primary production. In the United States, green water comprises nearly 87 percent of consumptive water use to grow crops (Marston et al., 2018). In 2018, only 8 percent of U.S. cropland and grazing land was irrigated, meaning that 92 percent of crop and grazing land depended solely on green water for successful production (USDA, 2019b, e). By food category, meat, poultry and eggs, followed by dairy, are the largest users of green water in the current U.S. diet (Birney et al., 2017). When both blue and green water are considered, primary production accounts more than 95 percent of the total consumptive water use of all U.S. economic production (Marston et al., 2018). While the data presented in this report is at national scale, water scarcity (also called water stress) typically occurs at a smaller scale. However, a regional analysis of water supply and demand was beyond the scope of this paper.

[4] In this context, "consumed" means taken up by the crop over its various growth stages for plant retention and evapotranspiration.

Pesticide and Fertilizer Application

Farmers use pesticides on their fields or pastures to protect against yield loss or damage (USDA, 2019b). Pesticides are substances or mixtures of substances intended for preventing, destroying, repelling, or mitigating plant or animal pests. Based on the type of crop grown and the pest(s) of concern, farmers may apply natural or synthetic herbicides, insecticides, fungicides, soil fumigants, plant growth regulators, defoliants, and/or desiccants to control pests (Hellerstein et al., 2019). Herbicides are the most applied pesticide (63 percent) in the United States, followed by sulfur and oil and fumigants (Atwood and Paisley-Jones, 2017). Corn (40 percent), soybeans (22 percent), and potatoes (10 percent) account for the greatest share of pounds of pesticides applied (Fernandez-Cornejo, 2014; Aktar et al., 2009). The application of pesticides can contaminate waterways, impact soil quality, and cause harm to ecosystems, and pose risks to non-target organisms including humans (Capel et al., 2018; U.S. EPA, 2005).

Synthetic and organic fertilizers increase crop yields through the addition of essential plant nutrients. The three major types of synthetic fertilizer used in the United States are nitrogen (N), phosphate (P), and potassium or potash (K). The type and amount of fertilizer applied to each crop varies based on local soil conditions, farm practices, and individual crop needs. In 2015, a total of 20 million metric tons of fertilizer were applied in the United States, comprised of 11.8 million metric tons of nitrogen, 3.9 million metric tons of phosphorous, and 4.3 million metric tons of potassium (USDA, 2019a). More than half of the fertilizer was applied to feed crops (i.e., to produce animal products), while the remainder was used primarily on grains and sweeteners (Toth and Dou, 2016).

Nitrogen (N) is found primarily in an organic form in soils but can also occur as nitrate, which is extremely soluble and mobile. Phosphorus (P) occurs in soil in several forms, both organic and inorganic. Phosphorus loss due to erosion is common, and phosphate, while less soluble than nitrate, can easily be transported in runoff. Potash is the oxide form of potassium (K); its principal forms as fertilizer are potassium chloride, potassium sulfate, and potassium nitrate. When used at recommended application rates, there are few to no adverse effects from potassium, but it is a common component of mixed fertilizers used for high crop yields (Weil, 2017).

Application of fertilizer can lead to adverse environmental impacts. Nutrient run off from nitrogen and phosphorous fertilizers can result in drinking water toxicity, eutrophication of streams, and algal blooms and fish kills (USGS, 2000). Additionally, the production of synthetic fertilizer and the application of organic and synthetic fertilizers produce greenhouse gas emissions which contribute to climate change (U.S. EPA, 2019b).

Energy Use

All stages of the cradle-to-consumer food supply chain require energy (i.e., electricity and/or fuel). Energy is used for everything from fueling tractors and pumping and distributing irrigation water to running food processing equipment to powering refrigeration. Between 2004 and 2015, the U.S. cradle-to-consumer food supply chain used an average of 11,800 PJ annually, equivalent to 11 percent of total U.S. energy use (Pagani et al., 2020; Vittuari et al., 2020).

Unlike with the inputs discussed previously, food processing (including packaging) is a significant energy user, accounting for roughly one-quarter of the cradle-to-consumer food system's energy use (Canning et al., 2020). Retail accounts for another quarter of energy use. The consumption stage accounts for more than one third of energy use (the largest share), primarily from refrigeration and cooking (Canning et al., 2020). Despite the level of attention it receives, transportation from farm to retail (or food service)[5] accounts for only approximately 6 percent of cradle-to-consumer food supply chain energy use (Pagani et al., 2020; Vittuari et al., 2020). By food category, energy use is highest for meat and dairy, followed by grains (Pagani et al., 2020; Vittuari et al., 2020).

[5] This estimate excludes transportation from retail to homes.

Greenhouse Gas Emissions and Climate Change

Greenhouse gases, including carbon dioxide, methane, nitrous oxide, and some synthetic chemicals, including chlorofluorocarbons, trap some of the Earth's outgoing energy, thus retaining heat in the atmosphere. Human activities are increasing the concentrations of GHGs in the atmosphere and are the primary cause of the 1 degree Celsius increase in global air surface temperature over the past 115 years (Wuebbles et al., 2017). The effects of climate change on global natural systems include increases in land, water and air temperatures, variation in precipitation timing and amounts, reduced snow pack, sea level rise, and wildfires and hurricanes (Dupigny-Giroux et al., 2018; Wuebbles et al., 2017). The Paris Agreement set global targets to limit warming below 2 degrees Celsius, with aspirations to keep warming to 1.5 degrees Celsius because warming beyond the 1.5 degrees Celsius target would lead to more catastrophic outcomes (IPCC, 2018; UNFCC, 2015). Multiple studies have concluded that reducing GHG emissions from our food system will be essential to feed the growing global population sustainably and keep food-related emissions in line with limiting global warming to below 2 degrees Celsius (Clark et al., 2020; Willett et al., 2019; Conijn et al., 2018; Springmann et al., 2018; Bajželj et al., 2014).

As shown in Figure 2-1, GHGs are emitted at all stages of the U.S. cradle-to-consumer food supply chain, with the amount and type varying by stage. Studies agree that the greatest amount of GHG emissions occur during primary production (Crippa et al., 2021; Canning et al., 2020; Boehm et al., 2018 ; Mohareb et al., 2018; Weber and Matthews, 2008). Examples include:

- Methane (CH_4) emitted from enteric fermentation[6], manure management and growing rice;
- Nitrous oxide (N_2O) emitted from nitrogen fertilization and manure management; and
- Carbon dioxide (CO_2) emitted from soil management practices (i.e., reduction in soil carbon sequestration resulting in release of CO_2 into the atmosphere), fertilizer production, and energy use by farm equipment.

Primary production in the United States releases approximately 4.72 kg CO_2e (CO_2 equivalents) per person per day (Heller et al., 2018) and is responsible for 39 percent of U.S. methane emissions and 80 percent of U.S. nitrous oxide emissions (U.S. EPA, 2021c). Both methane and nitrous oxide are potent greenhouse gases, with global warming potentials more than 25 and 265 times greater than CO_2 (U.S. EPA, 2021c). Methane has only a short (12-year) atmospheric life. Nitrous oxide is also the most significant ozone-depleting substance released to the atmosphere, damaging the stratospheric ozone layer that protects Earth from the sun's harmful radiation (Compton, 2021). Globally, land clearing and deforestation is also a major source of GHG emissions.

As shown in Figure 2-1, roughly half of the cradle-to-consumer food supply chain's GHG footprint is CO_2 emissions from energy use and land use change. Energy use drives the GHG emissions of all of the supply chain stages downstream from primary production, with the exception of retail, which emits chlorofluorocarbons (CFCs) from refrigerant leaks (Crippa et al., 2021) in addition to CO_2 from energy use. Transportation contributes a relatively small share of food system GHG emissions, representing from 7 to 11 percent of U.S. cradle-to-consumer food supply chain emissions, according to recent studies (Mohareb et al., 2018; Weber and Matthews, 2008).

Many studies have examined GHG emissions by food category. Despite differences in methodologies, portions of the food system covered, and other variables, most studies found that the production of meat (especially beef) results in the most GHG emissions per weight of food produced (Guo et al., 2020; Bozeman et al., 2019; D'Odorico et al., 2018; Birney et al., 2017; Heller and Keoleian, 2015; Venkat, 2012).

[6] Enteric fermentation is fermentation that takes place in the digestive systems of animals, resulting in methane that is exhaled or belched by animals.

Summary

In summary, the U.S. cradle-to-consumer food system is significant user of finite natural resources and contributes to a broad range of environmental impacts, including climate change. The inputs and environmental impacts of the food supply chain vary by both supply chain stage and by the category of food being produced. The primary production stage of the supply chain is responsible for most land, pesticide, and fertilizer use, and the greatest share of water withdrawals and GHG emissions. Energy use, however, is dominated by the consumption stage, followed by the food processing and packaging stage, thus these stages also contribute significantly to GHG emissions and climate change (Canning et al., 2020). In general, the production of animal products requires the greatest amount of land, water, and energy and results in the most GHG emissions per weight of food produced (Pagani et al., 2020; Vittuari et al., 2020; Bozeman et al., 2019; D'Odorico et al., 2018; Hilborn et al., 2018; Parker et al., 2018; Aleksandrowicz et al., 2016; Tom et al., 2016; Weber and Matthews, 2008).

2.4 Imports

U.S. consumers often rely on imported agricultural goods when domestic production is not possible (e.g., grapes during the U.S. winter season), when demand outweighs domestic production capacity, or for other reasons. For example, U.S. production of fruits and vegetables such as bananas and asparagus is able to meet less than 20 percent of domestic demand, whereas for other produce (e.g., apples, oranges, and cauliflower) the United States produces more than is demanded domestically and is a net exporter (FAO, 2018).

According to the USDA, almost one-fifth of the food consumed within the U.S. is imported. Fruits (26 percent) and vegetables (20 percent) constitute almost half (46 percent) of all agricultural imports combined, and imports supplied approximately 30 percent of the available vegetables and more than half of all the available fruits in the U.S. (USDA, 2019f, 2016). Fish and seafood are also frequently imported, with imports comprising over 80 percent of the seafood available to U.S. consumers (NOAA, 2021).

Geographic Differences in Environmental Footprint

Figure 2-2 shows U.S. food imports by country in 2019. While these imports come from diverse locations, most of the studies of the environmental footprint of FLW assume the entire U.S. food supply is produced domestically when calculating environmental footprint. This is due to the complexity of attributing imports to producer countries and estimating environmental impacts of each food in each producing country. The studies typically apply average U.S. resource use levels and emission factors to all food available to U.S. consumers, regardless of whether it was produced in the United States. Thus, the studies may over- or under-estimate the actual environmental footprint of production, since the environmental footprint of producing food in another country may vary greatly from that of producing food in the United States.

Differences in producing countries’ local environments, agricultural practices, yields, standards, and production methods can all impact the environmental footprint of a food item (Poore and Nemecek, 2018). For example, the production of imported goods can contribute to water scarcity or agricultural land use change and deforestation in exporting countries. While the level of land use for agriculture is relatively stable in the United States (USDA, 2017), natural ecosystems may be converted to produce crops or graze livestock in other countries. A recent study by Kim et al. (2020) compared the GHG footprint and blue and green water footprints of producing 74 food items in different countries and found substantial variation in impacts of food production by country. The authors found, for example, that the GHG footprint of beef produced in Australia (the top importer of beef to the U.S.) was nearly double that of beef produced in the United States, while the blue water footprints of rice produced in India and Thailand (leading importers of rice to the United States) were half that of rice produced domestically (Kim et al., 2020; USDA, 2020).

A few FLW studies presented in this report attempt to account for differences among producing countries. One study (Jalava et al., 2016) applied national average environmental factors to domestically produced food and global average environmental factors to imported food, while two others (Guo et al., 2020; Chen, 2019) applied global average environmental factors to all food (domestically produced and imported). A fourth study (Pagani et al., 2020; Vittuari et al., 2020) simply excluded imports from their analysis, thus underestimating the environmental footprint of FLW by not including the footprint of producing 20 percent of the U.S. food supply. No food waste studies applied country-specific data to imports when estimating environmental impacts of FLW.

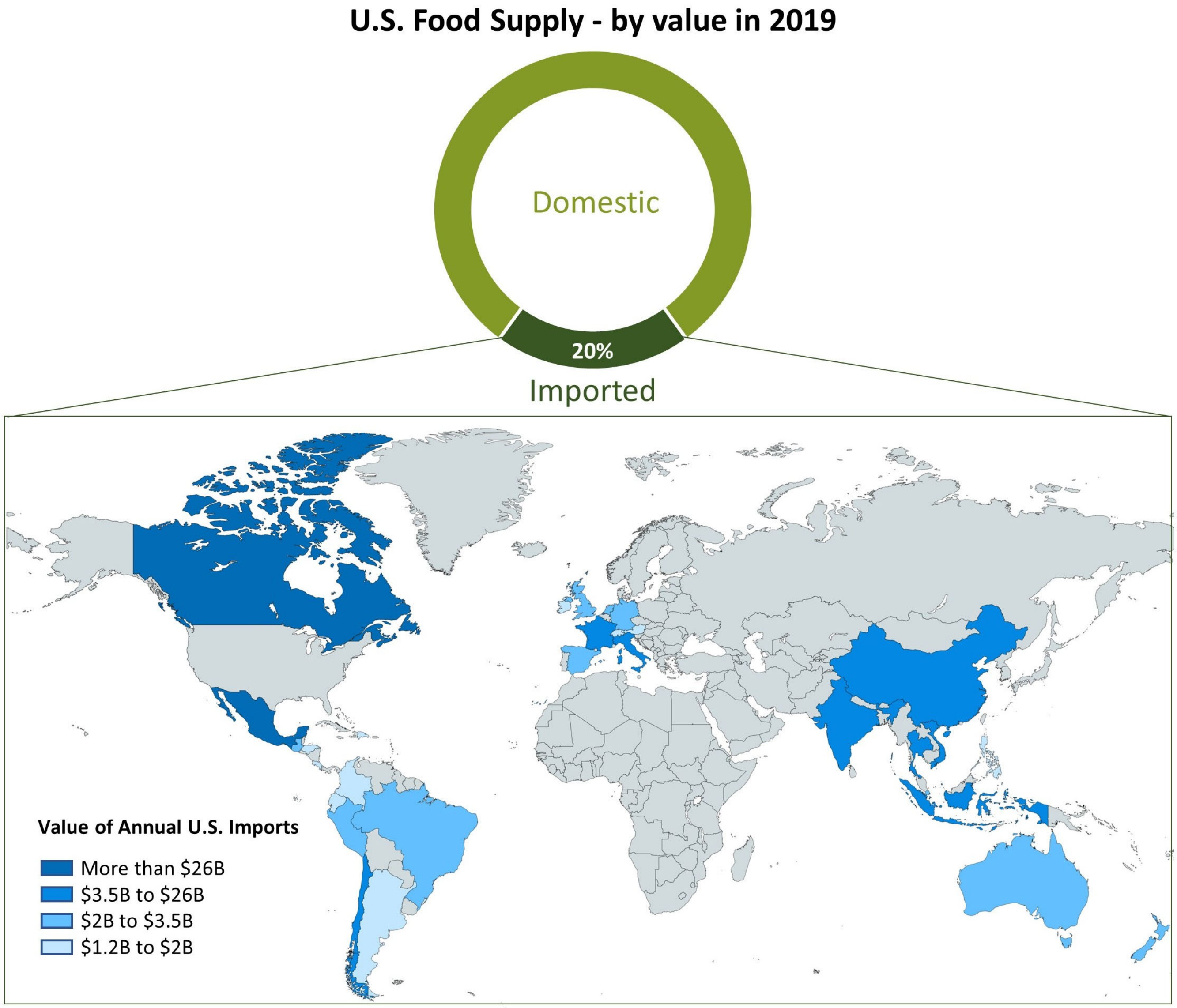

FIGURE 2-2. IMPORTS TO U.S. FOOD SUPPLY

Food imports to the United States are predominantly from Mexico and Canada, followed by France, Italy, Chile, China, India, and Indonesia, in order of value of imported food. Groupings in figure correspond to the 99th, 95th, 90th, and 85th percentiles across 201 importing countries. Data Source: CRS (2020); World Bank (2021)

Biodiversity Loss

In the studies presented in this report, agricultural land use is often used as an indicator of the potential for biodiversity loss, and many examples exist of species threats due to global trade. A systematic analysis linking threatened species, commodities, and complex international supply chains through 187 countries by Lenzen et al. (2012) showed that 30 percent of global species threats[7] are due to international trade. The study also concluded that the United States is the largest net exporter of biodiversity threats, meaning that primary production of foods and other goods imported into the U.S. (including coffee, tea, sugar, textiles, fish and other manufactured items) threaten the greatest number of species abroad.

[7] Excluding threats from invasive species.

Looking specifically at the biodiversity impacts of food imports, Chaudhary and Kastner (2016) used the countryside species area relationship (SAR) model, paired with bilateral trade data from FAO, to identify species lost due to agricultural land use for 170 crops in 184 countries. The model estimated that U.S. food imports are responsible for the loss of 115 species abroad, primarily in Mexico and Indonesia, and also in other Latin American countries (Chaudhary and Kastner, 2016). An additional study using the SAR model identified the export of agriculture-based products from Mexico and the Philippines and pasture-based products from Australia and Columbia, along with forestry-based products from Oceania, Indonesia, the Philippines, and Central Africa, as the greatest biodiversity impacts associated with global trade (Chaudhary and Brooks, 2019). In addition, some food products such as sugarcane, palm oil, and coffee have disproportionately high impacts on biodiversity relative to the amount of land occupied by their production (Chaudhary and Kastner, 2016); thus, the studies presented in this report may miss important impacts on biodiversity due to the use of broad categories of foods.

International Transportation

As imported foods require transportation from their country of origin to the United States, additional environmental impacts may occur from shipping and storage of food during transportation (e.g., refrigeration for perishable animal products or fruits, or freezer conditions for frozen fish or vegetables). Note, however, that depending on where food is produced and consumed, imported food could travel less distance than domestically grown food (e.g., wheat imported from western Canada to Minnesota compared with oranges grown in Florida and sold in Hawaii). Impacts from travel also vary considerably by method, with longer distance travel by boat sometimes resulting in lower GHG emissions than shorter distance travel by truck (Wakeland et al., 2012). Also, differences in GHG emissions related to production methods can outweigh those associated with transportation. Only one study of FLW presented in this report (Guo et al., 2020) accounted for international transportation when estimating GHG emissions. The authors found that it was equivalent to just 3 percent of the GHG emissions from primary production (measured in CO_2 equivalents).

2.5 Other Factors

Studies estimating the inputs and environmental impacts of each type of food (and FLW) at each stage of the U.S. food system utilize national or regional averages for inputs and environmental impacts, typically for broad categories of foods, such as all fruits or all grains. In reality, inputs and impacts vary depending on multiple factors, including:

- Type of food produced (within a broad category of food),
- Production method,
- Geographic location and timing of production,
- Type and amount of processing conducted (e.g., no processing for corn on the cob versus processing for corn meal or extensive processing for high-fructose corn syrup),
- Type and amount of packaging used,
- Type of storage required (e.g., refrigeration),
- Time between being produced and purchased (seasonality),
- Mode and distance of transportation at each stage,
- How the food is cooked, stored and prepared, and
- Other factors (Asem-Hiablie et al., 2019; Bozeman et al., 2019; Goossens et al., 2019; Heard et al., 2019; Niles et al., 2018; Clark and Tilman, 2017).

Each of these variables can affect the cumulative resource requirements of the finished food product as well as the type, amount, and cumulative environmental impacts of its production and distribution (Asem-Hiablie et al., 2019; Heard et al., 2019; Niles et al., 2018) – including all associated FLW. The studies presented in Chapters 4 through 6 of this report estimate the approximate average environmental impacts at each stage of the cradle-to-consumer food supply chain for each category of food lost or wasted. This means the studies do not calculate the precise environmental impacts accrued at each stage of the food system for specific FLW (e.g., the leftover steak, potatoes, and green beans one threw away in a household), but instead typically calculate the environmental impacts of the broad categories of FLW (e.g., meat and vegetables) during broad stages of the food supply chain (e.g., the consumption stage, which includes at home and away from home consumption).

CHAPTER 3.
Characterization of U.S. Food Loss and Waste

The American food system is a complex arrangement of farmers, processors, distributors, retailers, food service providers, and consumers. Key players can influence what is produced and how products move through the system (i.e., through business decisions and consumer preferences), but the system as a whole is driven by a multitude of factors, including domestic and global markets, costs, politics, laws and regulations, social organizations, plant and animal biology, science and technology, weather, and environmental conditions (IOM and NRC, 2015). Combined, these factors determine the total amount and types of food produced, consumed, lost, and wasted each year.

Understanding the amount of food produced for human consumption but ultimately lost or wasted is an important step toward assessing the magnitude of the environmental footprint of FLW. This chapter examines published estimates of the total amount of FLW generated in the United States along with details regarding the categories of food lost or wasted and the supply chain stage at which food is lost or wasted. This information is critical to building the estimates of the environmental footprint of U.S. FLW presented in Chapter 4 and to tailoring efforts to reduce food loss and waste.

KEY FINDINGS

- *The U.S. wastes more than one third of its food supply, from 73 to 152 million metric tons (161 to 335 billion pounds) per year or 223 to 468 kg (492 to 1,032 pounds) per person per year.*
- *U.S. FLW includes 1,110 to 1,520 calories per person per day.*
- *U.S. FLW per person increased over the last decade and total U.S. FLW tripled since1960.*
- *The consumption stage (restaurants and households) is responsible for roughly half of U.S. FLW.*
- *Fruits and vegetables are the most commonly wasted foods, followed by dairy and eggs.*

3.1 U.S. Food Surplus

America has an overabundance of food. According to the USDA, the amount of food available to U.S. consumers is far greater than the amount of food they consume. As shown in Figure 3-1, 3,796 to 4,000 calories were available[8] per person per day, compared to 2,081 calories consumed per person per day, in 2010 (USDA, 2019d, 2015a; Buzby et al., 2014; USDA, 2012).[9] This indicates that significant FLW is an outcome of the U.S. food system.

Wasted food also represents wasted nutrients, which vary by food category wasted. Spiker et. al (2017) found that food wasted by retailers and consumers in 2012 contained 33 grams protein, 5.9 grams dietary fiber, 1.7 micrograms vitamin D, 286 milligrams calcium, and 880 milligrams potassium per person per day (Spiker et al., 2017).

[8] Data on food availability come from USDA's Food Availability Per Capita Data Series (Buzby et al., 2014). 2010 is the most recent year for which complete data is available. The FAO provides an updated estimate of 3,782 calories per person per day in 2018 (FAO Food Balances, 2021).
[9] Data on consumption come from USDA's National Health and Nutrition Survey, What We Eat in America (2009-2010 data) (USDA, 2012). More recent estimates (2017-2018) from this data source indicate 2,093 calories consumed per person per day.

While food is abundant in the U.S., food insecurity persists. In 2019, more than 35 million Americans were food insecure (USDA, 2021a). However, this food insecurity is not driven by scarcity. As shown in Figure 3-1, studies indicate that even if every American was provided with enough calories to meet their current level of physical activity and body weight, a surplus of 1,050 to 1,400 calories daily per person would remain (Hiç et al., 2016; Hall et al., 2009)[10]. The amount of surplus food from retailers and consumers (141 trillion calories in 2010, according to Buzby et al. (2014)) is sufficient to feed 154 million people for a year (Wood et al., 2019), a far greater number than estimated by USDA to be food insecure. In addition, it is not always possible or appropriate to redistribute surplus food (Spiker et al., 2017). Therefore, increasing the redistribution of food cannot alone meet the U.S. goal to halve food waste by 2030. Solutions must include efforts to prevent the generation of surplus food and FLW in addition to efforts to redistribute surplus food where possible.

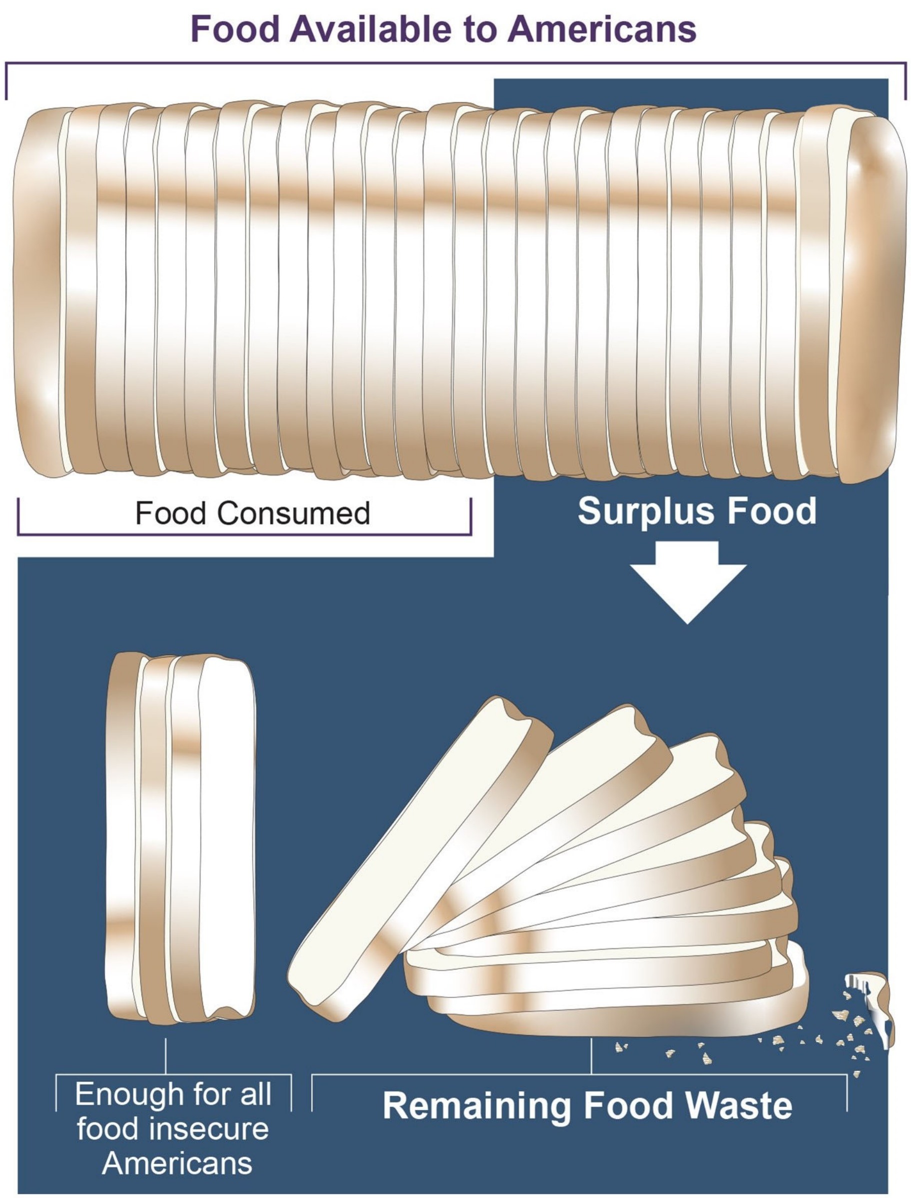

FIGURE 3-1. FOOD WASTE IN THE UNITED STATES

The amount of food available to Americans (in calories) exceeds the number of calories consumed plus the number of calories required to eliminate food insecurity. The figure depicts only edible food (i.e., inedible parts such as bones and shells are excluded from estimates). Data year 2010. Data Source: Buzby et al. (2014); USDA (2012); Hall et al. (2009); Hiç et al. (2016)

[10]Surplus calories are estimated using biological models for human energy requirements and loss adjusted food availability estimates. More information on the methods used to develop these estimates is available in section 3.7.

3.2 Total U.S. FLW

Given the size and dynamic complexity of the U.S. food system, no single agreed-upon comprehensive estimate of the total amount of U.S. FLW exists. Instead, the literature includes multiple credible estimates, which differ in scope and methodology, that together provide insights into the magnitude and distribution of U.S. FLW.

Table 3-1 provides a summary of the estimates of total U.S. FLW from the literature. All of the estimates include only food intended for human consumption. Three key variables that impact the magnitude of these estimates – data year, edibility, and supply chain coverage – are shown, and their effect will be discussed in the following three sections. Note that while there a large number of FLW estimates, many rely upon a similar data sources (most notably, data series from FAO and USDA). See Section 3.7 for a discussion of these methodologies.

Of the studies that include all FLW[11] from all stages of the food supply chain (from primary production to consumption), the estimates of U.S. FLW range from 73 to 152 million metric tons per year, or 223 to 468 kg per person per year (ReFED, 2021a; Guo et al., 2020; CEC, 2017). Two of these studies provide results in terms of percentage of the food supply, equating their estimates of FLW to 35 to 36 percent of the U.S. food supply (ReFED, 2021a; CEC, 2017).[12]

[11] Include edible and inedible FLW (discussed further in Section 3.4).
[12] Equating estimates of U.S. FLW to a percentage of the corresponding food supply can be complex, as each study defines it boundaries differently. In this report only percentages provided by the study authors are presented.

TABLE 3-1. ESTIMATES OF U.S. FOOD LOSS AND WASTE

Source Scope of FLW	U.S. Food Loss and Waste				
	Total million metric tons/year	**Percent Food Supply Lost or Wasted**	**Per Person** **By Weight** kg/year	**By Calories** cal/day	**Data Year**
CEC (2017)	69	33%	368	–	2007
CEC (2017)	126	36%	415	–	2007
FAO (Gustavsson et al., 2011) NAO	108	–	300	–	2007
Guo et al. (2020)	152•	–	468	–	2017
Kummu et al. (2012)[a] NAO	–	32%	–	1134	2005–2007
Lipinski et al. (2013) NAO	–	–	–	1520	2009
Pagani et al. (2020) and Vittuari et al. (2020)[b]	77	25%	240	1110	2001–2015
Read et al. (2020)	–	18% by monetary value	–	–	2007–2012
ReFED (2021a)[c]	73	35%	223•	–	2019
U.S. EPA (2020a)	93	–	286•	–	2018
Hiç et al. (2016)	–	–	–	1050	2010
NIH (Hall et al., 2009)	–	30%	–	1400	2003
Toth and Dou (2016)	97	45%	309•	–	2012
Venkat (2012)	55•	–	180	–	2009
FAO (2021)	61	–	187•	–	2018

Source Scope of FLW	U.S. Food Loss and Waste				
	Total million metric tons/yr	Percent Food Supply Lost or Wasted	Per Person By Weight kg/year	By Calories cal/day	Data Year
Birney et al. (2017)	71•	–	229	–	2010
Cuéllar and Webber (2010)	44•	–	145	–	2007
Heller and Keoleian (2015)	61•	31%	196	–	2010
Lopez Barrera and Hertel (2021)	–	35%	–	–	2013
Mekonnen and Fulton (2018)	69	34%	216	1237	2015
Spiker et al. (2017)	–	–	–	1217	2012
USDA (Buzby et al., 2014)	60	31%	195•	1249	2010
Chen et al. (2020)	57•	–	184•	709	2011
Conrad et al. (2018)	48	26%	154	795–840	2007–2014
van den Bos Verma et al. (2020)	–	–	–	1572	2011
Yu and Jaenicke (2020) only households	–	32% by monetary value	–	–	2012

= edible FLW only; = edible and inedible FLW

NAO = Indicates estimate for the North America and Oceania (NAO) Region

• = calculated value. Calculated values for total tons and weight per person used the same population factor as the study's data year.

= personal communication with the author. Q. Read (April 5, 2021; July 26, 2021) X. Guo (March 23, 2021); M. Pagani (April 20, 2021; September 1, 2021)

[a] Kummu et al. (2012) excludes animal products from FLW estimates. [b] Pagani et al. (2020) and Vittuari et al. (2020) exclude the waste of imported foods. Approx. one-fifth of U.S. food supply is imported. [c] ReFED (2021a) excludes animal products from estimates of FLW during primary production.

3.3 U.S. FLW Over Time

While trend data are not widely available, ReFED and EPA both provide helpful estimates of U.S. FLW over time. ReFED's Insights Engine Food Waste Monitor (2021a) provides the most comprehensive data available, including FLW from all stages of the supply chain.[13] Between 2010 and 2019, ReFED estimates that U.S. FLW increased by 12 percent, including a per person increase of 6 percent. According to ReFED, FLW rates have been relatively flat since 2016, showing less than a one percent change in both absolute and per person amounts.

U.S. EPA's "Facts and Figures" (2020b) provides data over a longer time period (1960 through 2017) but includes only FLW from the retail and consumption supply chain stages that is sent to landfills, incinerators, and compost facilities. Since 1960, EPA reports the amount of FLW in the U.S. has tripled. Between 2010 and 2017, EPA reports a 14 percent increase in FLW, including a per person increase of 8 percent.

In 2020, EPA revised its food measurement methodology to include additional food waste pathways, FLW generated by the food processing sector, and more recent studies (U.S. EPA, 2020f). The revised methodology includes FLW from each sector managed via the three original pathways (landfilling, combustion, and composting) plus the following six additional pathways: donation, animal feed, anaerobic digestion/co-digestion, land application, sewer/wastewater, and bio-based materials/biochemical processing.[14] This new methodology substantially increases EPA's estimate of U.S. FLW, as would be expected. Data from both EPA methodologies are available for the year 2016. In 2016, estimates for FLW from the retail and consumption supply chain stages from the new methodology (56 million metric tons) are more than 50 percent higher than those calculated using the former methodology (36 million metric tons) (U.S. EPA, 2020f) due to updated data sources and the addition of pathways. The addition of the food processing sector accounted for an additional 34 million metric tons; 94 percent of the food processing industry's food waste was managed through the six new pathways added (U.S. EPA, 2020a). Figure 3-2 portrays trends from ReFED data and both EPA data series.[15] All data series show an increase in FLW over the last decade.

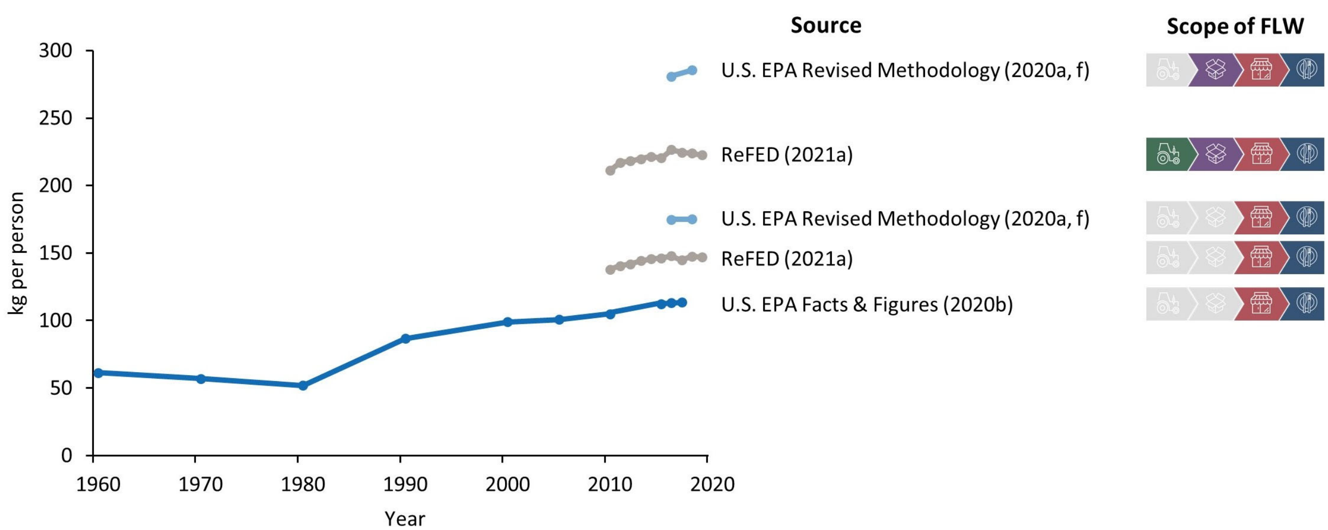

FIGURE 3-2. U.S. FLW PER PERSON OVER TIME

Over roughly the last decade, per person food loss and waste in the United States has increased by 6 to 8 percent (ReFED 2010-2019; U.S. EPA 2010-2017). Over the same time frame, total U.S. food loss and waste increased by 12 to 14 percent.

