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Scenarios of Global Food Consumption: Implications for Agriculture

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Abstract

The global land base is under increasing pressure to provide food for a growing population. This report describes how increasing population, income, and agricultural productivity may affect the production and consumption of crops and food products by 2050. Rising incomes have historically implied increasing consumption of animal products, with large increases in feed calories relative to increases in calories consumed as food. Crop calories are the unit of agricultural production in this report, allowing aggregation across multiple crop types, comparison to calories consumed as food, and providing an indicator of cropland requirements. The following questions are addressed: How do increasing population and income affect global demand for crop and food calories by 2050? What is the effect of agricultural productivity growth on food prices and cropland area expansion? Results show that in an income-driven food demand scenario, production of world crop calories increases by 47 percent from 2011 to 2050. Demand for food calories and crop calories increases over time in all scenarios, with most of the adjustment through increases in crop yield (intensification). The amount of cropland also increases (extensification) but less on a percentage basis.

Keywords: scenarios, food calories, crop calories, food balance sheets, general equilibrium, International Comparison Program, agricultural productivity, land use, crop yield, consumer demand, budget shares

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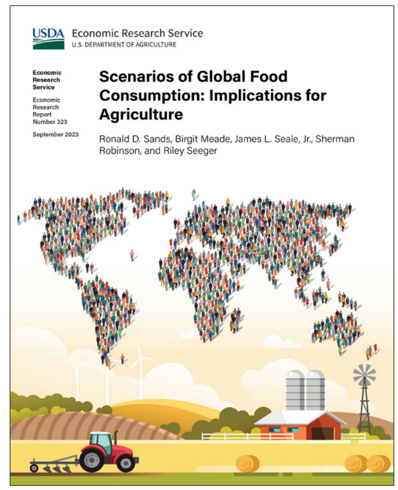


What Is the Issue?

The global land base is under increasing pressure to provide food for a growing population. Rising incomes have historically implied increasing consumption of animal products, along with an increased need for feed. To date, steady increases in agricultural productivity have allowed agricultural production to keep up with a growing population and per capita increases in food consumption. This report describes how changes in population, income, and agricultural productivity may affect the production and consumption of crops and food products by 2050 and addresses:

- How do increasing population and income affect global demand for crops and food products by 2050?
- What is the effect of agricultural productivity growth on food prices and cropland area expansion?
- How do alternative assumptions about population growth affect the size of the world agricultural system in 2050?

This study addresses the future of food consumption considering both physical output measures and the economics of production, consumption, and land use.

What Did the Study Find?

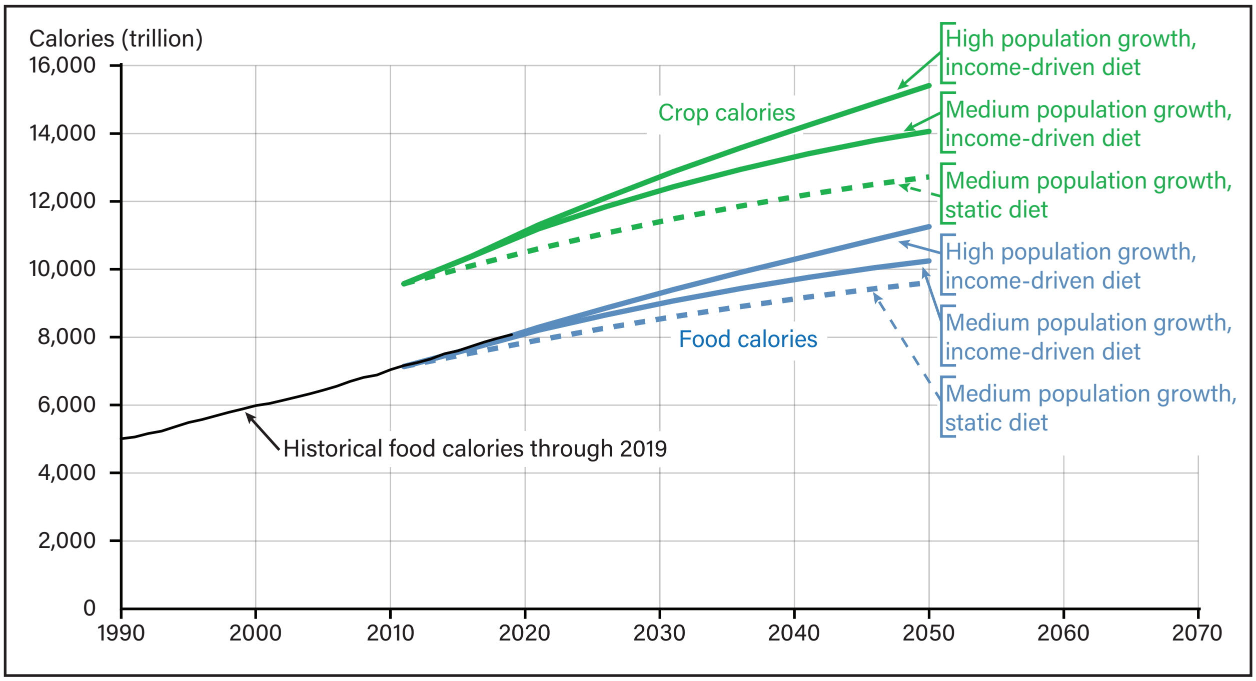
Primary (crop) calories are produced from the land before processing into food products. Crop calories are greater than food calories, due primarily to losses that occur as feed crops are converted to food products such as meat, dairy products, and eggs. Production of crop calories is a more complete measure of the agricultural system than food calories because it also includes these conversion losses. Research highlights are:

- Production of crop calories is a useful indicator of pressure on the land base. Crop calories are the product of population, per capita food calories available for consumption, and crop calories required per calorie of food. With an income-driven diet and population growth of 39 percent, available food calories grow by 44 percent, and crop calories grow by 47 percent from 2011 to 2050. Growth in crop calories reflects income-driven shifts to greater total food calories per person and an increasing share of animal products in food consumption.

- When moving from a low-productivity scenario to a high-productivity scenario, the decline in consumer food prices leads to an increase in world crop calorie production of 1.8 percent.
- Across scenarios, the largest expansion in cropland occurs with high population growth and low agricultural productivity growth. The largest increase in crop yield occurs with high population growth and high agricultural productivity growth.
- Using United Nations projections of world population, the production of crop calories would grow by 33 percent (low population growth), 47 percent (medium population growth), and 61 percent (high population growth) from 2011 to 2050.

The world production of calories across three scenarios is illustrated in the figure. Crop calories, an indicator of pressure on the land base, are greatest in the high population scenario.

Projections of world food calories and crop calories, 2011–50



Note: Three illustrative scenarios are shown: a static diet (per capita consumption of food calories remains constant at 2011 levels in all world regions) with medium population growth; an income-driven diet with medium population growth; and an income-driven diet with high population growth. The static diet is a point of comparison to quantify the effect of income growth on food consumption. Historical food calories in 2019 are slightly higher than the medium-population scenario in the Future Agricultural Resources Model (FARM). This indicates that food consumption continues to respond strongly to increases in per capita income. FARM simulations begin in 2011.

Source: USDA, Economic Research Service using historical food calories through 2019 from the Food and Agriculture Organization (FAO) of the United Nations and World Population Prospects 2017, United Nations. USDA, Economic Research Service simulations using FARM.

How Was the Study Conducted?

The authors simulated the effect of a static diet, income-driven diets, and other drivers on world agricultural production, prices, and land use from 2011 to 2050 across 10 “what-if” scenarios. The scenarios are designed to isolate the impacts of population growth, income growth, and growth in agricultural productivity. Crop calories are the unit of agricultural production, which allows aggregation across multiple crop types, comparison to calories consumed as food, and provide an indicator of cropland requirements. Scenarios are simulated in the Future Agricultural Resources Model (FARM), a global computable general equilibrium (CGE) model developed and maintained at the U.S. Department of Agriculture, Economic Research Service (USDA, ERS).

Scenarios of Global Food Consumption: Implications for Agriculture

Introduction

The global land base is under increasing pressure to provide food for a growing population. This report describes how increasing population, income, and agricultural productivity may affect the production and consumption of crops and food products through 2050. Rising incomes have historically implied increasing consumption of animal products, with large increases in feed calories relative to calories consumed as food. To date, steady increases in agricultural productivity have allowed agricultural production to keep up with a growing population and per capita increases in food consumption. However, it is important to understand how the demand for crops and land responds to alternative scenarios and economic adjustments needed for supply to meet demand.

This report addresses:

- How do increasing population and income affect global demand for crops and food products by 2050?
- What is the effect of agricultural productivity growth on food prices and cropland area expansion?
- How do alternative assumptions about population growth affect the size of the world agricultural system in 2050?

Six major drivers influence the path of global agriculture: population, per capita income, agricultural productivity, dietary preference, climate change effects on agriculture, and large-scale demand for bioenergy as part of a climate change mitigation strategy. The last two drivers are beyond the scope of this study, although climate change can affect the growth rate of agricultural productivity and where people live.

Other studies estimated world food production by 2050, most prominently by the Food and Agriculture Organization (FAO) of the United Nations (Alexandratos and Bruinsma, 2012; Food and Agriculture Organization, 2018). The 2012 FAO study published a frequently cited estimate: World food production would increase by 60 percent from 2005–07 to 2050 to meet the increasing demand for food. The 2012 and 2018 FAO studies used an economic volume index as a measure of world food production that is quite different from the calorie measures used in this report.[1] Alexandratos and Bruinsma (2012) noted that the choice of units matters when quantifying growth rates of aggregate agricultural production or consumption. The price-based volume index grows faster than the aggregate in physical units such as tons or calories.[2] This is mainly due to an income-driven shift to higher value food commodities, especially animal products.

This report builds on recent enhancements to the Future Agricultural Resources Model (FARM) to address the future of food consumption and the complex interactions between economics and physical metrics such as calories and land area. Areas of enhancement include matching economic flows with calorie flows in agricultural production and consumption, improved economics of land competition, and an economic consumer

[1] Several alternative measures are available, as mentioned by Alexandratos and Bruinsma (2012): "The volume index adds together very dissimilar products (oranges, grain, meat, milk, coffee, oilseeds, cotton, etc.) using price weights for aggregation. Anyone interested in food and agriculture futures can use more meaningful metrics, e.g., tonnes of grain, of meat, food consumption per capita in terms of kg/person/year or kcal/person/day, yields, land use, etc."

[2] Crop calories grow by 47 percent from 2011 to 2050 in the central scenario with income-driven diets and medium-fertility population growth.

demand system with limits on per capita calorie consumption by food group with rising incomes. This report follows the FAO recommendation of constructing meaningful metrics but in a general equilibrium economic model with income responses and price feedbacks between agricultural supply and demand. The primary contribution of this research is to address the future of food consumption, which is of general interest and the topic of other studies, in a model that maintains consistency between physical output measures and general equilibrium economics.

