United States Department of Agriculture

Economic
Research
Service

Economic
Research
Report
Number 273

May 2020

Resource Requirements of Food Demand in the United States

Patrick Canning, Sarah Rehkamp, Claudia Hitaj,
and Christian Peters

United States Department of Agriculture

Recommended citation format for this publication:

Canning Patrick, Sarah Rehkamp, Claudia Hitaj,and Christian Peters. *Resource Requirements of Food Demand in the United States*, ERR-273, May 2020.

Cover images from Getty Images.

Use of commercial and trade names does not imply approval or constitute endorsement by USDA.

To ensure the quality of its research reports and satisfy governmentwide standards, ERS requires that all research reports with substantively new material be reviewed by qualified technical research peers. This technical peer review process, coordinated by ERS' Peer Review Coordinating Council, allows experts who possess the technical background, perspective, and expertise to provide an objective and meaningful assessment of the output's substantive content and clarity of communication during the publication's review.

In accordance with Federal civil rights law and U.S. Department of Agriculture (USDA) civil rights regulations and policies, the USDA, its Agencies, offices, and employees, and institutions participating in or administering USDA programs are prohibited from discriminating based on race, color, national origin, religion, sex, gender identity (including gender expression), sexual orientation, disability, age, marital status, family/parental status, income derived from a public assistance program, political beliefs, or reprisal or retaliation for prior civil rights activity, in any program or activity conducted or funded by USDA (not all bases apply to all programs). Remedies and complaint filing deadlines vary by program or incident.

Persons with disabilities who require alternative means of communication for program information (e.g., Braille, large print, audiotape, American Sign Language, etc.) should contact the responsible Agency or USDA's TARGET Center at (202) 720-2600 (voice and TTY) or contact USDA through the Federal Relay Service at (800) 877-8339. Additionally, program information may be made available in languages other than English.

To file a program discrimination complaint, complete the USDA Program Discrimination Complaint Form, AD-3027, found online at How to File a Program Discrimination Complaint and at any USDA office or write a letter addressed to USDA and provide in the letter all of the information requested in the form. To request a copy of the complaint form, call (866) 632-9992. Submit your completed form or letter to USDA by: (1) mail: U.S. Department of Agriculture, Office of the Assistant Secretary for Civil Rights, 1400 Independence Avenue, SW, Washington, D.C. 20250-9410; (2) fax: (202) 690-7442; or (3) email: program.intake@usda.gov.

USDA is an equal opportunity provider, employer, and lender.

United States Department of Agriculture

Economic Research Service

Economic Research Report Number 273

May 2020

Resource Requirements of Food Demand in the United States

Patrick Canning, Sarah Rehkamp, Claudia Hitaj,
and Christian Peters

Abstract

Natural resources facilitate production of an adequate daily food supply for Americans. Food consumption in the United States, measured in total calories per day, increased about 50 percent over a recent 25-year span. Understanding how changes in food consumption impact the U.S. food system's use of the country's natural resources requires consideration of many factors. We find that diets, or food choices, are likely to be an important factor. For example, had the diets of Americans who met all the 2010 USDA Dietary Guidelines for Americans back in 2007 become the typical American diet of that time, then per capita consumption of the fruits, vegetables, legumes/nuts/seeds, eggs, and dairy categories would have increased, while per capita consumption in the sugars/sweets/beverages, fats/oils/salad dressings, grain products, and meat/poultry/fish/mixtures food groups would have declined. In such a scenario, under the production and marketing practices in 2007, nutrition and resource conservation goals would have been mostly complementary, or synergistic. As one notable exception, water conservation in particular may have required tradeoffs between competing goals, especially for production of fruits, vegetables, and dairy. This report combines empirical evidence of resource use in the system in 2007 with the presentation of a framework for a broader empirical study of sustainable pathways to producing a healthy and adequate food supply.

Keywords: diets, Dietary Guidelines for Americans, natural resources, sustainability, U.S. food system

Acknowledgments

The authors thank the following individuals for their reviews and comments: Marcel Aillery, Kelly Maguire, Constance Newman, Timothy Park, and Katherine Ralston, U.S. Department of Agriculture (USDA), Economic Research Service (ERS); Jared Creason, U.S. Environmental Protection Agency; Stephan Goetz, Pennsylvania State University; and Parke Wilde, Tufts University. Thanks also to Courtney Knauth and Andrea Pimm of USDA-ERS for editorial and design services.

This research was supported in part by the intramural research program of the U.S. Department of Agriculture, Economic Research Service. Christian Peters' contributions were supported, in part, by a cooperative agreement with ERS (Cooperative Agreement number 58-4000-5-0004).

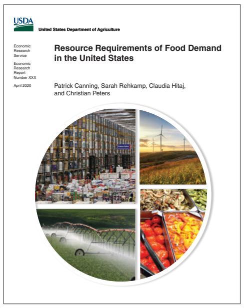
Contents

Errata

On September 15, 2020, *Resource Requirements of Food Demand in the United States* was revised to correctly identify the units for greenhouse gasses as metric tons throughout the report.

United States Department of Agriculture

A report summary from the Economic Research Service May 2020



United States Department of Agriculture

Economic
Research
Service

Economic
Research
Report
Number XXX

April 2020

Resource Requirements of Food Demand
in the United States

Patrick Canning, Sarah Rehkamp, Claudia Hitaj,
and Christian Peters

Resource Requirements of Food Demand in the United States

Patrick Canning, Sarah Rehkamp, Claudia Hitaj, and Christian Peters

What Is the Issue?

The U.S. food system comprises all businesses that are either directly or indirectly involved in producing and marketing food products, such as the producers of farm inputs like fertilizers and machinery, the farmers growing food and feed commodities, and the processors making food products, plus the food merchants and eating places where U.S. consumers spent over $1.8 trillion on food and beverages in 2018. Natural resources—land, water, minerals, air, and forests—provide materials and services necessary to produce and market the food we eat. To supply the food production to meet the food demand of a growing population, it is important to understand the U.S. food system's impact on these natural resources. This report concerns only the food system's production and marketing of food products for purchase by or for all American food consumers.

Three main factors determine the resource requirements of food demand: Population (how many consumers?), diet (what will they consume?), and technology (how will our food system produce, market, and preserve our food supply?). This study focused on the use of natural resources in the U.S. food system by examining recent research on one of these factors, diet, to illustrate how food choices can affect use of resources.

What Did the Study Find?

We estimated use of natural resources in the food system for a set of age and gender-specific Baseline diets, based on food consumption in 2007, and compared results to those for a set of Healthy American diets based on the 2010 Dietary Guidelines for Americans. The study produced the following insights:

1. **The 2007 Baseline diets were resource-intensive.** Since total annual expenditures on food in the United States were 8.6 percent of U.S. gross domestic product (GDP) in 2007, we considered use of a natural resource by the food system to be an intensive use if greater than 8.6 percent of the resource's 2007 domestic use was dedicated to food. To accommodate all Baseline diets, model results indicate the U.S. food system used 25.5 percent of the country's total land area, including over half (53 percent) of productive agricultural land. It used 28 percent of total freshwater withdrawals, 11.5 percent of total fossil fuel consumption, 18.1 percent of total greenhouse gas (GHG) emissions, and 7.2 percent of total marketed forest products. With the exception of forest products, each of these was intensive use of the resource by the food system.
2. **Substantial resource requirements occur beyond the farmgate**. The stages of the food system most reliant on natural resources differ substantially across the five resources considered. Land use and freshwater withdrawals were both resource-intensive on-farm in 2007. Conversely, agriculture accounts for less than half of total resource use for the Baseline diet of fossil fuels, air (as a GHG repository) and forestry products; the majority of these resource requirements are in supply-chain stages further downstream.

ERS is a primary source of economic research and analysis from the U.S. Department of Agriculture, providing timely information on economic and policy issues related to agriculture, food, the environment, and rural America.

3. **The modeled Healthy American diet would lead to significant changes in food consumption compared to Baseline diets**. The Healthy American diet is based on the diets of Americans who met all 2010 USDA Dietary Guidelines for Americans in 2007, as determined by an analysis of a nationally representative survey designed to assess the health and nutritional status of Americans. Consumption in the fruits, vegetables, legumes/nuts/seeds, eggs, and dairy categories would increase, while consumption in the sugars/sweets/beverages, fats/oils/salad dressings, grain products, and meat/poultry/fish/mixtures food groups would decline. The composition of food items within each food group would change, as well as the categories' total calories.

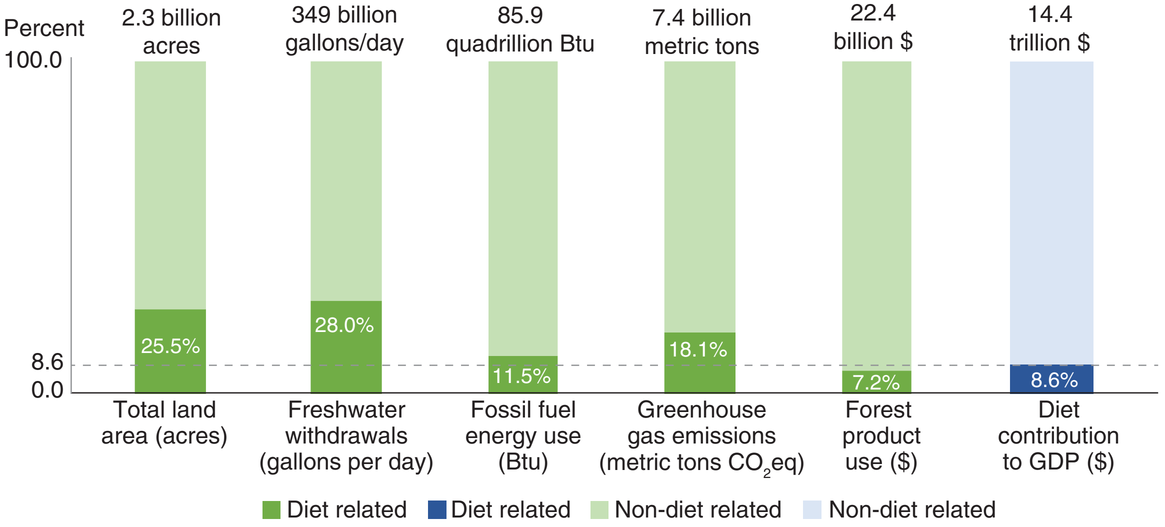
4. **A shift to the modeled Healthy American diet in 2007 would have decreased use of some resources but increased the use of others**. This scenario assumes a shift that aligned all Americans, on average, with the Healthy American diet, and that the food system had not changed its production methods. Use of productive agricultural land, fossil fuels, and forest products would have decreased, while freshwater withdrawals increased. Use of air as a repository for diet-related greenhouse gas emissions (GHG) would have remained essentially unchanged with a conversion to the Healthy American diet. Reductions in GHG emissions linked to reduced fossil fuel use would have been offset by increases linked to biogenic emissions.

This study also presents a framework for a broader empirical analysis of sustainable pathways to producing a healthy and adequate food supply that accounts for population and technology change. The authors found that several ERS models provide useful frameworks along these lines.

How Was the Study Conducted?