[13] Information on ReFED's methodology can be found in Section 3.7.
[14] Data was not available for all pathways for all sectors.
[15] Both data series include inedible parts such as bones and shells.

3.4 Edibility of U.S. FLW

One key difference among estimates of FLW is whether they include only edible FLW, or both edible and inedible FLW, such as bones, pits, and shells. Edibility is based upon the type or part of food, not whether the food was spoiled when wasted. For example, eggshells are always considered inedible, but the egg inside is always considered edible, regardless of its age. Estimates of edibility are inevitably rough, since determining and quantifying edible food parts is not straightforward. The definition of edible food is inherently ambiguous because what parts of food are intended for human consumption varies along the food supply chain and between individual consumers and depends on social and cultural preferences and technology factors. For example, the broccoli stalk is considered edible by some people or cultures but inedible by others. Whether the broccoli stalk is considered edible or inedible changes the FLW estimate for a head of broccoli by approximately 61 percent (Moreno, 2020).

Knowing the edible share of FLW (sometimes called avoidable FLW) is important because it provides perspective on how much of the FLW could have been eaten by people. Edible FLW could go towards feeding people and lessening food insecurity, whereas inedible FLW is material that, once produced, must be managed (i.e., through pathways such as composting, anaerobic digestion, or landfill). Knowing both the edible and inedible share of FLW facilitates resource efficiency and allows policymakers to make more informed decisions on FLW reduction and management approaches.

Broadly speaking, between 70 to 90 percent of the food lost or wasted in the United States is edible. As shown in Figure 3-3, the Commission for Environmental Cooperation (CEC) estimated that only 10 percent of FLW (by weight) from the full food supply chain is inedible (CEC, 2017).[16] Estimates of household FLW indicate a greater percentage of household FLW may be inedible. Kitchen diaries kept as a part of two studies – the Oregon Department of Environmental Quality's (ORDEQ) Oregon Wasted Food Study[17] (McDermott et al., 2019) and the Natural Resources Defense Council (NRDC)'s assessment of three cites[18] (Hoover and Moreno, 2017) – demonstrate that inedible FLW accounted for approximately 30 percent of total household FLW, by weight.

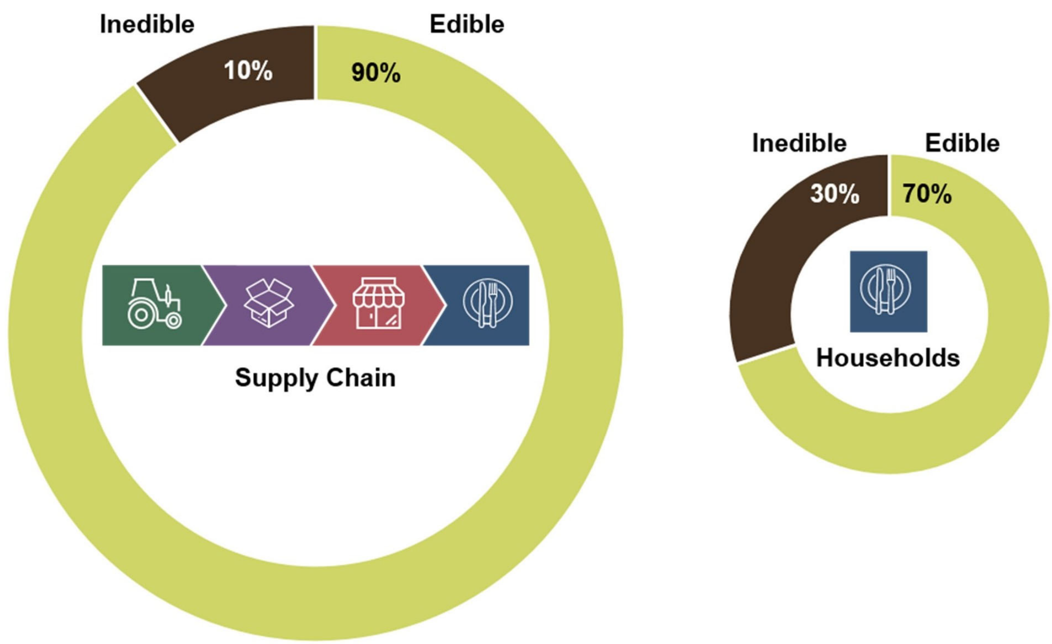

FIGURE 3-3. SHARE OF U.S. FLW CONSIDERED EDIBLE VERSUS INEDIBLE, BY WEIGHT

Available data indicates that only 10 percent of total U.S. food loss and waste (FLW) and 30 percent of U.S. household food waste (by weight) are made of inedible food parts, such as bones or shells.
Data Source: CEC (2017); McDermott et al. (2019); Hoover and Moreno (2017)

[16] To calculate this estimate, the CEC excluded the conversion factors from the FAO (2011) edible FLW estimates for NAO.
[17] Study covered rural and urban areas of Oregon in 2017. 182 households completed 7-day kitchen diaries.
[18] Study conducted in Nashville, Denver, and New York City in 2016 and 2017. 613 households completed 7-day kitchen diaries.

When measuring only edible FLW, estimates of total FLW are generally lower, as would be expected. The three studies discussed in Section 3.2 that assessed all U.S. FLW (i.e., edible and inedible) from all stages of the supply chain concluded that between 73 to 152 million metric tons, or 223 to 468 kg per person, of FLW per year (ReFED, 2021a; Guo et al., 2020; CEC, 2017), whereas estimates of edible U.S. FLW from all stages of the supply chain range from 78 to 112 million metric tons, or 240 to 368 kg per person, FLW per year (Pagani et al., 2020; Vittuari et al., 2020; CEC, 2017).

Examining only edible FLW also allows for an estimation of calories lost or wasted. Figure 3-4 presents estimates of U.S. FLW, measured by weight and then by calories. Only one estimate of U.S. FLW from all stages of the food supply chain, by calories, is available. A set of companion studies by Pagani et al. (2020) and Vittuari et al. (2020) estimate U.S. FLW to be 1,110 calories per person per day. Two additional studies provide comparable estimates for the North America and Oceania[19] (NAO) region, ranging from 1,134 (excluding calories from animal products) to 1,520 calories per person per day (Lipinski et al., 2013; Kummu et al., 2012).

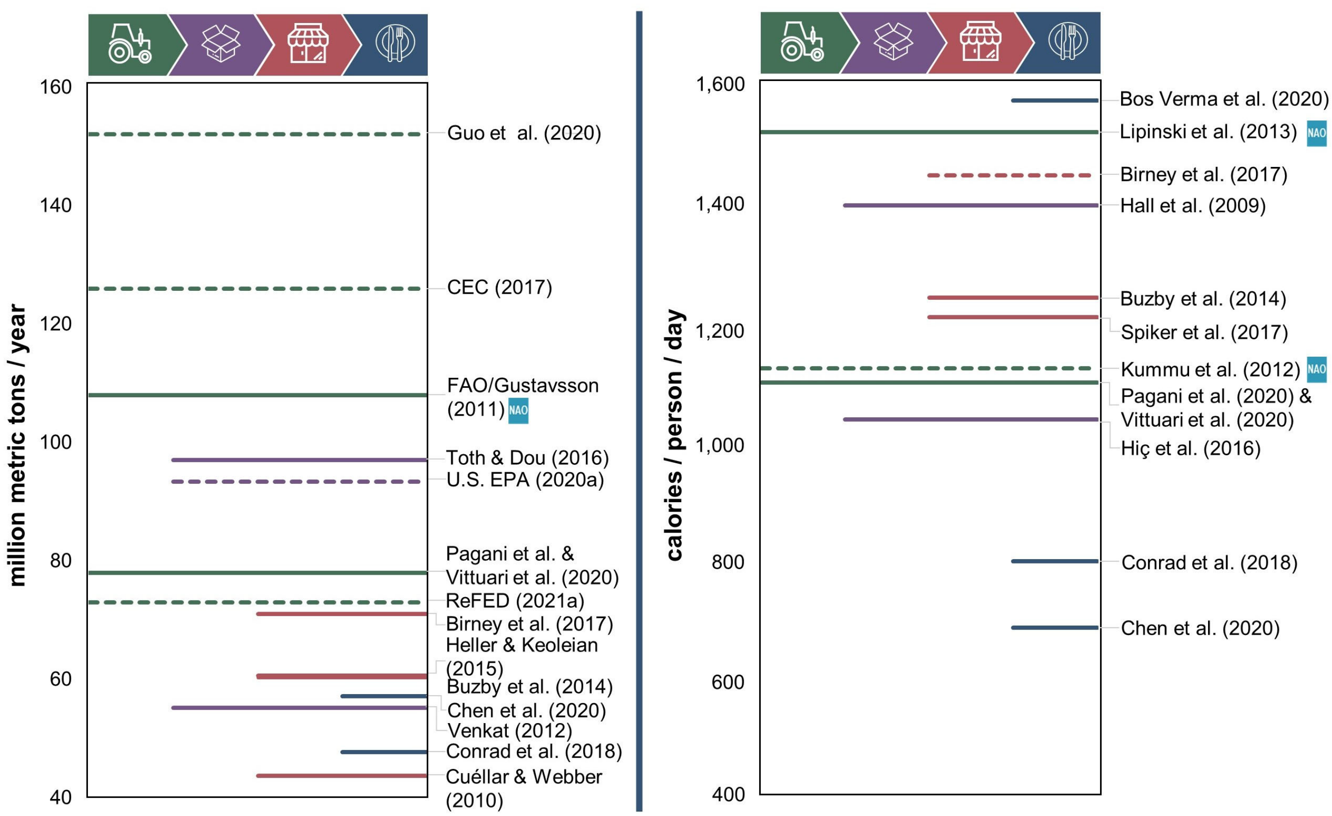

FIGURE 3-4. U.S. FLW BY ANNUAL WEIGHT AND BY DAILY CALORIES PER PERSON

The figure on the left shows annual estimates of total U.S. FLW by weight,
while the figure on the right shows daily estimates of per person U.S. FLW by calories.
Dotted lines indicate edible FLW only; solid lines represent all FLW, including inedible parts.
The length of each line indicates the stages of the food supply chain included in estimate.
Several studies provide estimates both by weight and by calories, allowing for comparison of changes in rank order.

[19] The NAO region, as defined by the FAO, includes the U.S., Canada, Australia, and New Zealand.

3.5 U.S. FLW, by Supply Chain Stage

Understanding when along the supply chain FLW occurs is essential to planning successful food waste reduction interventions. It is also essential for calculating accurate assessments of the environmental footprint of FLW, since as food moves through the supply chain, it uses additional inputs and creates additional environmental impacts. Thus, FLW that occurs further along the supply chain has a larger environmental footprint than similar amounts and categories of FLW that occur at an earlier stage.

Several studies provide estimates of FLW at each stage of the supply chain. Figure 3-5 shows the relative contribution to FLW from each supply chain stage, from each of the studies that examined FLW along the entire food supply chain. As shown in Figure 3-5, studies agree that the greatest share of U.S. FLW occurs during the consumption stage. The consumption stage accounts for roughly one half of total U.S. FLW. Together, the consumption and retail stages represent between half and three quarters of all U.S. FLW (ReFED, 2021a; Pagani et al., 2020; Vittuari et al., 2020; CEC, 2017).

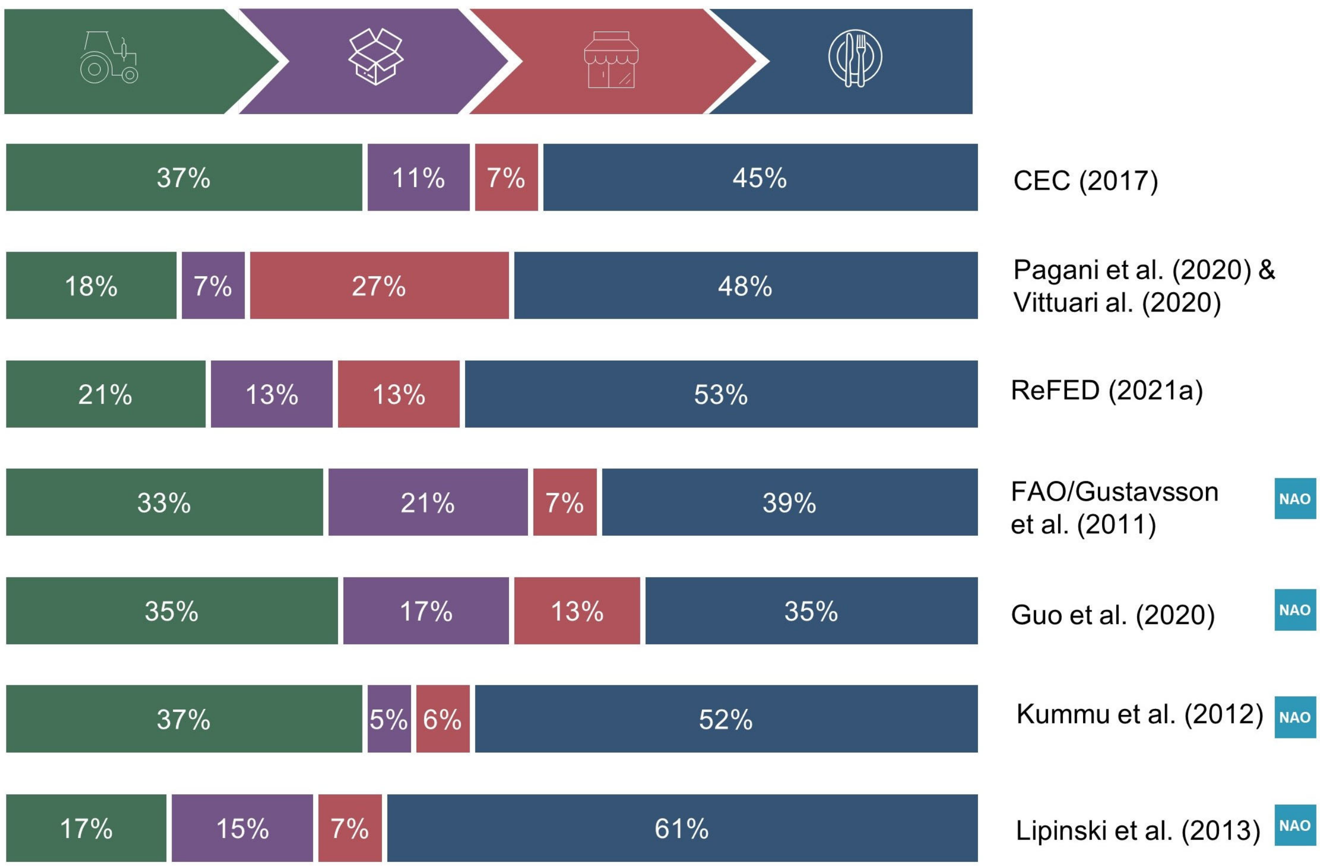

FIGURE 3-5. SHARE OF U.S. FLW, BY FOOD SUPPLY CHAIN STAGE

This figure illustrates the distribution of food loss and waste (FLW) by supply chain stage from reviewed studies that include all four stages of the cradle-to-consumer food supply chain. The distribution is by weight of FLW for all studies except Kummu et al. (2012) and Lipinski et al. (2013) which are by calories. The consumption stage (households and food service) accounts for roughly one half of U.S. FLW.

As shown in Figure 3-6, weight estimates of U.S. consumption stage FLW range from 34 to 57 million metric tons per year, equivalent to 110 to 188 kg per person per year. Estimates of combined U.S. consumption and retail stage waste (i.e., the scope of the U.S. *2030 Food Loss and Waste Reduction Goal*) range from 44 to 71 million metric tons edible FLW annually, or 143 to 229 kg per person per year.

Food loss during primary production is often left out of FLW estimates, and retail FLW estimates may be underestimated due to the FLW being attributed upstream or downstream from the retail sector (Read et al., 2020). Whether and where some FLW is attributed may be inconsistent among data sources, and in many cases the studies did not provide clear guidelines in this area. For example, when a retailer does not accept a shipment of produce, the FLW may be attributed to the distribution stage (since the distributor must manage the FLW), or to the retailer (since the retailer's standards caused the produce to be rejected), or to the consumer (since the retailer's standards may have been set to meet perceived customer requirements).

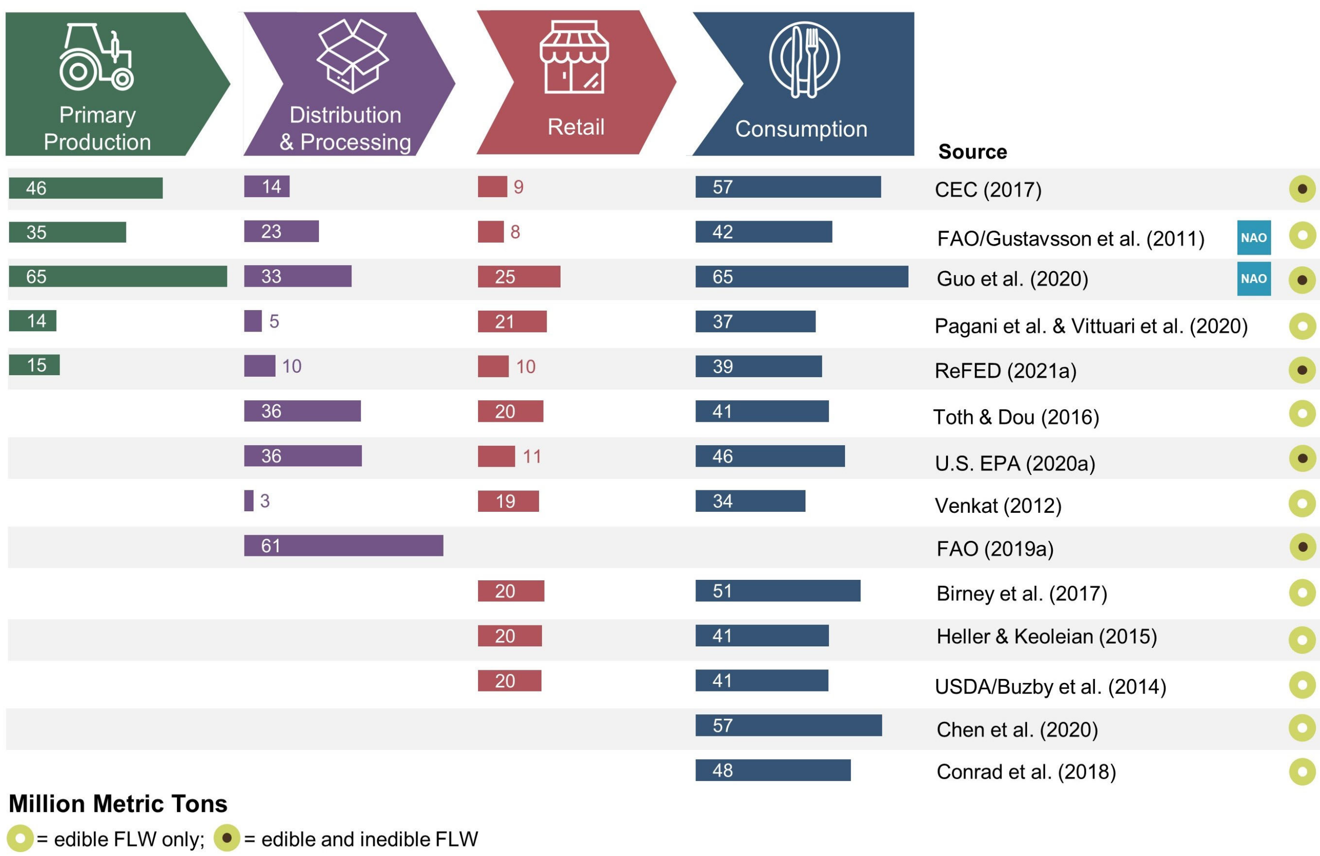

FIGURE 3-6. AMOUNT OF U.S. FLW, BY SUPPLY CHAIN STAGE, BY WEIGHT

The figure above depicts food loss and waste estimates from all reviewed studies.
Generally, estimates are highest for the consumption stage (households and food service).

Quantifying FLW during primary production

Of note, the primary production stage (i.e., farming and harvesting of plants and animals) is often partially or entirely absent from FLW estimates, due to limited data availability. This common exclusion of on-farm FLW, however, misses a potentially large portion of FLW. The major roadblocks to quantifying losses during primary production are the difficulty of measurement and the potential for wide variation among and within food categories, such as fruits and vegetables, seafood, and other animal products.

Studies that include FLW during primary production typically include the loss of fruits and vegetables, but limited data availability leads to very rough estimates. Fruits and vegetables may be lost in the field for a variety of reasons – of greatest interest to FLW stakeholders are the losses that may be preventable, such as those due to produce not meeting grade standards or buying specifications, or due to produce supply exceeding demand. FLW studies typically begin measuring fruit and vegetable losses once produce is ripe in the field (Johnson, 2020). Losses due to weather or pests are not included in the FLW estimates presented in this report.

Data from the Food and Agriculture Organization (FAO) of the United Nations serve as the basis for most estimates of primary production losses. For all fruits and vegetables, FAO applies a 20 percent loss factor, but this estimate is not based upon field measurement studies (Johnson, 2020). The limited data available from U.S. farms shows FAO may underestimate losses of fruits and vegetables, and that wide variation exists among produce types. For example, a recent field study of nine vegetables on a U.S. farm found an average field loss rate of 57 percent, including only the produce suitable for harvest and use—much greater than the 20 percent loss assumed in FAO data (Gustavsson et al., 2013). Another recent field study demonstrates the wide variation in FLW rates among produce in the U.S., ranging from 2 percent of potatoes destined for processing, to 56 percent of romaine lettuce (WWF, 2018).

Seafood losses can be particularly difficult to estimate since more than 80 percent of the seafood available to U.S. consumers is imported (NOAA, 2021). Bycatch (i.e., non-target aquatic species caught by fishing gear and discarded dead or injured into the ocean) is a major source of seafood loss. While some FLW estimates incorporate these losses, the primary method of accounting for these losses is to apply the FAO loss factor—an average bycatch rate of 12 percent (Gustavsson et al., 2013). However, bycatch rates vary widely between specific fisheries and species, making estimation difficult (Love et al., 2015), and the FAO factors is likely an underestimate. Bycatch estimates for the U.S. seafood supply range from 16 to 32 percent in the literature (Love et al., 2015). In addition, none of the FLW estimates presented in this report incorporate losses due to spoilage of seafood before distribution or losses in aquaculture. NOAA (2021) estimates that more than half of seafood imported into the U.S. is from aquaculture, making this a potentially significant source of seafood loss.

Animal products (e.g., meat and poultry) appear to have lower loss rates than produce or seafood (Lipinski, 2020). The FAO (Gustavsson et al., 2013)) estimates only losses for meat, based upon animal deaths prior to slaughter (less than 5 percent). In summary, only very limited and variable data on primary production losses is available, leading to exclusion of this potentially important area from FLW estimates.

3.6 U.S. FLW, by Food Category

As described in Chapter 2, the environmental footprint of food (and thus FLW) varies greatly by food category. An understanding of the categories of food that comprise U.S. FLW is essential to reducing FLW and to estimating its environmental footprint. When looking at FLW, by food category, across the entire food supply chain, the primary data source available is FAO (Gustavsson et al., 2011); however, these estimates are for the NAO region, rather than the U.S. specifically.

When examining FLW from all along the supply chain, the FAO reports that fruits and vegetables are the food category wasted in the greatest quantity (40 percent of FLW) in the NAO region, as shown in Figure 3-7. Data from ReFED (2021a) confirms that produce represents the greatest share (34 percent) of U.S. FLW. Both FAO and ReFED also note the significance of milk and dairy, and eggs as categories of FLW (20 percent and 16 percent of FLW, respectively).

For many other food categories, the data from ReFED is not directly comparable to that of FAO due to differences in the way food is categorized. The FAO data (and the USDA data, which is discussed subsequently) categorize wasted food by commodity ingredients (e.g., fish sticks are classified as fish), whereas ReFED categorizes foods as grocers do, in their retail form (e.g., fish sticks are classified as frozen foods).

The USDA also provides U.S.-specific data on FLW by food category; however, it is limited to FLW during the retail and consumption supply chain stages. As shown in Figure 3-7, USDA data (Buzby et al., 2014) demonstrates that fruits and vegetables (33 percent of FLW) and milk and eggs (15 percent) are the categories wasted in largest quantities in the retail and consumer stages, consistent with FAO results for all stages in the data presented above.

North America and Oceania

In some cases, FLW data are not available for the U.S. specifically, but are available for the broader North America and Oceania (NAO) region. For example, many studies presented in this report rely on FLW data developed by Gustavsson et al. (2011) for the Food and Agriculture Organization (FAO) of the UN, and this data is broken down by global regions rather than individual countries. The NAO region, as defined by the FAO, includes the U.S., Canada, Australia, and New Zealand.

While total FLW estimates for NAO are naturally larger than estimates for the U.S. alone, per person NAO estimates are slightly lower than those for the United States. Compared to the other NAO countries, the U.S. has a higher total and daily per person supply of calories, and a higher supply of meat per person, which has an outsized impact on many of the resource inputs and impacts discussed in Chapter 4 (FAO, 2017; Roser and Ritchie, 2013). Since the loss rates developed by Gustavsson et al. (2011) apply to all countries in NAO (assuming an equal rate of FLW across countries), the food availability or supply drives FLW estimates (i.e., supply is the only variable differs among the countries). In terms of FLW, the per person values of FLW for the U.S. are nearly the same as those of the NAO region (Chen et al., 2020; Guo et al., 2020).

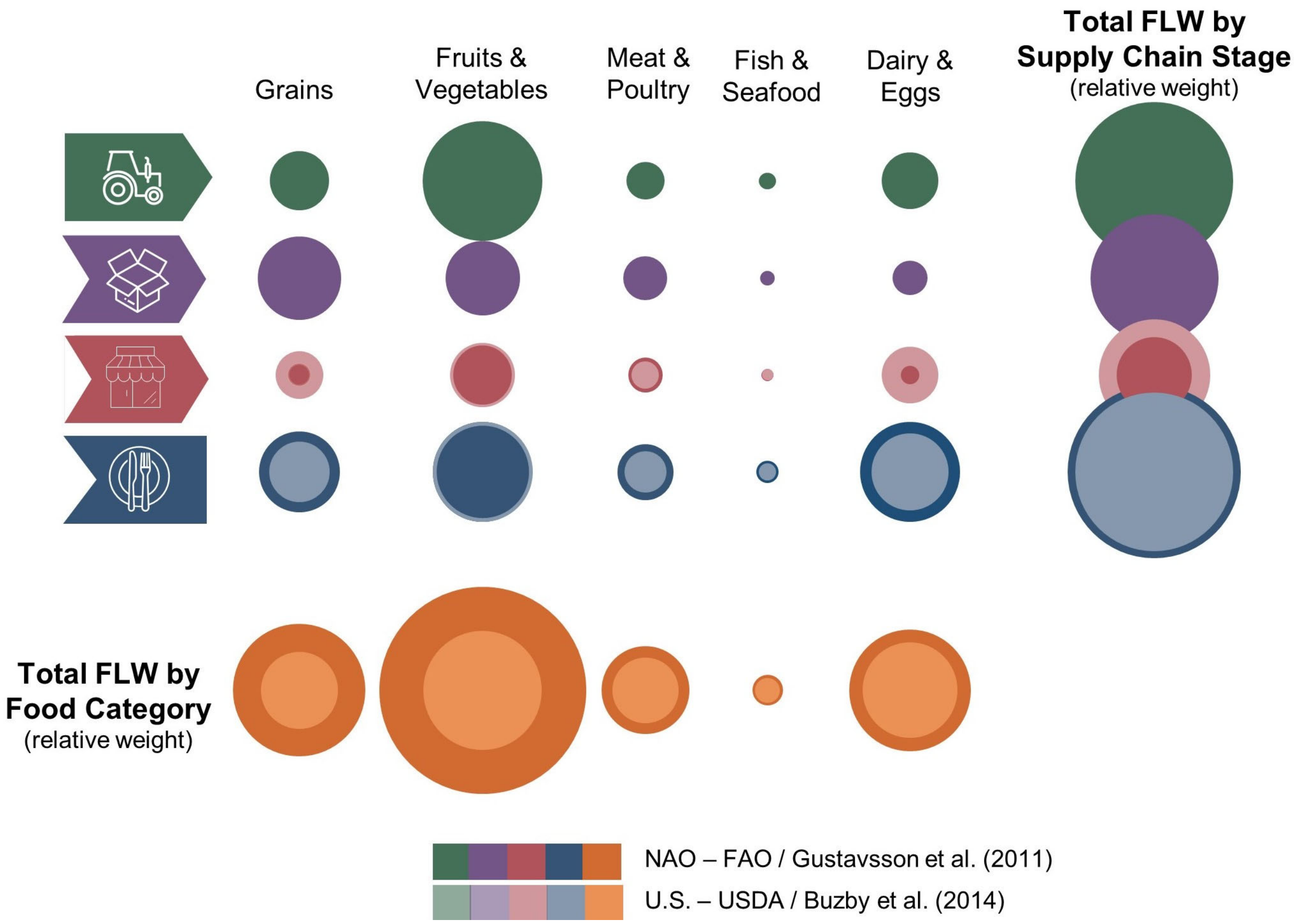

FIGURE 3-7. U.S. EDIBLE FLW BY RELATIVE WEIGHT, BY FOOD CATEGORY AND SUPPLY CHAIN STAGE

This figure compares food loss and waste (FLW) estimates, by food category and supply chain stage, from the Food and Agriculture Organization (FAO) of the United Nations for the North America and Oceania (NAO) region to those from the United States Department of Agriculture (USDA) for the United States only. The rows show FLW by supply chain stage, and the columns show FLW by food category. FLW at the consumer stage is the greatest, followed closely by FLW at the primary production stage. By weight, fruits and vegetables are the most lost and wasted food category.

Several additional studies dive deeper and provide additional detail on the consumption stage. A study by Conrad et al. (2018) built upon the USDA data by incorporating data on foods consumed (usually mixed dishes) from the USDA What We Eat in America survey (a component of the National Health and Nutrition Survey). This study examined the consumption supply chain stage (i.e., both at home and away from home) exclusively. The study found fruits and vegetables (39 percent) and dairy products (17 percent), followed by meat (14 percent) and grains (12 percent),[20] to be the predominant components of food waste during the consumption stage, akin to the findings of Buzby et al. (2014) shown above.

Two studies that directly measured household food waste – the OR DEQ's Oregon Wasted Food Study[21] (McDermott et al., 2019) and the NRDC's assessment of three cites[22] (Hoover and Moreno, 2017) – also support the finding that fruits and vegetables (40 percent) are the largest components of consumption stage food waste, followed by prepared foods and leftovers (23 to 28 percent). Dairy and egg, and meat and fish, however, were found to be smaller contributors than in above studies (dairy and egg at 3 to 7 percent, and meat and fish at 6 percent), possibly due to some being counted in the prepared foods category. Results from the two studies are presented in Figure 3-8. These data are from kitchen diaries kept by participating households. Trash sorts were conducted by the researchers in the second study, and the sorts confirmed the findings from the kitchen diaries (Hoover and Moreno, 2017).

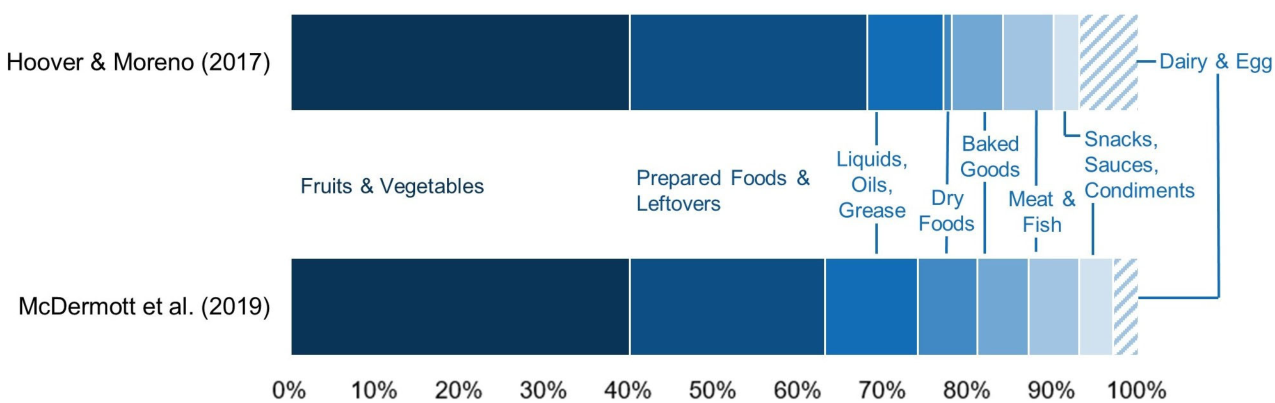

FIGURE 3-8. SHARE OF EDIBLE HOUSEHOLD FOOD WASTE, BY FOOD CATEGORY

This figure displays household food waste, by food category, recorded in kitchen diaries by participants in two U.S. studies.

In summary, across all stages of the food supply chain and during the retail and consumption stages, studies agree that fruits and vegetables are wasted in the greatest amounts, typically followed by dairy and eggs. Other animal products (i.e., meat and poultry) are wasted in smaller quantities than dairy and egg, according to most studies. Seafood is the least wasted food category according to the data; however, this may be due to the exclusion of many types of seafood losses during primary production (Love et al., 2015) and the relatively small amount of seafood available at the retail level (Buzby et al., 2014).

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[20] The categories in Conrad et al. (2018) all consider the main ingredient in a prepared dish and thus include "mixed dishes." For example, the fruits and vegetables category is defined as "fruits and vegetables, and mixed fruit and vegetable dishes".
[21] Study covered of rural and urban areas of Oregon in 2017. 182 households completed 7-day kitchen diaries.
[22] Study was conducted in Nashville, Denver, and New York City in 2016 and 2017. 613 households completed 7-day kitchen diaries.

3.7 Measurement Methodologies

The estimates of the environmental footprint of FLW presented in the subsequent chapters of this report rely upon the data sets presented in this chapter to estimate FLW, including the amount and categories of food lost and wasted and the supply chain stages at which the food was lost or wasted. Therefore, a general sense of the methodological approaches used to create these data sets can assist in understanding the results of these studies and in comparing results of multiple studies. FLW is typically estimated by comparing food availability to either food utilization or energy requirements, though other methodologies are also available. This section provides a brief overview of FLW measurement methodologies—those using a food balance approach (comparing food availability and utilization), those using an energy balance approach (comparing food availability and population's energy requirements), and those using mixed or other methods.

Food Availability & Utilization

Many FLW estimates rely upon a food balance approach, applying food loss and waste rates to estimates of food availability. Food availability is the difference between the amount available in the commodity supply (i.e., the sum of beginning stocks, production, and imports) and measured non-food uses (i.e., exports, farm and industrial uses including seed and animal feed, and ending stocks) (IOM and NRC, 2015). Food loss and waste rates (often called "loss rates" or "loss factors" regardless of supply chain stages covered) estimate the percent of available food that is ultimately lost or wasted, by food category. The two primary sources of food availability data and food loss and waste rates are:

1. U.S. Department of Agriculture (USDA) Economic Research Service (ERS)'s Loss-Adjusted Food Availability (LAFA) data series (Buzby et al., 2014), and

2. Food and Agriculture Organization of the United Nations (FAO) Food Balance Sheets (Gustavsson et al., 2011).

Many of the FLW estimates presented in this report rely on one of these data sources for food availability data or food loss and waste rates, or both. For example, many of the studies focused exclusively on the United States utilize USDA data, while studies seeking to compare regions or countries most often rely upon the FAO data. More details on studies' reliance on USDA or FAO data can be found in Appendix B.