Valin et al. (2014) provided scenarios of world food consumption through 2050 across 10 global economic models with an emphasis on the economics of consumer food demand systems used in these models. However, the analysis was not extended to crop calories used as animal feed. The World Resources Institute (WRI) used crop calories as a measure of total food production in its series of reports on “Creating a Sustainable Food Future” (Ranganathan et al., 2016; Searchinger et al., 2018) but with limited economics driving its scenarios. Crop calories in an illustrative WRI 2050 baseline are 72 percent greater than in 2006, a higher growth rate than the central scenario using the FARM. WRI used an expansive definition of crop calories, which may account for some of the differences; WRI included crops for biofuels and industrial uses in its definition.

The authors constructed 10 scenarios to isolate the contributions of major drivers of global food consumption, combining elements of other studies within a global general equilibrium economic model. The approach included price feedbacks to food consumption, competition for land between food and forest products, and consistent accounting between food calories and crop calories based on food balance sheets.

The treatment of dietary preference is quite simple: a single static diet scenario (per capita consumption of food calories remains constant over time in all world regions) provided a point of comparison for income-driven diet scenarios. Other studies have considered the impact of changing diets on climate change mitigation (Stehfest et al., 2009), on land requirements (Kastner et al., 2012; Alexander et al., 2016), on biodiversity (Henry et al., 2019), and on human health (Tilman and Clark, 2014; Springmann et al., 2016).

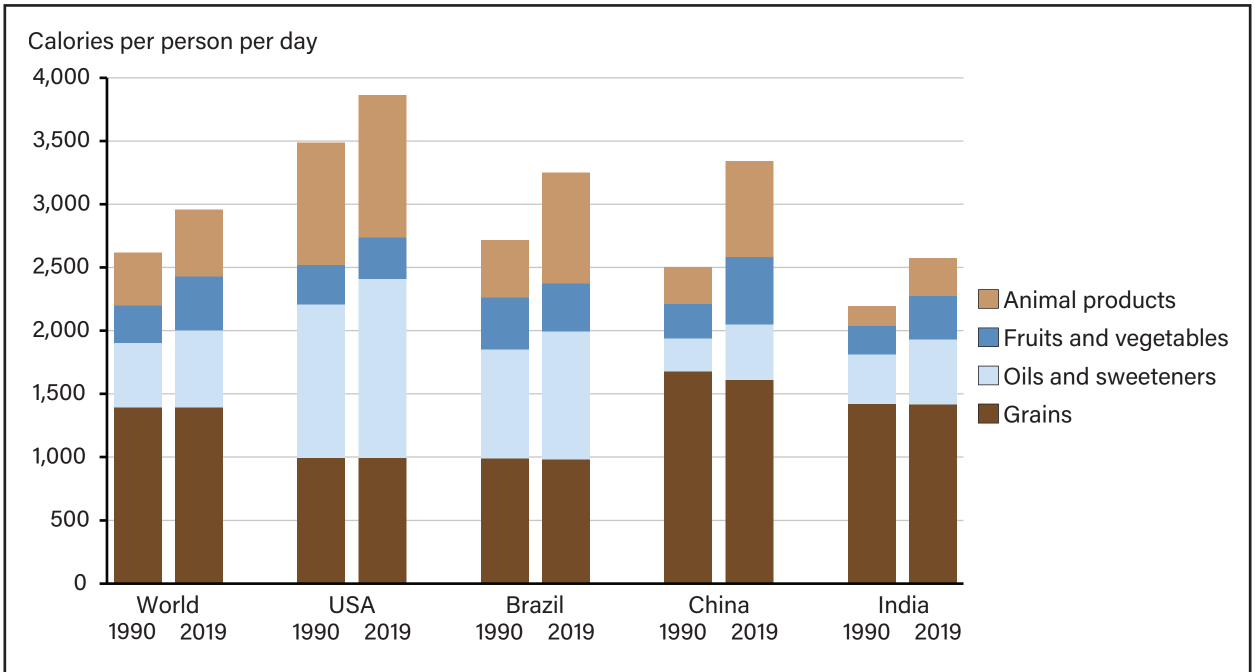
This study starts by looking at historical trends of food consumption by food type. A strong link exists between per capita income and consumption of sugar, vegetable oils, and animal products. This relationship appears over time and across regions in food balance sheets. These data show a wide range in food available for consumption across countries, in total calories, and in its composition across food commodities. Low-income countries tend to have diets with a large share of lower-cost grains, roots, and tubers. High-income countries tend to have more diverse diets with larger shares of vegetable oils and animal products. FARM, a global economic model of agricultural and energy systems developed and maintained at the U.S. Department of Agriculture, Economic Research Service (USDA, ERS), was used for scenario analysis through 2050. Model details, such as data requirements and the economics of consumer demand, are covered in appendix A.

Historical Growth in Food Consumption

From 1990 through 2019, world population grew by 45 percent to 7.7 billion people, while calories available for food consumption increased by 61 percent. Some food groups increased at a faster rate, especially fruits and vegetables, vegetable oils, and animal products. However, calories available from grains increased at about the same rate as world population. Figure 1 shows this trend, in calories per person per day, for the world average and four selected countries: United States, Brazil, China, and India.[3] Four broad groups of food are shown:

- wheat, rice, and other grains;
- fruits and vegetables, including roots and tubers;
- vegetable oils and sugar; and
- animal products (beef, lamb, pork, poultry, dairy, eggs, and fish).

Figure 1
Per capita calories available for consumption (selected countries), 1990 and 2019



USA = United States of America.

Source: USDA, Economic Research Service using food balance sheets from the Food and Agriculture Organization of the United Nations.

[3] These countries were selected because they are individual regions in FARM. They represent a range of total calorie consumption as well as a range of animal product consumption.

China was below the world average food consumption per person in 1990 but above the world average in 2019. The largest changes from 1990 to 2019 were in Brazil and China, with per capita food available for consumption increasing by 530 calories per person per day in Brazil and 840 calories in China.

The world average masks large differences among countries in total calories available per person per day and in calories available in each of the four food commodity groups. Income and culture are factors determining consumption levels of animal products. India was below the world average for total calories, and per capita consumption of animal products was very low. Per capita consumption of animal products grew rapidly in Brazil and China but was still below the U.S. level in 2019.

Food Balance Sheets

Food Balance Sheets (FBS) are the key source of data for the supply and use of food in a country. The Food and Agriculture Organization (FAO) of the United Nations provides annual food balances for 98 food commodities for nearly all countries, beginning in 1961 (FAO, 2001). Food Balance Sheets can be constructed for any group of countries by summing FBS elements across individual countries.

In each FBS for each food commodity, domestic supply equals domestic use measured in metric tons. Domestic supply is the quantity of food produced, plus imports, less exports, adjusted for change in storage. Domestic use includes crops used for seed, animal feed, processed food, non-food uses, and waste during storage and transportation. The remainder is food available for consumption, which is greater than food consumed due to food loss at home or in restaurants. Food Balance Sheets do not provide estimates of food loss at home or in restaurants but provide an estimate of waste during storage and transportation. Except for statistical error, domestic supply should equal domestic use in each country.

The basic unit of measurement is metric tons per year. The quantity of food available for consumption can be converted to other convenient measures using population data and the average nutritional content of each type of food commodity: kilograms/person/year, grams/person/day, calories/person/day, protein/person/day (grams), and fat/person/day (grams). Per capita availability of other nutrients can be calculated using food composition tables, which provide the ratio of nutrients per 100 grams of food.

Commodities are grouped into cereals, oil crops, starchy roots, sugar crops, pulses, tree nuts, fruits, vegetables, spices, stimulants, sugar and sweeteners, vegetable oils, alcoholic beverages, meats and animal fats, eggs, milk, fish, and seafood.

World Food Consumption Patterns and Income

The International Comparison Program (ICP) of the World Bank provides a key data set for the economic analysis of world food consumption. The ICP is a statistical initiative aimed at calculating internationally comparable measures of gross domestic product (GDP).[4] The 2011 ICP dataset contains expenditures for major consumption categories and food subcategories for 199 economies and is the most comprehensive data set of its kind (World Bank, 2015).

[4] The purpose of the International Comparison Program (ICP) is to allow comparisons of the value of economic output (gross domestic product or GDP) without exchange rate or price level distortions by calculating purchasing power parity (PPP) conversion rates. Results presented by the ICP are estimates of PPPs of currencies, real expenditures derived using PPPs, and price levels expressed relative to the world, which are available for GDP and its 25 sub-aggregates.

International Comparison Program Data From the World Bank

The primary goal of the International Comparison Program (ICP) is to measure the size of world economies based on purchasing power parity (PPP) instead of market exchange rates. A PPP rate is like an international currency exchange rate (e.g., Chinese yuan per U.S. dollar) but is based on surveys of the quantities of goods or services that can be purchased with each currency. For example, the size of China's economy is larger when measured with PPP rates than with market exchange rates.

Researchers at the University of Pennsylvania started the ICP in 1968. The first four phases are documented in Summers and Heston (1988). Since then, this effort has been repeated periodically, each time increasing the number of economies and improving the methods of data collection, processing, and calculation to arrive at more accurate estimates, eventually covering most economies (Feenstra et al., 2015). The 2011 survey includes 199 economies and is now truly global, with several improvements compared to the previous round.[1] ICP data are useful for analysis beyond estimating PPPs, including statistical modeling of food demand. Analysis in this section is an update of Muhammad et al. (2011).

- Phase I—10 economies (1970)
- Phase II—16 economies (1973)
- Phase III—34 economies (1975)
- Phase IV—60 economies (1980)
- 1986 ICP: 64 economies
- 1996 ICP: 115 economies
- 2005 ICP: 146 economies
- 2011 ICP: 199 economies

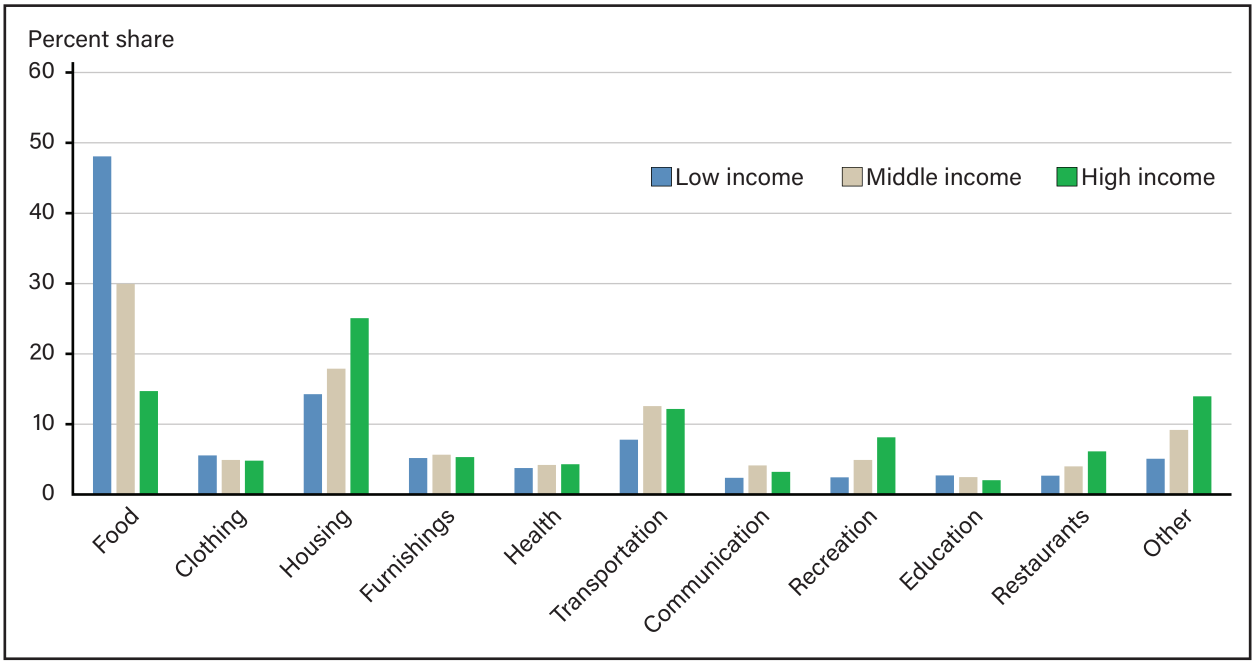
[1] Notable differences include adding 30 economies to the Latin America/Caribbean region. Data are considered more nationally representative of true expenditures. For the first time, rural outlets were widely included, and "importance indicators" were introduced to help determine whether a consumption item was a significant component of an economy's expenditures. Lastly, the statistical procedure for linking geographic regions and allowing interregional comparisons was much improved.