Given the high level of uncertainty about eating patterns and technologies looking ahead, we developed a range of scenarios with an array of model frameworks to study potential outcomes. At the time of the recent ERS analysis that this report builds on, the *2007 National Benchmark Make and Use Tables* for the production model of our analysis, published in 2015, provided the latest data of sufficient detail for this purpose, so our analysis is based on the 2007 U.S. food system. We use a mathematical optimization model to define diets using the attributes of individual food items consumed by Americans in 2007. We use an environmentally extended economic model, FEDS-EIO, to account for the use of natural resources throughout the entire food value chain from farm inputs through home kitchen operations. We use a biophysical model, Foodprint, to estimate land and animal inventory requirements of producing all food commodities embodied in the model-derived diets. Model results from this research do not include any international resource use embodied in imported food and ingredients and do not account for any U.S. resource use for the production of food exported to other countries.

Estimated diet-related share of total resource use across five categories, 2007



Notes: Btu = British thermal units. GDP = gross domestic product.

Source: USDA, Economic Research Service.

Introduction

The U.S. food system comprises all businesses that are either directly or indirectly involved in producing and marketing food products. Examples of businesses with direct involvement are the farmers growing the crops and animal food products, the mills and animal-processing plants that transform food grains, oil seeds, and meat animals into processed food ingredients and food commodities, and the supermarkets and restaurants that serve as points of purchase for U.S. food consumers, who spent over $1.8 trillion in 2018 on food and beverages (USDA, ERS, 2020). Examples of businesses with indirect involvement are the electric utility and paper mill companies that produce electric power and paper products for all businesses and households in their service area, including businesses running oilseed milling machinery and selling food products in paper packaging, and households running kitchen appliances and using napkins and paper towels for serving and cleaning up after meals. Additionally, the commercial cold storage facilities and in-home refrigerators and freezers used for food storage, and the transport of food and food ingredients (such as between businesses at different stages of the supply chain and personal travel to grocery stores) are part of our food system.

Natural resources are essential to the production of food for human consumption. From the farmland and freshwater that facilitate crop and animal product production, to the mineral and forest products used to make building materials and as sources for energy to power industry and preserve foods, to the air used to both extract nitrogen for fertilizers and as a repository for various byproducts of production and consumption, natural resources have a central role throughout our food system.

This report, which examines resource use throughout the U.S. food system, is concerned only with the food system's production and marketing of food products for purchase by or for all American food consumers. To study resource use implications of changes to U.S. food consumption, like the roughly 50-percent increase[1] in U.S. caloric consumption between 1985 and 2010, we begin with a conceptual framework for the measurement of food-related uses of natural resources. Our approach involves the use of extensive primary data sources covering food consumption, food production, and the use of natural resources. These data are used to compile models that produce estimates that link both observed and model-derived diet outcomes to estimates of how much natural resources are used to accommodate these diets.

The report then provides detailed descriptions of our approaches and data sources for measuring and modeling observed and alternative American diets and identifying and estimating resources used to produce the food that accommodates these diets. Next, results of the analysis are reported, focusing on diet-related changes to isolate the impact of diet change on resource use throughout the food system. In the final section we outline a more general approach to incorporate the other main factors affecting resource use in the food system—population and technology. We find that several ERS models provide useful frameworks for a broader empirical analysis of sustainable pathways to producing a healthy and adequate food supply that accounts for population and technology change.

---

[1] Calculated from the ERS Loss Adjusted Food Availability data product (USDA-ERS, 2019) using data from the total average daily per capita calories series (adjusted for spoilage and other waste) and the ERS estimate of resident plus Armed Forces population series.

Conceptual Framework

Total resource requirements of national food systems are determined by three main factors:[2]

a. Population (**p**) - how many total residents?

b. Diet (**D**) - what will the 'average' resident consume?

c. Technology (**T**) - how will the food system make, market, and preserve food supplies?

Measures of population in vector **p** are broken out into '*c*' different cohort groupings based on the various factors that influence diet choices—for example, a simple breakout by gender across 8 different age ranges. For each cohort grouping row in matrix **D**, average diets are measured across '*y*' columns representing different food commodity groupings—for example, 74 different broad food and beverage commodity groupings, such as '*fresh fruits*.' For each food commodity row in matrix **T**, average resource use per unit of commodity consumed is measured across '*r*' columns representing different types of natural resource materials or services—for example, *fresh groundwater withdrawals*—and further broken out across '*s*' supply chain stages—for example, use for *crop production*—for a total of $r \times s$ different matrix columns. To use the data in **p**, **D**, and **T** to measure how use of all natural resources (**R**) for food production changes over time, the role of these three main factors can be stated mathematically as follows:

$$1) \qquad \Delta\mathrm{R} \qquad \approx \left[\widehat{\mathrm{p}^0} \times \Delta\mathrm{D} \times \mathrm{T}^0\right] + \left[\Delta\hat{\mathrm{p}} \times \mathrm{D}^0 \times \mathrm{T}^0\right] + \left[\widehat{\mathrm{p}^0} \times \mathrm{D}^0 \times \Delta\mathrm{T}\right]$$

$$\left[\begin{array}{c}\textit{Change in}\\ \textit{resource use}\end{array}\right] \qquad \left[\begin{array}{c}\textit{Change due to}\\ \textit{average diet}\end{array}\right] \qquad \left[\begin{array}{c}\textit{Change due}\\ \textit{to population}\end{array}\right] \qquad \left[\begin{array}{c}\textit{Change due}\\ \textit{to technology}\end{array}\right]$$

In equation (1), the upper-case Greek delta (Δ) denotes the measurement of change over a fixed time interval—for example, change over one *minute*, *day*, *year*, *decade*, *etc.*—and the zero superscript (^{0}) denotes a measurement in the current time period. If we denote the future period that is one interval of time after the current period with a '^{1}', then the change in per capita diet expression in (1) is measured as $\Delta D = (D^1 - D^0)$. The symbol '^' above **p** (in change due to population) indicates the vector is changed into a diagonal matrix, which allows for the matrix multiplication of all expressions on the right side in (1) to produce the desired measures of change over time in total use of natural resources.

Equation 1 is only an exact measure when considering very small intervals of time. When considering other than small units of time we use the symbol '≈', which means '*is approximately equal to*'. An example of this approach by Canning et al. (2010) examined historical data to decompose how changes in the use of energy throughout the U.S. food system between 1997 and 2002, measured in British thermal units (Btu's), was influenced by the three measures on the right side of equation (1).

---

[2] Along with these main factors, a number of external factors are important, including, for example, climate change, changes in international terms of trade, and natural disaster, to name a few.

They found that change due to technology (ΔT) explained about half of the overall change and that changes due to diet (ΔD) and population (Δp) both explained about a quarter of the overall change.

We focus on diet change ($\Delta\mathbf{D}$). This term is in the first bracketed expression on the right side of equation (1), which also includes terms for the population and technologies in place during our baseline period of analysis, $\mathbf{p}^0$ and $\mathbf{T}^0$. This approach of only considering scenario changes to one term at a time is called *comparative static scenario analysis*. Although this report does not conduct comparative static scenario analysis of population change or technical change, we follow our scenario analysis of diet change with a discussion of a more general framework for studying these other two main factors, $\Delta\mathbf{p}$ and $\Delta\mathbf{T}$. Our focus is on the use of domestic natural resources to accommodate food demand in the United States.

How Do We Determine American Diets?

This analysis focuses in particular on the natural resource implications of a change from typical American diets to diets aligned with the Dietary Guidelines for Americans (DGA). It is consistently shown that U.S. dietary patterns do not align with the DGA (USDA and USDHHS, 2015). For example, many Americans exceed the Federal dietary recommendations for added sugars, saturated fats, and sodium, and could improve their eating patterns by increasing consumption of vegetables, fruits, and dairy (Figure 2-1 in USDA and USDHHS, 2015).

To represent the typical American diet, denoted as the Baseline diet, we used the 2007–08 National Health and Nutrition Examination Survey (NHANES) collected by the National Center for Health Statistics (USDHHS CDC NCHS, 2013a). NHANES is a nationally representative survey designed to assess the health and nutritional status of Americans and is released in 2-year cycles. The dietary data were collected through interviews in which respondents recalled what they ate in the previous 24 hours (USDHHS CDC NCHS, 2013b). As explained below, we use data from 2007-08 for consistency with other data sources available for use in the analysis. We compare the diets of respondents in the 2007-08 NHANES sample with the 2010 Dietary Guidelines for Americans and employ a model that estimates the most likely food intake by the respondents whose diets were consistent with all the guidelines.[3] This model-derived intake becomes the Healthy American diet scenario. This diet is derived from a model with nutrient, food pattern, and caloric targets for the moderate physical activity level (Appendix 6 in USDA and USDHHS, 2010).

Building on previous work by Canning et al. (2017) and Rehkamp and Canning (2018), the Healthy American diet is derived from a mathematical optimization model designed to minimize the difference between the Baseline diet and one that meets the DGA recommendations (USDA and USDHHS, 2010). We use 16 cohort populations that represent all Americans ages 2 and above, broken out by gender across 8 age ranges (see Appendix table A.3 in Canning et al., 2017). The maximum likelihood properties of the model we use to derive the Healthy American diet are the most representative diets among Americans who are aligned with the DGA. In terms of an underlying theory of consumption, this diet is most representative of the underlying preferences of U.S. consumers meeting all dietary guidelines as of 2007, given prevailing prices and incomes at the time across the 16 different cohort groups. Diets meeting the DGA represent healthier eating patterns than average American diets, and these recommendations aim to “help promote health and prevent chronic diseases for current and future generations” (USDA and USDHHS, 2015). This motivates our use of the Healthy American diet as our representative alternative diet scenario.[4]

The model’s dietary constraints include food group guidelines, defined by the USDA Food Patterns. The USDA Food Patterns recommend consumption amounts for each food group for 12 different calorie levels and serve as examples of how to follow the DGA (USDA-ARS, 2014). We also include caloric and 33 nutrition targets, all of which are outlined in the 2010 DGA appendixes (USDA and USDHHS, 2010). The nutrient targets are included for completeness, since the most nutrient-dense foods are not typically chosen by Americans (Britten et al., 2012). These dietary constraints are

---

[3] In our related research (e.g., Rehkamp and Canning, 2018; Hitaj et al, 2019), we compare our results to those of others in the literature who also used the 2010 DGA as a yardstick to measure healthy diets (Heller and Keoleian, 2015; Tom et al., 2016). We found only minor differences in diets when using the more recent 2015-2020 DGA (USDA and USDHHS, 2015) as a yardstick to measure healthy diets.