Both the USDA and FDA data sources provide annual total and per person food availability data for a wide variety of food categories (USDA data breaks food into 200 categories, while FAO uses 100 categories). The FAO estimates cover a larger geographic area (the NAO region) and scope (FLW during all four stages of cradle-to-consumer supply chain), than the USDA estimates (U.S. FLW at retail and consumption stages only) (Buzby et al., 2014; Gustavsson et al., 2011). Both sources also provide loss rates – the FAO loss estimates developed by Gustavsson et al. (2011), or the USDA's Loss Adjusted Food Availability (LAFA) data series (Buzby et al., 2014) – which can be applied to food availability data to calculate FLW. The loss rates from the two sources differ, and this (along with differences in availability estimates) impacts their estimates of FLW.

As shown in Figure 3-9, FAO (Gustavsson et al., 2011) and USDA (Buzby et al., 2014) loss rates differ substantially for some food categories. For example, while FAO assumes 42 percent of fruits and vegetables and 11 percent of meat and poultry are wasted during the consumption stage, USDA estimates 21 percent of each category are wasted.

After applying loss rates, the USDA per person estimates of FLW from the retail and consumption stages, and for consumption stage alone (229 kg and 132 kg, respectively) are higher than those of FAO (140 kg and 118 kg, respectively), which can impact the estimates of inputs and environmental impacts presented in Chapter 4 (Buzby et al., 2014; Gustavsson et al., 2011). This can be viewed in the rightmost column of Figure 3-7 in the previous section (Section 3.6).

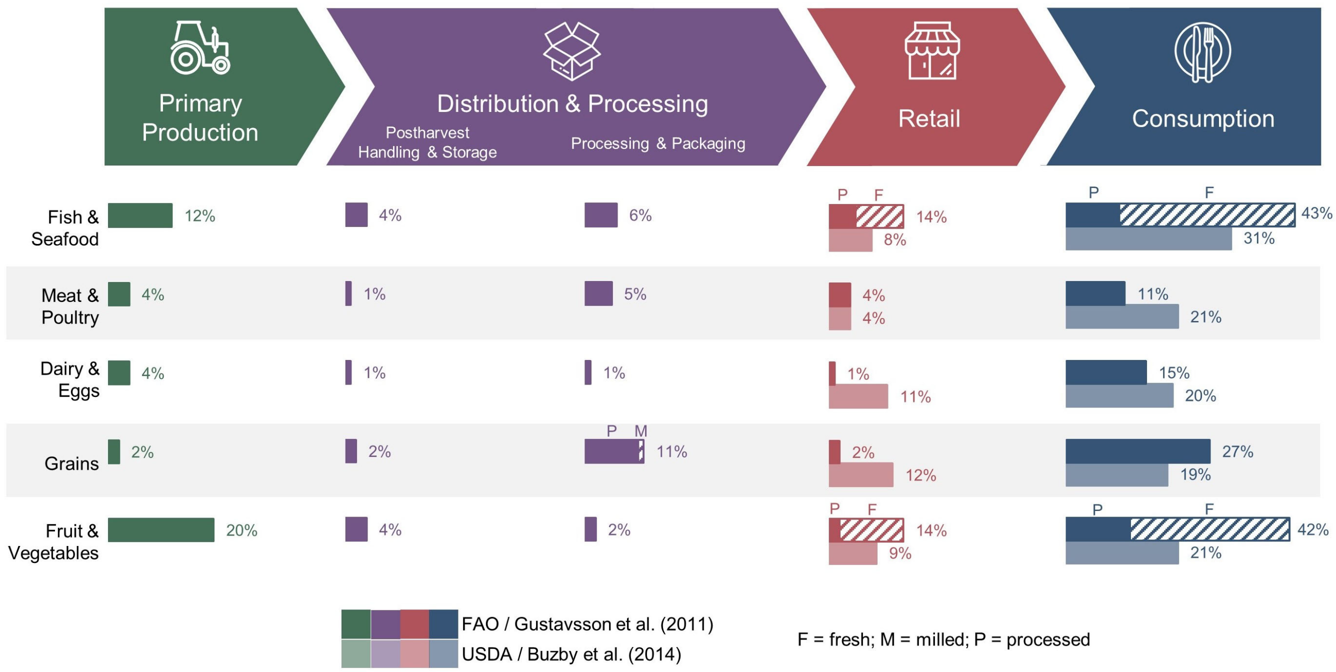

FIGURE 3-9. COMPARING FAO AND USDA LOSS RATES

This figure compares the loss rates (i.e., the percent of available food estimated to be lost or wasted) by food category and food supply chain stage from the Food and Agriculture Organization (FAO) of the United Nations and the United States Department of Agriculture (USDA). The USDA only estimates retail and consumption stage losses. Loss rates at the consumption stage, from both sources, include cooking losses.

Researchers must decide which food parts are edible, how they will quantify inedible parts, and to which supply chain stage they will attribute the waste (i.e., removal) of inedible parts when developing FLW estimates. In both the FAO and USDA data sets, researchers estimated how much of a given food group is typically edible and applied this conversion factor to the amount of food available to consumers from that food group. For example, to create the FAO estimates of edible FLW, Gustavsson et al. (2011) applied a conversion factor of 0.77 to all fruit and vegetable FLW to calculate and remove the portion that was inedible from the loss estimate. This results in 23 percent of the weight of fruits and vegetables being considered inedible (Gustavsson et al., 2013). Gustavsson et al. (2011) did not have conversion factors for meat and dairy, so the weight of bones is included in the edible values. By comparison, USDA uses data from the National Nutrient Database for Standard Reference that details the inedible portion of thousands of foods (USDA, 2018). For example, apples, broiler chickens, and broccoli are considered to be 10, 20, and 39 percent inedible by weight, respectively. Within the USDA data, inedible shares are removed at different stages within the food supply chain. For example, for meat and poultry the retail weights reflect the edible weight, but for fresh fruits and vegetables the retail weight includes the inedible portions and those are removed prior to the consumer weight (Buzby et al., 2014).

Food Availability & Energy Requirements

An alternative approach to estimating FLW is to subtract a populations' energy requirements (i.e., a surrogate for food consumption) from an estimate of food availability. Based on human metabolism models, researchers quantify the amount of energy, in the form of calories, that is needed to maintain a population's current physical activity levels and body weights.[23] Thus, the estimates must include assumptions on activity levels and metabolism and convert food tonnages to calories and nutrients. This approach, used by four studies presented in this chapter (Lopez Barrera and Hertel, 2020; van den Bos Verma et al., 2020; Hiç et al., 2016; Hall et al., 2009) can be a more dynamic way of quantifying food waste than applying static waste rates. It can capture recent changes in food waste and be used to evaluate impacts of interventions, unlike the food availability and utilization approach described above. Food availability data from USDA ERS Food Availability data series and FAO Food Balance Sheets (described above) are updated annually, and population demographics are readily available and frequently updated, whereas the loss factors such as those provided by USDA LAFA haven't been meaningfully updated since 2010.

Other Approaches

Rather than beginning with food availability data from USDA or FAO, like the two approaches described above, some studies (ReFED, 2021a; Pagani et al., 2020; Read et al., 2020; U.S. EPA, 2020a; Vittuari et al., 2020) used entirely different approaches to assess FLW. This group of studies includes two that are cited often in the next chapter – Read et al. (2020) and companion studies by Pagani et al. (2020) and Vittuari et al. (2020) – which both used models to estimate FLW.

Pagani et al. (2020) and Vittuari et al. (2020) created their own food balance model and FLW rates to quantify the amounts and types of fresh, processed, refrigerated, and non-refrigerated foods by supply chain stage. The authors quantified the energy consumption, food mass flow, and FLW along the U.S. food supply chain for 15 years to assess the average embodied energy losses and nutritional energy losses in FLW. Notably, this study excluded imports, thus knowingly underestimating food availability by roughly one-fifth.[24] Read et al. (2020) instead relied on monetary transactions as a surrogate for food availability, using environmentally extended input-output models (EEIO) to map the network of relationships between industry sectors at an economy-wide scale.[25] The authors identified the industries associated entirely or partially to the food supply chain and then calculated the percentage of each industry's output that is part of the food supply chain and its associated food category. Read et al. then applied the food loss and waste rates by food category from FAO (Gustavsson et al., 2011), supplemented with loss rates for sweeteners and beverages.

Two additional sources (ReFED, 2021a; U.S. EPA, 2020f) cited in this chapter also developed novel approaches to estimating FLW, using mixed methods and data sources. EPA quantified the FLW managed via each food waste management pathway (e.g., landfills, incinerators, compost facilities, and anaerobic digesters) by building and applying FLW generation factors for 17 sectors within the food processing, retail, and consumption supply chain stages of the food system. The FLW generation factors and basis for extrapolation for each sector were developed through a literature review of studies and waste sorts. EPA calculates annual FLW generation for each sector, then sums them to produce an estimate of total FLW generation annually. ReFED (2021a) modeled FLW from each of five stages (farm, manufacturing, retail, food service and residential) of the food supply chain independently, using a variety of data sources and methods. For example, farm surplus was calculated as the sum of unharvested fruits and vegetables, packhouse losses, and buyer rejections, while unsold product from food manufacturing was calculated as the amount of unutilized ingredients, finished product not shipped, and buyer rejections. ReFED utilized USDA data for some downstream sectors but integrated that data with data from other sources.

[23] Estimates include maintaining obesity (i.e., estimating actual consumption not consumption of a specifc recommended diet).
[24] Roughly one-fifth of U.S. food supply is imported (CRS, 2020).
[25] Read et al. (2020) did not publish an estimate of the quantity of FLW.

CHAPTER 4.

Environmental Footprint of U.S. Food Loss and Waste

Over the past decade, more than a dozen studies have assessed the environmental footprint of producing, storing, processing, packaging, distributing, and marketing food that is ultimately lost or wasted. Studies typically examine the use of resources (land, water, and energy) and other inputs (pesticides and fertilizers) as a proxy for the environmental impacts their use may cause (e.g., deforestation, water scarcity, or decreased water quality). Typically, GHG emissions are the only output of FLW directly estimated in the literature. Many of the other farm to kitchen environmental impacts of FLW discussed in Chapter 2, such as biodiversity loss, soil degradation, and GHG air emissions, are not quantified in the literature. While the environmental impacts may be considered a trade-off to an abundant supply of food, the impacts associated with food loss and waste are in many cases completely unnecessary and could be avoided.

Throughout the chapter, summary tables are provided for each input and environmental impact, with an analysis of all available estimates and a recommended value for policymakers to use in communicating the environmental footprint of FLW and decision-making among competing priorities (including FLW). Details about supply chain stages and food categories that contribute the most to each input or impact are also provided to assist policymakers in designing targeted FLW reduction strategies.

KEY FINDINGS

- *Each year, U.S. FLW embodies:*
    - ***Agricultural land:*** *560,000 km^2 (140 million acres)*
    - ***Blue water:*** *22 trillion L (5.9 trillion gallons)*
    - ***Fertilizer:*** *6,350 million kg (14 billion pounds)*
    - ***Energy:*** *2,400 million GJ (664 billion kWh)*
    - ***GHG emissions:*** *170 million $MTCO_2e$ GHG (excluding landfills)*
- *Inputs (e.g., land, water, fertilizer, or energy) are typically examined as a proxy for the environmental impacts their use may cause (e.g., deforestation, water scarcity, decreased water quality, or climate change)*
- *Animal products have an outsized contribution to the environmental footprint of U.S. FLW, representing the greatest use of resources (land, water, fertilizer, energy) and GHG emissions among categories of FLW, but a relatively small share of FLW. Fruits and vegetables are also leading contributors.*

4.1 Methodologies

Quantifying the farm to kitchen environmental footprint of FLW requires data on the amount and categories of food that are lost or wasted at each stage of the food supply chain (see Chapter 3) plus the environmental footprint of FLW at that stage and all previous stages (see Chapter 2). The impacts are cumulative; for example, food lost during primary production embodies the resources used to grow the food, whereas food wasted during the consumption stage embodies the resources used from the primary production stage to the point the food reached the consumer. A simplified depiction is presented in Figure 4-1.

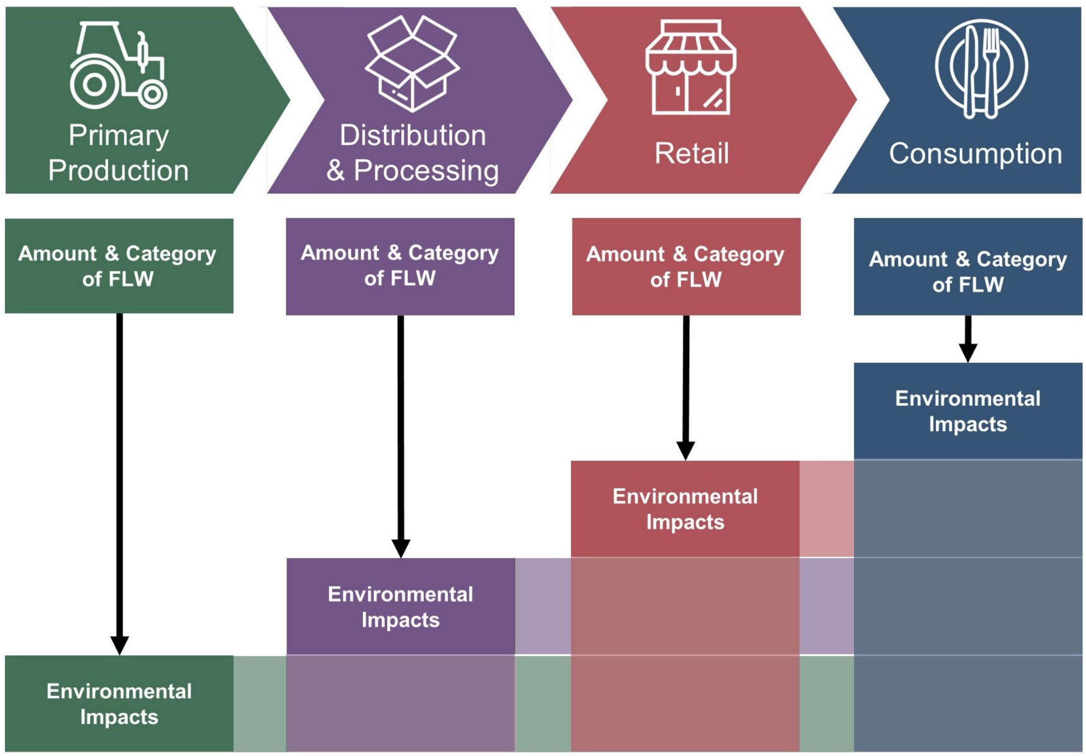

FIGURE 4-1. ESTIMATING THE CRADLE-TO-CONSUMER ENVIRONMENTAL FOOTPRINT OF U.S. FLW

Scope

The studies presented in this chapter rely on estimates and characterizations of FLW presented in Chapter 3. Key variables among the FLW estimates underlying the studies include:

- Edibility (i.e., whether the estimates include inedible food parts, such as bones and shells)
- Categories of food included (i.e., whether the estimate includes animal products and the feed needed to produce them)
- Supply chain stages (i.e., whether FLW from each supply chain stage was included)
- Geographic area (i.e., whether the estimate is U.S.-specific or for a broader region)

These factors can dramatically influence the magnitude of environmental estimates. For more detailed discussion of these variables, see Sections 3.4 to 3.6 including the text box about the NAO region.

Approaches

Two key methods are used to estimate the inputs and environmental impacts associated with FLW – life cycle assessment (LCA) and environmentally extended economic input-output models (EEIO). Life cycle assessment (LCA) takes a detailed look at the inputs and environmental impacts attributable to a product within the defined scope of the analysis (e.g., cradle-to-consumer). Within an LCA, life cycle inventory data are used to quantify the resource inputs (such as energy, water, and land use) and resulting outputs (such as emissions and wastes) for each stage of the product's life (Muth et al., 2019). Depending on the purpose of the study, LCAs can use national average data, data from multiple primary sources, or from a single source. When using LCA for estimating the environmental impacts of diets and food systems researchers might use an average across multiple LCAs to represent a single product or results from a single LCA. When LCAs of single products or commodities are compiled to represent activity at a broader level (e.g., nationally), some resolution may be lost (e.g., assuming that the LCA of one vegetable grown in Idaho represents all vegetables in that category grown in the U.S.).

In contrast, EEIO models map a network of relationships based on monetary transactions between industry sectors and their resulting products at an economy-wide scale. EEIO models incorporate life cycle inventory data into the input-output framework and enable the calculation of embedded direct and indirect inputs and environmental impacts of products (e.g., food). For example, assume that Industry A creates 100 widgets and, in the course of doing so, generates 100 kg of a concerning pollutant. If Industry B purchases 25 percent of the widgets, then 25 kg of the pollutant is associated with the demand created by Industry B. These 25 kg are "embedded" in the output produced by Industry B. When Industry C uses the product produced by Industry B, the 25 kg are "passed on" to the products of Industry C. In this way, impacts that occur throughout the U.S. are allocated to products (U.S. EPA, 2020e).

EPA's U.S. Environmentally-Extended Input-Output (USEEIO) Model (Yang et al., 2017), used in the study by Read et al. (2020). EPA's U.S. Environmentally-Extended Input-Output (USEEIO) Model (Yang et al., 2017), used in the study by Read et al. (2020) presented in this chapter, calculates environmental impacts and resource use at a national scale using publicly-available data. This capability comes with limitations. The most important is that the data are somewhat aggregated and coarse. Thus, the level of resolution is currently limited to national averages for a sector or product classification. However, the 26 aggregated agriculture and food manufacturing industries in the USEEIO provide a mechanism for examining the U.S. food system and the inputs and environmental impacts associated with FLW. EEIO models offer the advantage of capturing indirect impacts, such as those from producing equipment (which are often not included in process-level LCAs), as food moves along the supply chain. Thus, they may be expected to generate higher estimates than LCA studies (Heller and Keoleian, 2015). However, when one supply chain stage (e.g., primary production) is responsible for the majority of an impact (e.g., use of land, fertilizers, or pesticides), process-level models may be more useful and representative than sector-based models.

Other Considerations

A key limitation of all the studies presented in this chapter is the lack of accounting for differences in inputs and environmental impacts of imported foods (see Section 2.4). Most studies discussed in this chapter assume the U.S. food supply was produced entirely domestically and that U.S. average environmental factors apply. A couple – Chen et al. (2020) and Skaf et al. (2021) applied the same international lifecycle assessment and production factors for all the countries in the study, including the U.S. This may over- or underestimate the environmental inputs and impacts of the foods, depending upon where they originate. There are two excepted estimates, one is ReFED's (2021a) greenhouse gas impacts value and the other is the energy value associated with FLW from companion studies by Pagani et al. (2020), and Vittuari et al. (2020). ReFED's (2021a) analysis, conducted by Quantis and utilizing their internal life cycle inventory database, accounted for imports by matching the top producing countries for each food item with the available country-specific production data. Pagani et al. (2020) and Vittuari et al. (2020) excludes imports from the analysis due to the lack of reliable data on the energy embodied in foreign production and international transport, thus underestimating inputs and environmental impacts, since imports account for up to one-fifth of the U.S. food supply (USDA, 2019f).

The use of national average environmental factors may also over- or underestimate the environmental inputs and impacts of specific domestically produced foods, in cases where inputs and impacts vary widely within food groups or based upon production method, geographic location, seasonality, type and amount of processing conducted or packaging used, whether cold storage is required, or type and distance of transportation (see Section 2.5). When targeting FLW initiatives to maximize environmental benefits, it may be useful to consider these factors.

4.2 Agricultural Land Use

Land is a limited resource with many competing uses. While the U.S. has more suitable land for growing crops than most other countries, the amount of land used for growing food and animal feed in the U.S. has slightly declined since 1982, while developed land has increased and timberland has remained constant (U.S. EPA, 2020c). However, land use changes may occur in countries producing food for import into the U.S. and can significantly impact water quality, release GHG emissions (as carbon is held in healthy soils and trees), and result in deforestation and the loss of biodiversity and ecosystem services. In addition, as the global population rises and diets shift due to rising incomes, more land will be needed to produce food. Land "wasted" by producing food that is ultimately lost or wasted could instead reduce the conversion of more land to cropland.

Seven studies estimated the amount of land required to produce food that was ultimately lost or wasted in the U.S. Table 4-1 shows the values from these recent studies. Six of the studies (Chen et al., 2020; Conrad et al., 2018; Birney et al., 2017; Toth and Dou, 2016; Kummu et al., 2012) used a similar approach to calculate agricultural land use associated with FLW. These studies evaluated current diets and amounts of calories consumed or lost in the food system and multiplied the food categories by land use characterization factors to calculate the amount of land used in production of those foods. Read et al. (2020) instead used EEIO models, as described in Section 4.1 to quantify the inputs and environmental impacts of FLW using consumer expenditures. The authors first modified the EEIO model by Miller and Blair (2009) to represent the U.S. food supply chain and then used EPA's USEEIO model to estimate the embodied environmental inputs in FLW.

The estimate from Read et al. (2020) addressed the broadest scope of any study, including FLW from all stages of the food supply chain and including land used for animal feed and livestock grazing. As such, it is not surprising that the authors' estimate (561,000 km^2 per year) is larger than those from studies that only included FLW from part of the food system (Conrad et al., 2018; Birney et al., 2017; Toth and Dou, 2016) or did not include all land use related to livestock production (Chen et al., 2020; Kummu et al., 2012). Kummu et al. (2012), for example, included only crop products intended for direct human consumption, meaning animal products and the feed crops needed to produce them were both excluded throughout the study. Chen et al. (2020) excluded only pasture land. While pasture lands typically have no potential to become cropland, some studies include them due to potential negative effects on carbon storage and biodiversity (Bajželj et al., 2014). Studies also differed in the scope of FLW included, and studies that estimated larger scopes of FLW generally estimate greater inputs and environmental impacts. Despite differences in modeling approaches and methods for estimating food waste, estimates from all the reviewed studies are in relative agreement once these differences in scope are considered. While all agricultural land use occurs during primary production.

Note that a key limitation of all the estimates is the lack of accounting for differences in the environmental impact of imported foods (see Section ome of the land use quantified here may relate to deforestation or loss of biodiversity in the producing country. Also, assuming food that was ultimately lost or wasted was produced on the amount of land that would be used in the U.S. to produce it likely underestimates agricultural land use, as the U.S. has some of the world's most productive agricultural lands in the world (Conrad et al., 2018).

In summary, the agricultural land use estimate from Read et al. (2020) is the most comprehensive available, and thus may be the most useful to policymakers. Read estimates that 560,000 km^2 (140 million acres), or 1,800 m^2 (19,000 sq ft) per person, are used annually to produce food that is ultimately lost or wasted. This is equivalent to approximately 16 percent of agricultural land in the U.S. (including harvested and unharvested cropland, rangeland, and pastureland).

TABLE 4-1. ANNUAL AGRICULTURAL LAND USE ASSOCIATED WITH U.S. FLW

Source Scope of FLW	Land Use Total (km^2)	Per Person (m^2/person)	Scope of Land Use	Land Use Factors
Read et al. (2020)	560,000•	1,800		U.S.
		Used EPA's USEEIO model used to estimate land use associated with FLW.		
Kummu et al. (2012) NAO	178,000•	498		Intl
		Excludes loss and waste of animal products. Calculated the national cropland yield by commodity.		
Toth and Dou (2016)	260,000	830•		U.S.
		Excludes land for orchard fruit and nuts and perennial forage crops. Based on USDA National Census Data.		
Birney et al. (2017)	325,500•	1,051		U.S.
		Excludes land use to produce dairy. Includes only harvested cropland. Used FAOSTAT 2010 yield data. Supplemented with land requirements for poultry, eggs, pork, beef, and lamb from studies of New York State and North Carolina.		
Chen et al. (2020)	118,000•	378		Intl
		Matched recently available global average characterization factors per food group (i.e., cropland use [m^2/g]) to product resolution.		
Conrad et al. (2018)	120,000	390•		U.S.
		Used the U.S. Foodprint Model which models the U.S. as a closed food system.		
Skaf et al. (2021)	198,000	606.6		Intl
		Used LCA data from EcoInvent and applied the ReCiPe midpoint method for agricultural land occupation.		

In addition to cropland for direct human consumption, indicates inclusion of cropland for animal feed and indicates inclusion of pasture and rangeland.

NAO = Indicates estimate for the NAO Region rather than for the U.S. specifically.

• = Calculated values for total and per person used the same population factor as the study's data year.

= personal communication with the author.

Agricultural Land Use, By Food Category

While Read et al. (2020) provided the most comprehensive estimate of land use associated with FLW, other studies with smaller scopes provide greater insights into the food categories most responsible for the agricultural land use associated with FLW. As shown in Chapter 3, many studies rely on the detailed data on U.S. FLW by food category from USDA, which is available for the retail and consumer stages only.

Toth and Dou (2016), Birney et al. (2017), and Conrad et al. (2018) all provide estimates of agricultural land use, by category of FLW. This information may be useful for policymakers desiring to curb agricultural land use and its potential environmental impacts through FLW initiatives. For estimates of land use from producing animal products, each of the studies included land required to produce enough animal feed to support production of the animal-based foods.

As shown in Figure 4-2, the three studies found the vast majority of land use associated with FLW was attributable to animal products (including the land used to grow hay, feed grains, and oilseeds). This demonstrates that the loss and waste of animal products has an outsized effect on land use. While they represent only 30 percent of FLW along the supply chain (FAO, 2011), they account for roughly two-thirds of agricultural land use associated with FLW (Conrad et al., 2018; Birney et al., 2017; Toth and Dou, 2016). This also explains the large difference between agricultural land use estimates of Read et al. (2020) and Kummu et al. (2012) in the previous section, as Kummu et al.'s study excludes land used to produce animal products (including animal feed) and is roughly one-third of Read et al.'s estimate, which includes animal products and animal feed.

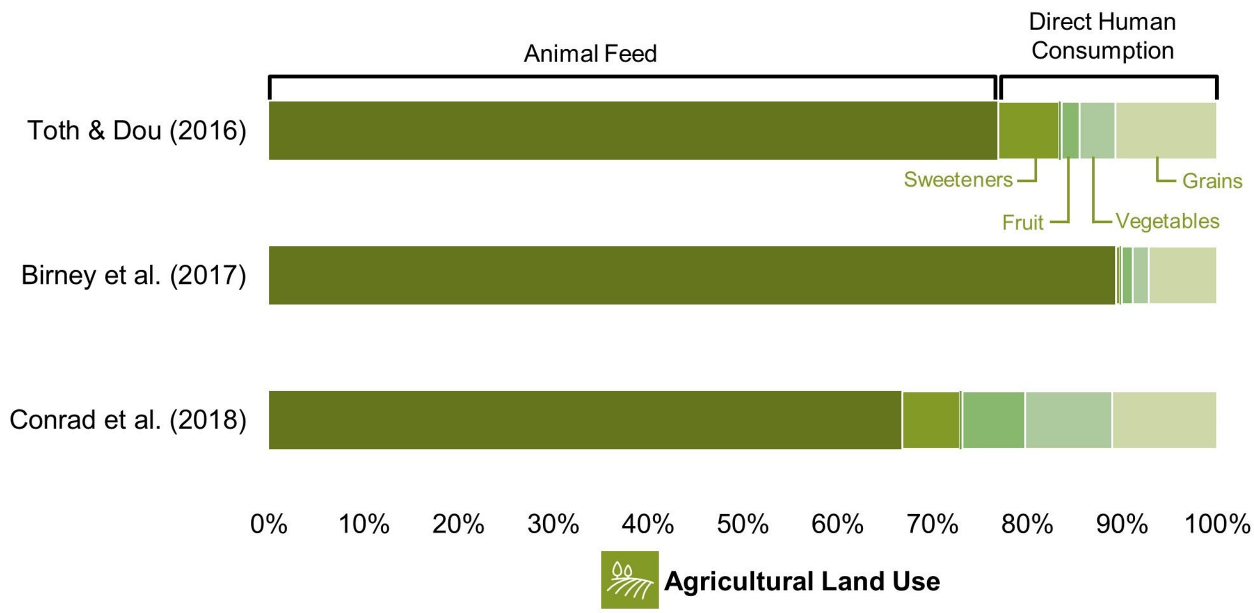

FIGURE 4-2. AGRICULTURAL LAND USE ASSOCIATED WITH U.S. FLW, BY FOOD CATEGORY

4.3 Water Use

Freshwater is a vital, natural resource used every day by plants, animals, people, and industries. The extent of water resources (their amount and distribution) and their condition (physical, chemical, and biological attributes) are critical to ecosystems, human uses, and the overall function and sustainability of the hydrologic cycle. When food is lost or wasted, so too is the water used to grow and produce it. Nine studies estimated the amount of water wasted from producing uneaten food in the U.S. Most studies utilize a bottom-up approach, where researchers assess how much of each food category was wasted and then apply factors approximating how much water is used to produce each unit of food in that category. Table 4-2 and Table 4-3 summarize the results.

All the studies presented in this chapter measure blue water use during primary production (e.g., for irrigation and livestock watering). Some measure only irrigation (Conrad et al., 2018; Toth and Dou, 2016; Kummu et al., 2012),[26] while others include livestock watering (Chen et al., 2020; Birney et al., 2017). Only Read et al. (2020) also accounts for uses of blue water during other supply chain stages, such as during food processing and food preparation;[27] thus, the other studies underestimate the cradle-to-consumer blue water footprint of FLW. As context, Canning et al. (2020) estimates that the primary production stage represents 65 percent of the water use of the cradle-to-consumer food system, with food distribution and processing an additional 3 percent and consumption accounting for another 20 percent.

Looking at water use throughout the entire cradle-to-consumer food system, Read et al. (2020) estimated 22 trillion liters of water use annually from FLW along the entire supply chain. Estimates from the other studies, which measured only blue water use during primary production, ranged from 11 to 53 trillion L, consistent with one another and lower than Read et al.'s (2020) estimate as would be expected. The highest estimate, from ReFED (2021a), stands out because of its similarities to Birney et al. (2017) yet higher end result. Both assessed similar amounts of FLW (73 and 71 million metric tons, respectively) and relied on blue water use factors for food production from Mekonnen and Hoestra (2011, 2012), but ReFED also included water use for additional supply chain stages, like food processing and manufacturing.

In addition to blue water use, agricultural production also utilizes green water flows (i.e., rainwater that is soaked up, staying on vegetation or in the soil) (Mekonnen and Hoekstra, 2011). Thus, the values for blue water use presented in the studies understate the full water footprint associated with FLW. Two studies (Mekonnen and Fulton, 2018; Birney et al., 2017) estimated green water use associated with FLW during the retail and consumption stages, finding that green water represents 88 percent of total water use (i.e., use of blue water plus use of green water) during primary production.

In summary, the blue water use estimate from Read et al. (2020) is the most comprehensive available. The authors estimate that all FLW is responsible for 22 trillion L (5.9 trillion gallons) of blue water use, or 71,000 L (19,000 gallons) per person, annually. This is equivalent to the annual blue water use of more than 50 million American family homes (U.S. EPA, 2018).

[26] Kummu et al. (2012) excluded irrigation of animal feed.

[27] Read et al. (2020) uses the USEEIO model which captures both direct and indirect resource use along the supply chain.

TABLE 4-2. ANNUAL BLUE WATER USE ASSOCIATED WITH U.S. FLW

Source Scope of FLW	Water Use – Blue Water			
	Total (trillion L)	**Per Person** (L/year)	**Scope of Water Use**	**Water Use Factors**
ReFED (2021a)	53	163,000		U.S.
		Used blue water factors from the Water Footprint Network which are based on water factors for production from Mekonnen & Hoekstra (2011 & 2012).		
Read et al. (2020)	22•	71,000		U.S.
		Used EPA's USEEIO model to estimate blue water consumed to produce wasted food. Included water use along cradle-to-consumer food supply chain.		
Kummu et al. (2012) NAO	15•	42,000		NAO
		Used data aggregated from NAO region to calculate the irrigation water used to produce vegetative food waste.		
Toth and Dou (2016)	17	54,000•		U.S.
		Used USDA-NASS irrigation survey data.		
Birney et al. (2017)	17•	54,000		U.S.
		Used Mekonnen and Hoekstra (2011) life cycle analysis of the blue and green water requirements for food.		
Mekonnen and Fulton (2018)	11	33,277		U.S.
		Used Mekonnen and Hoekstra (2011) for crop products; Mekonnen and Hoekstra (2012) for animal products, life cycle analysis of the water requirements for food products.		
Chen et al. (2020)	17•	54,930		Intl
		Matched available global average characterization factors per food group (i.e., water use [l/g]) to product resolution.		
Conrad et al. (2018)	16	51,000•		U.S.
		Used USDA-NASS farm and ranch irrigation survey data and applied those rates to the estimates of cropland associated with FLW.		
Skaf et al. (2021)	11	33,950		Intl
		Used LCA data from EcoInvent and applied the ReCiPe midpoint method for water depletion		

NAO = Indicates estimate for the NAO Region rather than specific to the U.S.

• = Calculated values for total and per person used the same population factor as the study's data year.

= personal communication with the author.

TABLE 4-3. ANNUAL GREEN WATER USE ASSOCIATED WITH U.S. FLW

Source Scope of FLW	Water Use – Green Water			
	Total (trillion L)	**Per Person** (L/year)	**Scope of Water Use**	**Water Use Factors**
Birney et al. (2017)	123•	397,000		U.S.
		Used Mekonnen and Hoekstra (2011) life cycle analysis of the blue and green water requirements for food items.		
Mekonnen and Fulton (2018)	79	247,400		U.S.
		Used Mekonnen and Hoekstra (2011) for crop products; Mekonnen and Hoekstra (2012) for animal products, life cycle analysis of the blue and green water requirements for food products		

• = calculated value used the same population factor as the study's data year.

Water Use, By Food Category

Three studies (Conrad et al., 2018; Mekonnen and Fulton, 2018; Birney et al., 2017) provide details by food category on blue water used to grow food that was ultimately wasted during consumption stage (Conrad et al., 2018) or the retail and consumption stages (Mekonnen and Fulton, 2018; Birney et al., 2017). Figure 4-3 shows the proportion of blue water used for each FLW food category.

All three studies showed animal products accounting for approximately a third to more than half of the water use associated with FLW. Fruits and vegetables also accounted for substantial water use, from roughly one-fifth to more than half of all water use associated with FLW. ReFED (2021a) also calculated water use by food category, but grouped foods by their retail form like frozen, prepared foods, and dry goods. Even with different groupings, ReFED found that fresh meat and seafood accounted for 30 percent of the water associated with FLW, whereas produce comprised 7 percent. A couple other studies (Read et al., 2020; Toth and Dou, 2016) similarly identified the waste of animal products and fruits and vegetables as having substantial contributions to the blue water footprint of food waste. Note that these analyses (other than Read et al. (2020) and ReFED (2021a)) do not include water use beyond primary production, such as during food processing or food preparation.