While the ICP covers 199 economies, this analysis includes 177 economies for which the full range of required data were available.[5] Authors summarized the underlying expenditure data by grouping all economies into low-, middle-, and high-income groups.[6] "Food at home" is by far the most important expenditure category for low- and middle-income economies, with average budget shares of 48 percent in low-income economies and 30 percent in middle-income economies. High-income economies, by contrast, spend on average, just 15 percent of their consumption expenditures on food at home but 25 percent on housing (figure 2). Food away from home, which increases with income, is included in restaurants.

[5] The 177 International Comparison Program economies cover 97 percent of the world's population and 99 percent of the world's gross domestic product at market exchange rates. See World Bank (2015) for a full list of economies.

[6] Low-income economies are defined as having per capita income less than 15 percent of the per capita income in the United States. Middle-income economies are those with per capita incomes between 15 and 45 percent, and high-income economies are those with greater than 45 percent of U.S. per capita income.

Figure 2
Budget shares for broad consumption categories, 2011



Note: Food away from home is included in Restaurants.

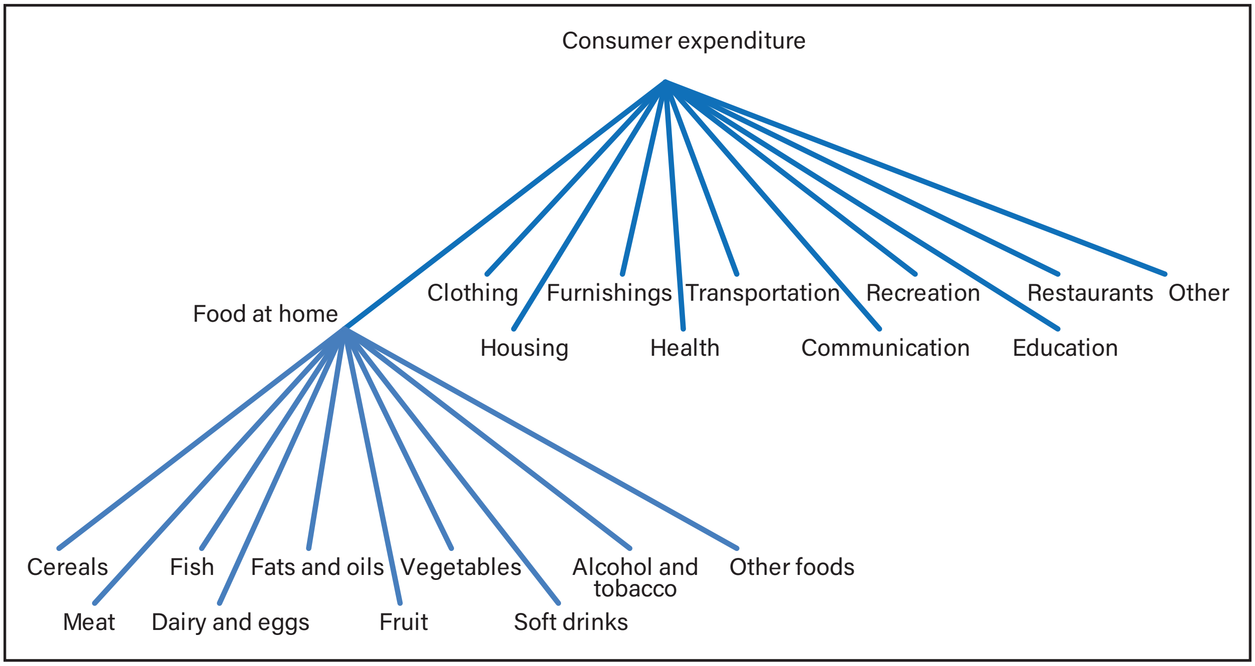
Source: USDA, Economic Research Service calculations based on the 2011 International Comparison Program.

As noted in previous rounds of the ICP, food budget shares exhibit a strong negative relationship to income, i.e., the lower the income, the higher the food budget share. This phenomenon is known as Engel's Law, named after the 19th century German statistician who first stated that poorer people tend to have a higher share of food spending than wealthy people (Chai and Moneta, 2010).

Projections of future food consumption rely on a relationship between changes in per capita income and the quantity of food consumed. Two sources of empirical support are FAO food balances (patterns of historical food consumption) and the ICP project (historical food expenditures and income).

Budget shares of commodity categories were calculated from ICP data as summary statistics, but further economic analysis requires a statistical model of consumer demand (Muhammad et al., 2011). Demand for food can be modeled in two stages to allow budget allocation step by step. The first stage focuses on 11 broad consumption goods, one of which is food and beverages, and the second stage concentrates on the allocation of the food and beverage budget component into 10 food subgroups (figure 3).

Figure 3
Two-stage consumer budgeting



Note: Two stages allow for the flexibility of substitution among food subgroups to differ from substitution among the larger categories of consumer expenditure.

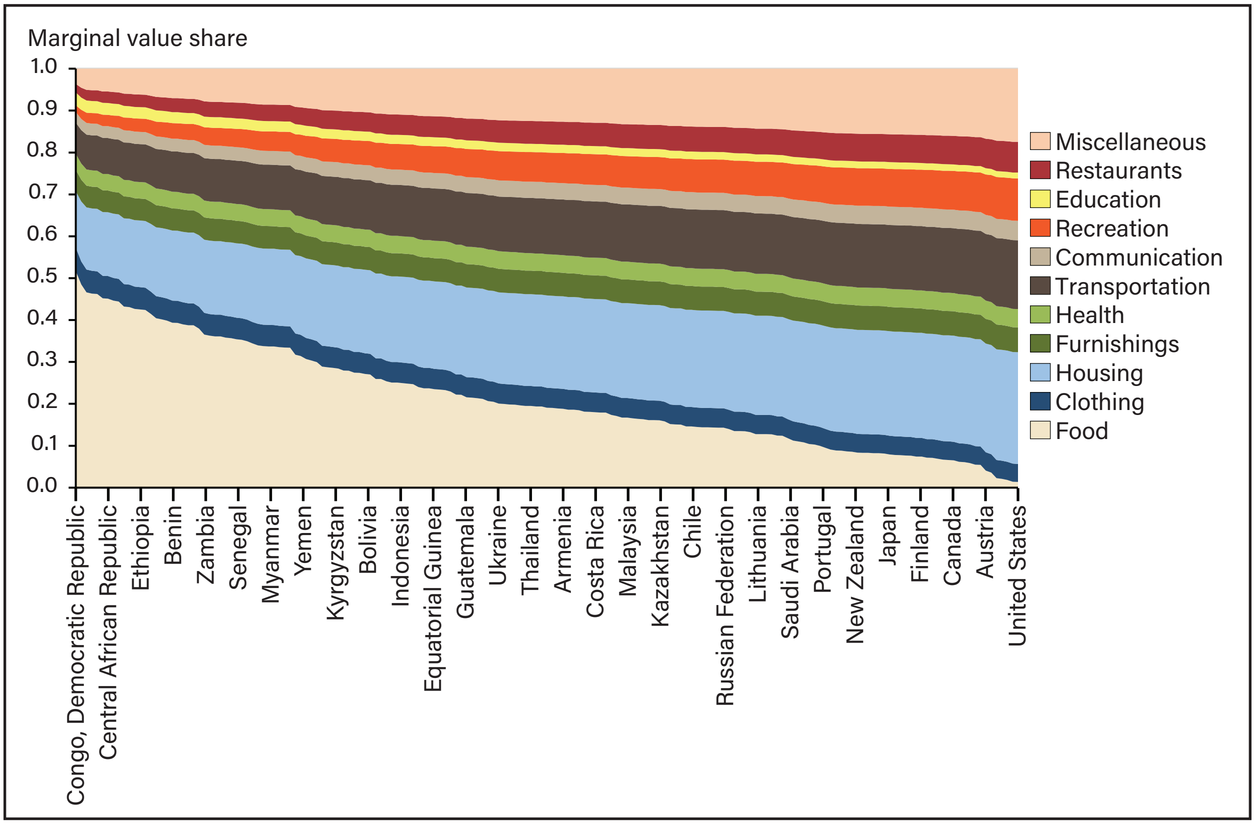
Source: USDA, Economic Research Service based on the 2011 International Comparison Program.

Consumer Demand Across Economies

While budget shares tell us how much consumers spend on each product category on average, marginal shares can be calculated to understand how a consumer allocates $1 of additional income (figure 4).[7] The pattern is similar to budget shares, with lowest income economies spending about 50 cents of an additional $1 in income on food and the highest income economies spending less than 10 cents on food. As economies become wealthier, marginal budget shares of food consumed at home become smaller, while marginal shares of food consumed at restaurants become larger.

[7] Authors calculated the relationship between changes in income and changes in food demand expressed as an income elasticity: the percent change in food demand divided by the percent change in income. An income elasticity is not constant; it varies by the initial level of income and over time as consumers become wealthier. See appendix B for background on calculating marginal expenditure shares.

Figure 4
Distribution of an additional $1 of income across 177 economies in 2011



Note: Economies are arranged in ascending order of affluence (income per capita) starting on the left. It is not possible to show all 177 economies on the horizontal axis: every sixth economy is listed, beginning with the least affluent (Congo, Democratic Republic).

Source: USDA, Economic Research Service calculations using 2011 International Comparison Program data.