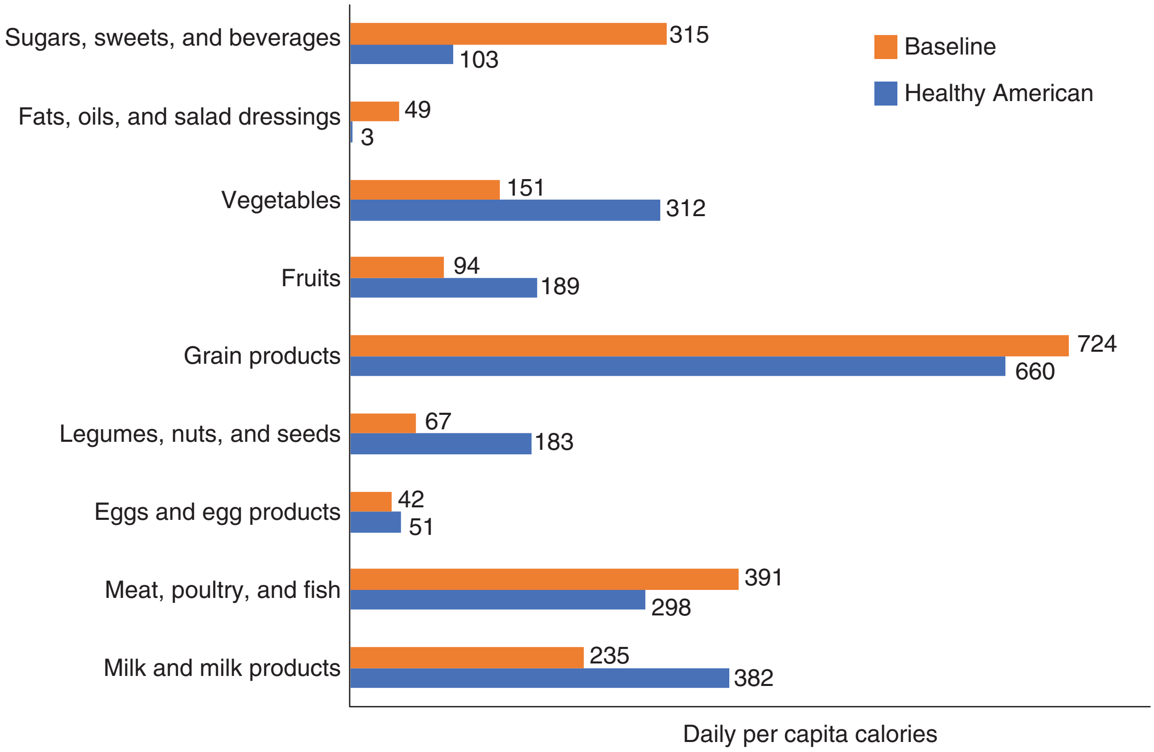
[4] The focus here on a single hypothetical alternative diet scenario can routinely be expanded to a range of potential diets, such as was done in Hitaj et al. (2019).

weighted based on the age and gender demographics of the NHANES participants. In addition to the dietary constraints, we also imposed a cost constraint requiring that the wholesale cost of the Healthy American diet be the same as or less than that of the Baseline diet. We allow a ±5-percent deviation from the caloric targets to give the model flexibility to solve. Overall, calories in our Healthy American diet are higher than in the Baseline diet but still within the calorie constraints. More technical details of the diet model and data sources can be found in Canning et al. (2017).

The Healthy American diet resulting from solution of the model is the shortest and least disruptive route to eating healthfully. Statistically, it is most representative of American diets meeting the DGA because of the model's construction. Because of the model's minimum-change objective, the Healthy American diet contains many of the same food items as the Baseline diet. For example, fluid milk, bananas, and tortillas are popular food items in both diets, but the quantities of the food items vary. Figure 1 summarizes the national average diets of all Americans for the two diets—Baseline and Healthy American. The summary measures are daily per capita caloric consumption across nine broad food categories that group the individual food items from NHANES that make up the two diets.

Figure 1

Per capita calories by food group: Baseline and Healthy American diets



Note: Baseline diet is measured from the 2007–08 National Health and Nutrition Examination Survey (NHANES) (USDHHS CDC NCHS, 2013a)—a nationally representative survey of food intake by all Americans ages 2 and above. Healthy American diet is from a model that estimates the most likely food intake by all Americans in the 2007–08 NHANES sample who are meeting all 2010 USDA dietary guidelines (USDA and USDHHS, 2010).

Source: USDA, Economic Research Service.

In moving from the Baseline diet to the Healthy American diet, the largest percentage reductions in consumption occur in the two categories, sugars/sweets/beverages and fats/oils/salad dressings, while the largest increases are for legumes/nuts/seeds and both fruits and vegetables. These overall shifts are consistent with our expectations on how diets would have to shift to be aligned with the DGA. In addition to caloric changes in overall food categories, there are within-category shifts of individual food items, changing dietary composition.

Differences between the two diets are substantial, which portends potentially large differences in use of the various natural resources required to accommodate each of them. Before we present measures of resource requirements, we discuss our approach to identifying and estimating these measures.

How Do We Identify and Measure Resources in the U.S. Food System?

We apply a consistent approach to identifying and measuring resource use and impacts across all markets and for all types of resources. Using our recently published research on this topic and new analysis, we are able to compile and synthesize diet/resource scenario analysis of a major metric for each of the five natural resource categories.[5]

Our approach is unique in that we estimate resource use directly at each point in the food supply chain using three data-rich models. We combine 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 across alternative diet outcomes. The integrated analysis links the diet choices of 16 different age/gender cohort populations over 4,000 food items, as reported in NHANES, to food purchases across over 70 commodity groups, to food production directly and indirectly involving over 300 industry groups, to resource use across the 5 categories. The limiting data source for this purpose is data for the production model, which must link the resource data on the input side to the food expenditure data of households and foodservice establishments on the output side. At the time of the recent ERS analysis that this report builds on, the 2007 National Benchmark Make and Use Tables published by the Bureau of Economic Analysis (USDOC BEA, 2015) provided the latest data of sufficient detail for this purpose, so our analysis of observed conditions is represented by the 2007 U.S. food system.

Which Resource Materials and Services Are Important to Food Production?

To produce the food that Americans consume each day, food system businesses employ workers to use their machinery and equipment, buildings, and purchased materials and services from other food system businesses. With these, the businesses produce outputs that are either consumer food products, such as plain nonfat yogurt, or are a product that they sell for use by other food system businesses, such as veterinary services sold to a dairy farm.

In addition, many of the food system establishments use materials and services provided from the country's endowment of natural resources. In terms of physical attributes, natural resources can be classified into five categories: land, water, air, minerals and forests.[6] To illustrate how these different natural resources are used in food production, consider the following example: Mining businesses extract potash, a mineral containing potassium. Farmers growing crops, such as wheat farmers, purchase potash products to fortify the plant nutrients embodied in the soils of their farmland in order to improve their wheat yields. The potash is material from the *mineral* group of natural

---

[5] This report synthesizes four primary publications on sustainable diets (Canning et al., 2017; Hitaj et al., 2019; Peters et al., 2016; Rehkamp and Canning, 2018). However, there is a burgeoning body of literature and interest in the environmental impacts of dietary patterns both in the United States (e.g., Boehm et al., 2018; Heller and Keoleian, 2015; Tichenor Blackstone et al., 2018; Tom, Fischbeck, and Hendrickson, 2016) and globally (e.g., IPCC, 2019; National Academies of Sciences, Engineering, and Medicine, 2019; Tilman and Clark, 2014; Willet et al., 2019).

[6] In this classification, minerals include fossil fuel materials, and forests are used instead of the more general 'vegetation and animals' since the latter also describes important intermediate products (crops and livestock) of the food system. The boundary of our analysis for land use is agricultural land, and so it excludes, for example, the use of land for food-related forest product production and the mining of fossil fuels.

resources, and the soil is material from the *land*-resource group. Major customers of the wheat farmers are flour mills that operate electric milling and packaging machinery to convert the purchased wheat into flour, which is then often packaged in paper products. The paper is made from wood pulp, a material from the *forest* resource group. The electricity that powers the mill is most likely produced by a process in which freshwater is diverted from a waterbody and heated with a fuel such as coal to create steam under high pressure to spin a turbine that produces electricity. The freshwater is a material from the *water* resources group and coal is from the *minerals* group. Two byproducts of electric power production are steam from the boiling of water and carbon from the burning of coal, which are discharged into the air. In this case, *air* (one of the resource groups) is providing disposal services.

But just as a flour mill requires a certain quality of wheat, businesses require natural resource materials and services of a minimum quality. Resource quality and availability is naturally managed and regulated by resource cycles, such as the *water*, *carbon*, and *soil nutrient* cycles. (See box, "Natural Resource Use in the U.S. Food System: An Overview" for an overview of the materials, services, and key cycles important to our food system.)

Recent research by ERS and our partners assesses how some materials and services that are important to the food system are used to accommodate baseline and alternative American diets. We synthesize findings from these studies with new analysis using existing ERS models and data (see Appendix Table 1 for a list of the materials and services studied and the case studies or ERS models this analysis draws from).

How Is Resource Use Measured in the U.S. Food System?

To measure resource requirements in the U.S. food system, ERS economists developed the Food Environment Data System, or *FEDS* (Canning et al., 2017). *FEDS* is a national data system that follows the material flows accounting framework adopted by the United Nations Statistical Commission (United Nations et al., 2014). While economists often study dollar units (i.e., prices or cost), *FEDS* also incorporates physical units of measurement. We are able to comprehensively estimate resources used throughout the food supply chain from the production of farm inputs, crops, and livestock through points of consumer food purchases and to the operation of home kitchens. For example, we can estimate total water use associated with a hamburger, such as the cattle's drinking needs, irrigating the crops that become livestock feed, water used in electricity generation that ultimately runs the refrigerators at the grocery store, and water for rinsing dishes in the kitchen sink. In this report, the terms *water use* and *water withdrawals* are used interchangeably. Both refer to water removed from the ground or diverted from a surface-water source for use.[7]

Detailed descriptions of FEDS data sources, and how the environmental input-output model, called *FEDS-EIO*, is used for the analysis in this report are summarized in our technical appendix (see section "Measuring Diet-Related Fossil Fuel Combustion and Water Withdrawals").

To account for land use in alternative diets in this report, we use a biophysical simulation model that calculates the per capita land requirements of complete diets and the potential carrying capacity of the agricultural land of the conterminous United States (Peters et al., 2016). The land requirement per gram of each food commodity consumed accounts for food loss and food waste occurring in preparation, distribution, and processing, but does not allow for technological change or productivity growth.

---

[7] Not all water use is a consumptive use, including water that is evaporated, transpired, or incorporated into products or crops, consumed by humans or livestock, or otherwise removed from an immediate water environment (see glossary in Dieter et al., 2018).

It also does not account for nonagricultural land use, such as for the production of forestry products or the mining of fossil fuels. Estimates for each food commodity in the diet are calculated based on nationally representative estimates of crop yield, grazing land productivity, and livestock feed efficiencies. The model adjusts for the multi-use nature of certain crops (e.g., soybeans produce vegetable oil and high-protein livestock feed) and prevents double-counting. These per gram land requirement calculations are applied to both the Baseline and Healthy American diets. Two revisions were made to the model for this study in order to measure livestock inventories linked to alternative diets. A detailed description of data sources and how the biophysical model, called Foodprint, is used for the analysis is reported in our technical appendix (see section "Measuring Land Use and Farm Animal Inventories"). Unlike the other resources considered in this report, our metric for land-*acres*--is not homogenous from a productive standpoint, and our current approach does not capture potential heterogeneities.[8]

Air is used as a repository for GHG emissions from both fossil fuel combustion in food production and from biogenic sources, including enteric fermentation and manure management emissions from livestock and soil management emissions from cropland. The Foodprint model gives the land requirements used to compute soil management emissions from both food and livestock feed production, as well as livestock inventory to calculate enteric fermentation and manure management emissions. GHG emissions from fossil fuel combustion are calculated from energy consumption by fuel, production stage, and subsector tracked through *FEDS-EIO*. The section "Measuring Air Use as a Repository for GHG emissions" in the technical appendix describes the data sources used for calculating GHG emissions associated with different diets.