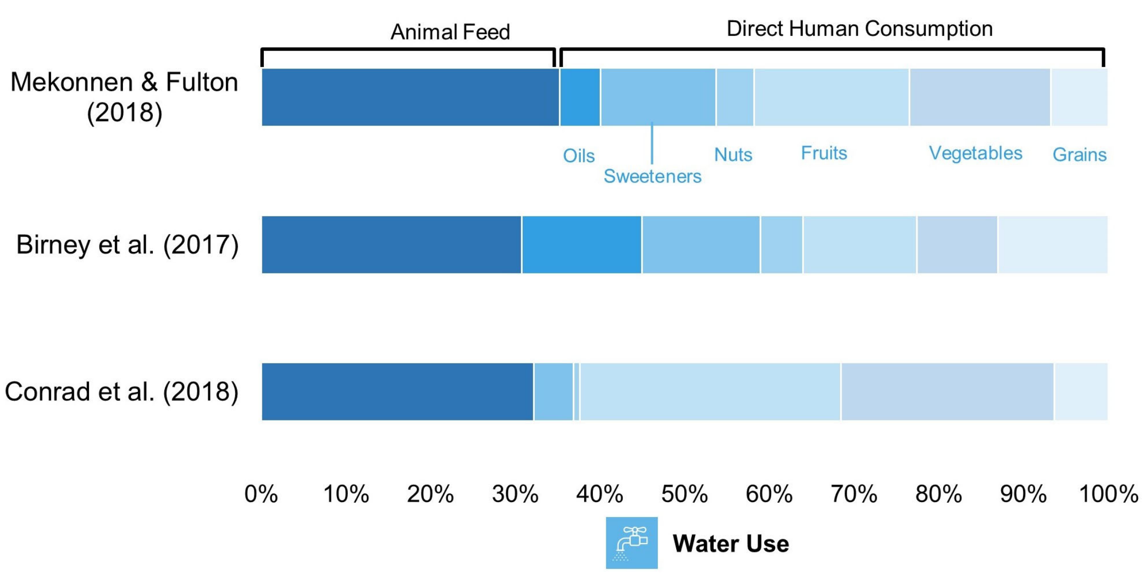

FIGURE 4-3. BLUE WATER USE ASSOCIATED WITH U.S. FLW, BY FOOD CATEGORY

4.4 Pesticide and Fertilizer Application

Application of pesticides and fertilizers help increase the productivity of croplands by reducing loss from insects and plant disease and ensuring that crops have the essential nutrients they need to grow; however, they can also have unintended consequences when they migrate from croplands to water bodies and surrounding areas. This section examines the use of pesticides and fertilizers during the primary production of food that is ultimately lost or wasted.

Pesticide Application

Only one study examined pesticide use associated with food that was ultimately lost or wasted. Conrad et al. (2018) estimated pesticide application associated with consumption stage FLW to be 354 million kg (778 million pounds) of pesticides annually, equivalent to 1 kg (2.5 pounds) per person per year, as shown in Table 4-4. No studies were available examining pesticide use associated with FLW during the other supply chain stages. For context, the consumption stage accounts for approximately half of U.S. FLW (Pagani et al., 2020; Vittuari et al., 2020; CEC, 2017).

TABLE 4-4. ANNUAL PESTICIDE APPLICATION ASSOCIATED WITH U.S. FLW

Source Scope of FLW	Pesticide Application			
	Total (million kg)	Per Person (kg/person)	Scope of Pesticide Application	Application Rates
Conrad et al. (2018)	350	1•		U.S.
	Used USDA National Agricultural Statistics Service agricultural survey data.			

In addition to pesticides applied to cropland grown for direct human consumption, indicates inclusion of pesticides applied to cropland for animal feed. • = calculated value used the same population factor as the study's data year.

Pesticide Application, By Food Category

Conrad et al. (2018) provided additional information on the pesticide application from each food category of consumption stage FLW. As shown in figure 4-4, fruits and vegetables account for more than one half of pesticide application among all food categories of FLW. An additional one quarter of wasted pesticides were applied to feed grains, oilseeds, and hay to support animal production. All other FLW accounted for the remaining 13 percent of pesticide application.

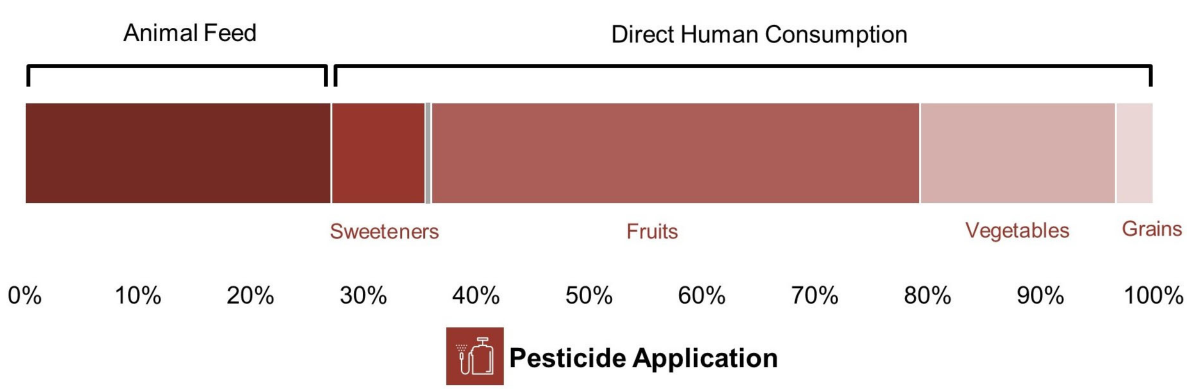

FIGURE 4-4. PESTICIDE APPLICATION ASSOCIATED WITH U.S. FLW, BY FOOD CATEGORY

Fertilizer Application

There are three major types of commercial fertilizer used in the U.S. – nitrogen, phosphate, and potassium (or potash). Nutrient runoff from nitrogen (N) and phosphorous (P) fertilizers can lead to eutrophication and algal growth in water bodies, and N fertilizer can also stimulate the release of nitrous oxide, a GHG, from soils (Davidson, 2009). When used at recommended application rates, there are few to no adverse effects from potassium (K) fertilizer. Where possible, the data on fertilizer application in this report is broken down into these components since the environmental impacts vary. Six studies assessed the amount of fertilizers used to produce food that was ultimately lost or wasted. To calculate estimates, the authors applied fertilizer application rates to estimates of the land used to produce the FLW. Table 4-55 summarizes the results.

Toth and Dou (2016) estimated 6.35 billion kg of fertilizer were used to grow food that ultimately was wasted. The authors' estimates were based on USDA-NASS survey data on crop-type specific fertilizer application rates and the percentage of acres fertilized for food and feed production. Examining the application of specific nutrients, Toth and Dou (2016) estimated 2.7 billion kg of nitrogen application and 1.5 billion kg of phosphorus application were associated with the production of FLW annually.

While the estimate of Toth and Dou (2016) is not comprehensive, since it excludes FLW during primary production, it is the most complete estimate available in the literature. Other studies presented in Table 4-5 exclude fertilizer use on animal feed crops (Birney et al., 2017; Kummu et al., 2012) or evaluate a more limited scope of FLW (Conrad et al., 2018; Birney et al., 2017), which would likely lead to underestimates of FLW. Estimates from the other studies are lower than that of Toth and Dou (2016), each at a scale roughly consistent with their smaller scope.

In addition, several of the studies relied on international rather than U.S.-specific fertilizer application rates (Chen et al., 2020; Birney et al., 2017; Kummu et al., 2012) which may affect the precision of the studies' estimates. According to FAO data, between 2002 and 2017, U.S. application rates (i.e., amount per unit of land) of phosphorous were consistently lower (by 12 to 27 percent) than the global average, while U.S. application rates of nitrogen were similar (3 percent higher) to the global average (Our World in Data, 2021). Thus, studies using international factors may over-estimate phosphorous application.

Another study, Read et al. (2020) includes FLW along the supply chain; however, it is not directly comparable to that of Toth and Dou (2016) or other studies. Rather than producing an estimate of fertilizer use, Read et al. (2020) estimates the "eutrophication potential" of the nitrogen fertilizer use associated with FLW. The authors use the life cycle impact indicator "eutrophication potential" by applying a fate and transport model to the amount of nitrogen fertilizer applied details not provided in the study) to cropland used to grow food that was ultimately wasted. The authors calculated eutrophication potential associated with FLW of 1.7 kg of nitrogen equivalent per person (i.e., that amount of nutrient reached a water body thereby impacting the water quality). While this metric may ultimately be more useful in estimating environmental impacts than simply quantifying inputs, details were sparse and a scale upon which to judge the value presented was not provided. Similarly, Skaf et al. (2021) calculated a freshwater eutrophication value of 0.51 kg phosphorus equivalent per person associated with consumer food waste.

In summary, Toth and Dou provide the most comprehensive estimate of the application of fertilizer associated with FLW – 6.35 billion kg of fertilizer (14 billion pounds) or 20.2 kg (44.5 pounds) per person, annually. This is equivalent to the average amount of fertilizer used on 100 million acres (U.S. EPA, 2019a). The fertilizer estimates can be broken down into elements, showing an estimated 8.5 kg per person of nitrogen application and 4.7 kg per person of phosphorus application each year.

TABLE 4-5. ANNUAL FERTILIZER APPLICATION ASSOCIATED WITH U.S. FLW

Source Scope of FLW	Fertilizer Application							
	Nitrogen (N)		Phosphorus (P_2O_5)		Total Fertilizer Sum of N, P_2O_5 & K_2O		Scope of Fertilizer Application	Application Rates
	Total (million kg)	Per Person (kg/person)	Total (million kg)	Per Person (kg/person)	Total (million kg)	Per Person (kg/person)		
Kummu et al. (2012) NAO	–	–	–	–	3,300•	9.3		Intl
					Based on national-level cropland area divided by national-level fertilizer use.			
Toth and Dou (2016)	2,670•	8.5•	1,460•	•	6,350	20.2•		U.S.
					Based on USDA-NASS census data of average annual fertilizer application rates and percent of acres fertilized for food and animal feed by crop type.			
Birney et al. (2017)	–	–	–	–	5,300•	17		Intl
					Used fertilizer consumption data from the International Fertilizer Industry Association and land use data from FAOSTAT.			
Chen et al. (2020)	850•	2.7 4.7	150•	0.5	–	–		Intl
					Fertilizer amounts determined by matching recently available global average characterization factors per food group (i.e., N and P_2O_5 application [g/g]) to product resolution.			
Conrad et al. (2018)	820	2.6•	680	2.2•	2,500	8•		U.S.
					Used USDA-NASS Agricultural Survey data.			

In addition to fertilizer application on cropland for direct human consumption, indicates inclusion of cropland for animal feed. NAO = Indicates estimate for the NAO Region rather than for the U.S. specifically. • = Calculated values for total and per person used the same population factor as the study's data year. For Toth and Dou (2016) values for total nitrogen and total phosphorus, the percentages reported by the authors total fertilizer application were applied to the authors' total for fertilizer associated with FLW.

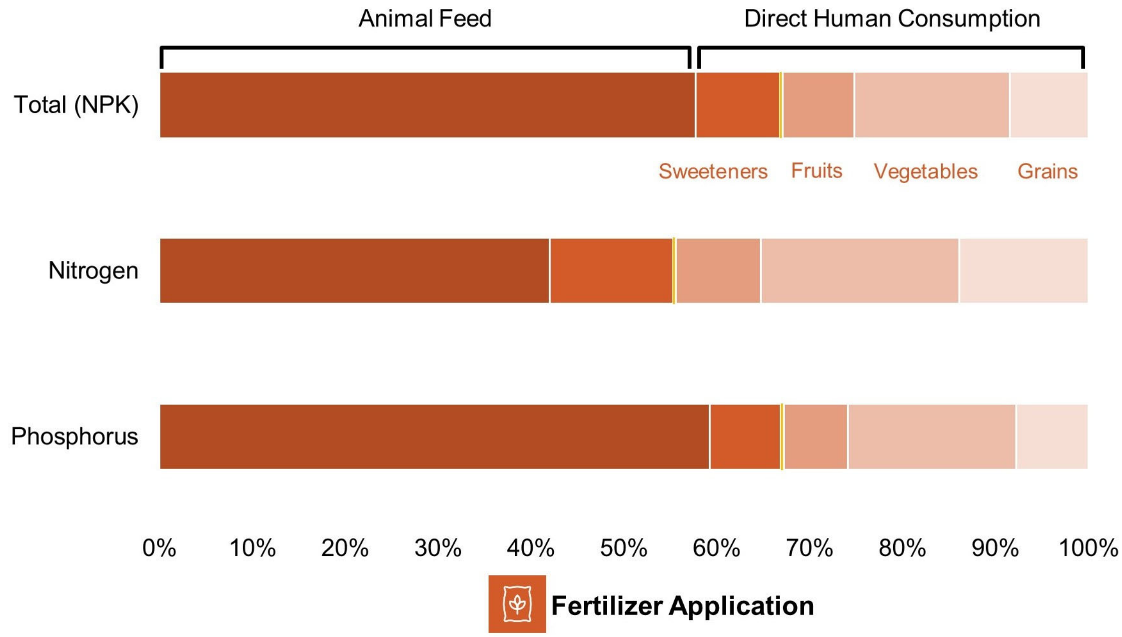

FIGURE 4-5. FERTILIZER APPLICATION ASSOCIATED WITH U.S. FLW, BY FOOD CATEGORY

Data Source: Conrad et al. (2018)

Fertilizer Application, By Food Category

In addition to estimating land use and pesticide application, Conrad et al. (2018) provides estimates of fertilizer application associated with consumption stage FLW by food category. As shown in Figure 4-5, the authors estimate that the largest share of nitrogen fertilizer application (over 40 percent) was from the production of feed grains, oilseeds, and hay grown to support animal products that were ultimately wasted. Conrad et al. (2018) also finds that fruits and vegetables comprise a substantial share (approximately 30 percent) of nitrogen fertilizer application. Examining phosphorous application, Conrad et al. (2018) finds similar results. The largest share of phosphorous application (almost 60 percent) is from feed grains, oilseeds, and hay grown to support animal products that were ultimately wasted, and the next largest share is attributable to fruits and vegetables (almost 25 percent). A study by Wood et al. (2019) confirms the prominence of animal products as a contributor to phosphorous fertilizer application and to ammonia air emissions (from nitrogen fertilizer application) associated with FLW.

This is consistent with the finding in Section 4.2 that the largest share of land use associated with FLW is attributable to animal products (and the feed grown to support them) and that these products comprise an outsized portion of inputs compared to their share of FLW, which is approximately 30 percent (FAO, 2011). In contrast, fruits and vegetables represent a slightly higher percentage of FLW (more than 40 percent) (FAO, 2011). The work of Chen et al. (2020), while potentially less precise due to its use of international fertilizer application rates, confirms this finding. They found that, for the NAO region, animal products were responsible for 26 percent and 31 percent of nitrogen and phosphorus use, followed by cereals (24 percent of N and 21 percent P) and fruits and vegetables (20 percent of N and 19 percent of P).[28]

[28] Chen et al. (2020) estimates are not included in Figure 4-3 since the study broke down FLW into different categories than Conrad et al. (2018), thus making comparison of the two studies' results difficult. Conrad et al. (2018) was selected over Chen et al. (2020) due to its use of U.S. application factors.

4.5 Energy Use

To describe the energy inputs that are used along the food supply chain to produce food for consumers, researchers often quantify the "embodied energy" of food types. Embodied energy is the cumulative amount of energy that was used to produce a food product through a given stage in the food system (e.g., from cradle-to-consumer). The further along the food supply chain, the higher the level of embodied energy because it is a summation of all the earlier inputs. Unlike the use of land or chemicals, which predominately occur on-farm, energy use occurs all along the supply chain, so the embodied energy of a food product is considerably higher at the consumption stage than during primary production.

Table 4-6 presents estimates of the embodied energy of U.S. FLW. All studies included energy use along the entire food supply chain. Unlike estimates for inputs such as water, these estimates are created using a top-down approach, starting with total U.S. energy consumption, typically from the U.S. Energy Information Administration (EIA), then distributing it to sectors (e.g., distribution and processing, or retail) and their functions (e.g., transportation or refrigeration), then associating the appropriate portion to FLW.

The analysis by Cuéllar and Webber (2010) brought to light the large amounts of energy used by the food system and the associated embodied energy in FLW. The authors estimated that 2.1 billion GJ, representing at least 2 percent of total energy consumption in the U.S. in 2007, was associated with edible FLW from the consumer and retail stages of the supply chain each year. Birney et al. (2017) updated this analysis with more recent FLW estimates[29], maintaining a similar scope, to produce an estimate of 2.5 billion GJ.

More recently, two studies examined the embodied energy use in FLW from all stages of the supply chain. Read et al. (2020) estimated embodied energy in their analysis using EEIO models. The authors estimated 2.0 billion GJ per person annually for all FLW. Companion studies by Pagani et al. (2020) and Vittuari et al. (2020) took a more detailed bottom-up approach to estimating energy use associated with U.S. FLW. Using their own estimates of FLW rates, the authors examined energy use between 2004 and 2015, using data from USDA, EIA, U.S. Geological Survey (USGS), EPA, and others to approximate FLW mass and energy use at each stage of the food system. The authors estimated that an average of 11.88 billion GJ of energy was used in the food system annually between 2004 and 2015, of which 2.4 billion GJ (17 percent) was embodied in FLW. Compared to Read et al. (2020), the only other study with a similarly comprehensive scope, Pagani et al. (2020) and Vittuari et al. (2020) provide a greater level of detail, descriptiveness, and transparency in methodology, and thus policymakers may find this estimate the most useful.

Notably, Pagani et al. (2020) and Vittuari et al. (2020) knowingly underestimated the energy use of FLW, as the authors excluded the loss and waste of imported foods from their analysis due to the lack of reliable data on the energy embodied in foreign production and international transport. One-fifth of the U.S. food supply is imported, and almost one-half of imported foods are fruits and vegetables (USDA, 2019f, 2016) which are lost and wasted at a relatively high rate (Buzby et al., 2014; Gustavsson et al., 2011), so impacts likely would have been substantially higher if the authors had included loss and waste of imported foods.

Unexpectedly, the estimates from Cuéllar and Webber (2010) and Birney et al. (2017), which represent only retail and consumption FLW are similar to estimates from Read et al. (2020), Pagani et al. (2020), and Vittuari et al. (2020), which encompass FLW from all stages of the supply chain. One would expect the latter estimates to be larger than the former. This can be partly explained by the exclusion of imported foods by Pagani et al. (2020) and Vittuari et al. (2020), potentially keeping their estimate roughly 20 percent lower than would be expected.

Taking all the reviewed modeling variables into account, the Pagani et al. (2020) and Vittuari et al. (2020) estimate of 2.395 billion GJ (664 billion kWh), or 7.7 GJ (2,140 kWh) per person, annually is likely the most precise current estimate of wasted energy inputs embodied in U.S. FLW, even though it excludes the loss and waste of imported foods. For context, this finding suggests that FLW accounts for 2 percent of total U.S. energy consumption and embodies enough energy to power approximately 56 million U.S. homes for a year (U.S. EPA, 2021b; EIA, 2020)[30].

[29] Cuéllar and Webber (2010) relied on 1995 USDA FLW data, while Birney et al. (2017) used 2010 data from the same source.

[30] Based upon 2019 usage levels of approximately 42.8 GJ/year

TABLE 4-6. ANNUAL ENERGY USE ASSOCIATED WITH U.S. FLW

Source Scope of FLW	Energy Use Total (billion GJ)	Per Person (GJ)	Scope of Energy Use	Energy Use Factors	
Pagani et al. (2020); Vittuari et al. (2020)	2.4	7.7•		U.S.	Analyzed the energy used in each part of the food supply chain. Excludes all exports and imports.
Read et al. (2020)	2•	5.5		U.S.	Used EPA's USEEIO model used to estimate energy use associated with FLW within each stage of the food supply chain.
Birney et al. (2017)	2.5•	8		U.S.	Extrapolated the per person energy use from Cuéllar and Webber (2010) and applied updated FLW estimates.
Cuéllar and Webber (2010)	2.1	7•		U.S.	Calculated the energy used to produce food from primary production (including aquaculture and fisheries), transportation, food processing, packaging, food services and residential energy consumption. Relied on one case study for food processing energy factors.
Skaf et al. (2021)	0.9•	2.7•		Intl	Calculated fossil fuel depletion in kg oil equivalent. Applied the same international food production process data from EcoInvent for all the studied countries, including the U.S.

• = Calculated values for tons and per person used the same population factor as the study's data year.
= personal communication with the author.

Energy Use, By Supply Chain Stage and Food Category

The companion studies by Vittuari et al. (2020) and Pagani et al. (2020) described above provide detailed estimates of the embodied energy of FLW, by supply chain stage and by food category. As shown in Figure 4-6, the authors found that the consumption stage of the supply chain embodied the largest amount of wasted energy from FLW in the food system—72 percent—at 1,723 million GJ. Within the consumption stage, the contribution of at-home FLW (1,101 million GJ) exceeded that of away-from-home FLW (622 million GJ). Even though the consumption stage accounts for a large share of FLW, its contribution to energy use is still outsized (47 percent of FLW but 72 percent of energy use associated with FLW[31]). The next largest contribution was from the retail sector. Together the consumption and retail stages account for 90 percent of energy use associated with FLW.

Of food categories examined, all categories entailed more energy use downstream than upstream on-farm or during processing. Animal products (including meat, milk, eggs, and fish) embodied the largest amount of wasted energy at 1418 million GJ (60 percent of the total wasted energy, despite representing only 34 percent of FLW). Among individual food categories, meat resulted in the largest cumulative embodied energy loss (629 million GJ or 26 percent of the total).

Pagani et al. (2020) and Vittuari et al. (2020) found that, in the upstream stages of the supply chain (primary production and processing) each kilogram of FLW carries a burden of 10 to 40 MJ (vegetal[32] products) or 30 to 75 MJ (animal products). In the downstream stages, the burden of each kilogram of FLW is 20-60 MJ (vegetal products) or 30 to 110 MJ (animal products).

Prior to this study, Cuéllar and Webber (2010) had examined the embodied energy loss of FLW by food category by pairing food categories with mass data and energy intensities at each stage of the food supply chain, then multiplying each category by FLW rates. Birney et al. (2017) later updated this analysis, using the same energy use intensities. These studies highlighted dairy, meat, vegetables, and poultry and fish as substantial contributors to the embodied energy of FLW. While categories like meat were the most energy-intensive to produce, the contribution of other categories such as vegetables were driven by the large amount wasted.

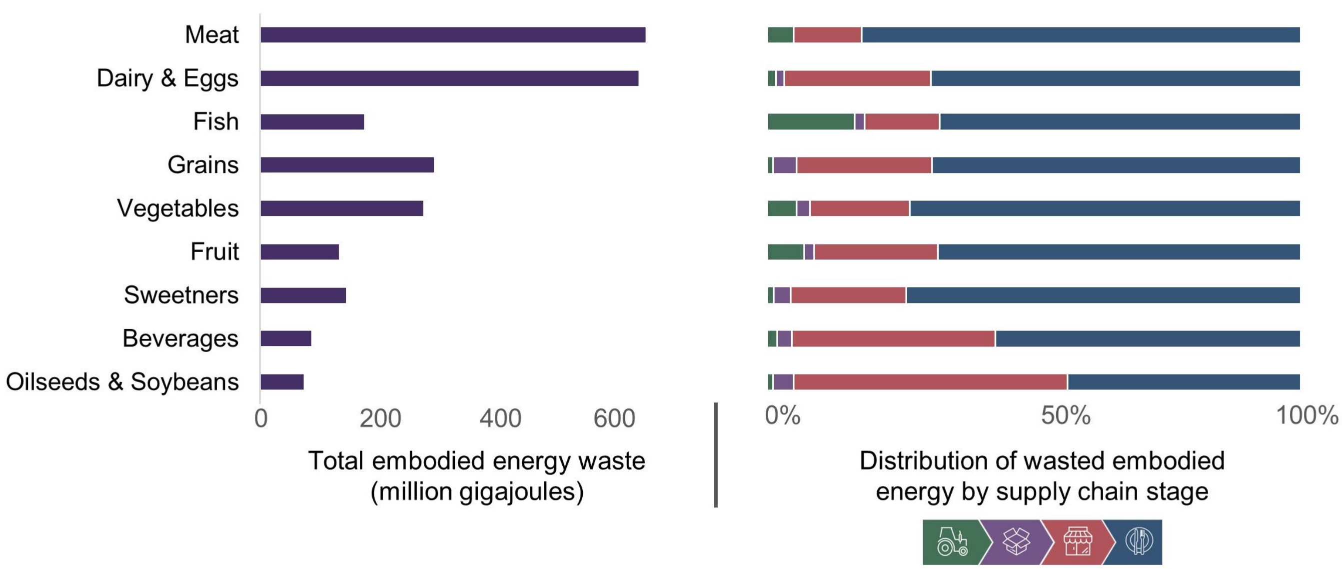

FIGURE 4-6. EMBODIED ENERGY OF U.S. FLW

Data Source: Pagani et al. (2020); Vittuari et al. (2020). Does not include energy use from packaging.

[31] According to data in Pagani et al. (2020) and Vittuari et al. (2020)

[32] The term “vegetal” here includes all food categories except animal products.

4.6 Greenhouse Gas Emissions

Increasing levels of carbon dioxide and other greenhouse gases in our atmosphere, caused by human activities, are contributing to changing earth's climate – rising temperatures, changes in precipitation, and more extreme climate events. The food system is a major contributor to anthropogenic GHG emissions. In the U.S., agriculture (primary production) is responsible for 10 percent of total domestic GHG emissions, not accounting for associated emissions from land use and land use change (U.S. EPA, 2021c). Including the carbon emissions impacts from agriculture driven land use and land use change, the North American food system accounts for 25 percent of total North American GHG emissions (Crippa et al., 2021).

The ten studies included in Tables 4-7 and 4-8 estimate the GHG emissions associated with food that was ultimately lost and wasted. None of the studies attempted to quantify the GHG emissions tied to land use and land use change from FLW, likely because it typically occurs outside the U.S.[33] In keeping with the scope of this report, emissions from landfills or other food waste management methods are not considered. Table 4-8 summarizes the results.

Methane and Nitrous Oxide Emissions

Two studies (Chen et al., 2020; Hiç et al., 2016) focused exclusively on the non-CO_2 emissions (CH_4 and N_2O) from primary production, thus producing the lowest estimates. The results of these studies are summarized in Table 4-7. The differences between the two estimates are not driven by the differences in scope of the studies or the FLW estimates underpinning the studies (both of which would predict Hiç et al.'s estimate being higher than Chen et al.'s estimate[34], but it is not), but may be driven by assumptions about the food category breakdown of the FLW (and thus the emissions intensity of the FLW). Chen et al. (2020) applied GHG emissions intensity factors to each food category within the FLW; however, Hiç et al.'s methodology did not provide information about the composition of the FLW by food category. Thus, Hiç et al. (2016) used just two emissions intensity factors, one for crops and the other for livestock to estimate the non-CO_2 emissions of FLW.[35]

TABLE 4-7. ANNUAL METHANE AND NITROUS OXIDE EMISSIONS ASSOCIATED WITH U.S. FLW

Source Scope of FLW	**GHG Emissions - CH_4 and N_2O emissions**			
	Total (million $MTCO_2e$)	**Per Person** (kg CO_2e)	**Scope of GHG Emissions**	**Emission Factors**
Hiç et al. (2016)	43	124		U.S.
		Estimated emissions using country-level data on agricultural emissions from FAOSTAT.		
Chen et al. (2020)	52•	167		Intl
		Determined emissions by matching recently available global average characterization factors per food group (i.e., cropland use [g CO_2e/g]) to product resolution.		

• = calculated value

[33] While food demand and consumption in the U.S. rises with a growing population, agricultural land use has remained relatively stable in the U.S. since the 1960's (USDA, 2017).
[34] Hiç et al. (2016) calculated 1050 daily calories per capita from all sectors except primary production, while Chen et al. (2020) estimated 709 daily calories per capita from the consumption sector alone.
[35] Hiç et al. (2016) did not provide the ratio of vegetal to animal products used in the analysis.

All Greenhouse Gas Emissions

The other eight studies evaluated all GHG emissions (including CO_2 and non-CO_2 emissions). Read et al. (2020) and ReFED (2021a) provide the broadest estimates, considering GHG emissions associated with FLW from all supply chain stages and including GHG emissions from all stages of the supply chain (including the consumption stage, which all other studies omitted). The six remaining studies (Guo et al., 2020; Birney et al., 2017; Heller and Keoleian, 2015; Venkat, 2012) considered a subset of food supply chain stages when calculating FLW and/or GHG emissions. Guo et al. (2020) also included emissions from international transportation, which no other study did.

The highest total estimates were from ReFED (2021a) followed by Guo et al. (2020). ReFED (2021a) quantified the GHG emissions related to FLW for the whole food supply chain, including imports and transportation. However, their GHG emissions value during primary production only covers fruits and vegetables. Guo et al. (2020) evaluated emissions from primary production as well as those from international transportation of food and food products. The study accounted for FLW from all stages of the supply chain. The authors estimated that 222 million $MTCO_2e$ were associated with the primary production and international transportation of edible and inedible FLW. Surprisingly, international transportation accounted for only 3 percent of the total emissions estimate.

Heller and Keoleian (2015), followed by Birney et al. (2017), calculated GHG emissions associated with a smaller scope of FLW but a larger scope of GHG emissions (i.e., from more supply chain stages) than Guo et al. (2020), making comparisons difficult. Both Heller and Keoleian (2015) and Birney et al. (2017) relied on GHG emissions factors for each food category based on a meta-analysis of LCAs of food production. The studies attribute a higher emissions intensity to animal product categories and oils than did Guo et al. (2020). Birney et al. (2017) estimate being higher than that of Heller and Keoleian (2015) may be partly attributable to more recent, higher estimates of FLW, including 40 percent higher estimates of fruit and vegetable FLW. Skaf et al. (2021) is the most recent study included, relying on food production data within EcoInvent. Their calculated GHG emissions value falls squarely between Birney et al, (2017) and Heller and Keoleian (2015) even though it only examines consumer food waste.

Covering more stages of FLW but similar stages of GHG emissions to Heller and Keoleian (2015) and Birney et al. (2017) above, Venkat (2012) used a proprietary database of LCAs and life cycle impact data of food products to calculate a much lower GHG footprint of edible FLW. This is the lowest estimate of the studies that examined all GHG emissions. This can be explained by Venkat using the smallest estimate of FLW (180 kg per person) and the lowest GHG emission intensities for meat, poultry, and eggs, which comprise the greatest portion of the FLW GHG footprint.

Looking at the studies that included all GHG emissions, only Read et al. (2020) considers FLW and GHG emissions from all stages of the supply chain, encompassing a larger scope than the other studies – however the study does not present the highest estimate.

There are advantages and disadvantages to each type of methodology. For example, while EEIO models (like the one used by Read et al. (2020) can provide coarse estimates due to their economy-wide view, rolling up individual food product LCAs (akin to methodology of Birney et al. (2017) and Heller and Keoleian (2015)) can possibly exaggerate data uncertainties and assumptions. The choice of FLW estimate and GHG emissions factors in all the studies influence final estimates. More research on GHG emissions associated with FLW is warranted. For now, the authors of this paper recommend use of the possibly conservative estimate from Read et al., with the understanding that other studies (except Venkat, 2012) indicate it may be an underestimate.

Taking all the reviewed modeling variables into account, Read et al. (2020) provides the most comprehensive estimate of GHG associated with FLW, at 170 million $MTCO_2e$, or 539 kg CO_2e per person, annually. This is equivalent to more than the emissions of 42 coal-fired power plants or 36 million passenger vehicles each year (U.S. EPA, 2021a). However, other studies with smaller scopes present consistently larger estimates, warranting further study.

TABLE 4-8. ANNUAL GHG EMISSIONS ASSOCIATED WITH U.S. FLW

Source Scope of FLW	GHG Emissions - All			
	Total (million $MTCO_2e$)	**Per Person** (kg CO_2e)	**Scope of GHG Emissions**	**Emission Factors**
ReFED (2021a)	270	822•		Varies
	Calculated the life cycling impacts, using Quantis' database, for 44 common food items to represent the US food market from the farm to residential stage.			
Read et al. (2020)	170•	539		U.S.
	Used EPA's USEEIO model to estimate GHG emissions associated with FLW.			
Guo et al. (2020)	222	683		FAO
	Included emissions from international transportation. Used regional and food specific emission factors from LCAs for primary production and FAO detailed trade matrix data and per-km emission factors for transportation.			
Venkat (2012)	113	368		Varies
	Estimates emissions for each food category based on an LCA framework.			
Birney et al. (2017)	208•	673		Varies
	Used Heller and Keoleian (2015) emissions data.			
Heller and Keoleian (2015)	160	511		Varies
	Emission factors based on meta-analysis of published LCA values for various food types from both domestic and international studies.			
EPA WARM (2019)[a]	200•	650•		U.S.
	Uses streamlined lifecycle emission factors for FLW including five primary food categories from primary production to retail, including transportation.			
Skaf et al. (2021)	172	527		Varies
	Used LCA data for food production from EcoInvent and applied the ReCiPe midpoint method.			

• = calculated value based on WARM emission factors applied to Buzby et al. (2014) FLW data.
= personal communication with the author

[a] EPA WARM is a tool that can calculate estimated lifecycle GHG emissions associated with food waste. The FLW values by food category from Buzby et al. (2014) were entered into WARM to develop these estimates.

EPA's Waste Reduction Model (WARM)

EPA's Waste Reduction Model (WARM) is a tool to compare the GHG emissions associated with different waste management pathways (e.g., landfill or composting) for many different material types, including food. WARM can also be used to see the GHG emissions associated with consumption stage FLW of beef, poultry, grains, bread, fruits and vegetables, and dairy products.

WARM employs a streamlined life cycle analysis, providing information on GHG emissions from the:

- *primary production of food;*
- *transport of materials from the production or processing facility to the retail/distribution point;*
- *manufacture and application of agricultural fertilizers;*
- *management of livestock manure;*
- *enteric fermentation resulting from livestock; and*
- *fugitive emissions of refrigerants used during refrigerated transport and storage.*

As seen in Figure 4-7, the resulting emission factors from primary production to consumption vary by food product from 33 MTCO2e/metric ton to 0.5 MTCO2e/metric ton for beef and fruits and vegetables, respectively. Applying the WARM GHG emission factors (excluding disposal) to the 2010 FLW estimate from Buzby et al. (2014) *results in an approximate GHG footprint of 650 kg of CO2e per a person. This falls within the range of 368 to 683 kg CO2e per person (Guo et al., 2020; Venkat, 2012) from the estimates discussed above that examined CO_2 and non-CO_2 emissions from food waste.*

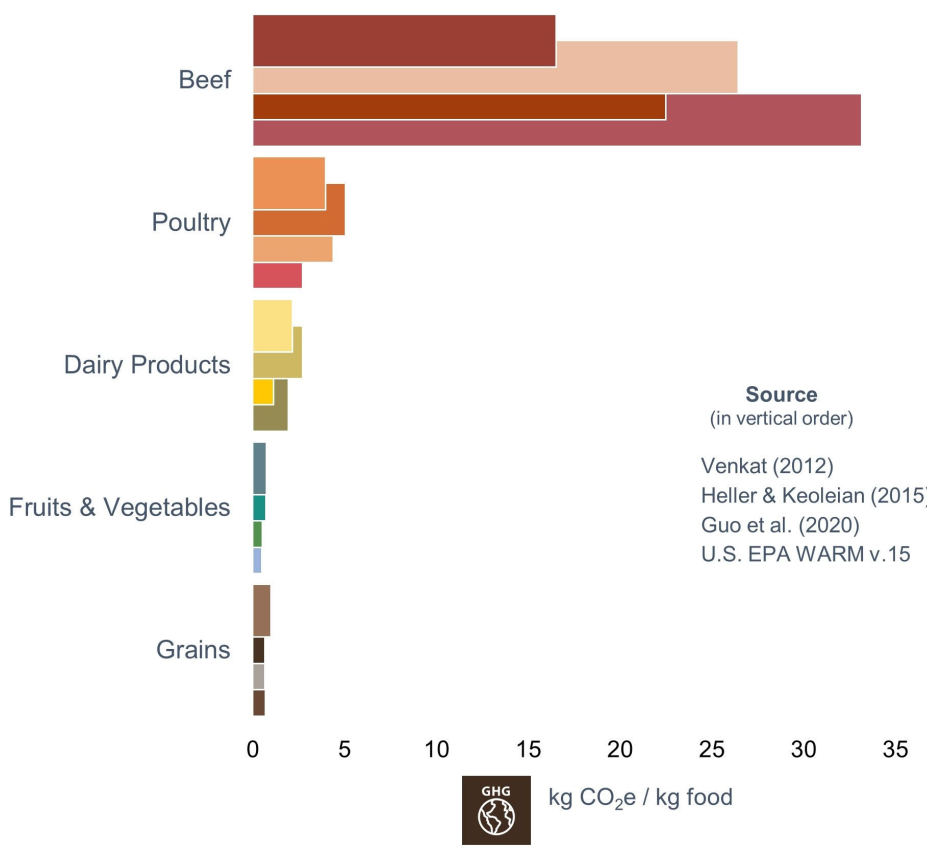

FIGURE 4-6. GHG EMISSIONS INTENSITIES, BY FOOD CATEGORY

Data from Guo et al. (2020) obtained from personal communication with X. Guo (March 23, 2021).