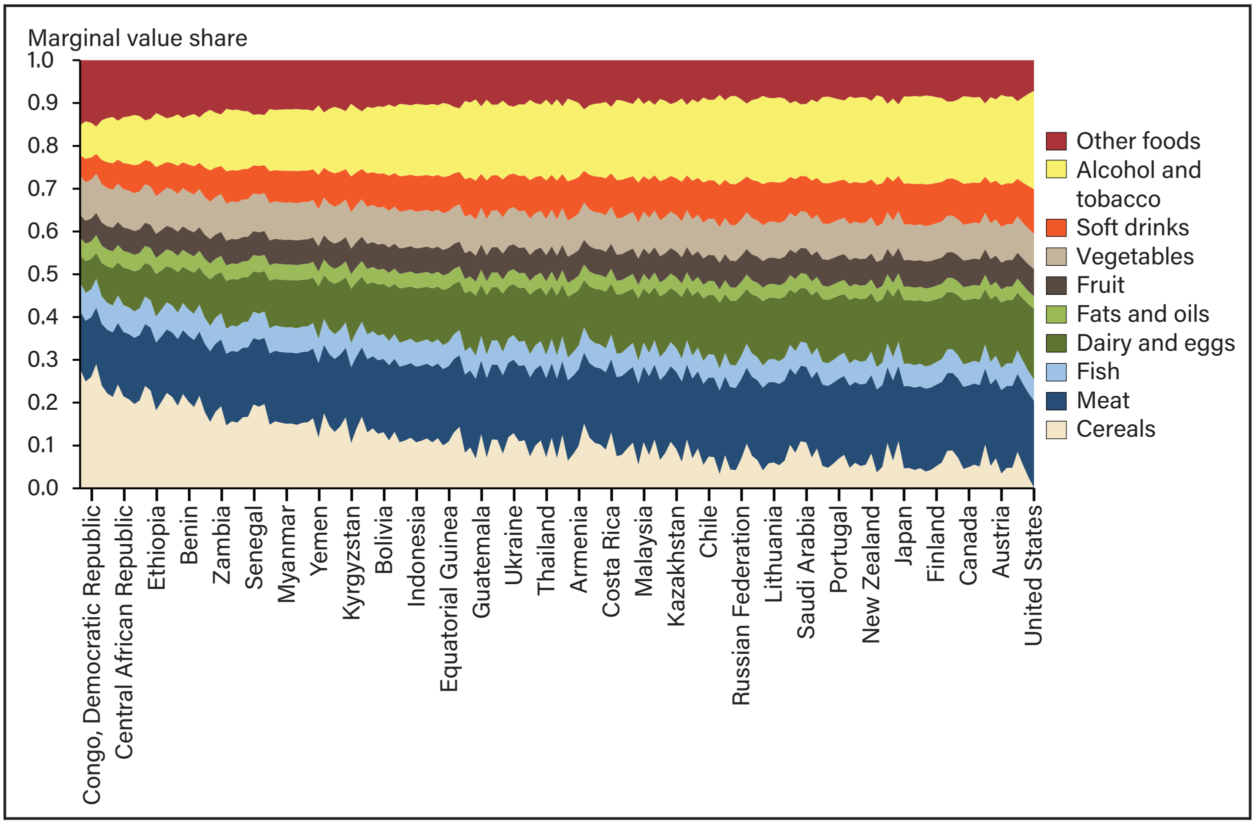
A similar chart can be constructed for the second budgeting stage that allocates food expenditure to 10 food commodities (figure 5). As per capita income increases, the food budget share of cereals declines, but the expenditure share of animal products (meat, dairy, and eggs) increases.[8]

ICP data can be converted to income elasticities for each food subgroup, exploiting variations in income across countries in 2011.[9] This helps inform the economic modeling framework described later in this report.

[8] Expenditure patterns in figures 4 and 5 were derived using a statistical model of consumer demand. The model is summarized in appendix B and more fully described in Muhammad et al. (2011).

[9] See figure A.3 in appendix A.

Figure 5
Distribution of an additional $1 of food expenditure across 177 economies in 2011



Note: Economies are arranged in ascending order of affluence (income per capita) starting on the left. It is not possible to show all 177 economies on the horizontal axis: every sixth economy is listed, beginning with the least affluent (Congo, Democratic Republic).

Source: USDA, Economic Research Service calculations using 2011 International Comparison Program data.

Framing the Future

Three key drivers of global change considered in the report are dietary preference, population growth, and agricultural productivity growth. These drivers affect food consumption, crop production, land use, income, and agricultural prices. The authors constructed scenarios based on combinations of these drivers through 2050.

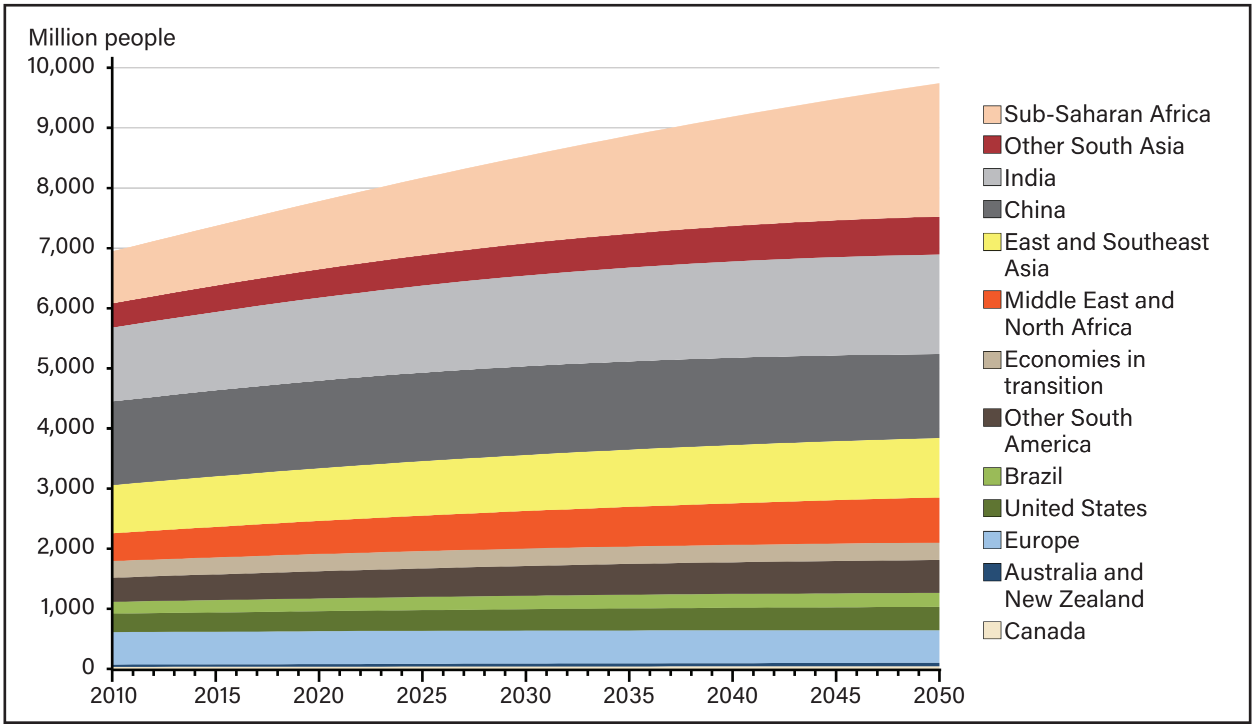
Dietary preference directly affects food consumption and the implied requirements for crop production. Two diet scenarios provide a range of food consumption, one with constant per capita consumption of all food products and another with increasing consumption of most food products:

- Static diet: Per capita consumption of food calories remains constant over time in all world regions at 2011 levels. There is no income or price response in this scenario.[10]
- Income-driven diet: This is based on historical food consumption patterns in response to increasing per capita income. The general pattern is for total per capita calories to increase, along with a greater share of animal products and vegetable oils in the diet.

[10] The authors used a 2011 historical diet based on the Food and Agriculture Organization of the United Nations food balance tables. Year 2011 is the year of the benchmark social accounting matrix used to calibrate the Future Agricultural Resources Model.

Population projections are from the United Nations World Population Prospects (United Nations, 2017). The world population in 2050 is projected to be 8.7 billion (low-fertility variant), 9.7 billion (medium-fertility variant, figure 6), or 10.8 billion people (high-fertility variant).[11] Much of the population growth is projected to be in Sub-Saharan Africa. Even with no change in individual diets, population growth alone will create a substantial increase in food demand from the present through 2050.

Figure 6
World population estimates (United Nations medium growth), 2010–50



Note: Economies in transition consist of members of the former Soviet Union.

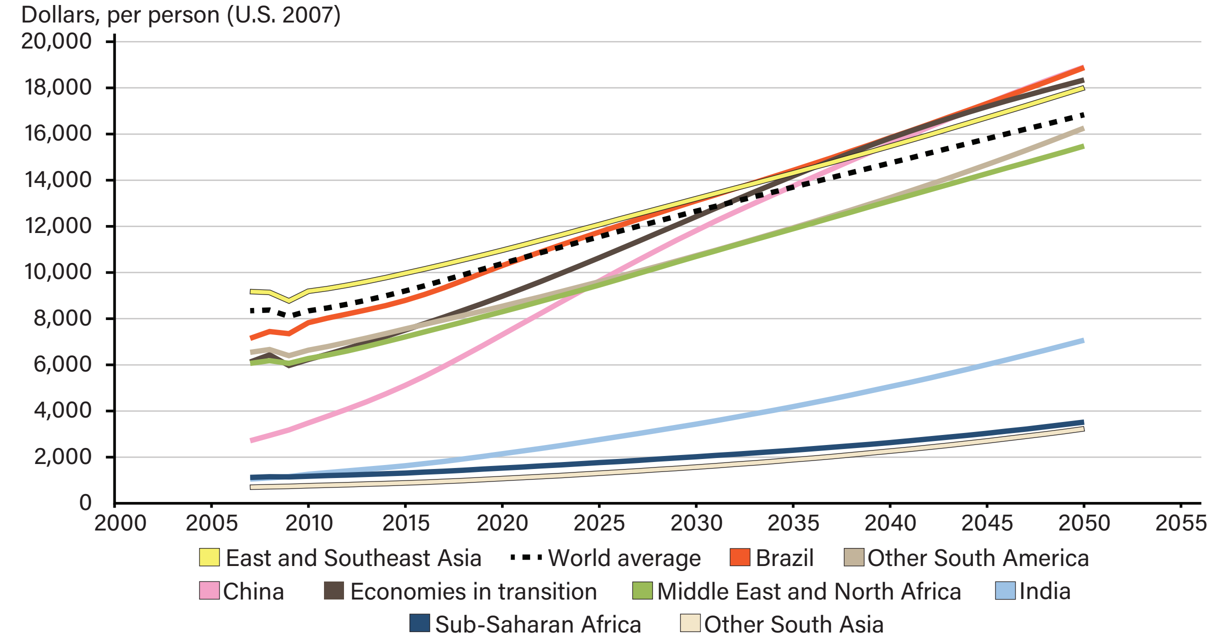
Source: USDA, Economic Research Service using World Population Prospects 2017, United Nations data.