Our approach to measuring use of forest products by supply chain stage is to develop value-added measures. This measure simply represents the monetized value of physical units for forest products. For this purpose, we employ the ERS Food Dollar model (Canning, 2011; Canning, Weersink, and Kelly, 2016). A detailed description of data sources and how the model is used for the analysis in this report is provided in our technical appendix (see section "Measuring Forest Product Use").

---

[8] A potential future refinement could be to develop productivity-weighted estimates of land use changes.

Natural Resource Use in the U.S. Food System: An Overview

Materials and services across all five natural resource categories are important inputs to the production, marketing, preparation, and disposal of food purchased by or for all Americans. These five natural resource categories are land, water, air, minerals, and forests.

Land: This resource provides suitable soils for use in growing food, feed, and fiber crops and provides space for grazing and tending farm livestock (Peters et al., 2016). Land also provides space for structures of all types used throughout the food system, plus for roads and other transportation infrastructure that connects nodes in the food system. It is a place for disposal of managed waste[1] from production and consumption (usually for a fee, such as in landfills), and is also a repository for material byproducts of production and consumption other than managed

---

[1] "*Managed waste*" refers to byproducts of production and consumption that the producer or consumer does repurpose or does purposefully and legally reposit (put away or store up).

continued

waste (usually with no fee, such as through runoff and soil leaching). Soil health, which is essential to achieving high crop yields, is naturally regulated by the soil nutrient cycle and can be enhanced through use of best-management practices (Bowman, Wallander, and Lynch, 2016).

Water: Freshwater is necessary for human consumption and is also used throughout the food system as a production input (including household production) for purposes including crop irrigation, livestock servicing, thermoelectric power generation, various industrial uses, and food preparation and cleanup (Rehkamp and Canning, 2018). Sources of freshwater withdrawals include surface and groundwater origins. Like land, waterbodies provide a place for disposal of managed production and consumption waste (sometimes for a fee, such as through issuance of point-source discharge permits), and also serve as a repository for unmanaged waste (usually with no fee, such as through non-point-source waterbody discharges (Ribaudo, Horan, and Smith, 1999). Water quality must be maintained for productive uses, and quality is naturally regulated by the water cycle.

Air: Air is a free resource that nonetheless provides vital materials and services throughout the food system. For example, oxygen and nitrogen manufactured using air separation processes have many industrial uses important in food production, such as agricultural fertilizers, steel manufacturing, and refrigerants. Air is also a repository for byproducts of fossil fuel consumption throughout the food system (Canning et al., 2017), and is both a source of key elements and a repository for byproducts of processes like enteric fermentation of livestock and manure and soil management (Hitaj et al., 2019). Air quality is essential to sustain life and maintain high productivity throughout the food system. One important natural regulator of air quality is the carbon cycle,[2] which includes the process of photosynthesis, whereby green plants use energy from sunlight to remove carbon from the air and replace it with oxygen.

Minerals: Minerals are naturally occurring inorganic substances that are typically obtained commercially from underground deposits. Commercially viable mineral products have properties that add value to a production process or are marketable as a consumer good. Examples of mineral products used throughout the food system include calcium, fossil fuels (refined crude oil products, coal products, and natural gas), metal products, phosphate, potash, and salt. The time it takes for new minerals to form is far longer than the human lifespan, and so mineral use is managed as a nonrenewable resource; minerals are used within the framework of optimal extraction with depletion and discovery (Conrad and Clark, 1987). For example, if we ignore the possibility of new mineral discoveries, then mineral use today reduces the total future availability of that same mineral by an equal amount. In this case, increasing a mineral's use in production today should only occur if the value it creates today exceeds the present (discounted) value of all possible future uses. That determination is typically made by the mineral owner.

Forests: Forest products used throughout the food system include lumber used as building material, paper products used as packaging and for office supplies, and both plant and animal food products. Forests are a renewable resource that is naturally managed by the forest life cycle[3] and are further managed through forestry best-management practices for either commercial or recreational-conservation purposes. Forests also play a major role in the carbon cycle, serving as a carbon reservoir and as a supplier of oxygen into the atmosphere (Lewandrowski et al., 2004).

---

[2] https://www.nrs.fs.fed.us/carbon/.

[3] www.oregonloggers.org/Forest_About_FullCycle.aspx.

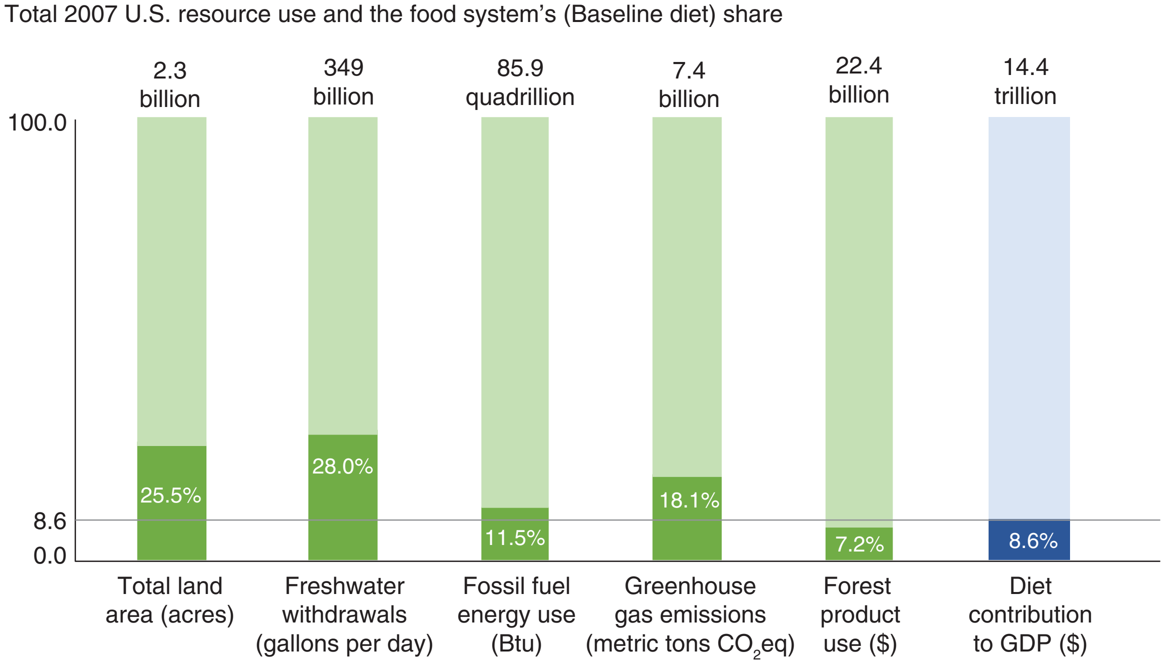
Results of Food Demand Scenarios

In the following comparative static scenario analysis, we consider diet-related changes and the associated adjustments in the use of natural resources—the first bracketed term in equation (1). This analysis holds population of the 16 cohort groups at their baseline levels ($\mathbf{p}^0$) and assumes the baseline production technologies ($\mathbf{T}^0$) for all possible diet outcomes. The purpose is to isolate the impact of diet change on resource use throughout the food system. In the next section we consider, but will not carry out, a more general approach to study the other main factors affecting resource use in the food system ($\Delta\mathbf{D}$ and $\Delta\mathbf{T}$).

Total Resource Requirements of the Baseline Diet

We synthesize and adapt research from five technical publications (Canning, 2011; Canning et al., 2017; Hitaj et al., 2019; Peters et al., 2016; Rehkamp and Canning, 2018) to answer the question, *What share of key domestic natural resources used throughout the economy is dedicated to accommodating observed (2007) American diets*? The results are summarized in Figure 2.

Figure 2
Estimated annual resource use in the Baseline diet across five categories, 2007



Btu=British thermal units. GDP=gross domestic product.

Note: Baseline diet is measured from the 2007–08 National Health and Nutrition Examination Survey (NHANES) (USDHHS CDC NCHS, 2013a)—a nationally representative survey of food intake by all Americans ages 2 and above.

Source: USDA, Economic Research Service.

Total annual expenditures on food in the United States were 8.6 percent of U.S. gross domestic product (GDP) in 2007.[9] We consider any natural resource having greater than 8.6 percent of its 2007 domestic use dedicated to food an intensive use of the resource by the food system. This is a relative measure that is similar in concept to the Heckscher-Ohlin (H-O) theorem of factor-abundance (see Chapter 11 in Blaug, 1992). An important concept of material-flows accounting (Bullard and Herendeen, 1975) leads to an accounting identity that 100 percent of all 'materials' used as production inputs throughout the economy, including natural resources, are embodied in real gross domestic product (GDP). Because our analysis is only for 1 year, nominal GDP is an acceptable substitute for real GDP. It is a straightforward calculation to show how any category of GDP—such as food, whose national share of resource use exceeds its national share of real GDP—is an intensive user of that resource, based on this H-O type measure for intensive use.

It is important to note that all embodied resources measured here only represent those used domestically for the purpose of accommodating all annual food and beverage purchases of the entire U.S. population, ages 2 and above. This does not include resources used for farm and food production for the export market and farm production for the nonfood domestic market. It also does not include resource use in other countries for the production of food and ingredients imported to the United States and purchased by U.S. food consumers, although it does include the resources used to transport and market these imports once they enter the country. Finally, it does not include the resources used to produce the food and beverages purchased by Americans traveling abroad. The focus here is to measure the share of each domestic annual resource budget (in physical units) that is dedicated to accommodating annual 2007 diets of all Americans ages 2 and above. When alternative diets are considered in the model, production coming from both domestic and imported sources adjusts to the new diet requirements by amounts that maintain their market shares. For example, should the new diet require a 5-percent decrease in total cheese production, then the sale of both domestic and imported cheeses to U.S.food consumers declines by 5 percent.

Results indicate that to accommodate all U.S. diets in 2007, the U.S. food system used 25.5 percent of the country's nearly 2.3 billion acres of total land area, including over half (53 percent) of productive agricultural land. This finding partially reflects the fact that much of U.S. cropland is devoted to nonfood crops, like cotton and corn for ethanol, and to export crops, like soybeans. The U.S. food system also used 28 percent of total freshwater withdrawals, 11.5 percent of the country's 85.9 quadrillion British thermal unit (Btu) annual fossil fuel budget, 18.1 percent of the roughly 7.4 billion metric tons of annual greenhouse gas (GHG) emissions, and 7.2 percent of the $22.4 billion of marketed forest products. With the exception of forest products, each was an intensive use of the resource by the food system.