GHG Emissions, By Supply Chain Stage and Food Category

Several insights about the distribution of FLW-associated GHG emissions along the supply chain are available in the literature, most notably that primary production is a far greater contributor to GHG emissions than transportation. Guo et al. (2020) examined GHG emissions from primary production and international transportation, and found international transportation accounted for only 3 percent of total emissions. Venkat (2012) assessed GHG emissions from primary production through retail (i.e., including emissions from domestic transportation and excluding emissions during the consumption stage), finding that primary production and food processing[36] accounted for 80 percent of the GHG emissions, followed by 14 percent from distribution and retail, and 6 percent from packaging. Distribution and retail would include both domestic transportation and energy use and refrigerant-related emissions at retail outlets. Neither study considered consumption stage emissions, which are likely to be significant based upon the energy use estimates presented in Section 4.5.

Looking at specific food groups' contributions to the GHG emission footprint of FLW, animal products, particularly ruminant-based FLW (i.e., dairy and beef) result in the majority of emissions. For example, Heller and Keoleian (2015) examined GHG emissions (excluding emissions from the consumption stage) from food lost or wasted at the retail and consumption stages. The authors found that the beef, veal, and lamb category accounted for the greatest GHG emissions, followed by dairy products (other than fluid milk) and pork. Together animal products (beef, veal, and lamb; milk and other dairy products; pork; poultry; fish and seafood; eggs) accounted for 73 percent of GHG emissions from retail and consumer FLW, while accounting for only 33 percent FLW by weight and 23 percent FLW by calories. Guo et al. (2020) similarly found that for consumption stage FLW in the NAO region, beef represented 44 percent of cradle-to-consumer GHG emissions associated with FLW; together with dairy, all ruminant FLW accounted for 60 percent of GHG emissions associated with FLW.

Figure 4-8 shows the contribution of each food category to the GHG footprint of FLW by displaying data from the four available studies. Figure 4-6 compares the GHG emissions intensities (i.e., the emissions per unit of food) of a few specific food categories, based upon data from three of these same studies, demonstrating that beef has the highest GHG emissions intensity.

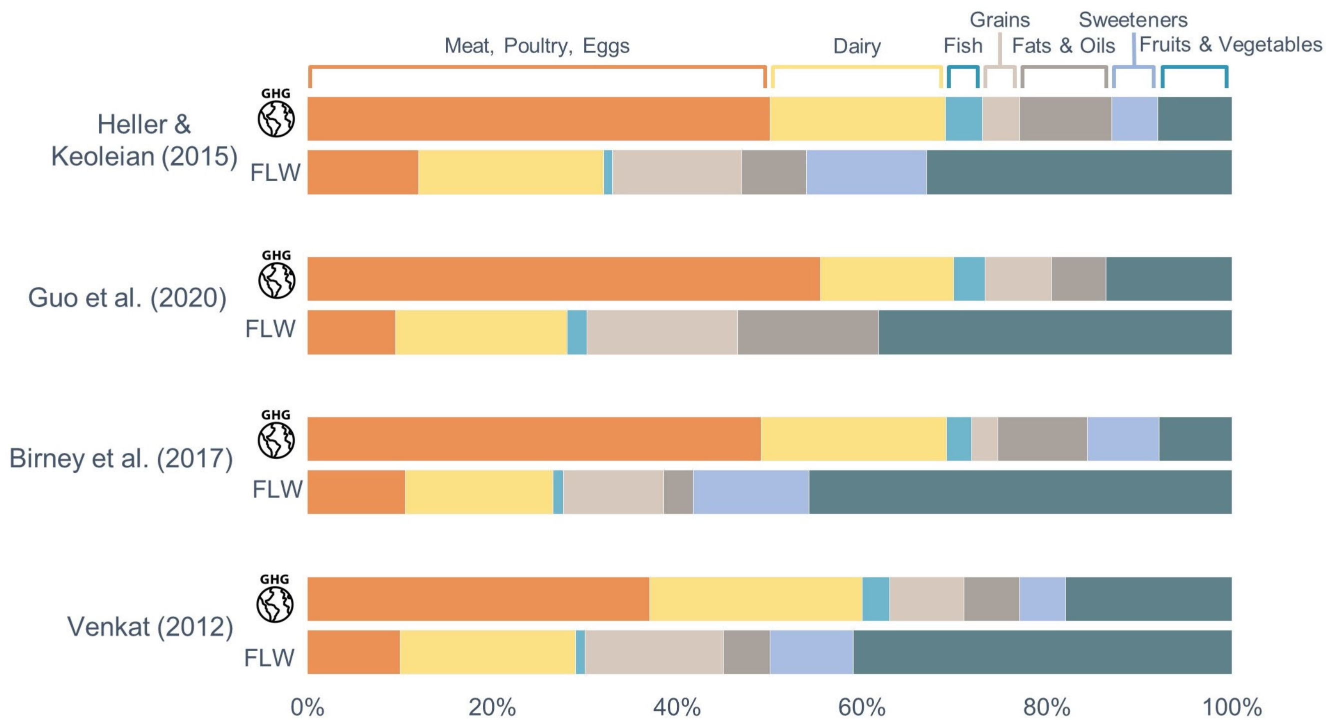

FIGURE 4-8. COMPARISON OF GHG FOOTPRINT TO FLW COMPOSITION

U.S. data from Guo et al. (2020) obtained through personal communication with the lead author.

[36] Primary production and processing are combined in Venkat (2012) published data, as are distribution and retail.

4.7 Summary of Environmental Footprint

Despite differences in study design, methodologies, data sets, time periods, and other factors, most estimates of the environmental impacts associated with food that is ultimately lost or wasted show general agreement once these factors are taken into consideration. Table 4-9 presents selected estimates of the annual cradle-to-consumer environmental impacts of FLW in the U.S. in absolute and per person terms. Figure 4-10 displays this data as a percentage of the environmental footprint of the entire U.S. cradle-to-consumer food system.

In general, studies show that roughly a third of the U.S. food supply is lost or wasted, and FLW accounts for roughly one-third of the inputs and environmental impacts of the cradle-to-consumer food system. For example, Birney et al. (2017) concluded that food lost or wasted during the retail and consumption stages uses approximately one-third of all resources of the food system,[37] as might be expected if FLW from along the entire chain had been included. Kummu et al. (2012) examined FLW along the entire supply chain, also finding one-third of resources to be associated with FLW.[38] Another study that did included FLW all along the supply chain, however, produced a lower estimate. Read et al. (2020) EEIO analysis found that approximately 16 to 18 percent of the total environmental impact[39] of the U.S. cradle-to-consumer food system is associated with food that is ultimately lost or wasted. Other studies produced estimates higher than one-third. For example, Toth and Dou (2016) estimated more than 40 percent of irrigation water and cropland were associated with FLW.

While a disparity between the amount of food lost or wasted and the portion of the food system's inputs and environmental impacts may be due in part to the point on the supply chain at which the food is lost or wasted and/or the mix of food categories lost or wasted, it could also imply that the relationship between FLW and food system impacts is more complex than it appears. Also, the differences in estimates above are difficult to compare, due to differences in scope and methodologies. Certainly it is clear that downstream FLW, especially at the consumption stage (i.e., at restaurants and at home), is more of an environmental burden that FLW further upstream, per unit of food, as the inputs and impacts accumulate as food moves along the supply chain.

While the estimates presented in Table 4-9 were chosen largely based upon their comprehensive scope, many credible methodologies presented in this report would produce higher estimates if their results were extrapolated to cover FLW along the whole supply chain. The estimates of Read et al. (2020) in particular should be considered conservative.

[37] Birney et al. (2017) includes energy, blue water, green water, GHGs, agricultural land, and fertilizer. The authors found FLW accounted for 5% of energy use, 34% of blue water use, 34% of GHG emissions, 31% of land use, and 35% of fertilizer use related to an individual's food-related resource consumption, i.e. their footprint.

[38] Kummu et al. (2012) included the use of blue water (35%), cropland (31%) and fertilizers (30%) in this estimate.

[39] Read et al. (2020) includes energy use, eutrophication potential, GHG warming potential, land use and water use (blue water withdrawals).

TABLE 4-9. SUMMARY OF THE ANNUAL CRADLE-TO-CONSUMER ENVIRONMENTAL FOOTPRINT OF U.S. FLW

Environmental Impact	Environmental Footprint				Source
	Total (Standard Units)	Per Person	Percentage of U.S. Cradle-to-Consumer Food System Footprint	Percentage of U.S. Footprint	Scope of FLW
Land Use	560,000 km^2 • (140 million acres)	1,800 m^2 (19,000 sq ft)	16% of agricultural land •	–	Read et al. (2020)
Water Use [a]	22 trillion L • (5.9 trillion gallons)	71,000 L (19,000 gallons)	17% of freshwater used •	5%	Read et al. (2020)
Pesticide Application	350 million kg [b] (780 million pounds)	1 kg • (2.5 pounds)	–	–	Conrad et al. (2018)
Fertilizer Application	6,350 million kg • (14 billion pounds)	20.2 kg •, [b] (44.5 pounds)	42% of total fertilizers used	–	Toth and Dou (2016)
Energy Use	2,400 million GJ (664 billion kWh)	7.7 GJ • (2,140 kWh)	20% of energy used	2%	Pagani et al. (2020); Vittuari et al. (2020)
GHG Emissions	170 million $MTCO_2e$ •	540 kg CO_2e	16% of GHG emissions •	2%	Read et al. (2020)

• = calculated
= personal communication with author
[a] Blue water use.
[b] Accounts for only consumer FLW

FIGURE 4-9. ANNUAL CRADLE-TO-CONSUMER ENVIRONMENTAL FOOTPRINT OF U.S. FLW

This figure depicts the annual environmental footprint of producing, storing, processing, packaging, distributing, and marketing food that is ultimately lost or wasted in the United States. Data Source: U.S. EPA (2021a); USCB (2021); Pagani et al. (2020); Read et al. (2020); U.S. DoE (2020); Vittuari et al. (2020); U.S. EPA (2018); Toth and Dou (2016)

For policymakers seeking credible estimates of the environmental footprint of retail and consumption stage FLW only, in line with the UN SDG Target 12.3 and the EPA and USDA goal, Birney et al. (2017) is the most useful resource. The authors estimate 325,500 km2 (80 million acres) agricultural land, 17 trillion L (4 trillion gallons) blue water, 123 trillion L (32 trillion gallons) green water, 5,266 million kg (12 billion pounds) fertilizer, 2.5 billion GJ (694 billion kWh) energy, and 208 million $MTCO_2e$ GHG emissions are associated with retail and consumption stage FLW annually, from cradle-to-consumer.

In addition to demonstrating the resource inputs and environmental impacts associated with U.S. FLW, the studies presented provide evidence of the factors (food categories and food supply chain stages) driving these estimates. This can provide policymakers with clues as to how to maximize environmental benefits of FLW reduction initiatives. For example, while the use of land, pesticides, fertilizers, and water chiefly occur during primary production, energy use and GHG emissions occur all along the supply chain. Studies illuminated that the consumption and distribution stages account for the greatest energy use, while the primary production stage accounts for the greatest GHG emissions.

The type of food lost or wasted also has a significant effect on the environmental footprint of FLW, and policymakers may prioritize interventions related to categories of FLW with the largest environmental impacts. Given the predominance of animal products and fruits and vegetables for each input and environmental impact, policymakers may want to consider FLW initiatives targeting these food types. Animal products[40] are responsible for more than half of the land and energy used, and GHGs emitted from FLW (Conrad et al., 2018; Birney et al., 2017; Toth and Dou, 2016) and accounted for the largest share of fertilizer and water use for irrigation (Conrad et al., 2018). Fruits and vegetables were also substantial users of inputs, ranking second behind animal products in many categories. Fruit also accounted for the greatest pesticide application, followed by animal products (Conrad et al., 2018). However, fruits and vegetables comprise a much larger share of U.S. FLW than animal products, demonstrating the outsized impact of the loss and waste of animal products.

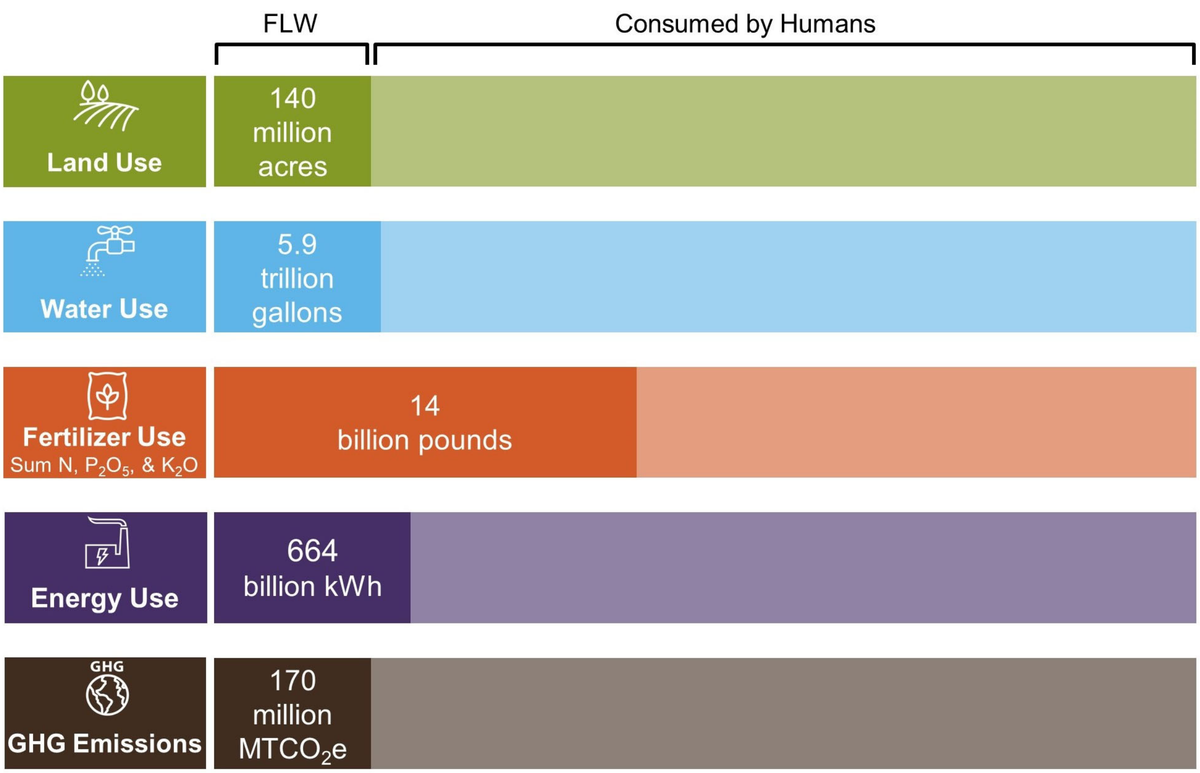

FIGURE 4-10. ANNUAL ENVIRONMENTAL FOOTPRINT OF U.S. FARM TO KITCHEN FOOD SUPPLY CHAIN

Data Source: Read et al. (2020) (land, water- blue water, and GHG) – noting that these are calculated values based from per capita data received in personal communication; Toth and Dou (2016) (fertilizer); Pagani et al. (2020) & Vittuari et al. (2020) (energy)

[40] Including the feed crops that support animal production

CHAPTER 5.

Environmental Benefits of Reducing U.S. Food Loss and Waste

Given the significant environmental impacts of FLW, halving FLW – as the U.S. aims to do – could meaningfully reduce the resource use and environmental impacts of the U.S. food system. This chapter examines the potential environmental benefits of halving FLW in the United States.

Building upon the analyses of the environmental footprint of FLW, as presented in Chapter 4, researchers have estimated the potential "savings" (i.e., avoided resource use and environmental impacts) that could be achieved by reducing U.S. FLW. When calculating savings, researchers must consider the supply chain stage at which the reduction was achieved and the category of food in which waste was prevented. The environmental benefits presented in this chapter can only be achieved through the prevention (i.e., source reduction) of food waste. Recycling food waste will not achieve these benefits.[41]

The methodologies upon which all these estimates are built assume that decreases in demand/consumption (from reducing FLW) will result in equivalent decreases in production. However, economic factors like rebound effects can impede reductions in production, and thus these estimates of environmental savings should be considered the upper bounds of savings that could be achieved.

KEY FINDINGS

- *Halving U.S. FLW could achieve the following annual savings:*
- ***Agricultural land:*** *More than 300,000 km^2 (75 million acres)*
    - ***Blue water:*** *12 trillion L (3.2 trillion gallons)*
    - ***Fertilizer:*** *Nearly 290,000 metric tons (640 million pounds) bioavailable nitrogen*
    - ***Energy:*** *940 million GJ (262 billion kWh)*
    - ***GHG emissions:*** *92 million $MTCO_2e$*
- *Halving FLW in households, restaurants, and the food processing sector will have the greatest environmental benefits. Halving the FLW in retail and institutional food service (schools) will have minimal environmental benefits.*
- *Reducing loss and waste of meats, cereals, and fresh fruits and vegetables will have the greatest environmental benefits, among food categories.*

5.1 Environmental Benefits, Relative to Current Footprint

Six recent studies estimated the percentage of the U.S. cradle-to-consumer food system's environmental footprint that could be saved (or avoided) if the U.S. reduced FLW. The studies considered inputs and environmental impacts similar to those discussed in Chapter 4 – the use of land for agriculture; use of blue water, fertilizer, and energy; and GHG emissions associated with FLW. Table 5-1 compares the methodologies and results of the six studies.

Four of the studies modeled halving U.S. FLW, while the remaining two studies modeled slightly greater reductions. ReFED (2021a) modeled 56 percent reduction, and Kummu et al. (2012) modeled a roughly 63 percent reduction. Kummu et al. (2012) derived its target by modeling a scenario where each of seven world regions (including NAO) achieved the lowest current FLW rate (among all seven regions) for each food category in each supply chain stage globally.

[41] EPA's forthcoming companion report (*The Environmental Impacts of U.S. Food Waste: Part 2*) will compare the environmental footprint of food waste prevention to that of food waste management pathways, such as landfills, combustion, composting, and anerobic digestion.

Other than the level of reduction modeled, the key difference among the six studies' methodologies is how they reported results. Four of the studies ((Read et al., 2020; Wood et al., 2019; Springmann et al., 2018; Jalava et al., 2016; Kummu et al., 2012) estimate savings associated with reducing FLW relative to the current environmental footprint of the food system, while Springmann et al. (2018) estimates savings relative to a future business-as-usual (BAU) scenario. ReFED (2021a) reported annual reductions only in absolute terms.

Examining estimates from the first four studies (Read et al., 2020; Wood et al., 2019; Springmann et al., 2018; Jalava et al., 2016; Kummu et al., 2012), there is general agreement among three of the studies—Kummu et al. (2012); Wood et al. (2019); and Jalava et al. (2016)—about the magnitude of environmental benefits that could be achieved by reducing U.S. FLW. The three studies estimate reductions ranging from 13 to 16 percent across the inputs and environmental impacts measured by more than one of the studies – use of land for agriculture, use of blue water, fertilizer, and energy; and GHG emissions.[42] Uniquely, Wood et al. (2019) estimated potential reductions in ammonia emissions from fertilizer use (14 percent) and Jalava et al. (2016) estimated potential savings of green water (12 percent). No other studies addressed these inputs, but these estimates present roughly similar magnitudes of savings to the other resources and impacts in the three studies.

The main differences among the three studies' methodologies include scope and treatment of imports. Wood et al. (2019) focused exclusively on halving FLW from retail and consumption stages, while all other studies in this chapter modeled reducing FLW all along the supply chain. While most studies presented in this chapter (and this report) assumed the U.S. food supply was domestically produced when calculating environmental impacts, Jalava et al. (2016) attempted to improve accuracy by applying the global (rather than U.S.) average water use factor to imported foods that were lost or wasted.

The estimates presented in the above studies are in line with modest expectations. If roughly one-third[43] of the U.S. food supply is lost or wasted (see Chapter 3), and FLW accounts for roughly one-third[44] of the inputs and environmental impacts of the U.S. food supply (see Chapter 4), then halving FLW would be expected to achieve savings of around one-sixth (i.e., one half of one third, or 17 percent) of the current food system's inputs and environmental impacts. Thus, the results of these three studies, at 12 to 16 percent, are not surprising. Differences between the makeup of FLW (e.g., food categories and supply chain stages at which food was lost or wasted) and the makeup of the overall food supply could account for the differences.

However, the percentage estimates of Read et al. (2020) are consistently lower than those of the other three studies, ranging from 9 to 10 percent. As described in Chapter 4, Read et al. (2020)'s use of an EEIO model may explain this difference; however, EEIO models' inclusion of intermediate inputs,[45] in addition to primary inputs, would be anticipated to increase both the inputs and savings, but the authors' results were lower than, not higher than, many other studies, once differences in scope are considered.

Looking at specific environmental measures, two other methodological differences emerge between Read et al. (2020) and other studies. First, while many other studies in this chapter and the previous chapter measure the use of fertilizer, Read et al. (2020) modeled eutrophication potential (i.e., nitrogen releases due to fertilizer use) by combining nitrogen fertilizer application data with published factors and models of loss. While this metric is potentially more useful than simply estimating fertilizer use, as it estimates the environmental impact, rather than just the input, the results are not directly comparable to that of the other presented studies. Read et al. (2020) did not publish an estimate of fertilizer use. Read et al. (2020) estimates a 10 percent reduction in eutrophication potential from halving U.S. FLW, while the others estimate a 14 to 16 percent reduction in nitrogen and phosphorous fertilizer application.

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[42] The percentages are in relation to each individual study's baseline which is influenced by the breadth of stages included and methodology. For example, Wood et al. (2019) estimates an environmental savings of 1.2 trillion L by halving FLW which represents a 14% reduction compared to her baseline. Read et al. (2020) estimates an environmental savings of 12.2 trillion L by halving FLW which represents a 9% reduction compared to his baseline. Wood was only examining the environmental impacts and potential savings of FLW reductions from the retail and consumption stages, whereas Read was looking across the full supply chain.

[43] Estimates range from 25 to 45 percent, when measured by weight or calories. See Table 3-1.

[44] Estimates vary by study and by input or environmental impact. Results from Read et al. (2020) excluded. Estimates reported in the literature as percentages of the total cradle-to-consumer food system include: 29 percent of GHG emissions (Venkat, 2012), approximately one third of blue water to produce crops and livestock and 30 percent agricultural land (Birney et al., 2017), and 42 percent of cultivated cropland and 44 percent of water used for irrigation (Toth and Dou, 2016). None of these studies include FLW from all supply chain stages

[45] For example, EEIO models include both the freshwater used in primary production, along with the additional inputs used to deliver that water, whereas the methodologies of Jalava et al. (2016), Kummu et al. (2012), and Wood et al. (2019) quantify just the first order inputs.

TABLE 5-1. MAXIMUM ENVIRONMENTAL BENEFITS OF HALVING U.S. FLW

Environmental Impact	Environmental Savings					
	Relative to Current Food System Footprint (as determined by source)					Relative to 2050 BAU Scenario
	Jalava et al. (2016) NAO	Kummu et al. (2012) NAO	Read et al. (2020)	ReFED (2021)	Wood et al. (2020)	Springmann et al. (2018)
Land (million m^2)		82,800 ↓14%	300,000 ↓9%		427,000 ↓16%	209,000 ↓13%
Water (million L)	↓13%	6,400,000 ↓15%	12,000,000 ↓9%	15,000,000	1,200,000 ↓14%	24,000,000 ↓15%
Fertilizer (million kg)		1,500 NPK ↓14%	[eutrophication indicator] ↓10%		• P ↓15%	2,930 N, 402 P ↓16%
Energy (million GJ)			↓9%	112	577 ↓15%	
GHG (million MTCO$_2$e)		940	92 ↓8.5%	75	87.5 ↓14%	41 ↓9%

All estimates represent results from a 50% FLW reduction, except Kummu et al., 2012, (63%) and ReFED, 2021a, (56%).

In addition, Read et al. (2020) estimates 6 percent lower energy savings than Wood et al. (2019) (9 and 15 percent, respectively), likely due to differences in the scope of energy use included in the two studies. Read et al. (2020) included energy use all along the cradle-to-consumer supply chain, while Wood et al. (2019) excluded energy use during the consumption stage. Energy use in the consumption stage of the food supply chain is chiefly for refrigeration and cooking (Vittuari et al., 2020), and it is unclear to the authors of this paper how the prevention of FLW would significantly reduce this type of energy use. If the food that was ultimately wasted was never purchased, for example, a household's refrigerator would still be running and it may, in fact, use more energy to cool a less full refrigerator. If Read et al.'s (2020) model accounted for this dynamic, it could be anticipated to produce lower energy savings in the consumption stage than in other stages. Given that consumption stage energy use accounts for the majority of the supply chain's energy use (Pagani et al., 2020; Vittuari et al., 2020), Wood et al. (2019) would be expected to project a larger decrease in energy use than Read et al. (2020).

ReFED (2021a) does not provide percentage values (nor do their estimates of savings rely on estimates of impacts of the total food supply chain); however, their estimated savings of water and GHG emissions are in line with the other studies. Their GHG emissions savings may be understated because the emissions from meat and dairy were not included within primary production.

5.2 Environmental Benefits, Relative to Future Footprint

Four of the five abovementioned studies (all but ReFED (2021a)) measured savings relative to the current environmental footprint of the cradle-to-consumer food system; however, the sixth study (Springmann et al., 2018) considered projected changes in food production and consumption between 2010 and 2050 (using the IMPACT model[46]) when estimating benefits of halving FLW. This is important (especially for the projections of global environmental benefits in the next chapter) as global food production and consumption are expected to change substantially in coming decades due to socioeconomic factors, such as population and income growth, and environmental pressures will increase as a result.

By halving FLW, Springmann et al. (2018) projects the U.S. could achieve reductions of 14 to 16 percent from a 2050 BAU food system footprint, with regard to agricultural land use, water use, and nitrogen application; and a 9 percent reduction in non-CO_2 GHG emissions from primary production. Note that Springmann et al. (2018) looked exclusively at CH_4 and N_2O emissions during primary production, rather than at all GHG emissions, during the entire cradle-to-consumer food system, like other studies described above (Read et al., 2020; Wood et al., 2019). Springmann et al.'s 2050 BAU scenario includes population growth and demographic changes but does not include any new dedicated measures to mitigate the environmental impacts of the food system, such as technological advances or shifts to less environmentally-intensive diets. Additionally, although yields are expected to increase by 2050, this study did not include any expected yield gains, or improvements in livestock or nitrogen efficiencies when developing the 2050 BAU scenario.

Many of the studies presented in this chapter also evaluated other measures to move toward a more sustainable future, including dietary shifts (toward healthier foods or towards less resource-intensive foods) and improvements in yields and resource efficiency. These studies compared the benefits of each strategy and evaluated combinations of strategies, pairing FLW reduction with some or all of the other strategies studied, finding greater benefits, as would be expected.

[46] IMPACT = International Model for Policy Analysis of Agricultural Commodities and Trade

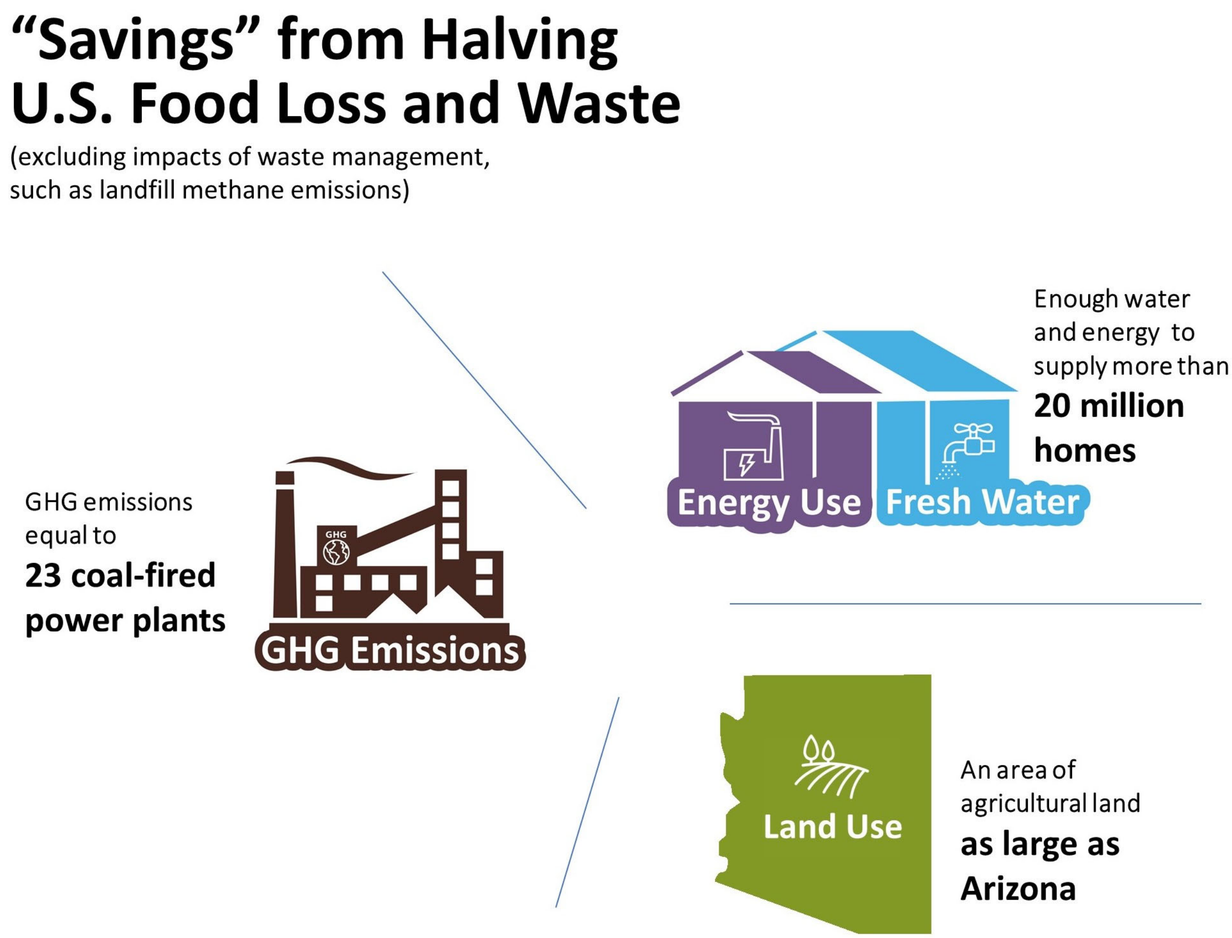

FIGURE 5-1. MAXIMUM ENVIRONMENTAL BENEFITS OF HALVING U.S. FLW

This figure depicts the projected annual savings from halving U.S. food loss and waste. The figure examines the cradle-to-consumer food supply chain only and thus excludes additional savings of methane emissions from landfills.
Data Source: Read et al. (2020); U.S. EPA (2021a, 2018); USCB (2021); U.S. DOE (2020)

5.3 Summary of Environmental Benefits

Taking all the reviewed methodologies into account, Read et al. (2020) provides the most comprehensive estimates of potential environmental savings from halving FLW in the U.S. However, as with the study's estimates of the total impacts of FLW, other studies' methodologies may estimate greater reductions if they were extrapolated to cover the same scope Read et al. (2020). Also, none of the studies presented here accounted for economic factors such as rebound effects that may impede realization of environmental benefits, and thus should be considered each authors' estimates of upper bound for benefits. In summary, Read et al. (2020) estimates the following annual environmental savings (i.e., avoided inputs and environmental impacts) from halving U.S. FLW:

- More than 300,000 square km^2 (75 million acres) agricultural land – an area greater than the State of Arizona;[47]
- 12 trillion L (3.2 trillion gallons) blue water – equal to the water use of 29 million American homes;[48]
- Nearly 290,000 metric tons (640 million pounds) of bioavailable nitrogen from agricultural fertilizer with the potential to reach a body of water, cause algal blooms and deteriorate water quality; [49]
- 940 million GJ (262 billion kWh) energy – enough to power 21.5 million U.S. homes;[50] and
- 92 million $MTCO_2e$ GHG – equal to the CO_2 emissions from 23 coal fired power plants in a year.[51]

For policymakers wanting to project the potential environmental benefits of halving FLW in only the retail and consumption stages, akin to UN SDG Target 12.3 and the EPA and USDA goal, Wood et al. (2019) may prove the most useful resource. The authors estimate the following maximum potential savings from halving U.S. retail and consumption stage FLW annually, from cradle-to-store: 427,000 km^2 (106 million acres) agricultural land, 1,200 trillion L (317 billion gallons) blue water, 337,000 million kg (743 billion pounds) phosphorous fertilizer, 577 million GJ (160 billion kWh) energy, and 88 million $MTCO_2e$.

5.4 Environmental Benefits, By Food Category and Supply Chain Stage

In addition to modeling the total benefits of halving FLW, Read et al. (2020) modeled the environmental impacts of halving each category of wasted food. Comparing across 13 food categories,[52] Read et al. (2020) found that reducing FLW in the meats and cereals categories resulted in the largest reductions in energy, eutrophication potential, land use, and GHG emissions, whereas reducing FLW in the cereals and fresh fruits and vegetables categories resulted in the largest reduction in blue water use. Wood et al. (2019) similarly identified animal products as the key contributor to phosphorous fertilizer application and ammonia emissions (due to nitrogen fertilizer application) associated with FLW, and the waste of fruits as the key contributor to the blue water footprint of FLW.

Read et al. (2020) also simulated the embodied environmental impacts of halving FLW at each stage in the supply chain, in order to identify the sectors in which reductions could provide the greatest environmental benefits. The authors modeled all four supply chain stages, further breaking down the consumption stage into three sectors: foodservice (restaurants), institutional food service (schools and hospitals), and households, for a total of six stages or sectors.

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[47] State of Arizona land base is 72.7 million acres and is the sixth largest U.S. state

[48] EPA WaterSense. "The average American family uses more than 300 gallons of water per day at home." (U.S. EPA, 2018).

[49] Explanation of the eutrophication indicator taken from the EPA User Manual for the Sustainable Materials Management Prioritization Tools, which is built on the USEEIO.

[50] "In 2018, 120.3 million homes in the United States consumed 1,462 billion kilowatt-hours (kWh) of electricity (U.S. DoE, 2020). On average, each home consumed 12,146 kWh of delivered electricity (U.S. DoE, 2020)". Source: (U.S. EPA, 2021a)

[51] EPA Greenhouse Gas Equivalencies Calculator (U.S. EPA, 2021a)

[52] Food categories included: beverages, cereals, eggs, fresh fish and seafood, processed fish and seafood, fresh fruits and vegetables, processed fruits and vegetables, meat, milk, oilseeds and pulses, fresh roots and tubers, processed roots, and tubers and sugar.