The authors used the Shared Socioeconomic Pathways (SSPs) developed by the global change research community (Riahi et al., 2017) for projections of income (Dellink et al., 2017). GDP is endogenous in the FARM, but labor productivity parameters were adjusted to closely approximate GDP to the "middle-of-the-road" SSPs.

The average per capita income in each country is the ratio of GDP to population. The result for a medium population scenario is shown in figure 7. World average per capita income masks large variation across world regions in reference scenario projections. For example, India's per capita GDP starts out very low, about $1,300 per person per year in 2010, and is projected to increase fivefold by 2050. However, India's per capita GDP stays far below the income of Europe and other developed countries in the estimate. China's per capita income is also projected to increase fivefold from 2010 through 2050, starting at $3,500 per year.

[11] United Nations population projections are based on probabilistic models of fertility and mortality (United Nations, 2022). The projections used here are low-, medium-, and high-fertility variants, along with medium mortality and migration assumptions.

Figure 7
Gross domestic product per capita for world regions outside the Organisation for Economic Co-operation and Development, 2007–50



GDP = Gross Domestic Product.

Note: World regions not shown have per capita incomes above $25,000 for all years. Market exchange rates are used for all income comparisons. Economies in transition consist of members of the former Soviet Union.

Source: USDA, Economic Research Service income projections from Dellink et al. (2017) and World Population Prospects 2017 (medium-fertility scenario), United Nations.

Inputs to production adjust to changing market conditions in two ways: through changes in relative prices (price-induced) and through productivity improvements. Even without changes in productivity, there can be substitution among inputs (e.g., land and capital) if land becomes expensive relative to capital. The FARM also has productivity parameters attached to each input to production. Productivity changes could be labor-augmenting, land-augmenting, or applied to intermediate inputs such as fertilizer. Exogenous changes to these parameters allow improvements in partial-factor productivity to represent technology that improves over time.

The authors used partial-factor productivity growth rates applied to land and intermediate inputs such as fertilizer. The growth rates were not applied to capital. Growth in labor productivity is not agriculture-specific; it was assumed to be the same across all sectors of the economy. Other assumptions about growth in agricultural labor productivity are possible. Robinson et al. (2014) provided examples where labor productivity growth in agriculture was greater or lower than other economic sectors. Three alternative time paths of partial-factor productivity improvement determine the influence of productivity change on model outputs, especially land use and crop yield.[12]

[12] Increasing productivity was modeled as a decline in input requirements per unit of output over time. Productivity change was applied to all inputs equally except for labor and capital. Labor productivity growth rates were set to match gross domestic product (GDP) targets by region based on the Shared Socioeconomic Pathways GDP projections (Dellink et al., 2017) and assumed to be the same in all economic production sectors. The following annual productivity growth rates applied to other inputs to crop production (e.g., land, energy, chemicals) in the medium growth scenario: 0.5 percent for all regions except India (0.7 percent), other South Asia (0.7 percent), and Sub-Saharan Africa (1.0 percent). Productivity growth rates were 0.2 percent lower per year for all regions in the low productivity scenario and 0.2 percent higher per year in the high productivity scenario. Productivity growth rates for ruminant and non-ruminant animals were set to zero for all regions in all time steps.

Global Modeling Framework

Historical data from FAO and ICP provide empirical support for simulating world food consumption. A key component is the relationship between per capita income and consumption of food commodities. This was useful for simulating food demand in the early years, but further information and a global economic model were needed to project food demand and land use forward to 2050.[13] The primary source of additional information for food consumption in 2050 is the FAO report (Alexandratos and Bruinsma, 2012), which relies on expert elicitation.

The authors simulated the effects on world agricultural production, prices, and land use through 2050 across 10 scenarios. Scenarios were simulated using the FARM developed and maintained at USDA, ERS (Sands et al., 2014 and 2017).[14] The United States is one of 13 world regions (table 1) simulated in 5-year steps from 2011 to 2051, with results for other years interpolated.[15] At the core of the analysis is an economic model of consumer demand embedded in FARM. The structure of the consumer demand component was designed to model food consumption over time as the world population becomes wealthier while keeping per capita food consumption in a plausible range in all countries.

Table 1
World regions in the Future Agricultural Resources Model

Region name	Notes
Sub-Saharan Africa	
India	
Other Asia (south)	
Brazil	
Other South America	Including Central America, Caribbean, and Mexico
Middle East and North Africa	Including Turkey
Economies in transition	Russia, Belarus, Ukraine, Kazakhstan, Kyrgyzstan, Armenia, Azerbaijan, Georgia, Tajikistan, Turkmenistan, and Uzbekistan
China	
Southeast and East Asia	Including Japan
United States	
Canada	
Europe	Including Estonia, Latvia, and Lithuania
Australia and New Zealand	Including Oceania

FARM = Future Agricultural Resources Model.

Source: USDA, Economic Research Service using FARM documentation (Sands et al., 2014).

[13] Extrapolating statistical models far outside the historical sample might be inconsistent with biophysical constraints (e.g., a realistic upper bound on per capita calorie consumption).

[14] The first version of the Future Agricultural Resources Model was constructed in the early 1990s (Darwin et al., 1995) to simulate the impact of a changed climate on global land use, agricultural production, and international trade. By partitioning land into land classes, this model provided a unique capability among computable general equilibrium models to simulate land use on a global scale. The model has evolved from comparative static to recursive dynamic and to represent economy-wide greenhouse gas mitigation strategies.

[15] All countries are mapped to one of 13 FARM world regions, except for a few very small countries. The total world population in FARM is, therefore, slightly smaller than the total world population in United Nations (2017).

Data requirements include a world economic database from the Global Trade Analysis Project (GTAP) at Purdue University, energy balances from the International Energy Agency (IEA), and land use and agricultural production from FAO. The FARM was constructed beginning with standard GTAP model equations (Corong et al., 2017) and converted to the General Algebraic Modeling System (GAMS) programming language (Lanz and Rutherford, 2016).[16] The GTAP 9 database provides input-output tables and bilateral trade flows for 140 world regions and 57 production sectors (Aguiar et al., 2016) with a 2011 base year.

These data were then aggregated to 13 world regions (table 1), corresponding to region definitions of the Agricultural Model Intercomparison and Improvement Project (AgMIP) and 38 production sectors. The production sectors retain all GTAP information related to primary agriculture, food processing, energy transformation, energy-intensive industries, and transportation (table 2).

[16] Future Agricultural Resources Model extensions beyond the standard Global Trade Analysis Project model are described in appendix A.

Table 2

Production sectors in the Future Agricultural Resources Model

Group	Subgroup	Description
Primary agriculture	Crops	Wheat
		Paddy rice
		Other grains
		Oilseeds
		Sugar (cane and beet)
		Vegetables and fruits
		Plant fibers
		Other crops
	Animal products	Cattle and other ruminants
		Raw milk
		Wool
		Other animal products
	Fisheries	Fish
	Forestry	Forestry
Food processing		Vegetable oils
		Processed rice
		Sugar
		Beverages and tobacco products
		Other food
		Meat from cattle and other ruminants
		Dairy products
		Other meat products
Energy	Production	Coal
		Crude oil
		Natural gas
	Transformation	Refined coal and petroleum products
		Electricity
Energy-intensive industries		Wood products
		Paper and pulp
		Chemicals, rubber, and plastic
		Nonmetallic minerals
		Iron and steel
		Nonferrous metals
Other industry		Other industry
Transportation		Land transportation
		Water transportation
		Air transportation
Services		Services

Note: 57 sectors from the Global Trade Analysis Project database were aggregated to 38 production sectors in the Future Agricultural Resources Model (FARM). Food commodities in table 2 include food consumed at home and in restaurants. All base-year (2011) food consumption in FARM is calibrated to Food and Agriculture Organization of the United Nations food balance sheets, a top-down estimate that includes all food consumed. See appendix A for details on calibration.

Source: USDA, Economic Research Service based on FARM model documentation (Sands et al., 2017).

An understanding of the difference between final (food) calories available for consumption and primary (crop) calorie production is necessary to interpret the tables and figures that follow. Final calories are those that are available for food consumption, covering all food products. Primary (crop) calories are produced from the land before processing into food products. Crop calories are greater than food calories, primarily due to losses as feed is converted to meat, dairy products, and eggs. Some losses also occur during conversion to other food products. At the country level, crop calories produced may be different than crop calories used due to international trade. At the world level, international trade nets to zero, and the supply of crop calories equals the use of crop calories.[17] Various concepts of food and crop calories are defined in table 3.

Table 3
Definitions of food consumption and production

Label	Definition	Unit
Large calorie	1 large calorie equals 1,000 small calories. The calories used in nutrition labels in U.S. grocery stores are large calories. FAO food balances use small calories, but they are always displayed as kilocalories (kcal). All calories in this report are large calories.	Calorie
Food calories available (per person per day)	Calories available from food products per day, with calories as a common unit for all food products. Calories available include post-retail food waste at home and in restaurants. (Example in figure 1.)	Calories/person/day
Food calories consumed (per person per day)	Calories consumed per person per day, excluding food waste.	Calories/person/day
Food calories available per year (world or country)	Total calories available for all final food products within a world region. An average person has approximately 1 million calories available for consumption per year. A world population of 7 billion therefore requires about 7,000 trillion calories per year.	Trillion calories
Crop calories used per year	Annual use of all crop calories within a country or world region, whether consumed as food, as animal feed, or for other uses.	Trillion calories
Crop calories produced per year	Annual production of all crop calories within a country or world region. Storage and international trade account for the difference between crop production and domestic crop use.	Trillion calories

FAO = Food and Agriculture Organization of the United Nations.

Note: Post-retail food waste is included in "Food calories available."

Source: USDA, Economic Research Service definitions based on food balance sheets from the Food and Agriculture Organization of the United Nations.

The static diet maintains historical per capita food consumption throughout the simulated time horizon. Much of the variation in diets across world regions is due to differences in the consumption of animal products. Per capita availability of animal products ranges from 200 calories per person per day in developing regions to 1,000 calories per day in the United States. Variation in consumption of animal products across world regions is greater than variation in total calories; some of the difference in animal products is offset by the consumption of other food types.

The following process was used to determine the response of food consumption to prices and income for the central income-driven scenario, shown in bold in table 4:

(1) Income in the FARM was endogenous, but labor productivity parameters were adjusted so that income in each world region closely approximates income growth in the Shared Socioeconomic Pathways (SSPs) "middle-of-the-road" scenario (Dellink et al., 2017).

(2) Population projections were exogenous to the FARM. The 2017 U.N. medium-fertility projections were used for the calibration of food consumption.

[17] Some of the supply may come from a change in stocks at the global level.

(3) Demand system parameters in the FARM were calibrated so that per capita food calorie consumption in 2050 approximates projections by FAO (Alexandratos and Bruinsma, 2012) as a function of per capita income derived from steps 1 and 2 above. Total food calories increased for all developing regions, along with increasing consumption of animal products and vegetable oils.[18] To simplify, the authors assumed that the income elasticity of food consumption in wealthy countries is zero (United States, Canada, Europe, Australia, and New Zealand).