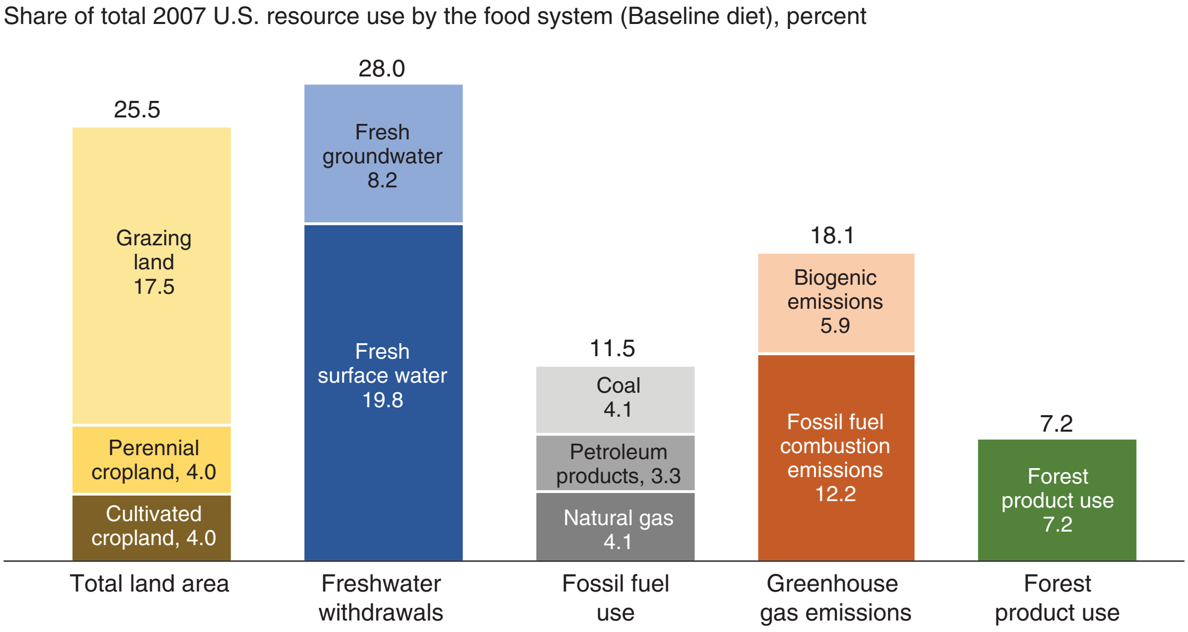
Figure 3 provides a closer look at diet-related resource use. Of the productive agricultural land dedicated to the Baseline diet, grazing land represents the largest portion—its 397-million acre requirement represents about 36 percent of total productive agricultural land and 54 percent of total grazing land use. Diet-related perennial forage cropland (land with herbaceous crops that are alive year-round, such as alfalfa and other hay crops fed to livestock) totaled 91 million acres and—while only representing about 8 percent of productive agricultural land—

---

[9] The Baseline diet is facilitated by domestic food expenditures. Food GDP in 2007 is measured as the sum of line 26 (Food and beverages purchased for off-premises consumption) plus line 82 (Food services) of table 2.4.5 of the National Income and Product Accounts (NIPA). Total GDP in 2007 is from line 1 of NIPA's table 1.1.5. (https://apps.bea.gov/iTable/index_nipa.cfm accessed on December 4, 2018).

accounted for 92 percent of all U.S. land used for perennial crops in 2007. Diet-related cultivated cropland totaled about 90 million acres, also representing about 8 percent of productive agricultural land and 35 percent of all U.S. land used for cultivated crops.

Figure 3
Detailed annual resource use estimates attributable to the Baseline diet, 2007



Note: Freshwater withdrawals refer to freshwater removed from the ground or diverted from a surface-water source for use; freshwater withdrawals may be different from freshwater consumption. Biogenic emissions include enteric fermentation (the digestive process of ruminant livestock such as cattle) and manure management emissions from livestock and soil management emissions from cropland. Baseline diet is measured from the 2007–08 National Health and Nutrition Examination Survey (NHANES) (USDHHS CDC NCHS, 2013a)—a nationally representative survey of food intake by all Americans ages 2 and above.

Source: USDA, Economic Research Service.

For freshwater, about 70 percent of food-related withdrawals came from surface water sources, with the remainder coming from groundwater. According to data from the U.S. Geological Survey (2005), over 75 percent of all freshwater withdrawals in 2005 were from surface water, which indicates that the U.S. food system is somewhat more reliant on groundwater sources than the nonfood economy.

Among sources of GHG emissions from the use of fossil fuels by households, businesses, and Government, 14 percent are attributed to the Baseline diet, whereas diet-related biogenic emissions of methane and nitrous oxide account for 44 percent of the U.S. total methane and nitrous oxide emissions in 2007. Overall, biogenic GHG emissions associated with the Baseline diet account for 5.9 percent of U.S. total GHG emissions. There are a number of agriculture-related GHG emissions that we do not account for by design, such as emissions related to the production of cotton or biofuel feedstocks or emissions related to the domestic production of food items exported to other countries. Thus, our estimate of biogenic GHG emissions accounting for 5.9 percent of U.S. total GHG emissions is lower than the 8.1 percent estimate for 2007 by the U.S. Environmental Protection Agency (U.S. EPA, 2017b).

Resource-Use Comparisons at Different Supply Chain Stages

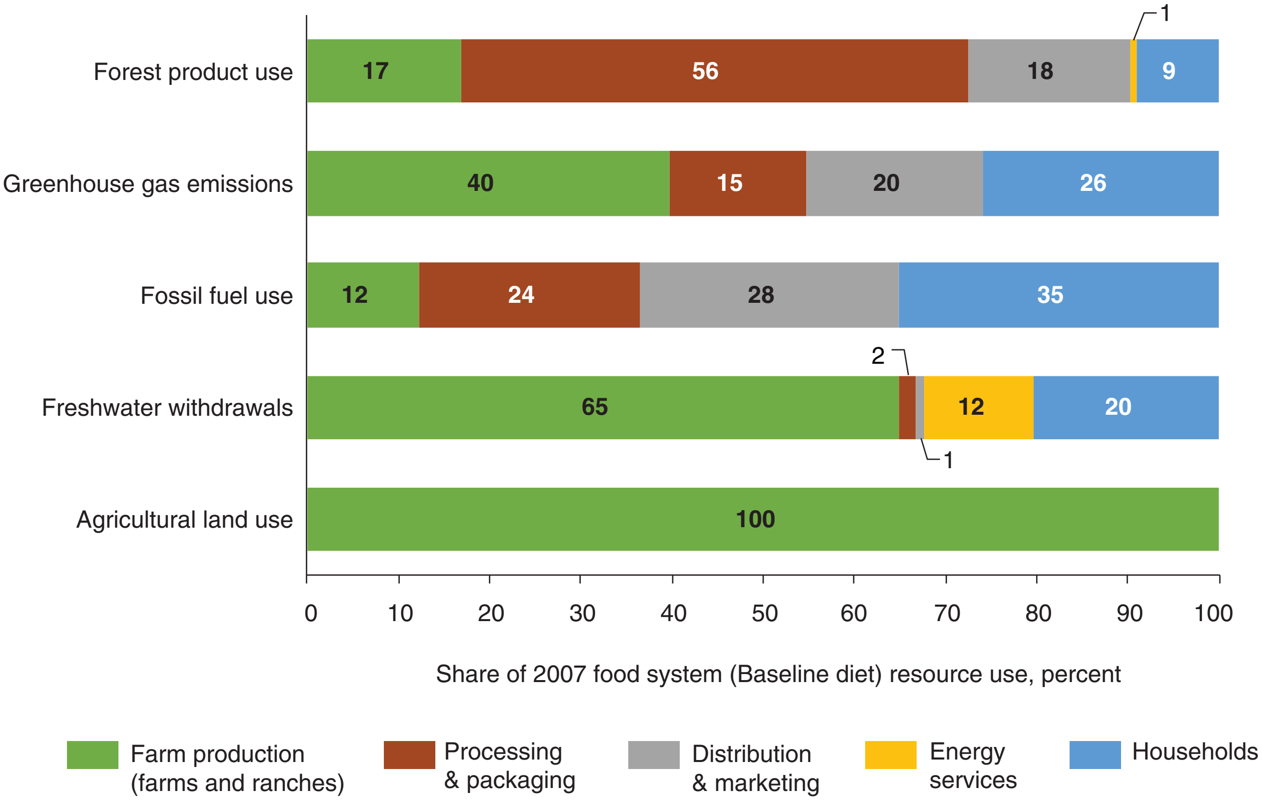
A supply chain analysis allows us to study the accumulation of resource use over the life cycle of specific domestic food commodity value chains from farm production through processing, packaging, distribution, marketing, and final food preparation and cleanup—both in home kitchens and at foodservice establishments. In addition, energy services are accounted for separately in the case of freshwater withdrawals and forest products due to the importance of these two resources in energy production. Knowing where resource use accumulates is fundamental to understanding what factors influence resource-use decisions. An interesting finding from the supply chain analysis is that the stages found to be most reliant on resource inputs differ substantially across the five resources considered. These findings are summarized in Figure 4, where the cumulative shares of total resource use are charted on horizontal stacked bar graphs, beginning with farm production (including farm inputs) on the left and culminating with household production (home kitchen operations plus travel to points of purchase) on the right.

The bottom two horizontal stacked bar columns depict agricultural land use and freshwater withdrawals. For these resources, the bulk of diet-related resource use occurs on-farm. Agriculture is the major land user in the United States. In 2007, agricultural uses occupied approximately 1.2 billion acres, 51 percent of all U.S. land and 61 percent of land in the lower 48 States, where nearly all agricultural land occurs (Nickerson et al., 2011). This analysis focuses on "productive agricultural land," which includes all cropland harvested for crops or used to pasture livestock, all grassland pasture and range, and forestlands used for grazing. It constitutes the vast majority of agricultural land, approximately 1.1 billion acres. The remaining fraction of agricultural land is made up of idle cropland, including land enrolled in the Conservation Reserve Program, fallow cropland, failed or abandoned crops, farmsteads, and farm roads. For freshwater withdrawals, it is not surprising that agriculture is the dominant user due to irrigation, but perhaps it is surprising that slightly over a third of water use in the Baseline diet occurs post-farmgate, including in household kitchen use (20 percent) and in the energy industry (12 percent). By comparison, water use at the processing and packaging and the distribution and marketing stages is relatively small.

Agriculture accounts for less than half of total diet-related resource use among the other three resources depicted in Figure 4, with little else in common among them. Fossil fuel use increases from left to right along its stacked horizontal bar, indicating that fossil fuel use for farm production (including inputs such as fossil fuels used in the production of chemical fertilizers) is the first and the smallest user in the life cycle of food, and households are the last and largest user for fossil fuels. Over 40 percent of GHG emissions in food production are from sources other than fossil fuel and largely emanate from agriculture. Enteric fermentation from the digestive process of ruminant livestock such as cattle emits methane (CH4), while manure management results in both methane and nitrous oxide (N2O) emissions (U.S. EPA, 2017a). Soil management results mainly in nitrous oxide emissions, though rice cultivation is a source of methane emissions. After agriculture, the largest share of GHG emissions comes from households, followed by distribution and marketing. For forest products, the greatest use occurs during processing and packaging, with packaging accounting for most of this total.