As shown in Figure 5-2, the authors found that halving FLW at every stage of the supply chain could reduce the environmental footprint of the U.S. cradle-to-consumer food supply chain by 8 to 10 percent. However, the bulk of these reductions could be achieved by halving FLW in only three of the six sectors analyzed: food processing, restaurants, and households. For example, halving FLW in those three stages (i.e., food processing, restaurants, and households) could reduce GHG emissions by almost 8 percent, while halving FLW in the three remaining stages (i.e., primary production, retail, and schools/hospitals) increased the reduction by less than 1 percent. Even when considering individual food categories there was little variation among which stages had the highest environmental benefits or the order in which they ranked (Read et al., 2020).

Among the six sectors, the authors found that the largest reductions in GHG emissions and energy use could be achieved by halving FLW in restaurants; the greatest reductions in agricultural land use and eutrophication potential (due to nitrogen fertilizer application) could be achieved through halving FLW from food processing; and the largest reduction in blue water use could be achieved by halving FLW in households. Overall, the authors found that halving FLW at retail and schools/hospitals carried minimal environmental benefits due to the relatively low current rate of FLW compared with other sectors (Read et al., 2020).

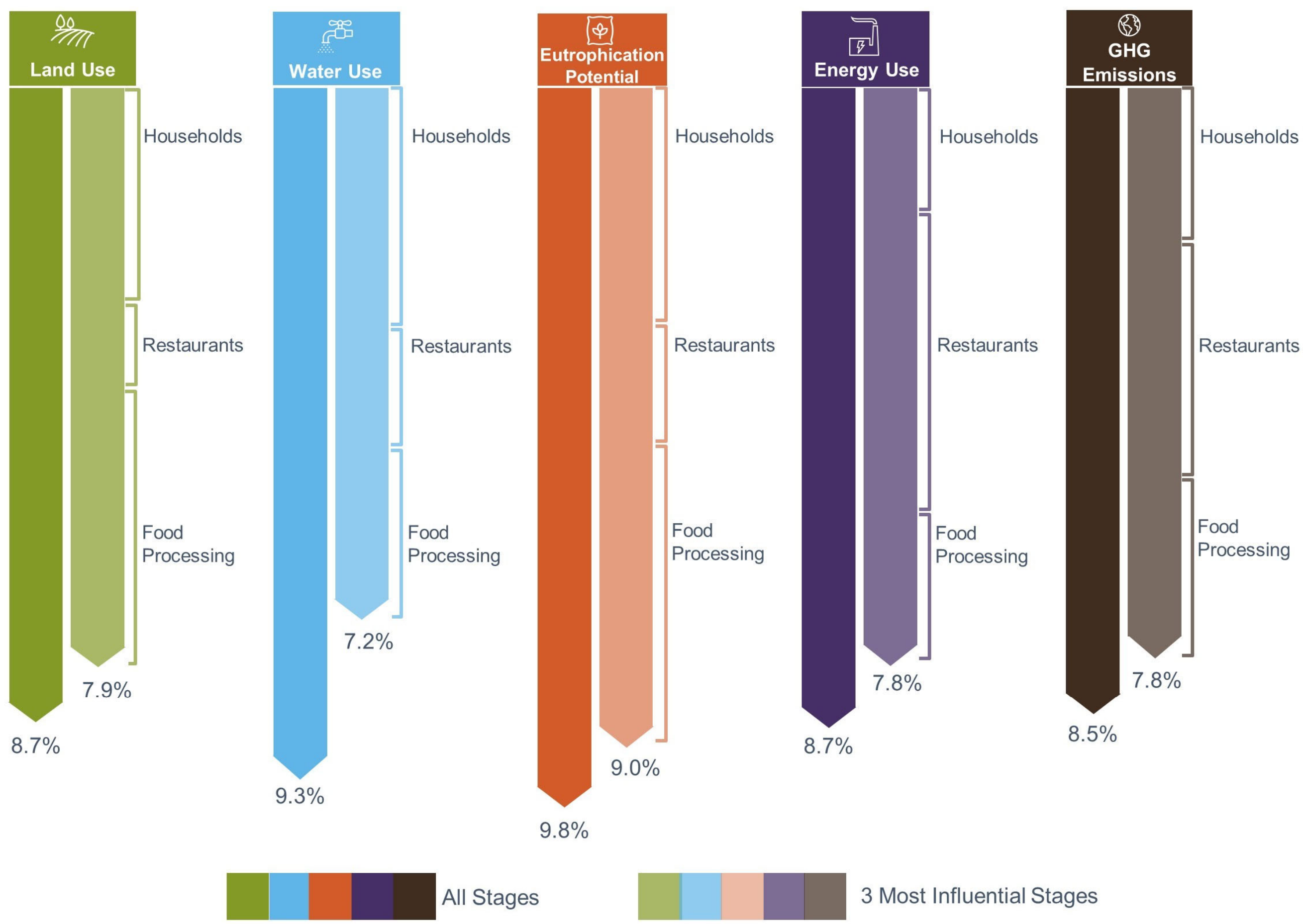

FIGURE 5-2. MAXIMUM ENVIRONMENTAL BENEFITS OF HALVING FLW, BY SUPPLY CHAIN STAGE

Data Source: Read et al. (2020)

CHAPTER 6.

U.S. Food Loss and Waste in Global Context

This chapter examines U.S. FLW in global context to evaluate the U.S. contribution to this global issue and to highlight key similarities and differences among regions and countries. This information can guide U.S. policymakers as they set priorities and tailor FLW reduction policies to maximize their environmental benefit, as the most effective solutions may vary across the globe. The chapter also provides a snapshot of the environmental benefits that could be achieved by global achievement of the UN Sustainable Development Goal Target 12.3 to halve FLW by 2030.

KEY FINDINGS

- *Global FLW contributes 3.7 gigatons of CO_2e annually, excluding landfill methane emissions.*
- *Several countries, including the U.K. and Japan, have reported significant progress toward halving FLW.*
- *The U.S. is responsible for 10 percent of global FLW, while accounting for less than 5 percent of global population.*
- *The U.S. exceeds the average per person FLW and FLW-related GHG emissions of high-income countries by roughly a third.*
- *Downstream FLW and animal product FLW comprise a greater share of U.S. FLW than of global FLW, thus the environmental footprint of each unit of U.S. FLW is substantially larger than the global average.*
- *Halving global FLW could reduce cumulative global food system greenhouse gas emissions by 24 percent between 2020 and 2100 (331 Gt CO_2e), relative to a business-as-usual scenario.*

6.1 U.S. Share of Global FLW

In 2007, the U.S. was responsible for approximately 10 percent of global edible FLW (by weight) but accounted for less than five percent of the world's population (UN, 2020a, b; CEC, 2017; FAO, 2011). As shown in Figure 6-1, the U.S. generated the third largest absolute amount of FLW by weight (168 million tons per year) of any country in 2017, preceded by China and India (Guo et al., 2020).

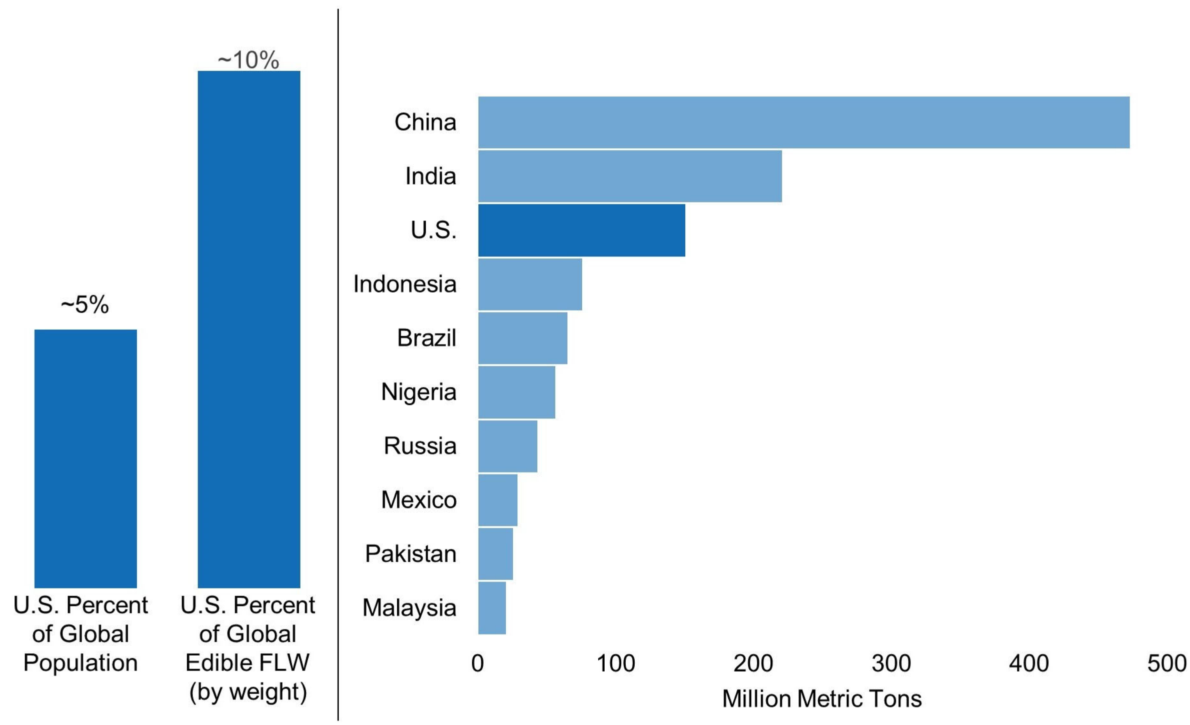

FIGURE 6-1. GLOBAL SIGNIFICANCE OF U.S. FLW

The U.S. has less than five percent of the world's population but generates approximately 10 percent of the world's food loss and waste (FLW). In 2017, the U.S. generated the third largest amount of FLW by weight (168 million tons per year) of any country. Data Source: UN (2020a, b); CEC (2017); FAO (2011); Guo et al. (2020)

6.2 Share of Food Supply Lost or Wasted

The FAO (2011) estimated that in 2007, approximately one-third of edible food, by weight, was lost or wasted globally.[53] Using FAO's regional data, the World Resources Institute (WRI) estimated that the 2009 average share of total food lost or wasted, was relatively similar across all seven major geographic regions of the world,[54] with 34 to 36 percent lost on average in all regions except South and Southeast Asia (26 percent) (Lipinski et al., 2013). More recently, Guo et al. (2020) estimated 29 percent of all food (edible and inedible parts) was lost or wasted globally in 2017.[55] By comparison, the U.S. lost or wasted 35 to 36 percent of food (edible and inedible parts), according to the most comprehensive estimates presented in Section 3.2 (ReFED, 2021a; CEC, 2017). While the share of food supply (by weight) that is lost or wasted may be similar across many world regions, the size of each region's food supply varies widely (even on a per person basis), limiting this metric's usefulness.

When FLW measured in calories instead of by weight, the share of total food lost or wasted is estimated to be much higher for the NAO region (which includes the U.S.) at 42 percent, compared with 15 to 25 percent in all other regions (Lipinski et al., 2013). In addition, the size of the per person food supply in the NAO region (4,230 calories per person per day) exceeds that of any other world region by more than 1,200 calories per person per day (Kummu et al., 2012).[56]

[53] FAO developed this estimate using a top-down approach that incorporated country-specific production volumes and food balance sheets and regional level waste generation factors across the different stages of the food supply chain. It should be noted that much of the consumption stage data for undeveloped regions were derived from limited to no primary data from these regions.
[54] Regions include: Sub-Saharan Africa; Europe (including Russia); Industrialized Asia; Latin America; North Africa and West-Central Asia; North America and Oceania; and South and Southeast Asia.
[55] Guo used FAO (2017) food balance sheets coupled with regional waste generation factors obtained from Porter et al. (2016).
[56] This study is one of the primary bases for the global goal to reduce FLW by 50 percent.

A comparative analysis of the potential to reduce FLW (using best available practices and technologies) found that the potential is greatest in regions where there is the least need for additional food supply, and smallest in regions with the greatest malnutrition challenges. For example, as of 2009, the study projects that the NAO region and Europe could reduce FLW by 63 percent compared to Africa which could likely only reduce FLW by 31 percent (Kummu et al., 2012).

6.3 Characterization of FLW

This section looks at key similarities and differences in the FLW of the United States and other countries, examining two factors that greatly affect the environmental footprint of FLW – when food is lost or wasted (i.e., at what stage of the supply chain) and what categories of food are lost or wasted.

Supply Chain Stage

In general, lower-income nations lose a greater share of food during primary production, handling, and storage than higher income nations, often due to insufficient infrastructure (e.g., cold chains) and technologies. Conversely, higher-income nations, where consumers have more financial resources to purchase excess food, waste a greater share of food during the consumption stage than lower income nations (FAO, 2019b; Spang et al., 2019; FAO, 2013a, 2011). Note that this FLW during the consumption stage may be driven by forces beyond individual and interpersonal factors, such as policies, marketing, media, or actions of the food industry (NASEM, 2020).

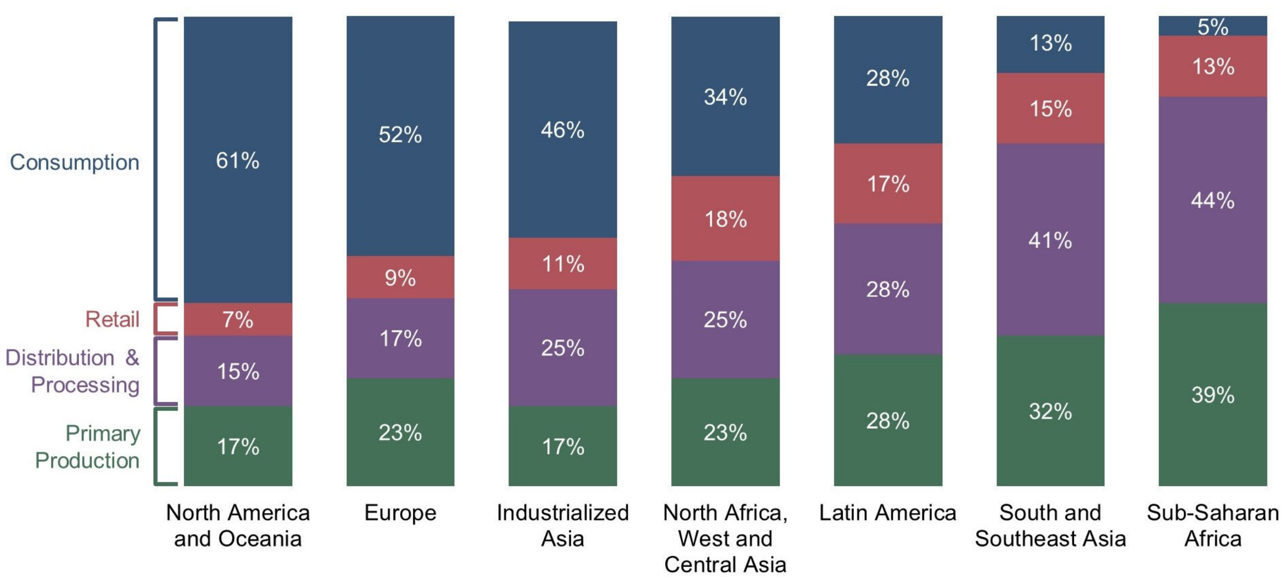

FIGURE 6-2. SHARE OF CALORIES LOST AND WASTED, BY SUPPLY CHAIN STAGE, FOR EACH GLOBAL REGION

In higher income, more developed regions like North America and Oceania the largest share of food loss and waste (FLW) is generated during the consumption stage (i.e., households and food service). In lower income, less developed regions like Sub-Saharan Africa, the primary production and distribution and processing (including storage) stages contribute the largest share of FLW.
Data Source: Lipinski et al. (2013)

The FAO (2011) estimates that in low-income countries, approximately 40 percent of FLW occurs during production and processing, whereas in medium- and high-income countries, approximately 40 percent of FLW occurs during retail and consumption. This pattern is further illustrated by the WRI analysis (Lipinski et al., 2013) of the regional FAO (2011) data. Figure 6-2 shows the distribution of FLW by stage of the food system for each world region. The production, handling and storage stages contribute substantially to FLW for less developed regions like sub-Saharan Africa (72 percent), whereas the consumption stage contributes the largest share of FLW in more developed regions, such as the NAO Region (58 percent). This is consistent with the U.S.-specific estimates presented in Section 3.5.

Food Category

Globally and in the NAO region, fruits and vegetables comprise the largest share of FLW, and fish and seafood comprise the smallest share.[57] One key difference between NAO and the global average is the waste of animal products, including meat, and milk and eggs; both categories account for a greater share of FLW in the NAO region than in any other region (FAO, 2013a). See Figure 6-3 for the relative FLW of each food type by region, according to FAO data (FAO, 2013a). Chen et al. (2020) provides additional detail at the country level, estimating that the U.S. wastes 7.5 times more dairy, 3.5 times more meat, and 2 times more fruits and vegetables than the global average.

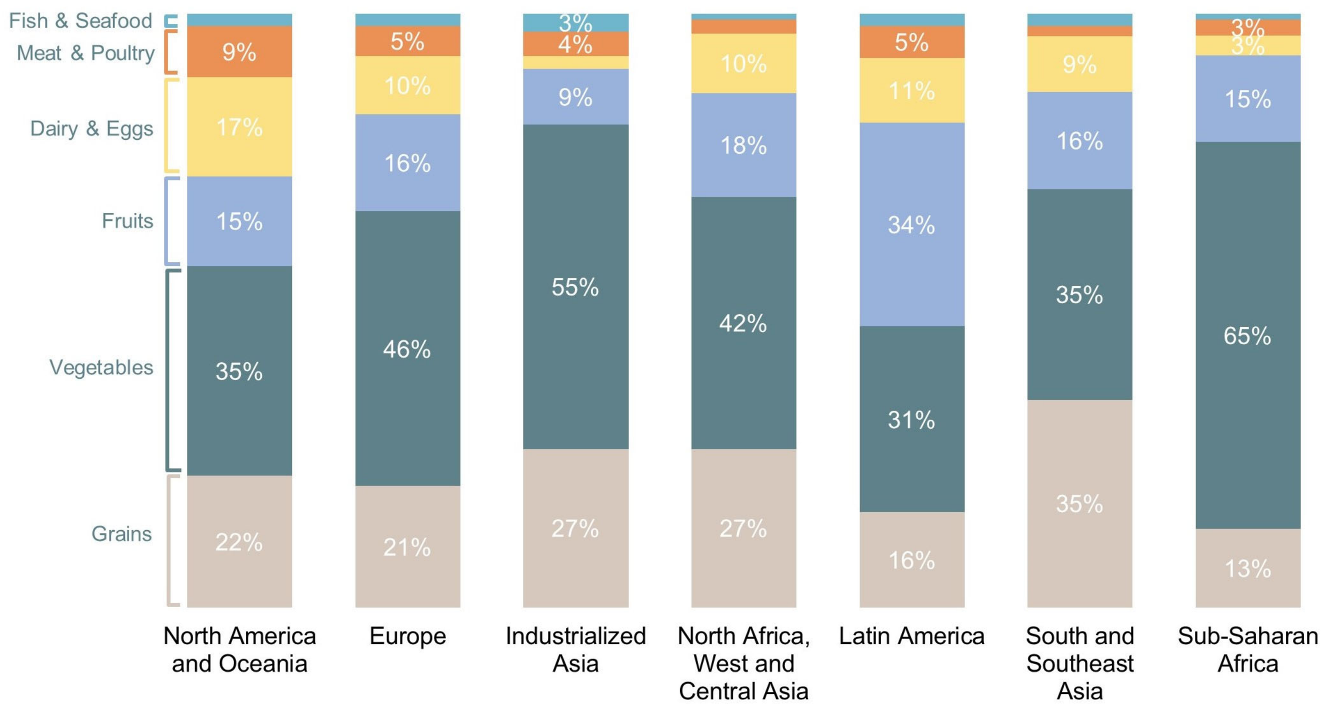

FIGURE 6-3. SHARE OF FLW, BY FOOD CATEGORY, FOR EACH GLOBAL REGION

Fruits and vegetables make up the largest share of food loss and waste (FLW) in every region. The loss and waste of animal products (including meat, fish and seafood, milk and eggs) varies across regions, from 28 percent in North America and Oceania to 7 percent in Sub-Saharan Africa.
Data Source: (FAO, 2013a, b)

[57] Seafood losses are typically undercounted (Love et al., 2015).

6.4 Per Person FLW

Per person measures allow for meaningful comparisons among countries of different sizes, thus the UN Sustainable Development Goal (SDG) Target 12.3 for FLW and many national FLW goals, including the U.S. goal, are set on this basis. Three studies in the literature (Chen et al., 2020; Hiç et al., 2016; Lipinski et al., 2013) allow for comparison of global and U.S. (or NAO regional) per person edible FLW (i.e., each study produces a global estimate and a U.S. or NAO estimate). While all three studies relied on FAO food availability data, their scope and methodology of each study differs. Chen et al. (2020) examines consumption stage FLW exclusively, while the other two studies include FLW from additional stages of the supply chain. See Figure 6-4 for a comparison of the results. All studies indicate per person FLW in the U.S. is more than double the global average, whether measured by weight or calories.

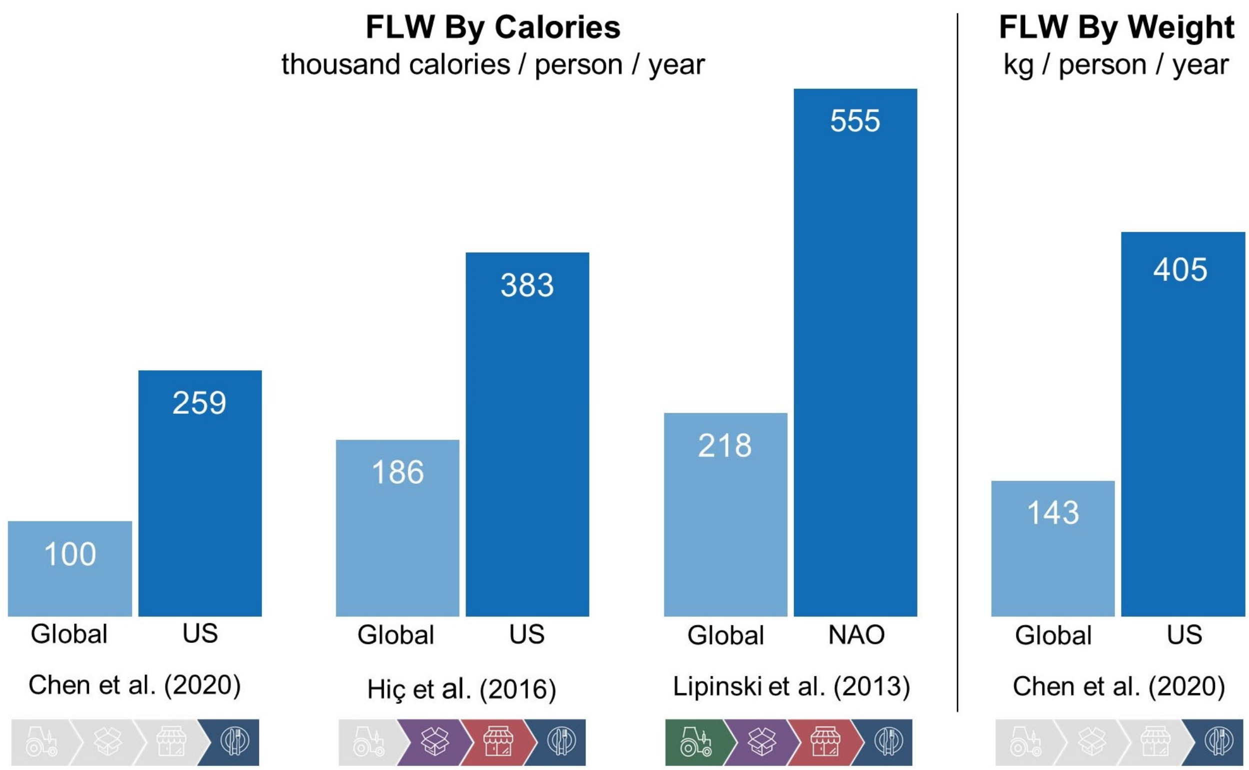

FIGURE 6-4. GLOBAL AND U.S. PER PERSON ANNUAL EDIBLE FLW

Food loss and waste (FLW) per person in the United States is more than double the global average, whether measured by weight or calories. All these estimates include only edible FLW, excluding inedible parts such as bones or shells.

Hiç et al. (2016) estimated per person FLW in calories in 111 countries in 2010 by calculating the difference between food availability and the current dietary calorie requirements in each country. The authors calculated calorie requirements for each country based upon demographic and anthropometric data (such as body weight) from the UN and other sources.[58] Hiç et al. demonstrated that the following eight countries exhibited food surpluses, by calories, greater than 60 percent: the United States, plus Austria, Belgium, Egypt, France, Ireland, Italy, and Turkey.

[58] The study calculated country-specific dietary calorie requirements, noting the highest dietary requirements for the U.S., Lithuania, and United Arab Emirates of 2700-2800 calories/person/day.

Lipinski et al. (2013) highlights that per person edible FLW, by calories, in the NAO region (1,520 cal/person/day) is double that of any other world region (other regions range from 414 to 748 cal/person/day). Chen et al. (2020) provides country-specific estimates of per person edible FLW[59], by weight, finding that the United States generates more than double the global average of per person edible FLW (503 g/person/day, as compared to 178 g/person/day). The authors also demonstrated that the U.S. ranked third highest of 151 countries examined in per person edible FLW, behind Ireland and New Zealand.

Chen et al. (2020) went a step further to examine the nutrient composition (beyond calories) of the food that is lost and wasted by each country during the consumption supplly chain stage (i.e., households and food service). The authors estimated per person edible FLW for 151 countries in 2011 by combining edible amounts and nutrient composition for 225 food items per country from the GENuS dataset (Smith et al. (2016), as cited in Chen et al. (2020)) with region-specific FLW ratios from FAO. This analysis allowed them to produce a nutrition-related metric for FLW – the "wasted daily diets" (WDD) contained in each country's per person FLW. A WDD represents the number of daily nutritious diets (i.e., including recommended amounts of 25 nutrients) that could be provided based on a country's per person FLW. By definition, this amount is equal to or lower than the number of daily diets that could be provided based solely upon calorie requirements. Note that these estimates include only consumption stage FLW[60], thus underestimating the full potential of FLW.

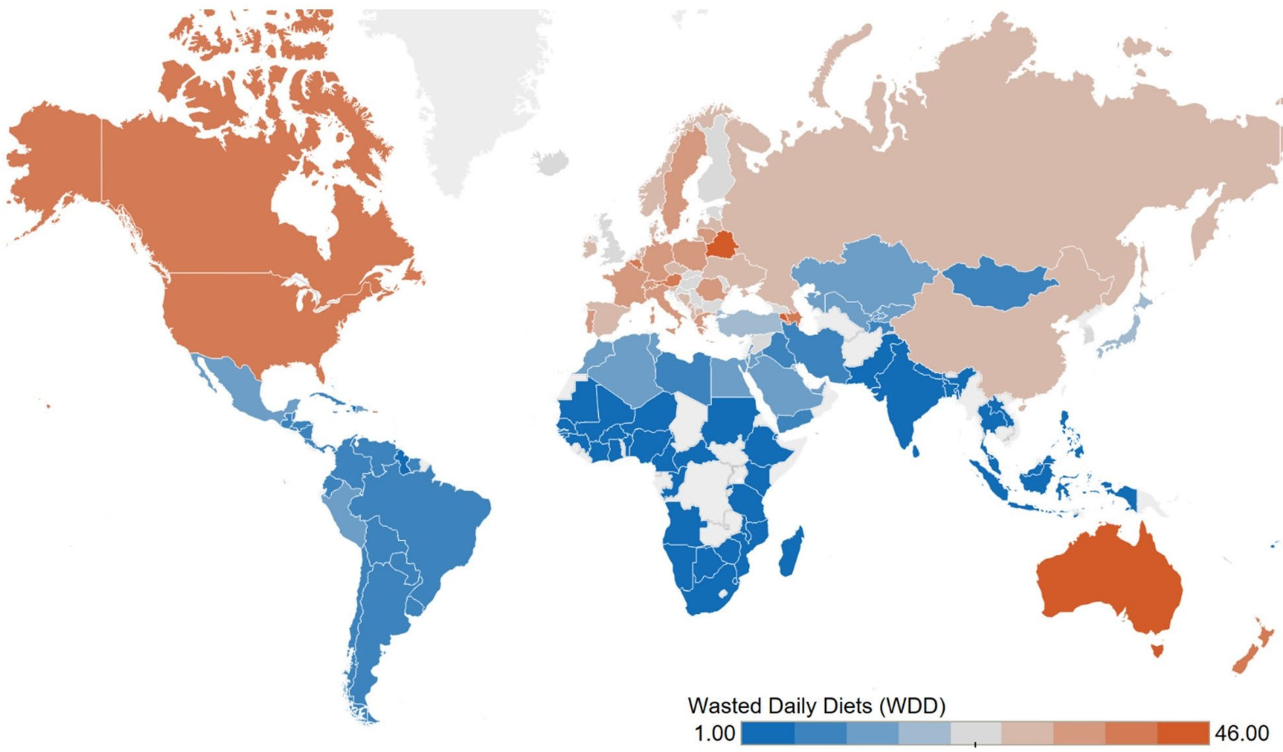

FIGURE 6-5. WASTED DAILY DIETS

This figure shows a heatmap of Wasted Daily Diets (WDDs). Orange indicates the largest number of WDDs and blue indicates the fewest number of WDDs. WDDs represent the number of daily nutritious diets (including recommended amount of 25 nutrients) that could be provided based on a country's annual per person food waste at the consumption supply chain stage (i.e., households and food service). Average global per person consumption-stage food waste embodies 18 WDDs; the United States embodies 41 WDDs, ranking fourth highest among 151 countries.
Data Source: Chen et al. (2020)

[59] Lipinski et al. (2013) and Chen et al. (2020) both used loss rates from Gustavsson et al. (2013); however, Lipinski et al. (2013) used the 2009 FAO FBS data and Chen used the 2011 GENuS data set which is a disaggregated version of the 2009 FAO FBS data.
[60] In the U.S., the consumption stage accounts for approximately one half of total FLW (ReFED, 2021a; Pagani et al., 2020; Vittuari et al., 2020; CEC, 2017).

According to Chen at al. (2020)'s calculations, average global annual per person FLW at the consumption stage embodies 18 WDDs, meaning an average person's consumption stage FLW over one year could fulfill the dietary requirements for one person for 18 days (or 18 people for one day). In contrast, the U.S. per person FLW embodies 41 WDDs,[61] ranking fourth highest among 151 countries. Figure 6-5 shows a heatmap of the WDDs for each country. The map shows that high-income countries, including the U.S., Canada, Australia, New Zealand, and many of the European member states have the highest WDDs globally.

In general, affluence is highly correlated with higher per person FLW rates, regardless of the metric (e.g., weight, calories or nutrients). The United States and other wealthy countries (i.e., upper-middle- and high-income countries) all have higher per person FLW than less wealthy countries and the global average (Chen et al., 2020; Xue and Liu, 2019; Vilariño et al., 2017; FAO, 2013a, 2011). Chen et al. (2020) demonstrated that mean FLW, by weight, in high-income countries is almost two times that in upper-middle-income countries and four to six times that in low-middle income and low-income countries. This pattern is consistent with a study by van den Bos Verma et al. (2020) which found a logarithmic relationship between consumer affluence and FLW at the consumption stage; at a threshold of affluence, the rate of consumption stage FLW increases with the level of affluence. Hiç et al. (2016) also demonstrates a correlation between affluence and FLW – showing the ratios of available to required calories increase with the Human Development Index (HDI). The HDI is a summary measure of average achievement in three key dimensions of human development: a long and healthy life, being knowledgeable, and a decent standard of living (UN, 2020b). However, Japan, with a relatively high HDI and low food surplus, provides an example of how this correlation need not be the case (Hiç et al., 2016).

U.S. per person FLW is notable in that it ranks third among all 151 countries, and, as shown in Figure 6-6, exceeds the average for high-income countries[62] by 64 percent (132 grams per day) (Chen et al., 2020).

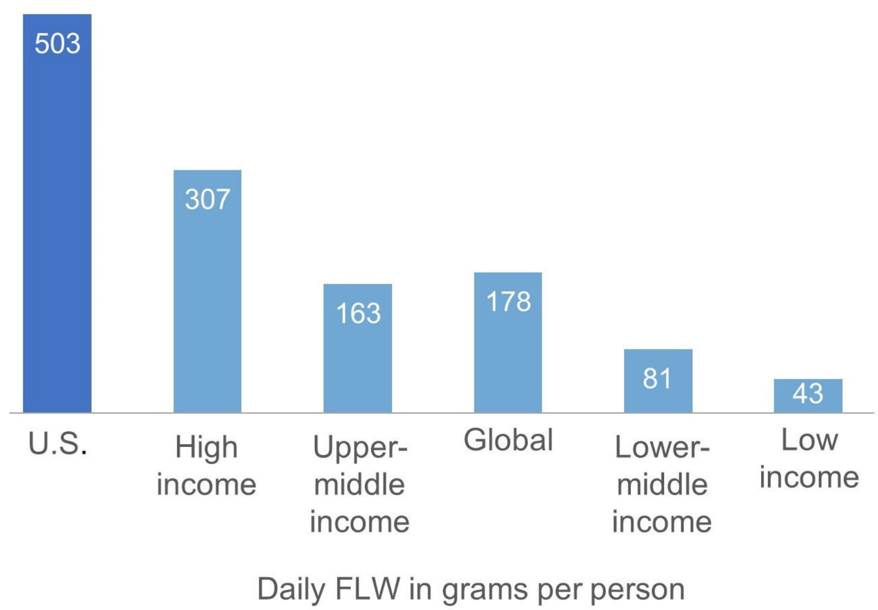

FIGURE 6-6. MEAN FLW PER PERSON, BY GLOBAL INCOME GROUP

Food waste during the consumption supply chain stage (i.e., households and food service) in the United States exceeds the mean for high-income countries (as defined by the World Bank) by 64 percent.
Data Source: Chen et al. (2020)

[61] In the U.S. an average person's FLW over one year provides enough calories to feed 133 people and enough protein to feed 117 people. When the 25 nutrients are considered, the limiting nutrient is vitamin E, followed by choline. For example, if Vitamin E were excluded from the analysis, the U.S. would have 54 WDDs rather than 41.

[62] The World Bank (2021) divides countries into four groups (low income, lower-middle income, upper-middle income, and high income) based upon gross national income (GNI) per capita data in U.S. dollars, converted from local currency using the World Bank Atlas method.

6.5 Progress Towards Reducing Per Person FLW

As described in Chapter 1, the United States is one of many countries to adopt a national goal to halve per person FLW at the retail and consumption stages by 2030, similar to the UN Sustainable Development Goal Target 12.3 (FAO, 2020). While the U.S. has not made progress toward halving FLW by 2030 (see Section 3.4), several countries have reported significant reductions in FLW. For example:

- The United Kingdom reduced per person edible FLW by 27 percent, and total per person FLW (i.e., FLW with inedible parts included) by 21 percent between 2007 and 2018 (WRAP, 2020).
- The Netherlands reduced per person edible household FLW by 29 percent between 2010 and 2019 (Champions 12.3, 2017b).
- Norway reduced per person FLW across industry, wholesale, retail, and households by 12 percent between 2010 and 2015, including an 11 percent reduction in per person edible household FLW (Stensgard and Hanssen, 2016).
- Denmark reduced per person edible household FLW by 8 percent per person, and five percent in total, between 2011 and 2017 (Danish EPA, 2018).
- Japan reduced household FLW by 13 percent between 2005 to 2009, achieving the majority of the reduction in the first year (Parry et al., 2015).

These countries have taken a variety of actions to achieve these reductions, including setting goals, developing national strategies with milestones, sponsoring educational campaigns, and developing partnerships with organizations and businesses across the food system.

Additional data will likely become available as more countries establish FLW baselines and implement FLW reduction programs. As of this writing, no country had announced that it had achieved Target 12.3, but the U.N. Environment Programme has established the Food Waste Index to compare countries' progress toward the goal (UN, 2021).