(4) Demand system parameters derived in step 3 were carried over to all other income-driven scenarios, which allowed for price feedbacks in the FARM. For example, a scenario with high population growth leads to an increase in food prices, which feeds back to a decline in food consumption.[19]

It would be convenient to simply substitute income elasticities derived from ICP data into the longrun economic modeling framework described later in this report. This is useful in the near term but can generate implausibly high levels of per capita calorie consumption in model simulations to 2050.[20]

These assumptions ensured the central scenario replicates calorie consumption assumptions in step 3 above. The same demand system parameters were carried over to other scenarios to allow price feedbacks in response to population and productivity drivers. Gouel and Guimbard (2018) constructed an alternative food demand system based on statistical relationships across FAO food balance sheets. Bodirsky et al. (2015) also estimated the statistical relationships of food demand based on income and FAO food balance sheets. However, these studies focused on the demand side only and did not consider interactions with the supply side.

Land use can shift among crops, pasture, and managed forests in response to population growth and changes in income. Most forest land in the FARM is protected and not available for conversion to other uses. Demand for forest products (i.e., paper products, wood for construction) was modeled in the same way as food products, increasing with population and per capita income. Most grassland is available for grazing only, but some can be used for pasture or crops. Land in each FARM world region was partitioned into agro-ecological zones (AEZ) (Monfreda et al., 2009), with as many as 18 AEZs in any world region. Land was allocated among competing uses within each AEZ until rates of return (U.S. dollars per hectare) were equal.

In an economic equilibrium, prices adjust to equate supply and demand for agricultural products. Supply and demand for crop calories can be partitioned into factors. Supply of crop calories is area times yield, but both vary in response to prices.

$$\text{Crop calories} = \text{Area} \times \frac{\text{Crop calories}}{\text{Hectare}}$$

Agricultural land moves to uses with greater economic returns. Crop yield adjusts over time with underlying productivity trends, and at any point in time to prices of commodities and inputs to production.

[18] Food and Agriculture Organization of the United Nations projections begin with exogenous levels of per capita income applied to Engel functions, followed by "several rounds of iterations and adjustments in consultation with specialists on the different countries and disciplines" (Alexandratos and Bruinsma, 2012, appendix 2).

[19] The income response can be summarized as an elasticity—the percent change in consumption divided by the percent change in income. Income elasticities for selected world regions, and how they change over time, are provided in appendix A. Income elasticities fall over time as per capita income increases.

[20] This can be shown for animal products in China by comparing per capita income growth (figure 7) with International Comparison Program elasticities (figure A.3). Further explanation is provided in appendix A after figure A.3.

The demand side is more complex with terms for dietary preference and efficiency of conversion from crop calories to animal products. Demand for crop calories can be partitioned into the following factors:

$$\text{Crop calories} = \text{Population} \times \frac{\text{Food calories available}}{\text{Person}} \times \frac{\text{Crop calories}}{\text{Food calories available}}$$

Population is the primary driver of demand for food crops. The first ratio is the dietary preference in terms of calories available for consumption. The second ratio is greater than 1 and reflects the efficiency of converting feed to meat, dairy, and eggs. This decomposition can be expressed for any food commodity in any world region or at an aggregate level summed over all food commodities and all world regions. These expressions provide a way to frame simulation results in the next section.

Simulation to 2050—Global Results

The authors simulated world agricultural production, food calories available for consumption, and land use from 2011 to 2050 for 10 scenarios listed as rows in table 4. Columns 2–5 define exogenous inputs to each scenario according to diet, productivity growth, and population growth. Endogenous output variables are listed in columns 6–10. The effect on land resources is captured in each scenario by the calories provided by crops and the amount of land used for crops, considering competition for land from forests and pasture. Average crop yield is calculated as crop calories divided by food crop area. The first row of table 4 provides historical data for 2011. A central scenario in bold text uses medium-fertility U.N. population projections, the medium agricultural productivity assumption, and income-driven diets. The second row of this table is the same as the central scenario, except that a static diet replaces the income-driven diet. Two other scenarios differ from the central scenario only by population projections. All other scenarios cover interactions between population and productivity.

The central scenario has a particular role—it was used to calibrate labor productivity and consumer demand parameters. Labor productivity was adjusted so that GDP in the central scenario closely approximates the path in Shared Socioeconomic Pathway 2 for each world region. Consumer demand parameters were calibrated to approximate FAO projections of per capita food demand in 2050. Calibrated parameters were carried over to all other scenarios so that per capita income and food demand become endogenous in those scenarios. For example, GDP is greater in high population scenarios than in the central scenario because of a greater labor resource. Population growth was exogenous in all scenarios.

Table 4
World agricultural indicators across scenarios, 2011 and 2050

Year	Diet scenario	Agricultural productivity growth	Population	Population (billion)	Food calories (trillion cal.)	Crop calories (trillion cal.)	Total crop area (Mha)	Food crop area (Mha)	Yield (Mcal per ha)
2011	Historical	Historical	Historical	7.03	7,140	9,570	1,470	1,240	7.7
2050	Static	Medium	U.N. med.	9.75	9,610	12,720	1,500	1,270	10.0
2050	Income/ price responsive	Low	U.N. low	8.73	9,240	12,640	1,530	1,280	9.9
2050	Income/ price responsive	Low	U.N. med.	9.75	10,200	13,930	1,570	1,330	10.5
2050	Income/ price responsive	Low	U.N. high	10.82	11,210	15,240	1,610	1,380	11.1
2050	Income/ price responsive	Medium	U.N. low	8.73	9,280	12,740	1,500	1,240	10.2
2050	**Central**	**Medium**	**U.N. med.**	**9.75**	**10,250**	**14,060**	**1,540**	**1,290**	**10.9**
2050	Income/ price responsive	Medium	U.N. high	10.82	11,260	15,410	1,580	1,340	11.5
2050	Income/ price responsive	High	U.N. low	8.73	9,320	12,840	1,470	1,210	10.6
2050	Income/ price responsive	High	U.N. med.	9.75	10,300	14,190	1,510	1,260	11.3
2050	Income/ price responsive	High	U.N. high	10.82	11,320	15,570	1,550	1,300	12.0

Cal. = calories. Mha = million hectares. Mcal = million calories. ha = hectare (2.47 acres). U.N. = United Nations.

Note: Food crop area excludes nonfood crops such as cotton and hay but includes food crops fed to animals. Agricultural productivity growth and population are exogenous to each scenario. Endogenous variables include total food calories, total crop calories, land use, and crop yield. Crop yield is calculated as crop calories divided by food crop area. Crop yield is endogenous because inputs to agricultural production respond to changes in relative prices. The static diet is exogenous—per capita consumption of calories by food group is fixed at 2011 levels in each world region. In the central scenario, demand system parameters (elasticities) are adjusted to approximate the Food and Agriculture Organization of the United Nations' estimates of per capita food consumption in 2050. Elasticities are carried over from the central scenario to other diet scenarios—this allows food consumption to respond to changes in food prices driven by agricultural productivity growth or population growth that are different than the central scenario.

Source: USDA, Economic Research Service simulations using the Future Agricultural Resources Model.

FAO food balances provided the quantitative link from food consumption back to derived demand for primary (crop) calories. The 2011 data used to benchmark the FARM is a hybrid of economic data from GTAP and quantity data from FAO food balance sheets. Details are provided in appendix A. The consumer demand system calculated food calories consumed per person per day; a food waste multiplier was applied to convert calories consumed to calories available for consumption.

Food Calories and Crop Calories

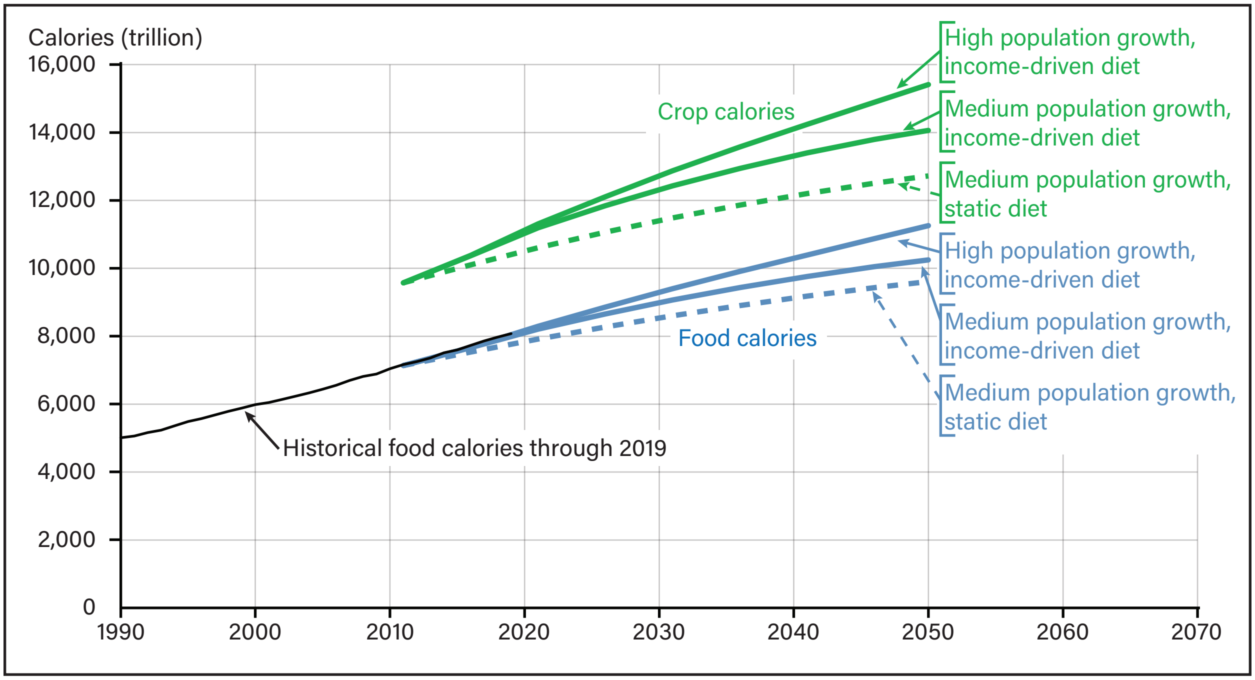
Figure 8 displays the growth path of world food calories and crop calories for three scenarios, along with historical food calories. FAO provides historical data on calories available for consumption through 2019. Food calories available for consumption were 7,140 trillion calories in 2011, with the production of crop calories at 9,570 trillion calories. Two results stand out in this figure:

- Crop calories are always larger than food calories.
- The difference in crop calories in 2050 between the central (medium population and agricultural productivity growth, and income-driven diet) and static diet scenarios (1,340 trillion calories) is more than double the range of food calories (640 trillion calories) across the same scenarios.

Food calories and crop calories grow at a slower rate than population in the static diet scenario because developing countries, whose people consume a smaller amount of calories per person than developed countries, become an increasing share of the world population. The static diet scenario was constructed as a point of comparison for other scenarios. The world population would grow from 7.03 billion to 9.75 billion people (39 percent) from 2011 to 2050 with medium-fertility population growth. With a static diet, available food calories would grow by 35 percent and crop calories by 33 percent.