Overall, the results summarized in Figure 4 show that resource use linked to Baseline diets extends far beyond agriculture and that the patterns of use by supply chain stage vary across the five resources considered. A critical question that we next turn to is whether conservation goals can be achieved across all five resources through changes in diet alone, or if there are tradeoffs in conservation outcomes among the resources.

Figure 4
Share of estimated total resource use by U.S. food system supply chain stage for Baseline diet



Note: Baseline diet is measured from the 2007–08 National Health and Nutrition Examination Survey (NHANES) (USDHHS CDC NCHS, 2013a)—a nationally representative survey of food intake by all Americans ages 2 and above.

Source: USDA, Economic Research Service.

Evidence of Synergies and Tradeoffs in Food Demand Scenarios

The previous sections detailed resource use associated with the Baseline diet, which we used to compile our *FEDS-EIO* and Foodprint models, since that scenario represents the status quo for the period of analysis. In this section,s we conduct the same analysis for the Healthy American diet and compare resource use between the two diets.[10] Specifically, for each of the five natural resources we measure the percentage change to total use in going from the Baseline to the Healthy American diet. With resource conservation as the objective, a measured decline in use of a resource indicates it is synergistic with a shift to the Healthy American diet. The results are reported in Figure 5.

---

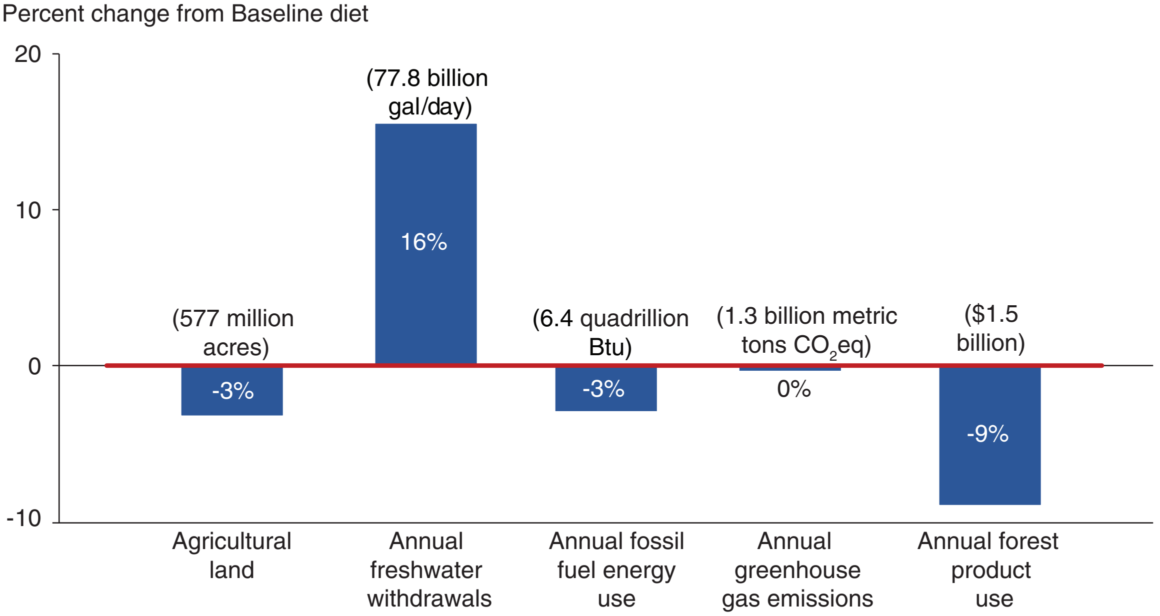
[10] For the comparative static scenario analysis, we model the food system supply chain stages except for households, since we do not know how household resource use would change with different diets.

Productive agricultural land use declines slightly over 3 percent, about 19 million acres, using the assumptions associated with a Healthy American diet. This acreage reduction is roughly equal to the total land area of South Carolina.[11] In particular, grazing land and perennial cropland use decline by about 13 and 8 million acres, respectively, while cultivated cropland use increases by about 2 million acres. The effect of the overall reduction in agricultural land use on resource conservation depends on what happens to the land taken out of agricultural production. The reduction in grazing land and perennial cropland could result in improved environmental outcomes, for example, if the land is enrolled in the Conservation Reserve Program. If it is instead converted to developed land with buildings, the environmental effect of this land-use change would likely be negative, resulting, for example, in a loss of wildlife habitat. The increase in cultivated cropland, if it comes from less-intensive land uses such as grazing land, would likely result in an increase in environmental costs, such as greater erosion potential and a loss of sequestered soil carbon; the net effect, however, would hinge on the types of practices put in place on the converted land (e.g., conventional versus conservation tillage).

Fossil fuel use is found to be synergistic with a conversion to the Healthy American diet. The finding that fossil fuel use declines by 3 percent is based an assumption that fossil fuels remain a constant share of total food-related energy use in both diets and a finding that overall energy use (including nuclear power and renewable sources) declines 3 percent. A 3-percent decline of total diet-related energy use in 2007 equals the reduced gasoline consumption that would occur if 3.7 million automobiles were removed from use for 1 year.

Figure 5

Estimated percent change in resource use going from Baseline to Healthy American diet



Btu = British thermal units. Note: Baseline diet is measured from the 2007–08 National Health and Nutrition Examination Survey (NHANES) (USDHHS CDC NCHS, 2013a)—a nationally representative survey of food intake by all Americans ages 2 and above. All diets are linked to the annual 2007 U.S. personal consumption expenditures on food (BEA, 2015). Healthy American diet is from a model that estimates the most likely food intake by all Americans in the 2007–08 NHANES sample who are meeting all 2010 *Dietary Guidelines for Americans* (USDA and USDHHS, 2010).

Source: USDA, Economic Research Service.

---

[11] Total area within the State boundary minus perennial water area, as reported by the Census Bureau (U.S. Census Bureau, unpublished data from the MAF/TIGER database), using a conversion rate of 640 acres per square mile.

Another natural resource found to be synergistic with a conversion to the Healthy American diet was forestry. A 9-percent reduction in annual forest product use was measured in terms of production value. A conversion of this measure to volume (ft^3) is obtained by assuming that the average roundwood equivalent price per unit of forestry and logging products purchased for diet-related uses was the same as the average price across all uses. Under this assumption, the reduction in use of forest and logging products with a conversion to the Healthy American diet was 1.6 billion ft^3. For perspective, this volume is 11 percent of total domestic production of timber products (15 billion ft^3) in 2007 (Howard and Jones, 2016).

Freshwater withdrawals increase 16 percent with a transition from the Baseline to the Healthy American diet.[12] This increase translates to the additional average daily freshwater withdrawals of 12.1 billion gallons. The largest production increases with a conversion to the Healthy American diet occur among fruit, vegetable, legume/nut/seed, and dairy products (Figure 1), and the arid U.S. West accounts for a dominant share of total domestic production of the farm commodities embodied in these products (Parr et al., 2018; Perez and Plattner, 2015).

Use of air as a repository for diet-related GHG emissions declines only minimally (-0.4 percent) with a conversion to the Healthy American diet. Reductions in GHG emissions from the production of sugars, sweets, and beverages are offset by increased emissions from dairy, fruit, vegetable, and nut production.

Overall, we find mixed relationships among the five natural resources studied. There is a potential for both synergistic and opposing relationships among conservation and nutrition goals—both USDA priorities. These findings are important and informative to a consideration of resource requirements of food demand in the United States. In the next section, we discuss the implications of our findings in the context of a broader assessment of how population and technology change could be accounted for in a more complete assessment of resource requirements for accommodating U.S. food demand.

---

[12] The prospects for such an increase are constrained by other factors, such as water availability and institutions governing access. This is particularly so for the arid West, where a significant share of U.S. specialty crop production is concentrated.

Future Directions

A future extension of the analysis presented above is to link the diet model, the economic model, and the biophysical model, still within the comparative static framework, and perform a multi-objective optimization study. That is, we could minimize the use of one natural resource while meeting DGA and cost targets and evaluate how this would affect the other resources, or we could optimize outcomes across all resource conservation and nutritional goals simultaneously. For example, in Canning et al. (2017), a model was specified to minimize the use of energy inputs while meeting national dietary targets. In Rehkamp and Canning (2018), a similar model was specified to minimize freshwater withdrawals. Other research within this framework introduces approaches for measuring consumer willingness to pay (or be compensated) for marginal changes in diets (Irz et al., 2016), and the social value of changes to the use of either a single resource (IWGSCC, 2015) or of multiple resources (Gustafson et al., 2016). Incorporation of these extensions, or variations that can be validated with U.S. specific market and nonmarket valuation information, would facilitate a more general optimization model to quantify the optimal mix of conservation and nutrition outcomes across multiple household groupings and for numerous natural resources. Given the spatial nature of land and water resource availability and quality, and the many region-specific factors governing resource use, regional-scale analysis could potentially help inform the national assessment.[13]

As discussed, nearly one-half of farmland use is dedicated to production for markets other than U.S. food consumers. This includes the export market for U.S. crops and animal products, and both the fiber (e.g., cotton) and biofuel (e.g., corn for ethanol) commodity markets. This finding highlights the importance of recognizing the role of producer feedback in response to changing market conditions. With reference back to equation (1), this concerns changes to technologies (ΔT). For example, figure 1 highlights the differences in consumption between the Baseline and Healthy American diets, including a substantial dropoff in the meat, poultry, fish, and mixtures category and substantial increases in the fruit and vegetable categories. The fruit and vegetable increases are behind the finding of increased freshwater use in the Healthy American diet. But it is not known a priori that animal product producers, such as beef cattle operations, will reduce production rather than redirect their sales to export markets, or that fruit and vegetable growers will increase the volume of water used for irrigation in the same proportions as other production inputs in order to meet the increased consumer demand. Alternatively, more fruits and vegetables could be imported. For these reasons, optimization models of the agricultural sector that quantify all markets for agricultural production and the associated use of production inputs, including land, water, and other natural resources, are needed to inform our understanding of how producers will respond to changing market conditions.[14]

ERS's Regional Environment and Agriculture Programming Model (REAP) is an economic model that simulates producer crop choice, land use, and price response for the U.S. agricultural sector (Johansson et al., 2007). In a recent application (Crane-Droesch, et al., 2019), REAP was used to simulate acreage allocation and market price under alternative yield scenarios to determine joint yield and price distributions for corn, soybeans, and winter wheat across the country for several climate and weather realizations and associated yields. In a similar manner, alternative diet scenarios with their

---

[13] This framework represents a top-down approach that provides a macro/messo-level analysis. Top-down analysis such as this is not well-suited for questions often addressed in microlevel LCA (Life Cycle Assessment) studies, such as an analysis that distinguishes between brown- versus white-rice consumption. A potential future direction for this line of research might be to look at hybrid approaches that combine macro/messo analysis with other bottom-up microlevel analysis.

[14] Import and export assumptions are especially important here and should be the basis for future extensions.

associated farm commodity “purchase orders” could be simulated to measure impacts to the same metrics. This approach can also be adapted to consider alternative international terms of trade scenarios that allow for changing roles of international trade in meeting U.S. domestic food demand.