6.6 Global Environmental Footprint of FLW

The global food supply chain is a major driver of environmental degradation and natural resouce depletion. Globally the food system uses 70% of all freshwater withdrawals, occupies about 40% of ice-free land, produces 34% of anthropogenic greenhouse gas (GHG) emissions, and is the largest contributor to biodiversity loss and water pollution related to disruptions in the nitrogen and phosphorus cycles (Crippa et al., 2021; Tilman et al., 2017; Diaz and Rosenberg, 2008; Ramankutty et al., 2008; Molden, 2007).

Global FLW places a tremendous burden on the planet, embedding roughly one quarter of the total global use of cropland, freshwater resources, and fertilizers for food production, without accounting for the loss and waste of animal products (Kummu et al., 2012). Global FLW also contributes 3.7 gigatons of CO_2e[63] annually, not including emissions related to landfills (Mbow et al., 2019; WRAP, 2015; FAO, 2013a). If FLW were a country, in 2010 it would have been the third largest GHG emitter globally after China (21 percent of global emissions) and the United States (13 percent of global emissions) (Ritchie and Roser, 2020; FAO, 2013a).

As world population and incomes rise, leading to dietary shifts, pressures on the environment from the food system will rise as well. Studies project that food demand will increase by more than 50 percent between 2010 and 2050, and demand for more resource-intensive foods (i.e., animal products) will grow by nearly 70 percent during the same time period (UN, 2020a; Searchinger et al., 2019). Reducing FLW provides one pathway toward a more sustainable agricultural system (see Section 6.7).

As the U.S. chooses strategies to reduce FLW—and the environmental impact of FLW—it can be helpful for policymakers to understand how the inputs and environmental impacts associated with U.S. FLW compare to those of other countries.

[63] With emissions associated with the disposal of FLW included, FLW accounts for 4.4 gigatons of CO_2e (FAO, 2015a, 2013a).

Total Environmental Footprint of FLW

There are major differences in the magnitude of the environmental impact of FLW among countries, resulting from differences in absolute and per person amounts of FLW (see Sections 6.1 and 6.4) as well as the breakdown among the food categories lost or wasted and the supply chain stages at which food was lost or wasted in each country (see Section 6.3). Environmental footprint increases as FLW increases, even more so if more of the FLW happens downstream where embodied environmental impacts are greatest or more of the FLW is animal products or fruits and vegetables (see Section 3.5 and Section 3.6 for discussion).

Given that the U.S. has greater FLW and greater per person FLW than the global average, and that downstream FLW and animal product FLW comprise a greater share of U.S. FLW than of global FLW, it can be expected that the environmental footprint of U.S. FLW will be substantially larger than the global average. Three studies (Chen et al., 2020; Guo et al., 2020; Hiç et al., 2016) allow for a direct comparison of the inputs and environmental impacts of per person U.S. FLW to the global average and to other countries specifically.

Chen et al. (2020) estimated country-specific environmental footprints (including non-CO_2 GHG emissions, blue water use, cropland use, and nitrogen and phosphorous fertilizer application) of FLW per person per day in 2011 using global average characterization factors (i.e., the amount of environmental impact per gram of food) for 28 food groups. This method takes into account the amount and types of FLW in each country but does not account for regional or country-specific environmental impacts (e.g., differences in climate or production methods).

Figure 6-7 and Figure 6-8 show detailed results for countries grouped by world region and income groups, respectively, in order from highest to lowest per person daily FLW (Chen et al., 2020). Both figures also include U.S.-specific estimates (calculated by the study's authors) for comparison purposes. As shown in Figure 6-7 and Figure 6-8, high- and upper-middle-income countries and North America[64], Europe and Central Asia, and East Asia and the Pacific all had higher-than-world-average environmental footprint from producing wasted food (Chen et al., 2020). Of note, the authors also found that GHG emissions per person from only the meat that was lost or wasted in high-income countries exceeded the average GHG emissions per person of all FLW globally.

Chen et al. (2020) estimates that on average, global per person daily FLW is responsible for 124 g CO_2e (from non-CO_2 GHG emissions), 58 L blue water, 0.36 m^2 cropland, and 3.38 g fertilizer (combined phosphorous and nitrogen). For comparison, per person daily FLW in the U.S. accounts for 457 g CO_2e, 151 L blue water, 103 m^2 cropland, and 9 g fertilizer.

Examining the data at the country level, Chen et al. (2020) finds that per person U.S. FLW accounts for more blue water use and fertilizer application than that of any of the other 150 countries evaluated. Additional studies report that the U.S., along with China and India, accounts for the largest volumes of blue water associated with FLW (Conrad et al., 2018; Birney et al., 2017; Lundqvist et al., 2008).

Per person U.S. FLW also accounts for the third highest amount of non-CO_2 GHG emissions and fourth highest amount of cropland use, among all 151 countries. In addition, for each environmental criteria, the U.S. estimates exceeded the per person average for high-income countries by more than 24 percent (Chen et al., 2020).

[64] Chen et al. (2020) defines North America as U.S. and Canada.

	FLW g	Cropland m^2	Freshwater L	Fertilizer g N + g P	Non-CO_2 GHG Emissions g CO_2e
U.S.	503	103	151	9	457
North America	501	103	149	9	450
Europe & Central Asia	337	76	106	6	254
East Asia and Pacific	222	44	79	5	130
Middle East & North Africa	141	29	51	3	96
Latin America & Caribbean	121	28	45	3	143
South Asia	38	7	15	1	22
Sub-Saharan Africa	25	4	5	<1	17

FIGURE 6-7. DAILY PER PERSON FLW AND ASSOCIATED ENVIRONMENTAL FOOTPRINT, BY GLOBAL REGION

Per person food waste during the consumption supply chain stage (i.e., households and food service) in the United States and its associated cropland, freshwater, and fertilizer use, and greenhouse gas emissions exceed that of all world regions.
Data Source: Chen et al. (2020)

	FLW g	Cropland m^2	Freshwater L	Fertilizer g N + g P	Non-CO_2 GHG Emissions g CO_2e
U.S.	503	103	151	9	457
High Income	307	81	118	7	315
Upper-Middle Income	163	45	77	5	144
Lower-Middle Income	81	10	19	1	33
Low Income	43	8	12	1	32

FIGURE 6-8. DAILY PER PERSON FLW AND ASSOCIATED ENVIRONMENTAL FOOTPRINT, BY GLOBAL INCOME GROUP

Food waste during the consumption supply chain stage (i.e., households and food service) in the United States and its associated cropland, freshwater, and fertilizer use, and greenhouse gas emissions exceed the average for high-income countries.
Data Source: Chen et al. (2020)

Greenhouse Gas Emissions

Two other studies (Guo et al., 2020; Hiç et al., 2016) looked exclusively at GHG emissions from FLW. Unlike Chen et al. (2020) discussed above, these studies used GHG emissions data specific to each country (Hiç et al., 2016) or FAO region (Guo et al. (2020). Figure 6-9 compares the results of all three studies.

Like Chen et al. (2020) discussed above, Hiç et al. (2016) focused exclusively on CH_4 and N_2O from producing food that is ultimately wasted. Hiç et al. (2016) used agricultural emissions data in FAOSTAT[65] to estimate emissions from crop and livestock production. Globally, the authors estimate that by 2050, GHG emissions from FLW will increase to equal the total GHG emissions of the United States currently (Hiç et al. (2016).

Hiç et al. (2016) found, based upon 2010 data, that emissions associated with FLW in Northern America[66] were 340 g CO_2e per person and 42.7 million MTCO_2e total annually, similar to Western Europe (332 g CO_2e per person) and less than Australia & New Zealand, South America, and Northern Europe (848, 684, and 407 g CO_2e per person, respectively). Northern America also ranked fourth for total emissions, behind Eastern Asia, South America, and Southern Asia, accounting for approximately 8 percent of global non-CO_2 GHG emissions from FLW. The estimates of Hiç et al. (2016) are lower than those of Chen et al. (2020), as would be expected due to the difference in geographic boundaries of the studies (Northern America and the United States, respectively), since U.S. FLW-related GHG emissions exceed those of Canada and Mexico (Chen et al., 2020).

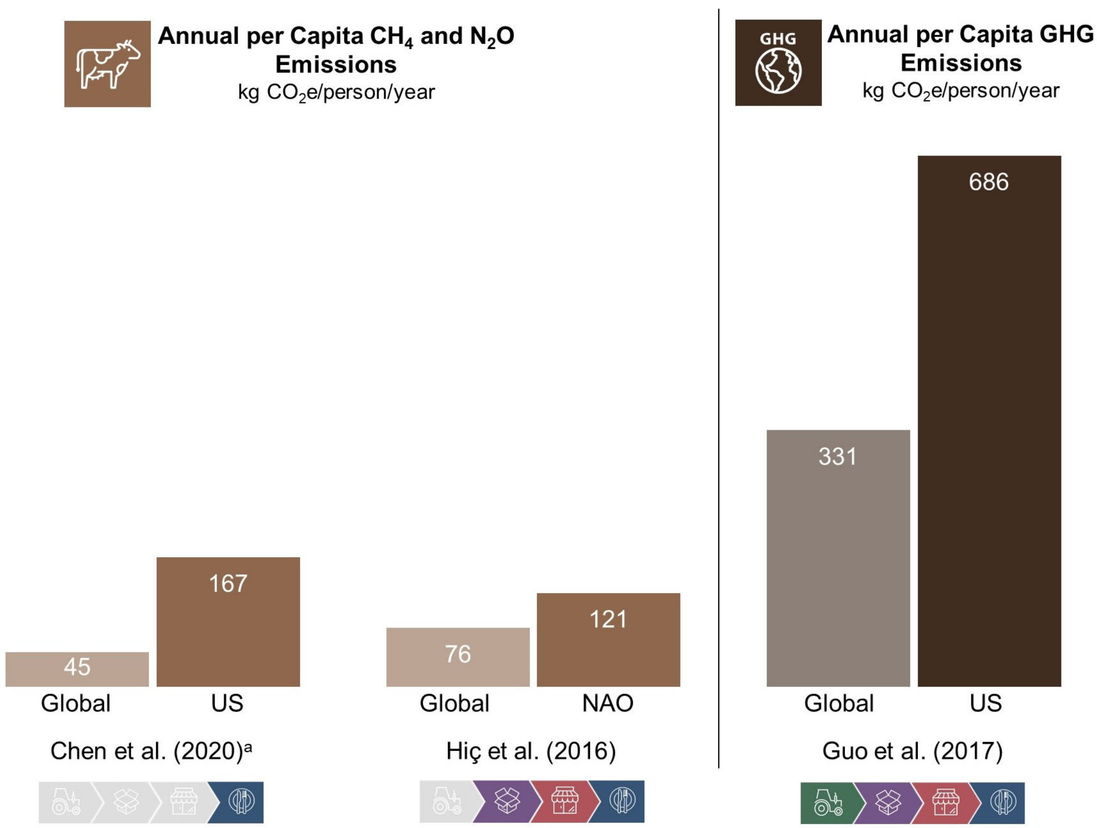

FIGURE 6-9. PRIMARY PRODUCTION STAGE GHG EMISSIONS ASSOCIATED WITH FLW

The United States or the North America and Oceania Region exceed global averages for greenhouse gas emissions during the primary production of food. Guo et al. (2020) also included GHG emissions from international transportation.

[65] FAOSTAT considers the following agricultural production and management activities to estimate agricultural GHG emissions: enteric fermentation, manure management, manure applied to soils, manure left on pasture, crop residues, cultivation of organic soils, burning crop residues and savanna, rice cultivation, and synthetic fertilizer applications.
[66] Hiç et al. (2016) breaks America in to Northern, Central, and South regions, likely including Mexico in Northern America, whereas other studies examining NAO region excluded Mexico (categorizing it as part of Latin America region, with Central and South America). The study uses a system of 19 world regions, different than other studies presented in this paper.

More recently, Guo et al. (2020) determined the region- and country-specific GHGs associated with FLW using updated FAO FLW data for 2017 (FAO, 2019a). Guo et al. (2020) used an expanded scope, including emissions of all GHGs from primary production and international transportation – as compared to Chen et al. (2020) and Hiç et al. (2016), which focused exclusively on non-CO2 GHG emissions from primary production. None of the three studies presented here included GHG emissions from other stages of the food supply chain, such as processing, distribution (domestic), retail or consumption. Interestingly, the authors found that the emissions from international transportation were marginal compared to those from primary production, representing only 3 percent of total emissions examined.

Guo et al. (2020) found that the United States has the third largest FLW-associated GHG emissions (222 million metric tons CO_2e per year) in the world after China and India. Note that the United States is the only developed country[67] on the list of top 10 FLW-GHG-generating countries, indicating that all other developed countries have lower rates of FLW-associated GHG emissions generation. The top 10 countries (China, India, United States, Indonesia, Brazil, Nigeria, Russia, Pakistan, Mexico and Malaysia) account for approximately 60 percent of global FLW and FLW-associated GHG emissions (Guo et al., 2020).

6.7 Environmental Benefits of Halving Global FLW

The potential environmental benefits of halving global FLW are similar to those of halving FLW domestically (see Chapter 5) – decreasing key inputs and environmental impacts such as the use of land for agriculture; use of blue water, fertilizer, and energy; and GHG emissions. Researchers also agree that reducing FLW will increase the production and consumption efficiency of the food system (i.e., increase the amount of food produced per unit of resources) (Cattaneo et al., 2020; Pagani et al., 2020).[68] This increased efficiency from FLW reductions can increase the amount of food that can be produced for the same impacts, which will be increasingly important, as the world population and incomes grow, leading to increased global demand for food, and particularly demand for foods with greater environmental impacts such as meat, dairy and processed foods (Searchinger et al., 2019; Tilman and Clark, 2014; Godfray et al., 2010). Reducing FLW can help meet increased global demand for food without the full projected increase in environmental impacts. It is not expected that the current rate of yield increases can meet expected food demand in 2050 without further deforestation and biodiversity loss (Ray et al., 2013; Garnett, 2011).

Over the past two decades, eight studies have estimated the environmental benefits of reducing FLW globally. While all of the studies used the FAO (2013a, 2011) food balance sheets and FLW rates, the studies vary in geographic coverage, years covered, and methods to estimate the environmental impacts of producing food and reducing FLW. Note that all the studies estimate maximum environmental benefits and do not consider economic factors that may impede the realization of benefits.

A key difference among the studies' methodologies is that the first two studies (Jalava et al., 2016; Kummu et al., 2012) estimate savings associated with reducing FLW relative to the current environmental footprint of the food system, while the latter six studies (Clark et al., 2020 ; Searchinger et al., 2019; Springmann et al., 2018; Röös et al., 2017; Bajželj et al., 2014; Tilman and Clark, 2014) estimate savings relative to a projected future BAU scenario. The results of all studies are presented in Table 6-1.

[67] As classified by the United Nations.

[68] Using wheat as a hypothetical example, producing food (e.g., growing 10 acres of wheat) requires inputs (e.g., water, land, energy, crop inputs) and results in environmental impacts (e.g., GHG emissions, water quality impacts). At a current FLW rate of 30 percent, out of 30,000 pounds of wheat produced on 10 acres, only 21,000 pounds are currently consumed, meaning the current efficiency is: (21,000 pounds wheat/[environmental footprint]). If FLW rates were reduced by half overall (e.g., 15 percent FLW) the efficiency of wheat production would increase: (25,500 pounds wheat/[environmental footprint]). Assuming that the reduction in FLW does not result in increased resource use and change the environmental footprint.

TABLE 6-1. MAXIMUM ENVIRONMENTAL BENEFITS OF HALVING GLOBAL FOOD WASTE

Environmental Impact	Environmental Savings							
	Relative to Current Food System Footprint		Relative to 2050 BAU Scenario					2020 Relative to 2100
	Jalava et al. (2016)	Kummu et al. (2012)	Bajželj et al. (2014)	Röös et al. (2017)	Searchinger et al. (2019)	Springmann et al. (2018)	Tilman & Clark (2014)	Clark et al. (2020)[d]
Land [a] (million m^2)	–	766,410 ↓ 9%	6,400,000 ↓ 11%	↓ 11%	3,140,000 ↓ 6%	2,891,000 ↓ 14%		–
Water [b] (million L)	↓ 12%	77,940,000 ↓ 11%	960,000,000 ↓ 15%	–	–	387,702,000 ↓ 13%	–	–
Fertilizer (million kg)	–	11,691 ↓ 10%	18,000 ↓ 12%	–	–	29,280 [c] ↓ 16%	–	–
GHG (million $MTCO_2e$)	–	–	4,500 ↓ 22%	↓ 9%	1,500 ↓ 10%	614 ↓ 6%	500 ↓ 12%	4,134• ↓ 24%

All studies examined food loss and waste from all four cradle-to-consumer supply chain stages. However, Kummu et al. (2012) excluded animal products (and the pastureland and feed needed to produce them).

[a] In all studies, except for Kummu et al. (2012) and Springmann et al. (2018), total land reduction is based on the combined average land reduction of cropland and pasture. Kummu et al. (2012) and Springmann et al. (2018) only included cropland.

[b] Water only includes "blue water" (water used for irrigation). All estimates are for consumptive use except for Bajzelji et al. (2014) which used data on water withdrawals.

[c] Values are 17% reduction for nitrogen fertilizer and 16% reduction for phosphorus fertilizer. Potassium fertilizer is not included in the analysis.

[d] The study also reports an estimate of 27% reduction as CO_2 warming-equivalent (CO_2-we). The Clark et al. (2020) cumulative savings value of 331 cumulative GWP100 Gt CO_2e was divided by the time period (80 years) to calculate an annualized estimate.

Environmental Benefits, Relative to the Current Footprint

Two studies (Jalava et al., 2016; Kummu et al., 2012) estimate the potential environmental benefits of halving global FLW, relative to the current environmental footprint of the cradle-to-consumer food system. Kummu et al. (2012) estimated the maximum cropland (excluding feed crops), blue water, and fertilizer savings that could be achieved in a global “minimum possible FLW” scenario. The study defines this scenario as each of the seven world regions achieving the lowest current FLW rate (among all regions) for each food category in each supply chain stage, as described in Section 5.1 Under this scenario, global FLW is reduced by 48 percent. Kummu et al. (2012), however, excludes the loss and waste of animal products, which have significant environmental footprints relative to other food categories (see Chapter 2 and Chapter 4).

Kummu et al. (2012) estimated that, globally, the amount of water currently wasted due to FLW could be reduced by 44 percent, wasted cropland could be reduced by 39 percent, and wasted fertilizer could be reduced by 42 percent. For the NAO region specifically, the study found that greater reductions were possible, estimating that the amount of water currently wasted due to FLW could be reduced by 57 percent, wasted cropland could be reduced by 53 percent, and wasted fertilizer could be reduced by 54 percent. The ability of the NAO region to make greater reductions than the global average is driven by the region’s ability to reduce the amount of food lost or wasted by 63 percent, as compared to a global average reduction of 48 percent (i.e., it is due to its higher current FLW rate). Note that these values are the percent reduction of wasted inputs (i.e., not total inputs) that would occur from reducing FLW. The values do not show the percent reduction that would occur compared to the whole environmental footprint of the global food supply system.

Table 6-1 compares Kummu et al. (2012) results with the footprint of the global food supply system, showing an 11 percent reduction of water use, a 9 percent reduction of land use, and a 10 percent reduction of fertilizer use from reducing FLW globally. In comparison, Kummu et al. (2012) estimates the NAO region can reduce the environmental footprint of its food system by 14 to 15 percent by reducing FLW (see Section 5.1 for discussion).

Jalava et al. (2016) looked exclusively at potential water use savings from halving FLW. The study applied water use data from the Water Footprint Network to estimate the impact of halving FLW on water use in each of the same seven global regions considered by Kummu et al. (2012). The authors estimated an overall global reduction of 12 percent of blue water use, ranging from an 11 percent reduction in South and Southeast Asia to a 15 percent reduction in the Middle East and North African region and Latin America. The study also estimated a 12 percent global reduction of green water use. The authors also provided country-level estimates. For the U.S. specifically, Jalava et al. (2016) estimated one percent greater blue water reduction potential (i.e., 13 percent compared to 12 percent) and equal potential for green water reductions (i.e., 12 percent) as compared to the global average.

Environmental Benefits, Relative to the Future Footprint

As the human population continues to grow, there is concern that the increases in food production required to feed the growing population may exceed global environmental limits. In addition, as incomes rise, global food production is projected to shift to a higher percentage of more resource-intensive foods, such as animal products and fruits and vegetables, leading to a larger environmental footprint than the current mix of food produced (Springmann et al., 2018; Tilman and Clark, 2014).

As such, six studies (Clark et al., 2020; Searchinger et al., 2019; Springmann et al., 2018; Röös et al., 2017; Bajželj et al., 2014; Tilman and Clark, 2014) estimated the future environmental impacts of the global food system by comparing a BAU scenario to a scenario in which FLW is halved. FLW data were derived from FAO food balance sheets in all studies. The BAU scenarios were based upon UN midrange (i.e., medium fertility) population estimates and demonstrate increasing environmental pressures in the absence of new mitigation strategies, such as major technological advances, dietary shifts, or FLW reductions. Note that while the studies include projections of economic and consumption trends, they do not account for economic factors such as rebound effects. All the studies predicted that all studied aspects of the environmental footprint of the global food system would increase from 2009 to 2050 under the BAU and halving FLW scenarios, but that halving FLW would decrease the impact compared with the BAU scenario.

Five of the studies examined reductions from 2050 BAU scenario (Searchinger et al., 2019;Springmann et al., 2018; Röös et al., 2017; Bajželj et al., 2014; Tilman and Clark, 2014). The studies used a wide array of assumptions and methods to develop their 2050 BAU scenario. To estimate demand, the five studies used similar estimates of population growth but varying methods and data sources for socio-economic changes and accompanying changes in dietary patterns. To estimate production and its environmental impacts, some studies (Springmann et al., 2018; Röös et al., 2017) kept current conditions while others (Searchinger et al., 2019; Bajželj et al., 2014; Tilman and Clark, 2014) extended current trajectories (to capture expected improvements) in agricultural efficiencies, such as yield increases and nitrogen use efficiency gains.

As shown in Table 6-1, the studies estimate halving FLW could reduce projections of agricultural land requirements, water use, and fertilizer use, and greenhouse gas emissions by 6 to 22 percent, depending on the study's boundary. Expected savings in water (12 to 15 percent) and fertilizer (12 to 16 percent) use were fairly consistent across studies; however estimates of agricultural land use and greenhouse gas emissions varied more widely, likely due to differences in study scopes.

When measuring changes in land use, one study (Springmann et al., 2018) looked exclusively at cropland while others (Bajzelj et al., 2014; Searchinger et al., 2019;Röös et al., 2017) included pasture land as well, dramatically increasing the amount of land being evaluated. Differences in absolute land savings in Bajzelji et al. (2014) and Searchinger et al. (2019) are most likely attributable to differences in methods for modeling future land use shifts and productivity gains. Searchinger et al. (2019) projected increased cropping intensities, more efficienct grazing, and improved pasture productivity, which results in greater livestock output per hectare. Additionally, Searchinger et al. (2019) linked expected productivity gains in BAU 2050 with limitations on shifting agricultural land into new regions.

The study by Bajželj et al. (2014) is unique in that it also estimated the changes in net forest cover and tropical pristine forests associated with halving FLW, as shown in Figure 6-10. To measure this change, Bajželj et al. (2014) considered the distribution of land expansion across different biomes and used data on estimated agricultural land expansion, current land use, and agricultural suitability of land. Overlaying this data allowed for predictions in forest losses.

The studies also differed in how they addressed greenhouse gas emissions. While Springmann et al. (2018) looked exclusively at CH_4 and N_2O emissions, projecting a 6 percent decrease; the other four studies considered all greenhouse gas emissions and found larger reductions possible (9 to 22 percent). The studies also varied in their boundaries for which activities were covered. All studies considered emissions from enteric fermentation and rice cultivation, for example, but only two of the five studies (Searchinger et al., 2019; Bajzelj et al., 2014) also included emissions from land use change. Emissions from land use change can vary considerably based on where land expansion occurs, and the two studies considering emissions from land use change maped land expansion differently. Additionally, Searchinger et al. (2019) assumed that in the BAU 2050 scenario reforestation of lands with little agricultural potential would provide offsets for agricultural land expansion, potentially leading to lower reductions compared to Bajzelji et al. (2014). Studies also differed in their expected emissions factors for certain activities. The study by Röös et al. (2017) was unique in that they included a 10% reduction in emissions from livestock associated with expected breeding and feeding improvements realized by 2050. Searchinger et al. (2019) included a 25% decrease in emissions from on-farm energy use, projecting a shift away from fossil energy sources. Given the myriad assumptions used, future projections remain largely uncertain, yet all studies consistently showed that halving food loss and waste was an integral intervention for reducing food system impacts.

Considering the U.S. specifically, Springmann et al. (2018) estimated roughly similar reductions (i.e., within one percent) for the U.S. and the world for land, water, and fertilizer use; however, the study estimated the United States could achieve a 2 percent greater reduction in CH_4 and N_2O emissions from primary production, relative to BAU in 2050, likely due to the greater amount of animal products wasted in the U.S. The other studies did not provide country-specific projections.

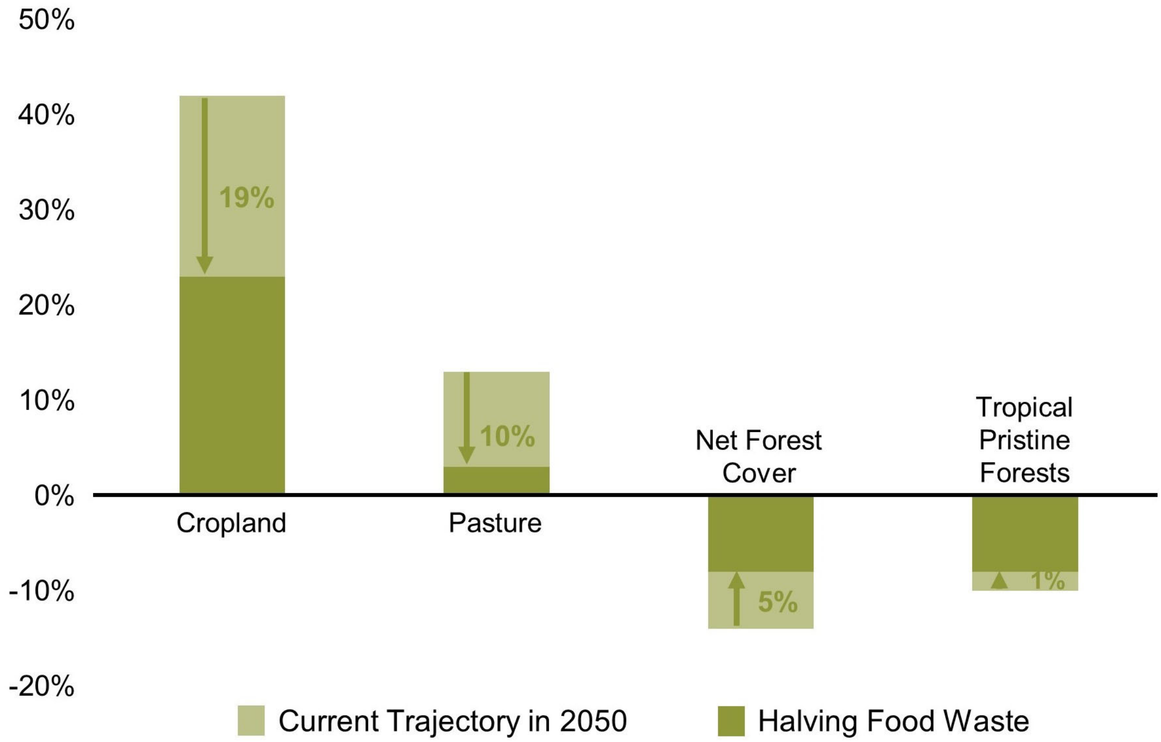

FIGURE 6-10. PROJECTED BENEFITS FROM HALVING GLOBAL FLW

To meet rising food demands associated with population growth and changing dietary patterns, agricultural land will need to expand in 2050 (+42 percent cropland, +13 percent pasture). Increases in land for agriculture will require reductions in total net forest coverage (-14 percent) and tropical pristine forest (-10 percent). If global food loss and waste were halved, agricultural land expansion could be attenuated by 19 percent for cropland and 10 percent for pasture, and encroachment on net forest cover and tropical pristine forests could be reduced by 5 percent and 1 percent, respectively. Data Source: Bajželj et al. (2014)

Clark et al. (2020) covers a different time period than the other two studies, estimating cumulative reductions between 2020 and 2100. The authors focused exclusively on GHG emissions reductions during primary production (including emissions from land use change), finding that gradually halving FLW between 2020 and 2050 could result in a 24 percent cumulative reduction in primary production GHG emissions, when measured in 100-year global warming potential, and 27 percent cumulative reduction, when measured as warming-equivalents (CO_2-we), compared with the BAU scenario (Clark et al., 2020). This study primarily reported "warming equivalents," rather than the 100-year global warming potential like all other studies presented in this report, to account for the short-lived nature of methane. Between 2020 and 2100 the authors project savings of 331 Gt CO_2e (364 Gt CO_2-we) during primary production from halving food loss and waste (Clark et al., 2020).

Importantly, Clark et al. (2020) analysis shows that food system emissions reductions are essential to achievement of limiting global warming to below 1.5° and 2° Celsius, compared to pre-industrial levels. Even if fossil fuel emissions were immediately halted, current trends in the food system (including increasing yields at the current rate) could preclude the achievement of these targets. The analysis shows this FLW-related reduction in GHGs increases the likelihood that the global climate will remain below the maximum increase of 2°C target outlined in the Paris Agreement (UNFCC, 2015).

Many of these studies compared a variety of strategies—including closing yield gaps, increasing resource efficiency, dietary shifts, and reducing FLW—finding that only in combinations could these strategies achieve a sustainable agricultural future (Clark et al., 2020; Searchinger et al., 2019; Springmann et al., 2018; Röös et al., 2017; Bajželj et al., 2014; Tilman and Clark, 2014).

CHAPTER 7.

Conclusions and Research Gaps

This report summarizes available data on the cradle-to-consumer (farm-to-kitchen) environmental footprint of U.S. FLW and the potential environmental benefits that could be realized by reducing FLW. General conclusions are presented in Section 7.1, while specific strategies to maximize the environmental benefits of FLW reduction efforts are presented in Section 7.2. The report concludes with identification of priority research areas in Section 7.3.

7.1 Conclusions

More than one-third of the U.S. food supply is not consumed, resulting in a "waste" of resources—including agricultural land, water, pesticides, fertilizers, and energy—and the generation of environmental impacts—including greenhouse gas emissions and climate change, consumption and degradation of freshwater resources, loss of biodiversity and ecosystem services, and degradation of soil quality and air quality (U.S. EPA, 2019b; IOM and NRC, 2015; U.S. EPA, 2015).

Despite differences in study design, methodologies, data sets, time periods, and other factors, most estimates of the environmental impacts associated with food that is ultimately lost or wasted show general agreement once these factors are taken into consideration. The most comprehensive credible estimates available in the literature estimate that each year, uneaten food in the United States embodies:

- 560,000 km^2 (140 million acres) agricultural land – approximately 16 percent of U.S. agricultural land (Read et al., 2020);
- 22 trillion L (5.9 trillion gallons) blue water – equal to the annual water use of more than 50 million American homes (Read et al., 2020);
- 350 million kg (778 million pounds) pesticides (Conrad et al., 2018);
- 6,350 million kg (14 billion pounds) fertilizer (Toth and Dou, 2016);
- 2,400 million GJ (664 billion kWh) energy – enough energy to power more than 50 million U.S. homes (Pagani, et al., 2020; Vittuari et al., 2020); and
- 170 million $MTCO_2e$ GHG emissions (excluding landfill emissions) each year – equal to emissions of 42 coal-fired power plants (Read et al., 2020).

This uneaten food also contains enough calories to feed more than 150 million people each year, far more than the 35 million estimated Americans experiencing food insecurity (USDA, 2021a; Wood et al., 2019; Buzby et al., 2014). While the estimates presented above were chosen largely based upon their comprehensive scope, many credible methodologies presented in this report would produce higher estimates if their results were extrapolated to cover FLW along the whole supply chain. The estimates above from Read et al. (2020) in particular should be considered conservative.

As global populations and incomes rise, and the environment faces pressures from increased food production, reducing the per person environmental footprint of agriculture will be essential to the sustainability of the planet (Clark et al., 2020; Springmann et al., 2018). Limited options are available to sustainably increase the global food supply to meet growing demand. Closing yield gaps and increasing productivity alone will likely be insufficient to prevent further deforestation and environmental degradation (Hayek et al., 2021; Bajželj et al., 2014). Even under the most promising scenarios of yield increases, up to 20 percent more land will be needed by 2050 (Bajželj et al., 2014). Thus demand-side measures, such as reducing FLW or dietary shifts, will also be needed to sustainably increase the food supply (Rosenzweig et al., 2021; Wood et al., 2019; Röös et al., 2017; Foley et al., 2011). Many researchers have noted that policymakers may find reducing FLW less controversial and more tractable than dietary shifts (Birney et al., 2017; Neff et al., 2015; Smith et al., 2013).

While halving FLW cannot alone make the global food system sustainable, it can play a significant role and may well be essential (Gerten et al., 2020). The most comprehensive (though likely conservative, as noted above) estimates of annual environmental savings (i.e., avoided inputs and environmental impacts) from halving U.S. FLW include:

- More than 300,000 square km^2 (75 million acres) agricultural land – an area greater than the State of Arizona;
- 12 trillion L (3.2 trillion gallons) blue water – equal to the water use of 29 million American homes;
- Nearly 290,000 metric tons (640 million pounds) of bioavailable nitrogen from agricultural fertilizer with the potential to reach a body of water, cause algal blooms and deteriorate water quality;
- 940 million GJ (262 billion kWh) energy – enough to power 21.5 million U.S. homes; and
- 92 million $MTCO_2e$ GHG – equal to the CO_2 emissions from 23 coal fired power plants (Read et al., 2020).

These savings can only be achieved through prevention (i.e., source reduction) of FLW. Recycling of food waste cannot achieve these benefits since a substantial fraction of the impacts occur during the primary production of food.

In global context, the United States is a major producer of food loss and waste, wasting more food (total) and more food per person than most other nations. Only two countries generate more food waste and more food waste per person than the United States (China and India, and New Zealand and Ireland, respectively) (Guo et al, 2020; Chen et al., 2020). The environmental impact of U.S. food loss and waste is also substantial relative to other countries, as the U.S. wastes more food downstream and more animal products than the global average (Lipinski et al., 2013; FAO, 2013a, b). Studies consistently show the United States using more resources and creating more environmental impacts per unit of food waste than the global average (Chen et al., 2020; Guo et al, 2020; Hiç et al., 2016).

The United States is one of many countries to adopt a national goal to halve per person FLW at the retail and consumption stages by 2030, similar to the UN Sustainable Development Goal Target 12.3 (FAO, 2020). While the U.S. has not made progress toward halving FLW by 2030, examples of significant progress in similar countries are emerging. For example, the UK has reduced per person edible FLW by 27 percent, achieving the bulk of the reduction within four years (WRAP, 2020), and Japan has reduced household FLW by 13 percent in four years, achieving the majority of progress in one year (Parry et al., 2015).

Scientists project halving global FLW could result in a 24 percent reduction in cumulative global food system greenhouse gas emissions between 2020 and 2100 (331 Gt CO_2e), relative to a business-as-usual scenario (Clark et al., 2020). Significant reductions (6 to 16 percent) could also be achieved in the amounts of agricultural land, water, and fertilizer used in 2050 (compared to business-as-usual scenario) by halving global food loss and waste (Searchinger et al., 2019; Springmann et al., 2018; Röös et al., 2017; Jalava et al., 2016; Bajželj et al., 2014; Kummu et al., 2012).