With income-driven diets, food calories and crop calories grow faster than population. With an income-driven diet and medium-fertility population growth, available food calories would grow by 44 percent and crop calories would grow by 47 percent. Crop calories grow faster than available food calories in this scenario because per capita consumption of animal products grows faster than other food commodities.

Figure 8
Projections of world food calories and crop calories, 2011–50

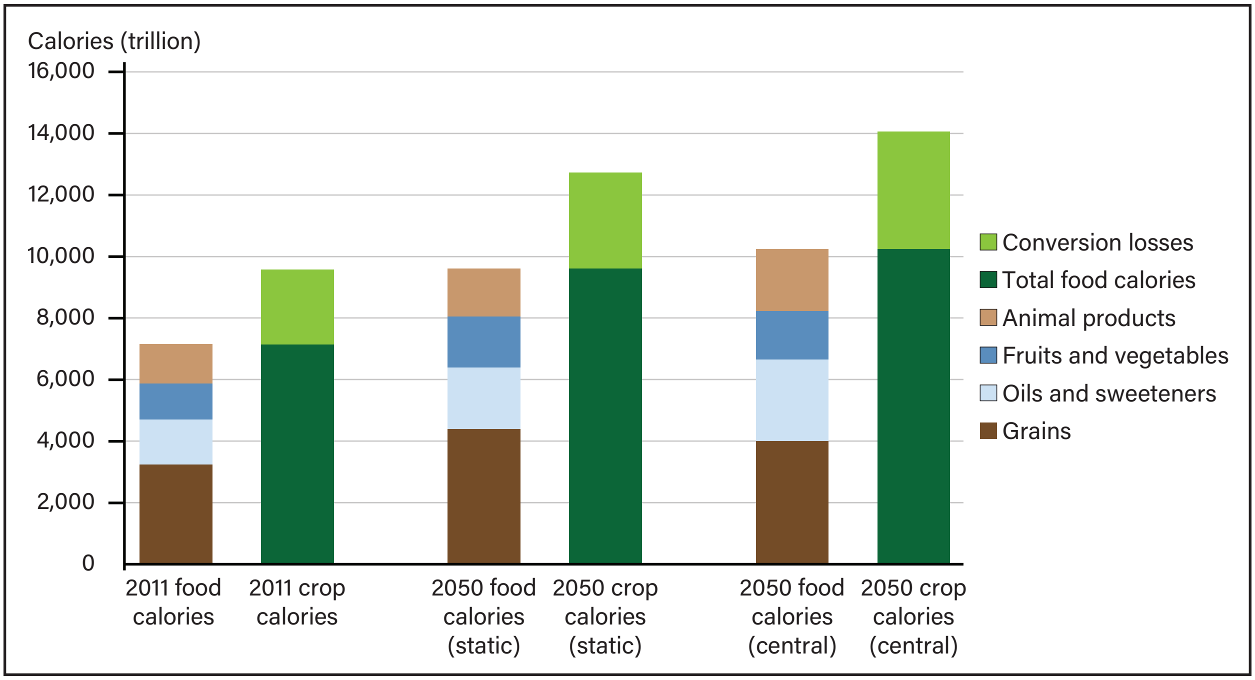


Notes: Three illustrative scenarios are shown: a static diet (per capita consumption of food calories remains constant at 2011 levels in all world regions) with medium population growth; an income-driven diet with medium population growth; and an income-driven diet with high population growth. The static diet is a point of comparison to quantify the effect of income growth on food consumption. Historical food calories in 2019 are slightly higher than the medium-population scenario in the Future Agricultural Resources Model (FARM). This indicates that food consumption continues to respond strongly to increases in per capita income. FARM simulations begin in 2011.

Source: USDA, Economic Research Service using historical food calories through 2019 from the Food and Agriculture Organization of the United Nations and World Population Prospects 2017, United Nations. USDA, Economic Research Service simulations using the FARM.

Another view of the difference between food calories and crop calories is displayed in figure 9 for the static diet scenario and central scenario. Conversion losses are the difference between total crop calories and total food calories. Most, but not all, conversion losses are due to the production of animal products. In all scenarios, conversion losses are much larger than calories of animal products. This reflects the large caloric requirement for animal feed for each final calorie of animal product.

Figure 9
Food calories by food group compared to crop calories (world total), 2011 and 2050



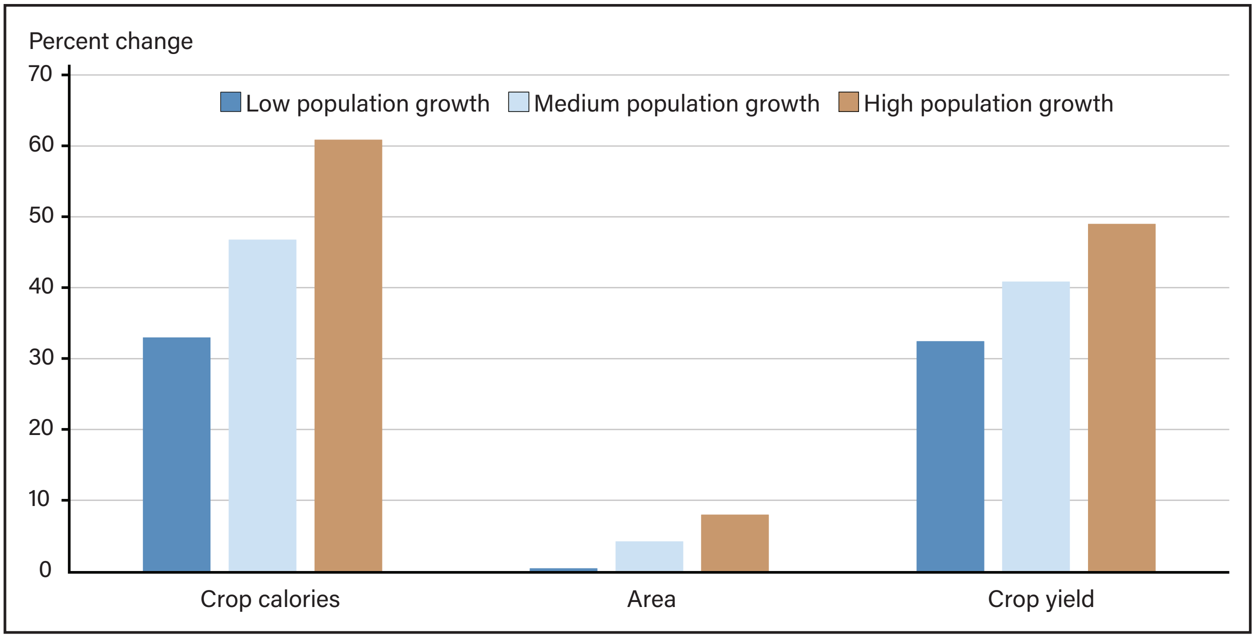
Note: Crop calories in this figure exclude other uses: seed, waste in transportation and storage, and biofuels. Most, but not all, conversion losses are due to the production of animal products.

Source: USDA, Economic Research Service simulations using the Future Agricultural Resources Model.

Response to Population Growth

Two scenarios in table 4 are designed to show how calorie consumption changes with population. All else being equal, the consumption of crop calories scales with the population (figure 10). This is not quite the case because food prices are higher in the high-population scenario, which reduces food demand. Even with this price feedback, the production of crop calories varies widely across population scenarios. Adjustments occur through increases in cropland area, crop yield, and food prices.

Figure 10
Response of key indicators to population growth under three scenarios, 2011–50



Note: Each indicator is shown as percent change relative to 2011 to allow comparison across indicators with different units. All scenarios assume medium agricultural productivity growth and income-based food consumption. Percentage rates of population growth are 24 percent (low growth), 39 percent (medium growth), and 54 percent (high growth).

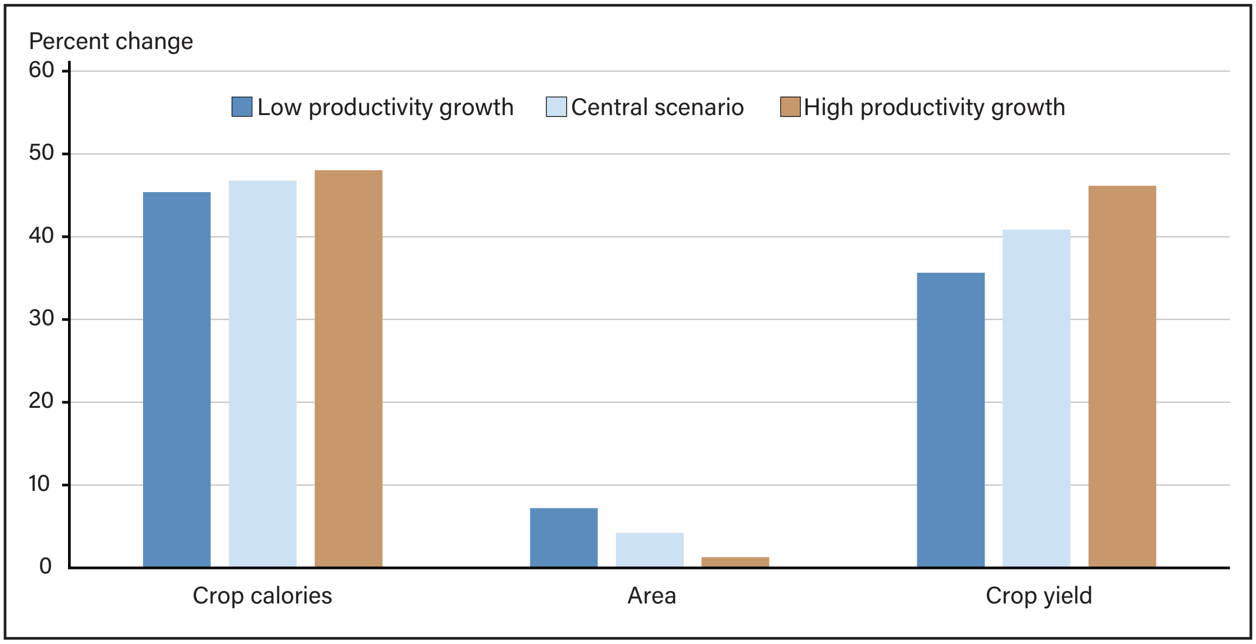
Source: USDA, Economic Research Service simulations using the Future Agricultural Resources Model.

Impact of Agricultural Productivity

Two more scenarios in table 4 illustrate the effect of agricultural productivity on crop calorie production, cropland area, and crop yield (figure 11). Productivity growth rates affect food prices and the amount of land used to grow crops. Food prices are lower in high productivity scenarios than in other scenarios, which allows greater consumption, including greater consumption of animal products. Low productivity growth means more land and non-land resources are brought into agricultural production, increasing the price of agricultural products. Productivity increases in all scenarios, and in all world regions, but at different rates. With higher productivity, crop yield provides more of the adjustment than cropland area. If productivity growth were high enough, cropland area could decline. Yield growth is a combination of exogenous efficiency improvements and price-induced adjustments to quantities of inputs to production.