As shown in Figure 4, substantial resource requirements occur beyond the farmgate. In a 2010 ERS study of energy use in the U.S. food system (Canning et al., 2010), a structural analysis was carried out to decompose the main drivers of change in food system energy use between 1997 and 2002—a period in which food system-wide energy use increased by over 22 percent. The analysis showed that diet change and population growth each explained about one-quarter of the total increase over the 5-year interval. Technical change explained the other half of the increase and was most pronounced among food processors. Energy prices were declining over the 1997 to 2002 period, and, as reported in Canning et al. (2017), the food system is very responsive to persistent change in energy prices. Computable general equilibrium (CGE) models offer a model framework to account for food system-wide producer feedback and to simultaneously account for consumer feedback in response to changing consumer prices and household incomes. In this framework, it is possible to account for the main drivers of change in resource use over time—diet, population, and technology.

Canning and Tsigas (2000) develop a U.S. multiregional applied general equilibrium (MAGE) model to capture short-run adjustments throughout the U.S. food system and by U.S. food consumers to changing market conditions. In this framework it is not possible to impose a national diet outcome, since doing so would require the treatment of household decisions as exogenous, which is a disequilibrium scenario. However, with sufficient breakout of household cohort groupings representing an array of baseline diet profiles, one can exogenously adjust the population counts across cohorts to follow a range of diet evolution scenarios and determine how production and consumption behaviors interact in the face of resource and primary production-factor constraints. Like the REAP model, this approach will allow for producer feedback in response to changing diet outcomes. REAP provides an unprecedented accounting of agricultural production practices and an array of farm resource-use decisions that are typically not captured in the MAGE framework; the MAGE, however, allows for both consumer feedback in response to production decisions and vice versa. MAGE also captures resource-use decisions beyond the farmgate, which this report has shown to be a substantial share of total food system resource use.

Both population and productivity are important drivers in determining the role of resource use in the food system. The models discussed so far have either ignored these factors or have treated them as exogenous factors that can be used to develop alterative scenario analysis. The ERS Future Agricultural Resources Model (FARM) is a global computable general equilibrium (GCGE) economic model with 13 world regions that operates in 5-year steps from 2007 to 2052 (Sands et al., 2017). In the model, land use can shift among crops, pasture, and forests in response to population growth, changes in agricultural productivity, and policies. Although still not technically a dynamic equilibrium framework, this model brings a systematic accounting of the role that productivity and population growth—both in the United States and worldwide—can have in determining the potential resource requirements of food demand in the United States.

Given the high level of uncertainty about the outlook for production, market structures, and technologies, it is important to develop a range of outlook scenarios and use an array of model frameworks to study potential outcomes. In all cases, there is a need for a multimarket, multiresource modeling framework such as the framework presented in this report. However, models with producer and consumer feedback are necessary in order to assess how technology adoption affects resource needs of food demand. Models are also needed to account for growth in population and productivity. Several ERS models are found to provide useful frameworks along these lines.

Conclusion

By focusing on how diets affect the use of natural resources for meeting food demand, this report demonstrates an approach to link food consumption and nutrition data with a diet optimization model, an environmentally extended economic model of food production and marketing, and a biophysical model to measure land and animal inventory requirements. The diet model uses mathematical optimization to define diets using the attributes of individual food items as consumed by Americans. The economic model, *FEDS-EIO*, accounts for the use of natural resources, and the entire food value chain is represented, from farm inputs through home kitchen operations. The biophysical model, Foodprint, estimates land and animal inventory requirements of producing all food commodities embodied in the model-derived diets.

This report produced several key insights. First, the food system was natural-resource intensive in 2007. Second, substantial resource requirements occur beyond the farmgate. Third, a healthy diet would produce large changes in food purchases and lead to increases in some resource uses and decreases in others; Thus, there is a potential for both synergistic and opposing relationships among resource conservation and nutrition outcomes. These findings highlight a need for a multimarket, multiresource modeling framework to research questions of sufficient scale and scope. Given the high level of uncertainty about the future, it is important to develop a range of outlook scenarios and use an array of model frameworks. Several ERS models are found to provide useful frameworks along these lines.

The various models described in the discussion of future research directions represent frameworks of varying dimensions, but they all can be informed by the framework and synthesis of analysis presented in this report. Specifically, they address some or all of the factors that are ignored in our scenario analysis (which holds everything other than diet outcomes constant) for estimating the effect of diets on resource requirements of food demand in the United States. The key insights of the analysis and the approach of linking detailed food consumption data, diet models, and biophysical models also apply to each of these extensions and will inform our adaptation of these models in future analysis.

References

Blaug, M. 1992. *The Methodology of Economics: Or, How Economists Explain*. Cambridge: Cambridge University Press. doi:10.1017/CBO9780511528224.013

Boehm, R., P.E. Wilde, M. Ver Ploeg, C. Costello, and S.B. Cash. 2018. "A Comprehensive Life Cycle Assessment of Greenhouse Gas Emissions from U.S. Household Food Choices." *Food Policy* 67-76.

Bowman, M., S. Wallander, and L. Lynch. 2016. "An Economic Perspective on Soil Health," *Amber Waves* (September 6).

Britten, P., L.E. Cleveland, K.L. Koegel, K.J. Kuczynski, and S.M. Nickols-Richardson. 2012. "Impact of Typical Rather than Nutrient-Dense Food Choices in the US Department of Agriculture Food Patterns," Journal of the Academy of Nutrition and Dietetics 112(10):1560-69.

Canning, P., S. Rehkamp, A. Waters, and H. Etemadnia. 2017. The Role of Fossil Fuels in the U.S. Food System and the American Diet, ERR-224, U.S. Department of Agriculture, Economic Research Service.

Canning, P., A. Weersink, and J. Kelly. 2016. "Farm share of the food dollar: an IO approach for the United States and Canada," *Agricultural Economics* 47:505-12.

Canning, P. 2011. *A Revised and Expanded Food Dollar Series: A Better Understanding of Our Food Costs,* ERR-114. U.S. Department of Agriculture, Economic Research Service.

Canning, P., A. Charles, S. Huang, K.R. Polenske, and A. Waters. 2010. *Energy Use in the U.S. Food System*. ERR-94. U.S. Department of Agriculture, Economic Research Service.

Canning, P., and M. Tsigas. 2000. *Regionalism, Federalism, and Taxation: A Food and Farm Perspective*, Technical Bulletin 1882. U.S. Department of Agriculture, Economic Research Service.

Conrad, J., and C. Clark. 1987. *Natural resource economics: Notes and problems*. Cambridge University Press. doi:10.1017/CBO9781139173575

Crane-Droesch, A., E. Marshall, S. Rosch, A. Riddle, J. Cooper, and S. Wallander. 2019. *Climate Change and Agricultural Risk Management Into the 21st Century*, ERR-266, U.S. Department of Agriculture, Economic Research Service.

Dieter, C.A., M.A. Maupin, R.R. Caldwell, M.A. Harris, T.I. Ivahnenko, J.K. Lovelace, N.L. Barber, and K.S. Linsey. 2018. Estimated use of water in the United States in 2015: U.S. Geological Survey Circular 1441, 65 pp.

Gustafson, D., A. Gutman, W. Leet, A. Drewnowski, J. Fanzo, and J. Ingram. 2016. "Seven Food System Metrics of Sustainable Nutrition Security," *Sustainability* 8(196):1-17. doi:10.3390/su8030196

Heller, M.C., and G.A. Keoleian. 2015. “Greenhouse Gas Emission Estimates of U.S. Dietary Choices and Food Loss,” *Journal of Industrial Ecology* 19(3):391-401.

Hitaj, C., S. Rehkamp, P. Canning, and C. Peters. 2019. “Greenhouse Gas Emissions in the US Food System: Current and Healthy Diets,” *Environmental Science & Technology* 53(9): 5493-5503. doi: 10.1021/acs.est.8b06828

Howard, J.L., and K.C. Jones. 2016. *U.S. timber production, trade, consumption, and price statistics, 1965-2013*. FPL-RP-679. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 91 pp.

Interagency Working Group on Social Cost of Carbon (IWGSCC). 2015. *Technical update of the social cost of carbon for regulatory impact analysis*. Technical Support Document (July).

Intergovernmental Panel on Climate Change (IPCC). 2019. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.* Working Group III Technical Support Unit, Imperial College, London, UK.

Irz, X., P. Leroy, V. Requillart, and L.G. Soler. 2016. “Welfare and sustainability effects of dietary recommendations,” *Ecological Economics* 130:139-55.

Johansson, R., M. Peters, and R. House. 2007. *Regional Environment and Agriculture Programming Model (REAP)*, Technical Bulletin 1916, U.S. Department of Agriculture, Economic Research Service.

Krebs-Smith, S.M., P.M. Guenther, A.F. Subar, S.I. Kirkpatrick, and K.W. Dodd. 2010. “Americans Do Not Meet Federal Dietary Recommendations,” *Journal of Nutrition* 140(10):1832–38.

Lewandrowski, J., M. Peters, C. Jones, R. House, M. Sperow, and K. Paustian. 2004. *Economics of Sequestering Carbon in the U.S. Agricultural Sector*, Technical Bulletin 1909, U.S. Department of Agriculture, Economic Research Service.

National Academies of Sciences, Engineering, and Medicine. 2019. *Sustainable Diets, Food, and Nutrition: Proceedings of a Workshop*. Washington, D.C.: The National Academies Press. doi: https://doi.org/10.17226/25192.

Nickerson, C., R. Ebel, A. Borchers, and F. Carriazo. 2011. *Major Uses of Land in the United States, 2007*, EIB-89, U.S. Department of Agriculture, Economic Research Service (December).

Parr, B., J. Bond, and T. Minor. 2018. “Vegetables and Pulses Outlook,” VGS-361, U.S. Department of Agriculture, Economic Research Service (October 26).

Perez, A., and K. Plattner. 2015. “Fruit and Tree Nuts Outlook: Economic Insight,” FTS-359SA, U.S. Department of Agriculture, Economic Research Service (June 30).

Peters, C.J., J.A. Picardy, A. Darrouzet-Nardi, and T.S. Griffin. 2014. “Feed conversions, ration compositions, and land use efficiencies of major livestock products in US agricultural systems,” *Agricultural Systems* 130(C):35-43.

Peters, C.J., J. Picardy, A.F. Darrouzet-Nardi, J.L. Wilkins, T. Griffin, and G.W. Fick. 2016. "Carrying capacity of U.S. agricultural land: Ten diet scenarios," *Elementa: Science of the Anthropocene* (4:000116):1-15.

Rehkamp, S., and P. Canning. 2017. "The Potential for Healthier and Energy Efficient American Diets," *Choices,* Quarter 3.

Rehkamp, S., and P. Canning. 2018. "Measuring Embodied Blue Water in American Diets: An EIO Supply Chain Approach," *Ecological Economics* (147):179-88.

Ribaudo, M., R. Horan, and M. Smith. 1999. *Economics of Water Quality Protection From Nonpoint Sources: Theory and Practice*, AER-782. U.S. Department of Agriculture, Economic Research Service.

Sands, R., S.A. Malcolm, S.A. Suttles, and E. Marshall. 2017. *Dedicated Energy Crops and Competition for Agricultural Land*, ERR-223. U.S. Department of Agriculture, Economic Research Service.