Many of the studies presented in this report compared a variety of strategies—including closing yield gaps, increasing resource efficiency, dietary shifts, and reducing FLW—finding that only in combinations could these strategies achieve a sustainable agricultural future (Clark et al., 2020; Searchinger et al., 2019; Springmann et al., 2018; Röös et al., 2017; Bajželj et al., 2014; Tilman and Clark, 2014). This report demonstrates the substantial contribution halving food loss and waste, both domestically and internationally.

7.2 Strategies to Maximize the Environmental Benefits of Halving U.S. FLW

The recent literature reviewed in this report provides many insights as to how policymakers might tailor FLW programs and policies to maximize environmental benefits. Specifically, it provides three key guiding principles:

(1) **The greatest environmental benefits can be achieved through prevention rather than recycling.** Given that significant inputs and environmental impacts (use of land, water, pesticides and fertilizer, plus GHG emissions) associated with FLW occur during primary production, the greatest benefits can be achieved by avoiding the production of unnecessary food (or lessening the need for additional food production). The estimates of the maximum environmental benefits of reducing FLW presented in this report all rely upon the assumption that decreases in demand (from reducing FLW) will result in equivalent decreases in production. While not all prevention activities may achieve this (due to economic factors outside the scope of this report), wasting food and then recycling it does not provide a similar opportunity to achieve these maximum benefits. Recycling will not signal demand for a smaller per person food supply or “undo” the impacts of primary production.

(2) **The largest energy and greenhouse gas emissions benefits can be obtained by reducing consumption stage (households and restaurants) FLW**. In the U.S. the consumption stage represents roughly half of all FLW (ReFED, 2021a; Pagani et al., 2020; Vittuari et al., 2020; CEC, 2017) and, as the last stage in the cradle-to-consumer supply chain, accounts for the greatest environmental impacts (since impacts are cumulative). While use of land for agriculture and the use of water, pesticides and fertilizers occur chiefly during primary production, energy use and GHG emissions occur all along the supply chain and thus the embodied energy use and GHG emissions increase as food moves along the supply chain. In a study projecting the environmental benefits of halving U.S. FLW in each of seven sectors, the authors found that the bulk of the environmental benefits could be achieved by halving FLW in only three sectors: households, restaurants, and food processing (Read et al., 2020). The same study suggests that a focus on institutional food service (e.g., schools or hospitals) or retail (also downstream sectors) will yield minimal environmental results. Note, however, that upstream factors can drive consumption stage waste, and solutions to reducing FLW in one sector may be implemented in that sector or upstream from that sector (e.g., reducing consumer FLW by making changes in supermarkets and restaurants) (NASEM, 2020).

(3) **Focusing on reducing FLW of the most resource-intensive foods, such as animal products and fruits and vegetables, can yield the greatest environmental benefits**. These two categories consistently rank as top contributors to many of the environmental impacts associated with FLW. Animal products (especially beef) have a particularly outsized contribution. Making up less than one-third of U.S. FLW, animal products are responsible for the largest share of agricultural land use, nitrogen and phosphorous fertilizer application, energy use, and GHG emissions, plus one quarter of pesticide application and at least a third of blue water use (Chen et al., 2020; Guo et al., 2020; Pagani et al., 2020; Vittuari et al., 2020; Wood et al., 2019; Conrad et al., 2018; Mekonnen and Fulton, 2018; Birney et al., 2017; Toth and Dou, 2016; Heller and Keoleian, 2015; Buzby et al., 2014; Gustavsson et al., 2013; Cuéllar and Webber, 2010). Fruits and vegetables make up a larger portion of U.S. FLW than animal products and are the leading contributor to pesticide application and blue water use associated with FLW (Conrad et al., 2018; Mekonnen and Fulton, 2018; Birney et al., 2017). Fruits and vegetables are also responsible for the second largest share of fertilizer application, behind animal products (Chen et al., 2020; Wood et al., 2019; Conrad et al., 2018). Thus, achieving reductions in the loss and waste of these food categories should have more substantial environmental benefits than in other food categories. Studies projecting environmental benefits of halving FLW largely confirm this proposition, adding grains as an additional FLW food category worth attention (Read et al., 2020) and noting the potential of reducing FLW of animal products to also most significantly reduce ammonia emissions from nitrogen fertilizer application (Wood et al., 2019).

7.3 Research Gaps

In recent years, a myriad of domestic and international food loss and waste reduction initiatives, including the U.S. *2030 Food Loss and Waste Reduction Goal*, have spurred research on understanding and reducing FLW. However, there are still data gaps and uncertainties associated with estimating the amount and characteristics of FLW, the embodied environmental footprint of FLW, and the potential environmental benefits from FLW reductions. Further research is needed to refine estimation methods and to improve the availability, quality, consistency, and frequency of updates of necessary data. In addition, a deeper understanding of the interplay between supply chain stages and the unique drivers of FLW in the United States could lead to more successful policies and programs. Science-based answers to these research questions and others will increase U.S. policymakers' understanding of U.S. FLW and help them to tailor FLW strategies to meeting the *Food Loss and Waste Reduction Goal* with maximum environmental benefits.

EPA is currently undertaking projects to advance FLW knowledge in three areas relevant to this report, including:

- **Evaluating the comprehensive net environmental footprint of U.S. FLW.** EPA will integrate the data in this report (the cradle-to-consumer footprint) with data from EPA's forthcoming report on the environmental impacts of U.S. food waste management pathways (such as landfill, combustion, composting and anaerobic digestion) to assess the net environmental footprint of U.S. FLW from cradle-to-grave.

- **Creating environmental indicators to track the environmental footprint of U.S. FLW over time.** EPA will develop indicators, as a part of the Report on the Environment, to track the amount of FLW and its associated inputs and environmental impacts over time, beginning with greenhouse gas emissions.

- **Enhancing modeling of the food system including the generation of FLW by updating the USEEIO model and creating a WARM/USEEIO hybrid model.** EPA is partnering with USDA, Argonne National Laboratory, and Cornell University to build a more refined food system model within the USEEIO. Additionally, EPA is working to incorporate additional life cycle analysis data on the end-of-life management pathways for food waste and their associated environmental impacts.

New, original research is needed to fill these additional priority knowledge gaps:

- **Enhance the data on U.S. FLW and address data gaps.** Research is needed to update data, address data gaps, and understand key differences among FAO, USDA, and EPA estimates of the amount, food category, and supply chain stage at which food is currently lost or wasted in the United States. The accuracy of all the data sets could be improved. Additional data needs to be collected to inform more precise estimates of FLW during primary production (including fisheries and aquaculture) and food processing.

- **Increase frequency at which the United States can track progress in reducing FLW.** Methods and tools need to be developed to track changes in the amount of edible and inedible FLW in the United States with greater frequency and without the use of static FLW rates. Currently FLW rates (also known as loss factors) for each food category are updated once a decade, making it difficult to assess progress and gauge success of programs to reduce FLW.

- **Quantify the environmental impacts occurring in other countries that are associated with U.S. waste of imported foods.** Research is needed to estimate the environmental impacts, including deforestation (and associated carbon and biodiversity loss) and water scarcity, of producing food that is exported to and ultimately wasted in the United States. Linking FLW to specific locations of environmental degradation or resource use can help policymakers target FLW programs to decrease pressure to convert land to agriculture, especially in the tropics, or to use limited water resources in water-stressed areas. The estimates of inputs and environmental impacts presented in this report generally assume the entire U.S. food supply is produced domestically and do not account for differences in local environments, agricultural practices, standards, and production methods among countries. This data would also help to refine projections of environmental savings possible through halving U.S. FLW.

- **Strengthen our understanding of the interaction among food system supply chain stages with regard to FLW**. Food is produced and supplied by a complex, multistage system that includes many industries and participants. As a whole, the food system functions not as a sequential farm-to-kitchen food chain but as a complex system of interdependencies and feedbacks that responds to myriad economic, environmental, and social factors. Research is needed to assess how changes in downstream demand affect upstream production and supply (e.g., under what conditions will reducing consumer food demand decrease production/supply accordingly, thus resulting in maximum environmental savings), including the effect of economic factors. Research is also needed to identify where solutions to FLW in one stage may be best implemented upstream from that stage (e.g., manufacturers and supermarkets making changes to help households waste less food).

- **Explore how current trends in the U.S. food system will affect FLW and its environmental footprint in the future.** Research is needed to project the impact of trends such as the increasing use of online grocery shopping and changes in household size, on the amount and characteristics of U.S. FLW in order to help policymakers design successful long-term FLW reduction strategies.

- **Evaluate the life cycle impacts of proposed FLW prevention strategies.** To achieve the full environmental benefits projected in this report, half of current U.S. FLW must be prevented, not just recycled. A variety of FLW prevention solutions exist and new ideas and technologies are coming online. In some cases, these solutions may require resources or present potential environmental impacts. Research is needed to estimate the net benefits of solutions such as the use of innovative or additional packaging or choosing frozen, canned, or dried produce over fresh produce to inform decisions and policies to reduce FLW and its environmental impacts.

- **Improve precision of food loss and waste estimates.** Additional data on loss and waste of specific food types (within the food categories currently measured) would allow link to more precise life cycle analysis data and improve the accuracy of environmental impact estimates as well as allow for more specific targeting of higher impact foods during FLW interventions, such as education about optimal storage conditions.

- **Deepen our understanding of drivers of FLW unique to the United States.** While many of the key drivers of FLW are common across similar countries, this report identified several factors unique to the U.S. which impact FLW. For example, the U.S. food supply per person is far greater than in other parts of the world. Identifying and examining systemic or institutional contributors to U.S. FLW can lead to more successful solutions. Research is needed to explore drivers of over-supply of food (i.e., supply beyond demand) in the United States, beyond levels seen in other developed, high-income countries, and to identify unique forces in the U.S. food system that consistently result in significant food loss and waste. Research could also lead to improved management methods for surplus food.

- **Evaluate effectiveness of policy and program options to reduce FLW.** Research and evaluation are needed to determine which types of interventions could be the most successful in reducing FLW—and its associated environmental impacts—and to identify synergies and conflicts with other policy objectives, such as improving health and reducing food insecurity.

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Appendix A: Inputs and Environmental Impacts

TABLE A-1. MAJOR INPUTS AND RESOURCES REQUIRED FOR U.S. CRADLE-TO-CONSUMER FOOD SYSTEM

Food System Stage	Category/ Type of Food	Inputs					
		Water	Energy (Electricity or Fuels)	Land	Pesticides	Fertilizer	Sources
Primary Production	Plants (commodity crops and horticultural)	Irrigation	Farm equipment fuel for planting, fertilizing, harvesting, transportation	Planting commodities and horticultural and specialty crops	Applied to many commodities and horticultural and specialty crops	Applied to many commodities and horticultural and specialty crops	D'Odorico et al. (2018); Niles et al. (2018); IOM and NRC (2015)
	Farm animals	Feed production, drinking	Feed production, animal feeding, animal housing, manure handling, transportation	Feed production, grazing, animal housing	Applied to many commodities used for feed possibly also to forage plants	Applied to many commodities used for feed possibly also to forage plants	Asem-Hiablie et al. (2019); Rotz et al. (2019); D'Odorico et al. (2018); Niles et al. (2018); IOM and NRC (2015)
	Seafood: wild caught	Limited usage, but requires functional aquatic ecosystems	Boat fuel, cold storage of caught organisms	N/A	N/A	N/A	Niles et al. (2018); Parker et al. (2018); Avadi Tapia et al. (2016)
	Seafood: farmed	Large water storage requirements (both for commercial and feed organisms)	Boat fuel, and cold storage of caught organisms for feed, electricity for infrastructure and maintenance (both for commercial and feed organisms)	Space for infrastructure, growth of commercial and feed organisms	Antibiotics and anti-parasite chemicals are used in some operations	N/A	Bohnes et al. (2019); Fry et al. (2019); Tlusty et al. (2019); Niles et al. (2018)

Food System Stage	Food Category	Inputs						
		Water	Energy (Electricity or Fuels)	Land	Pesticides	Fertilizer	Other	Sources
Handling and Storage	Farm animals	Drinking and cleaning	Transportation fuel, energy for climatized conditions for animals, cold storage for dairy products	Infrastructure for storage and transportation	N/A	N/A	N/A	Asem-Hiablie et al. (2019); Niles et al. (2018)
	Plants	Washing some products	Transportation fuel, energy for cold storage for some horticultural products	Infrastructure for storage and transportation	N/A	N/A	N/A	Niles et al. (2018)
	Seafood: wild caught and farmed	N/A	Transportation fuel, energy for cold storage	Infrastructure for storage and for transportation	N/A	N/A	N/A	Niles et al. (2018)
Processing and Packaging	Farm animals, plants, and seafood: wild caught and farmed	Food safety and processing needs	Energy for food conversion from raw materials to final products (e.g., slaughtering animals for meat and other biproducts, pasteurizing milk, producing high-fructose corn syrup from corn, filleting fish), cold storage after	Infrastructure for processing and storage	N/A	N/A	Packaging materials, consumables, chemicals	Asem-Hiablie et al. (2019); Niles et al. (2018)

Food System Stage	Food Category	Inputs						
		Water	Energy (Electricity or Fuels)	Land	Pesticides	Fertilizer	Other	Sources
			processing prior to distribution(?)					
Distribution and Market	Farm animals, plants, and seafood: wild caught and farmed	N/A	Transportation fuel, energy for cold storage for some products	Infrastructure for transportation	N/A	N/A	N/A	Asem-Hiablie et al. (2019); Niles et al. (2018)
Consumption	Farm animals, plants, and seafood: wild caught and farmed	Food processing, cooking and food safety needs	Energy for refrigeration and cooking, fuel for transportation	N/A	N/A	N/A	N/A	Canning et al. (2020); Pagani et al. (2020); Vittuari et al. (2020); Asem-Hiablie et al. (2019); Niles et al. (2018)

N/A = not applicable.

TABLE A-2. MAJOR ENVIRONMENTAL BURDENS ASSOCIATED WITH THE U.S. CRADLE-TO-CONSUMER FOOD SYSTEM

Food System Stage	Category/ Type of Food	Impacts							
		Biodiversity	Land	Water Use	Water Quality	Worker Health	GHGs	Other Air	Sources
Primary Production	Plants (commodity crops and horticultural)	Conversion of land from higher biodiversity to plant production; can be affected by pesticide application	Soil degradation, loss, compaction from tillage, reduction of soil carbon	Depletion of water resources; reduced availability of ground and surface water for other uses	Nitrogen and phosphorus fertilizer runoff of PO_4^{-3}, NO_3^-, NH_4^+ leading to water eutrophication	Volatilization of pesticides and herbicides during application, runoff of pesticides into water, nitrate contamination of drinking water	N_2O emissions from nitrogen fertilizer application, CO_2 emissions from farm equipment energy use, loss of CO_2 sequestration	Land emissions of CO_2, methane, odors, fine particulate matter	D'Odorico et al. (2018); Niles et al. (2018); IOM and NRC (2015)
	Farm animals	Conversion of land from higher biodiversity to animal feed and/or animal production	Soil degradation, loss, and compaction from over grazing, leaching from manure management	Depletion of water resources; reduced availability of ground and surface water for other uses	Manure management runoff of PO_4^{-3}, NO_3^-, NH_4^+ leading to water eutrophication, nitrate contamination of drinking water	During application, runoff of pesticides into water, microbial pathogens from manure, nitrate contamination of drinking water	CH_4 from enteric fermentation and manure, N_2O from manure, pasture, range and cropland, CO_2 from fuel combustion	Manure and land emissions of NO_x, CO_2, ammonia, methane, odors, fine particulate matter, ozone depletion	Asem-Hiablie et al. (2019); Rotz et al. (2019); D'Odorico et al. (2018); Niles et al. (2018); IOM and NRC (2015)
	Seafood: wild caught	Overfishing can result in biodiversity collapse; trawling can damage sea floor; gear loss can	N/A	Minimal impacts	Gear loss and synthetic fishing fibers can result in micro-plastic accumulation in marine ecosystems	Minimal impacts	GHG emissions from energy use for boat fleets	Odors	Lebreton et al. (2018); Niles et al. (2018); Parker et al. (2018); Avadi Tapia et al. (2016)

Food System Stage	Category/ Type of Food	Impacts							
		Biodiversity	Land	Water Use	Water Quality	Worker Health	GHGs	Other Air	Sources
		result in damage to ecosystems							
	Seafood: farmed	Ecotoxicity of local ecosystems through chemical use and introduction of nonindigenous species	Land conversion and degradation from intensive use	Intensive use of water in production stage (i.e., growing organisms)	Eutrophication of water from nitrogen and phosphorus from food waste and organism feces	Toxicity from chlorine and other cleaning products, increased potential for disease resistance from antibiotic use	GHG emissions from energy use for infrastructure, equipment, transportation of feed and materials	Odors	Bohnes et al. (2019); Fry et al. (2019); Tlusty et al. (2019); Niles et al. (2018)

Food System Stage	Food Category	Impacts							
		Biodiversity	Land	Water Use	Water Quality	Worker Health	GHGs	Other Air	Sources
Handling and Storage	Farm animals	Minimal impacts	Minimal impacts	Depletion of water resources; reduced availability of ground and surface water for other uses	Minimal impacts	Minimal impacts	GHG emissions from energy use for transportation, climatized conditions, and cold storage	Ozone depletion, refrigerant leakage	Asem-Hiablie et al. (2019); Niles et al. (2018)
	Plants	Minimal impacts	Minimal impacts	Minimal impacts	Minimal impacts	Minimal impacts	GHG emissions from energy use for transportation, and cold storage	Ozone depletion, refrigerant leakage	Niles et al. (2018)
	Seafood: wild caught and farmed	Minimal impacts	Minimal impacts	Minimal impacts	Minimal impacts	Minimal impacts	GHG emissions from energy use for transportation, and cold storage	Ozone depletion, refrigerant leakage	Niles et al. (2018)
Processing and Packaging	Farm animals, plants, and seafood: wild caught and farmed	Minimal impacts	Minimal impacts	Depletion of water resources; reduced availability of ground and surface water for other uses	Production of wastewater	Minimal impacts	GHG emissions from energy for processing	Ozone depletion, volatile organic compounds, refrigerant leakage	Asem-Hiablie et al. (2019); Niles et al. (2018)
Distribution and market	Farm animals, plants, and seafood: wild	Minimal impacts	Minimal impacts	Depletion of water resources; reduced availability of	Production of wastewater	Minimal impacts	GHG emissions from energy use for transportation	Ozone depletion	Asem-Hiablie et al. (2019); Niles et al. (2018)

Food System Stage	Food Category	Impacts							
		Biodiversity	Land	Water Use	Water Quality	Worker Health	GHGs	Other Air	Sources
	caught and farmed			ground and surface water for other uses			, and cold storage		
Consumption	Farm animals, plants, and seafood: wild caught and farmed	Minimal impacts	Minimal impacts	Depletion of water resources; reduced availability of ground and surface water for other uses	Production of wastewater	Minimal impacts	GHG emissions from energy use for refrigeration and cooking and transportation	Ozone depletion	Canning et al. (2020); Pagani et al. (2020); Vittuari et al. (2020); Asem-Hiablie et al. (2019); Niles et al. (2018)

Appendix B: USDA and FAO FLW Data

Many of the FLW estimates presented in this report rely on data from USDA (Buzby et al., 2014's LAFA data) or FAO (Gustavsson et al., 2011) for food availability data or food loss and waste rates, or both. For example, Cuellar and Webber (2010), Venkat (2012), Heller and Keoleian (2015), Toth and Dou (2016), Spiker et al. (2017), Birney et al. (2017), and Conrad et al. (2018) utilized USDA LAFA data. Whereas, CEC (2017), Chen et al. (2020), Kummu et al. (2012) and Lipinski et al. (2013) relied on FAO/Gustavsson et al. (2011) food availability and loss rates. This appendix provides more detail on the use of this data.

Several studies have relied on the USDA LAFA data and its loss rates. The loss rates within the LAFA data have not been significantly updated since 2010 by Buzby et al. (2014). Consequently, researchers using differing years of the LAFA data set have similar results. Cuellar and Webber (2010), Venkat (2012) and Heller and Keoleian (2015) all used LAFA data without much additional manipulation and as expected, their per capita FLW estimates are fairly aligned, 145, 180, 196 kg/capita/year, respectively. Mekonnen and Fulton (2018) used the 2015 LAFA data resulting in an FLW estimate of 216 kg/capita/year and 1,237 daily calories per capita. Similarly, Spiker et al. (2017) calculated the nutritional value of 2012 LAFA retail- and consumption-stage waste to be 1,217 daily calories per capita which is close to the 2010 estimate by Buzby et al. (2014) of 1,249 daily calories per capita.

Toth and Dou (2016) and Birney et al. (2017) supplemented the LAFA data. Toth and Dou (2016) estimated FLW from post-harvest, distribution and processing sector to be 36 million metric tons, based on their calculations derived from the LAFA data, which combined with losses from the retail and consumption stages, equaled approximately 100 million metric tons. Birney et al. (2017) didn't expand the stages included, but rather focused on getting a more accurate estimate of the calories consumed, acknowledging that the Buzby et al. (2014) proxy food consumption (which is food availability minus loss) estimate of 2,547 calories per capita per day overstates what a typical American actually eats. Using the results of a study (Tom et al., 2016) which relied on USDA's National Health and Nutrition Examination Survey (NHANES) data that calculates the average American's daily calories, Birney et al. adjusted the LAFA food category calories to an estimated actual consumption of 2,390 calories per capita per day. The difference in food availability and actual consumption is considered FLW, hence the higher overall FLW estimates.

NHANES, a nationwide survey conducted by the CDC, uses interviews and physical examination to collect demographic and health information of the U.S. population. The dietary component of NHANES, known as What We Eat in America (WWEIA), is a dietary recall survey of food eaten by about 5,000 individuals. Although other sources of actual consumption are available from smaller studies of specific populations, NHANES is the largest and most nationally representative source available. It is commonly cited for estimates of U.S. food consumption. USDA's (2019c) analysis indicates mean consumption of 2,044 calories per capita per day from 2007 through 2010 of individuals 2 years old and older, with approximately 70 percent consumed at home and 30 percent away from home.

Using the WWEIA data in NHANES, Conrad et al. (2018) quantified the amount of food consumed, identified its comprised ingredients, and then back calculated how much of each ingredient needed to be produced given the waste rates (using LAFA data for the portion of each ingredient that is lost or wasted at the consumer level). Since Conrad et al. (2018) were focused on consumption stage waste, with a narrower scope, it follows that their FLW estimates, by weight and calories, are lower than studies that included additional stages.

The FAO regional food loss and waste estimates developed by Gustavsson et al. (2011) and applied to the 2007 FAO Food Balance Sheet (FBS) data include edible FLW from production through the consumption stage for eight categories of food at their primary commodity level. The methodology was described in greater detail by Gustavsson et al. (2013). For the North America and Oceania region, Gustavsson et al. (2011) used a mix of U.S. (predominantly from the USDA) and European data sources for the food loss and waste rates for each food category within each stage of the food supply chain. Given the expansiveness of the scope and limited data, some broad assumptions and extrapolations are used. For example, the loss rates for fruits and vegetables in North America and Oceania are based on a study of carrots grown in Sweden and a statement about the percentage of British-grown fruits and vegetables rejected by retailers (Gustavsson et al., 2013). Nonetheless, the work by Gustavsson et al. (2011, 2013), captured the available information on FLW across all stages and enables comparisons between global regions.

The FAO FLW data developed by Gustavsson et al. (2011, 2013) have been used by many studies, particularly those making comparisons between countries and regions. The Commission for Environmental Cooperation (CEC, 2017) used the 2007 FAO FBS data for the United States and Gustavsson et al. (2013) loss assumptions for the NAO region, but included the inedible fractions of FLW (by excluding the conversion factors used by Gustavsson et al.), which resulted in a higher per capita estimate. Also including inedible FLW but using more recent food balance data and different loss rates, Guo et al. (2020) used the FAO FBS data for 2017 and applied FLW rates from Porter et al. (2016). Read et al. (2020) relied on the Gustavsson et al. (2013) loss rates for North America and Oceania to the USEEIO model. Since Gustavsson et al. (2011, 2013) doesn’t include sweetners and beverages, Read et al. (2020) supplemented the data set with Buzby et al. (2014) loss rate for sweetners, and data from the United Kingdom WRAP program for loss estimates for beverages.

Lipinski et al (2013) applied the FLW estimated developed by Gustavsson et al. (2011, 2013) to the 2009 FAO FBS data and converted the resulting food category weights into calories. Additionally, Kummu et al. (2012) also converted the resulting FLW food category weights to calories. However, they excluded animal products, so their per capita daily calories estimate is lower. Kummu et al. (2012) applied the Gustavsson et. al (2011, 2013) loss rates to the FAO FBS data for vegetal products averaged over the years 2005-2007.

Taking a closer examination of the calories and nutrients in FLW at the consumption stage, Chen et al. (2020) used the GENuS data set for the year 2011 for food availability (Smith et al., 2016) and applied the consumption stage FLW rates from Gustavasson et al. (2011). In creating GENuS, Smith et al. (2016) disaggregated FAO’s FBS 94 food categories to 225, allowing for more detailed pairing with nutrition information. The resulting estimates from Chen et al. (2020) are considerably lower than other studies using FAO data, which is expected given that they were specifically examining the consumption stage waste. Even though the data sets differed, the consumption stage food waste estimates from Chen et al. (2020) and Conrad et al. (2018) are within a similar range, 184 kg and 154 kg per capita annually, respectively.

Appendix C: Literature Search Methodology

This appendix presents the literature search methodology used to identify, screen, and manage literature sources for *From Farm to Kitchen: The Environmental Impacts of U.S. Food Waste (Part 1)* and associated issue papers. The objective of this literature search was to identify the latest scientific information about food waste and food waste reduction, including emerging technologies and approaches for prevention, reuse, and recycling. In addition, analysis of the literature helped to identify knowledge gaps and the most important areas for future scientific research.

Section B.1 describes the literature search methodology for peer-reviewed literature sources, and Section B.2 describes the identification of governmental and non-governmental reports that are not published in the peer-reviewed scientific literature, referred to as “gray literature” in this methodology.

This literature search identified and prioritized 3,219 peer-reviewed sources, 1,723 of which were screened as relevant to the scope of the From Farm to Kitchen report and issue papers. These source, as well as the key gray literature (see Section B.2) and additional key sources identified in supplemental, targeted literature searches, served as the primary corpus of literature from which literature synthesis and report development were performed. The report and associated issue papers were developed by primarily using the literature identified through this methodology, but were not limited to this set of literature as additional sources were identified subsequently (e.g., from peer-review recommendations).

C.1. Methodology for Peer-Reviewed Literature

Peer-reviewed literature was identified with a search of selected publication databases using keywords and Boolean logic defined in this section. Titles and abstracts of the publications returned by the literature search were processed to eliminate duplicates and then screened to identify a subset of “key” sources that meet criteria for relevance and usefulness for the report or issue papers. Key sources were “tagged” to pre-defined topics to assist authors in identifying the most relevant sources for particular topics covered in the report.

Peer-Reviewed Literature Search Strategy

The search of peer-reviewed literature focused on references relevant to the scope of the food waste report and issue papers from 2010–present, with special priority given to more recent papers, which were considered to be 2017–present. A targeted search to identify review papers from 2014–present was performed. During development of the report and issue papers, additional targeted searches were performed as needed within the 2010–present corpus of literature, and subject matter experts also identified key sources, some of which were dated in 2020 or 2021.

The following databases were searched for relevant peer-reviewed literature:

- AGRICOLA (AGRICultural OnLine Access): AGRICOLA records describe publications and resources encompassing all aspects of agriculture and allied disciplines, including animal and veterinary sciences, entomology, plant sciences, forestry, aquaculture and fisheries, farming and farming systems, agricultural economics, extension and education, food and human nutrition, and earth and environmental sciences; Produced by the National Agricultural Library (NAL), U.S. Department of Agriculture.

- AGRIS: AGRIS facilitates access to publications, journal articles, monographs, book chapters, and grey literature - including unpublished science and technical reports, theses, dissertations and conference papers in the area of agriculture and related sciences; Maintained by the Food and Agriculture Organization of the United Nations (FAO).

- EBSCO: EBSCOhost Research Databases: Academic Search Complete; Energy & Power Source.

- PubMed: US National Library of Medicine National Institutes of Health.

- Web of Science: Web of Science Core Collection, refined by Research Area. Clarivate Analytics.

Table A-1 outlines the searches performed and the combinations of keyword sets and Boolean operators used to search each database. Four distinct sets of keywords were used to capture references with relevance to food waste, pathways of food waste and food waste reduction, environmental impacts of food waste, and emerging issues in the area of food waste. Sets were combined using Boolean logic to identify relevant references for screening and evaluation. Search results were limited to publications written in English.

For each search, all references were downloaded into EndNote and then DeDuper was used to remove duplicate references (i.e., references that appeared in more than one of the databases searched). DeDuper is a tool that uses a two-phase approach to identify and resolve duplicates: (1) it locates duplicates using automated logic, and (2) it employs machine learning to predict likely duplicates which are then verified manually.

TABLE C-1. SEARCH STRATEGY KEYWORDS

Set	Search Keywords and Boolean Logic
Food Waste	Food AND (waste OR loss OR "FLW") AND (prevention OR system OR consumed OR Surplus OR Excess OR Uneaten OR reduction OR supply OR demand OR Per person OR Edible OR Inedible OR Safety OR recall OR packaging OR Preventable OR Drivers OR Spoilage OR perishable OR Freshness OR harvest OR transportation OR Processing OR manufacturing OR supermarket OR grocer* OR reuse OR recycling OR seasonal OR projection OR future OR economic)
Pathways	("Source reduction" OR Awareness OR education OR campaign OR LeanPath OR Photodiary OR storage OR Labeling OR (Refrigerator AND temperature) OR Cellar OR Frozen OR "Meal kits" OR packaging OR Donation OR Upcycling OR "Animal feed" OR "Anaerobic digestion" OR Co-digestion OR "Aerobic processes" OR Composting OR "Controlled combustion" OR Incineration OR Landfill OR "Land application" OR de-packaging OR "shelf life")
Environment	Environment* AND (use OR usage OR impacts) AND (climate OR "Air emissions" OR "Water pollution" OR Pesticide OR Land OR Irrigation OR Energy OR fertilizer OR water OR Herbicides))
Emerging Issues	((Compost* or compostable) AND (packaging OR serviceware OR utensil OR tableware OR plate OR bowl))

To efficiently screen results, references were prioritized using topic extraction, also referred to as clustering, with ICF's Document Classification and Topic Extraction Resource (DoCTER) software. The titles and abstracts from all search results (i.e., AGRICOLA, AGRIS, EBSCO, PubMed, and Web of Science) were run through DoCTER's topic extraction function. Each study was assigned to a single cluster based on text similarities in titles and abstracts. Clusters were prioritized or eliminated for screening based on the relevance of the keywords identified. Only prioritized studies published from 2014–present were screened for relevance.

Peer-Reviewed Literature Screening and Tagging

The sources identified by the literature search were screened to identify those that are considered "key" sources for the report and issue papers. To be considered a key source, a publication had to be relevant to the project scope and exhibit at least most of the general attributes provided in EPA's Quality Assurance Instructions for Contractors Citing Secondary Data, summarized below:

- Focus: the work not only addresses the area of inquiry under consideration but also contributes to its understanding.

- Verify: the work is consistent with accepted knowledge in the field or, if not, the new or varying information is documented within the work; the work fits within the context of the literature and is intellectually honest and authentic.
- Integrity: Is the work structurally sound? In a piece of research, is the design or research rationale logical and appropriate?
- Rigor: the work is important, meaningful, and non-trivial relative to the field and exhibits enough depth of intellect rather than superficial or simplistic reasoning.
- Utility: the work is useful and professionally relevant; it contributes to the field in terms of the practitioners' understanding or decision-making on the topic.
- Clarity: Is it written clearly and appropriately for the nature of the study?

Relevance to the project scope was evaluated against the specific topics and criteria. In particular, relevant topics included:

- Characterization of U.S. food waste, including but not limited to kinds of food, sources, amounts, and reasons for loss or waste.
- Reduction strategies, including composting, anaerobic digestion, secondary industrial uses, animal feed, donation, and source reduction.
- Lifecycle environmental costs and benefits of choices between and within levels of the EPA food recovery hierarchy.
- Pre-processing technologies (e.g., grinding, heating, digestion) and their environmental implications in use, including their potential to help reduce food waste.
- Food packaging and service ware and their relationships to food waste, including ways packaging may impact prevention and recycling of food waste or use and value of products created by recycling.
- Chemical contaminants (e.g., PFOS, PFAS, persistent herbicides) and the risk and problems posed in food waste streams.
- Food system trends to identify well-recognized trends in the U.S. food system that may impact food waste and summarize what has been written about their potential impacts.
- Unharvested or unutilized crops that do not reach the consumer market.
- Waste or loss during transportation, food processing/manufacturing/packaging facilities, or wholesale food distributors.
- Waste or loss at supermarkets (e.g., unsold or spoiled products), restaurants, and households.
- Existing economic, social, and cultural drivers of food waste or barriers to food waste prevention, reuse, and recycling efforts.

The following topics were not considered relevant:

- Unutilized livestock (e.g., due to market forces, routine mortality) or unharvested or unutilized feed crops.
- Regulatory drivers of food waste or barriers to food waste prevention, reuse, and recycling efforts.
- Broad economic impacts (e.g., on the agricultural sector) of food waste production, prevention, reuse, and recycling efforts; economic costs and benefits for entities resulting from food waste production and reduction strategies.

The litstream™ tool was used to screen for key sources based on reference titles and abstracts. litstream™ facilitates screening by one or two independent reviewers, automatically compares categories, and identifies discrepancies for resolution by another individual. litstream™ also allows users to design flexible data-extraction forms, thus enabling the review team to perform the screening and tagging steps of the systematic review within one software tool.

For publications identified as key sources, full text files were retrieved with EPA's Health & Environmental Research Online (HERO) database as requested by authors. Then, authors used the full text of the key sources to confirm topic area relevance and incorporate them into their literature synthesis.

A screening and tagging guidance document was developed to provide instructions and keywords associated with the tags. To ensure internal consistency and accuracy of the litstream™ screening and tagging, a pilot screening of 5–10 reference (per reviewer) was performed to provide feedback to the screening team. Additionally, 10% of each reviewer's assigned citations were reviewed by a second reviewer. Discrepancies between the primary and secondary reviews were resolved by lead authors.

C.2. Methodology for Grey Literature

Identifying key sources in the "grey literature" was essential to a comprehensive review and synthesis of the report and issue papers. The review methodology for grey literature included a search strategy and approaches for screening and tagging key sources.

Grey Literature Search Strategy

The peer-reviewed literature search was supplemented with relevant grey literature from the sources listed below:

- Grey literature publications cited by key sources identified by the EPA from prior related research. These sources were screened as potential key sources.
- Grey literature publications identified by peer reviewers and subject matter experts who reviewed pre-peer review drafts of the reports and issue papers (see the acknowledgments sections in the report and each issue paper). These sources were considered key sources without screening.
- Targeted google and domain searches for selected governmental or non-governmental organizations.

The titles and URLs of potential sources identified by the searches were compiled in an Excel file used for subsequent screening.

Grey Literature Screening and Tagging

Grey literature was screened in Excel using the key source criteria defined for peer-reviewed literature (see Section A.1). Screeners applied the criteria to each of the potential sources in the database file described above (i.e., titles and URLs identified from searches). For each URL, the screeners evaluated the sources by reviewing abstracts, executive summaries, forewords, keyword lists, or tables of contents. When a screener identified a key source, they recorded additional information including publishing organization, author names, and year for the source to proceed to tagging.

Tagging was only performed for the grey literature identified as key sources, and the same tags as used for peer-reviewed literature (see Section A.1) were used for grey literature. screeners applied the tags in columns within Excel.

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