Tichenor Blackstone, N., N.G. El-Abbadi, M.S. McCabe, T.S. Griffin, and M. Nelson. 2018. "Linking Sustainability to the Healthy Eating Patterns of the Dietary Guidelines for Americans: A Modelling Study," *The Lancet Planetary Health* 2(8):e344-3352.

Tilman, D., and M. Clark. 2014. "Global Diets Link Environmental Sustainability and Human Health." *Nature* 515:518-22.

Tom, M.S., P.S. Fischbeck, and C.T. Hendrickson. 2016. "Energy Use, Blue Water Footprint, and Greenhouse Gas Emissions for Current Food Consumption Patterns and Dietary Recommendations in the U.S." *Environment Systems and Decisions* 36(1):92-103.

United Nations, European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development, and World Bank. 2014. *System of environmental-economic accounting 2012—Central framework.* Series F, No. 109 (ST/ESA/STAT/Ser.F/109).

U.S. Department of Agriculture, Agricultural Research Service (USDA ARS). 2014. *FPED 2007-2008: Food Patterns Equivalents for Foods in the WWEIA, NHANES 2007–08*. Data files.

U.S. Department of Agriculture, Agricultural Research Service (USDA ARS). 2017. *Food Intakes Converted to Retail Commodities*. Data files.

U.S. Department of Agriculture, Economic Research Service (USDA ERS). 2019. Loss Adjusted Food Availability. Data product.

U.S. Department of Agriculture, Economic Research Service (USDA ERS). 2020. Food Expenditure Series. Data product.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA NRCS). 2018. "NRI Pastureland Resource Assessment." (June).

U.S. Department of Agriculture and U.S. Department of Health and Human Services (USDA and USDHHS). 2010. *Dietary Guidelines for Americans, 2010.* (7th edition). Washington, DC: U.S. Government Printing Office.

U.S. Department of Agriculture and U.S. Department of Health and Human Services (USDA and USDHHS). 2015. *Dietary Guidelines for Americans, 2015-2020.* (8th edition). Washington, DC: U.S. Government Printing Office.

U.S. Department of Commerce, Bureau of Economic Analysis. USDOC BEA. 2015. "Supply-Use Tables for the United States," Survey of Current Business, BEA Briefing (September): 1-8.

U.S. Department of Energy, Energy Information Administration (USDOE EIA). 2015. *State Energy Data System*. Data files.

U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Health Statistics (USDHHS CDC NCHS). 2013a. *National Health and Nutrition Examination Survey, 2007-2008 Data Documentation, Codebook, and Frequencies.* Data files.

U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Health Statistics (USDHHS CDC NCHS). 2013b. *NHANES 2007-2008 Dietary Data*. Data files.

U.S. Department of the Interior, U.S. Geological Survey (USDOI USGS). 2005. *Water Use in the United States. Estimated Use of Water in the United States, County-Level Data for 2005.* Data files.

U.S. Environmental Protection Agency (USEPA). 2017a. "Greenhouse Gas Emissions: Understanding Global Warming Potentials." Web article, February 14.

U.S. Environmental Protection Agency (USEPA). 2017b. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015*. EPA-430-P-17-01.

U.S. Environmental Protection Agency (USEPA). 2015. *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions 1990-2013*. EPA-420F-15-032.

Willett, W., et al. 2019. "Food in the Anthropocene: the EAT-*Lancet* Commission on Healthy Diets from Sustainable Food Systems," *The Lancet* 393(10170):447-92.

Technical Appendix: Methods for Measuring Diets, Production, and Resources

Materials and services studied, the resource groups they are from, the natural cycles that regulate their quality and availability, and a reference to the relevant publications behind this research are summarized in the following table.

Appendix Table 1

Natural resource material and service case studies

Material or service	Resource group	Unit of measurement	Key resource cycles	Source of case study or model documentation
Suitable soils and space	Land	Acres	Soil nutrient cycle	Peters et al., 2014; Peters et al., 2016
Freshwater	Water	Gallons	Water cycle	Rehkamp & Canning, 2018
Fossil fuels	Minerals	Btu*	Nonrenewable	Canning et al., 2017
Disposal services (GHG)	Air	CO_2-eq**	Carbon cycle	Hitaj et al., 2019
Forest products	Forests	Dollars	Forest life cycle; Carbon cycle	Canning, 2011; Canning, Weersink and Kelly, 2016

*British thermal units. **Carbon dioxide equivalent.

Source: USDA, Economic Research Service.

Brief descriptions of our methodologies and data sources, and/or references to publications where methods and data sources are described, follow.

Modeling Healthy Diets

See Canning et al. (2017) for technical details of the diet modeling and Rehkamp and Canning (2017) for more description of the diets.

Measuring Diet-Related Fossil Fuel Combustion and Water Withdrawals

Multiregional environmental input-output (EIO) models extend conventional input-output multiplier analysis to consider the physical flows linked to gross domestic product for materials of environmental consequence. Based on the Food Environmental Data System (*FEDS*), we employ the *FEDS-EIO* model (Canning et al., 2017; Rehkamp and Canning, 2018), which extends the official U.S. System of National Accounts (SNA) in order to represent key attributes of the U.S. food system that are obscured in the SNA. We use a matrix-reduction procedure that facilitates supply chain decomposition analysis of fossil fuel combustion and freshwater withdrawals (see section 2.2 in Rehkamp and Canning, 2018).

To facilitate a link between *FEDS-EIO* and the diet model (discussed above), *FEDS-EIO* uses food industry data to expand the number of consumer food commodities from the 22 covered in the 2007 SNA to a total of 74 commodity groups, which are further broken out into at-home (e.g., grocery stores) and away-from-home (e.g., restaurants) purchases (see appendix table 1 in Canning et al., 2017). For example, in the SNA expenditure category ‘Processed Fruits and Vegetables’ are disaggregated into multiple expenditure categories based on product shipment data from the 2007 U.S. Economic Census. The individual food items from NHANES are mapped to the 74 expenditure groups based on composition.

FEDS-EIO represents all U.S. annual production broken out into 344 industry aggregates (see appendix table 2 in Canning et al., 2017), and international imports are also categorized into these 344 commodity groups. For each industry/commodity, annual 2007 production and imports are allocated to U.S. States. For production, energy use per unit of output is calculated using EIA’s State Energy Data System (SEDS), which reports State data on energy use for more than 10 primary fuel sources by type of end user (USDOE EIA, 2015). Water withdrawals per unit of output are calculated using the 2005 USGS data on water withdrawals in all U.S. counties broken out into surface water and groundwater sources (USDOI USGS, 2005). These calculations are aggregated up to U.S. totals to produce energy and waterflow multipliers for each of six energy commodities and two water sources. These multipliers and the other model features are used to translate gross output by industry linked to both the Baseline and Healthy American diet scenarios into total embodied energy- and water-use estimates by type of energy commodity and water source, across each supply chain stage.

Measuring Land Use and Farm Animal Inventories

To account for land use in alternative diets in this report, we use the *U.S. Foodprint Model* (referred to hereafter as Foodprint). Foodprint is a biophysical simulation model that calculates the per capita land requirements of complete diets and the potential carrying capacity of the agricultural land of the conterminous United States (Peters et al, 2016). Starting with an estimate of dietary intake by food group, Foodprint determines the quantities of food and agricultural commodities required to supply a given amount of intake after accounting for losses and waste that occur in food preparation, distribution, and processing. The land requirement for producing each food commodity in the diet is calculated based on nationally representative estimates of crop yield, grazing land productivity, and livestock feed efficiencies. A land requirement for the complete diet is also calculated, which adjusts for the multi-use nature of certain crops (e.g., soybeans produce vegetable oil and high-protein livestock feed) and prevents double counting.

Two revisions were made to the Foodprint model for this analysis. First, the categories of food intake were expanded from the 25 foods and food groups in the original model to 65 retail food commodity categories (USDA-ARS, 2017). Second, the revised Foodprint model calculates the number of animals associated with the per capita intake in each diet scenario. Livestock inventories were estimated based on the amount of animal product (milk, eggs, or meat) required to support each scenario, with estimates of the number of animals associated with each unit of food output from Peters et al. (2014). In the original Foodprint model, the numbers of livestock needed to support a diet are implicitly accounted for in the feed requirements for producing animal-based foods (from Peters et al., 2014). The revised Foodprint model simply makes these calculations explicit.

Measuring Air Use as a Repository for GHG Emissions

Emission rates from fossil fuel combustion, measured with FEDS-EIO, vary across fuel source but also by activity. Rather than assuming a single emission rate for each fuel, we use specific emission rates for each activity, such as natural gas consumption in foodservice versus for packaging production in pulp paper and paperboard mills (Table S2 in Hitaj et al., 2019). We have activity-specific GHG emission rates for 70 percent of natural gas, petroleum, coal, and electricity consumption. For the remainder, we assume an industry average of carbon dioxide, methane, and nitrous oxide emission rate for each type of fuel (Table S3 in Hitaj et al., 2019). For GHG emissions produced in the power generation sector, we use the State-level emission rates provided in the EPA's Emissions & Generation Resource Integrated Database (eGRID) for the year 2007.

Hydrofluorocarbons (HFCs), a group of very potent GHGs, are used as coolants in refrigeration and air conditioning. While HFC emissions are occurring throughout the food system, we are only able to account for them in the transportation sector, where specific HFC emission rates are available (EPA, 2015); we are unable to tie HFC emissions from manufacturing and distribution to particular processes and food items, as would be necessary for our study. Accounting for HFC emissions from outside the transportation sector would therefore increase our estimate of total GHG emissions from the food sector.

Soil management nitrous oxide and methane emission factors (Table S4 in Hitaj et al., 2019) range from 340 kg CO2eq per acre of nitrous oxide emissions for soybeans to 3,508 kg CO2eq methane emissions per acre for rice production. Table S5 in Hitaj et al. shows the methane and nitrous oxide emission factors based on EPA (2017b) from enteric fermentation and manure management for 34 different categories of livestock (beef and dairy cattle, broilers, layers, turkeys, and swine) at various stages in their production cycle.

Measuring Forest Product Use

Whereas industrial uses for both energy commodities and water withdrawals are measured in physical units by major recurring Federal survey instruments, a data program for U.S. forest products does not exist at a similar level of detail. To overcome this data gap, our approach to measuring use by supply chain stage is to develop a value-added measure of forest product use simply represented by the monetized value of physical units for forest products. For this purpose, we employ the ERS Food Dollar model (Canning, 2011; Canning, Weersink, and Kelly, 2016). The Food Dollar model is exactly analogous to *FEDS-EIO* except for the units of measurement. For the present purposes, we base our estimates on the same 2007 SNA data described above for *FEDS-EIO* and documented in Canning et al. (2017). Because the Food Dollar model is a national model with no regional breakouts, we are able to use national-level data on 2007 U.S. timber production statistics (Howard and Jones, 2016) to make national-level conversions of hardwood equivalent volumes of forest product use by supply chain stage. Conversions are based on a strong assumption that all industrial users of forest products face the same hardwood-equivalent prices for the various products they use. It is likely that there are numerous exceptions to this assumption; however, we are aware of no compelling evidence that suggests this assumption introduces a systematic bias on our results reported in physical units. Further, this potential issue does not apply to our results reported in monetary units.