Figure 11

Agricultural productivity growth: Feedbacks under three scenarios to crop demand, land use, and crop yield, 2011–50

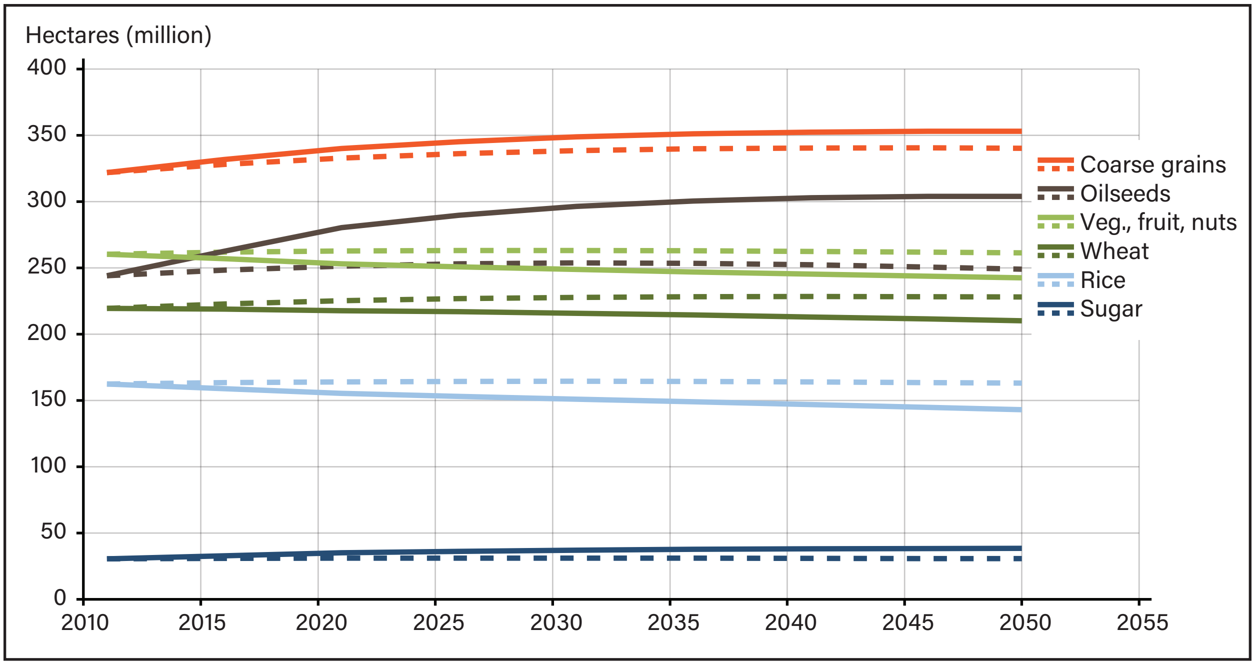


Note: Each indicator is shown as percent change relative to 2011 to allow comparison across indicators with different units. The feedback from agricultural productivity growth to demand for crop calories is indirect—productivity growth reduces food prices, and consumers increase food consumption. Without this feedback through food prices, demand for crop calories would be equal across productivity scenarios and the bars for crop calories would be the same height. All scenarios assume medium-fertility population growth and income-based food consumption.

Source: USDA, Economic Research Service simulations using the Future Agricultural Resources Model.

In the central income-driven diet scenario, land for feed grains (coarse grains and oil seeds) increases, but land for food grains (rice and wheat) declines relative to the static scenario (figure 12). Area for sugar crops also increases. Total area for food crops is nearly the same between the static diet and income-driven diet scenarios, but land area for each crop is relatively stable over time in the static diet scenario.

Figure 12
World land use by major food crop (million hectares), 2011–50



Veg. = vegetables.

Note: Dashed lines are static diet. Solid lines are central income-driven diet.
Source: USDA, Economic Research Service simulations using the Future Agricultural Resources Model.

Simulation to 2050—Selected Regional Results

A table with summary statistics by scenario like table 4 can be constructed for any of 13 world regions in the FARM. Because of low historical crop yield and rapid population growth, Sub-Saharan Africa was selected for table 5. The average crop yield in 2011 was 3.5 million calories per hectare, less than half the world average at that time. The population would more than double in the medium-fertility variant, as does crop yield in the central income-driven scenario.[21] However, average crop yield in 2050 (8.5 million calories per hectare) would remain less than the world average in 2050 (10.9 million calories per hectare).

[21] Food and Agriculture Organization of the United Nations (FAO) projects that coarse grain yield in Sub-Saharan Africa will more than double from 2006 to 2050, increasing from 1.04 to 2.30 metric tons per hectare (Alexandratos and Bruinsma, 2012). The FAO report also notes that this would be a departure from past trends of nearly stagnant yields.

Table 5

Agricultural indicators across scenarios for Sub-Saharan Africa, 2011 and 2050

Year	Diet scenario	Agricultural productivity growth	Population	Population (million)	Food calories (trillion cal)	Crop calories (trillion cal)	Total crop area (Mha)	Food crop area (Mha)	Yield (Mcal per ha)
2011	Historical	Historical	Historical	893	710	669	210	193	3.5
2050	Static	Medium	U.N. med.	2,223	1,787	1,844	239	222	7.6
2050	Income/price-responsive	Low	U.N. low	2,009	1,778	1,905	245	225	7.8
2050	Income/price-responsive	Low	U.N. med.	2,223	1,928	2,041	244	225	8.2
2050	Income/price-responsive	Low	U.N. high	2,447	2,077	2,166	243	226	8.5
2050	Income/price-responsive	Medium	U.N. low	2,009	1,798	1,940	243	223	8.0
2050	**Central**	**Medium**	**U.N. med.**	**2,223**	**1,954**	**2,087**	**243**	**224**	**8.5**
2050	Income/price-responsive	Medium	U.N. high	2,447	2,108	2,225	242	224	8.9
2050	Income/price-responsive	High	U.N. low	2,009	1,816	1,969	240	220	8.3
2050	Income/price-responsive	High	U.N. med.	2,223	1,977	2,128	241	221	8.8
2050	Income/price-responsive	High	U.N. high	2,447	2,137	2,277	241	222	9.3

Cal. = calories. Mha = million hectares. Mcal = million calories. ha = hectare (2.47 acres). U.N. = United Nations.

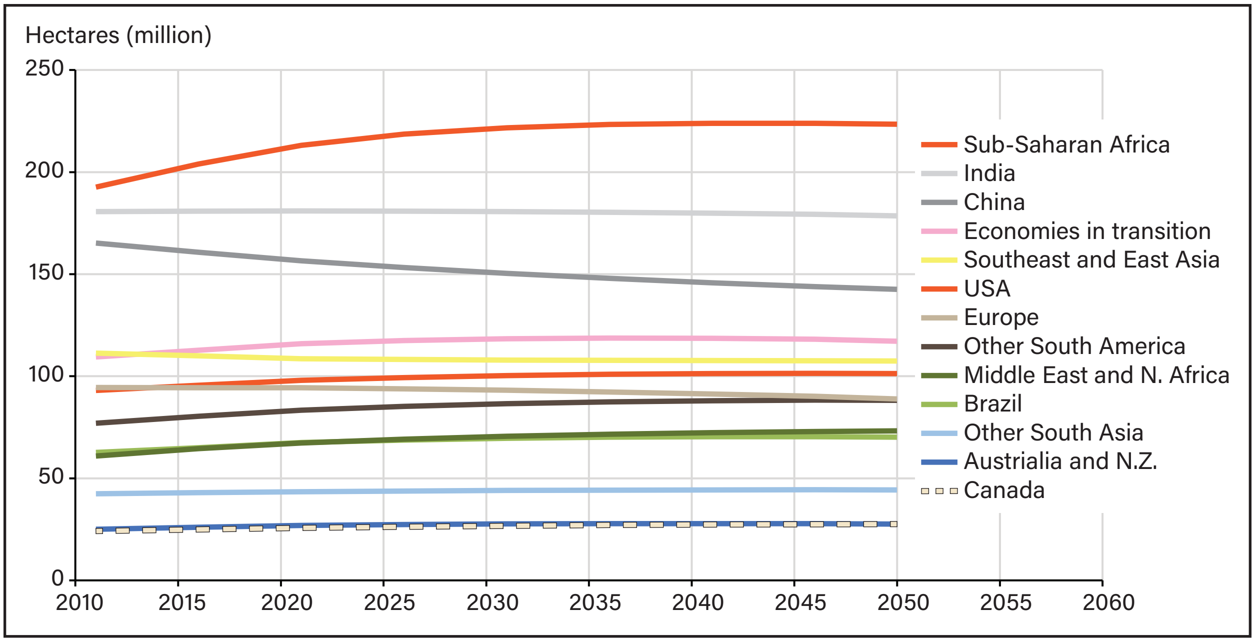
Note: Food crop area excludes non-food crops such as cotton and hay but includes food crops fed to animals. Agricultural productivity growth and population are exogenous to each scenario. Endogenous variables include total food calories, total crop calories, land use, and crop yield. Crop yield is calculated as crop calories divided by food crop area. Crop yield is endogenous because inputs to agricultural production respond to changes in relative prices. The static diet is exogenous—per capita consumption of calories by food group is fixed at 2011 levels in each world region. In the central scenario, demand system parameters (elasticities) are adjusted to approximate the Food and Agriculture Organization of the United Nations' estimates of per capita food consumption in 2050. Elasticities are carried over from the central scenario to other diet scenarios. This allows food consumption to respond to changes in food prices driven by agricultural productivity growth or population growth that are different from the central scenario.

Source: USDA, Economic Research Service simulations using the Future Agricultural Resources Model.

Impact on Land Use

Crop area and crop yield adjust to provide crop calories needed for each scenario. Most of the adjustment is through crop yield, with crop area relatively stable across diet scenarios. Crop yield can increase by using more non-land inputs (e.g., fertilizer) even if underlying productivity trends do not change. Changes in forest land are constrained in the FARM: natural forest land must remain as forest, while forests used for the production of wood and paper products compete with grazing and food crops. Therefore, changes in cropland across scenarios are offset mostly by changes in grassland. In the central scenario, the global food crop area expands from 1,240 million to 1,290 million hectares from 2011 to 2050. Area for food crops has the greatest increase in Sub-Saharan Africa and the greatest decline in China, mainly due to changes in population (figure 13).

Figure 13
Land use by region for food crops, income-driven diet scenario (million hectares), 2011–50



USA = United States of America. N.Z. = New Zealand. Economies in transition = Russia, Belarus, Ukraine, Kazakhstan, Kyrgyzstan, Armenia, Azerbaijan, Georgia, Tajikistan, Turkmenistan, and Uzbekistan.

Source: USDA, Economic Research Service simulations using the Future Agricultural Resources Model.

Regional Calories Available for Consumption

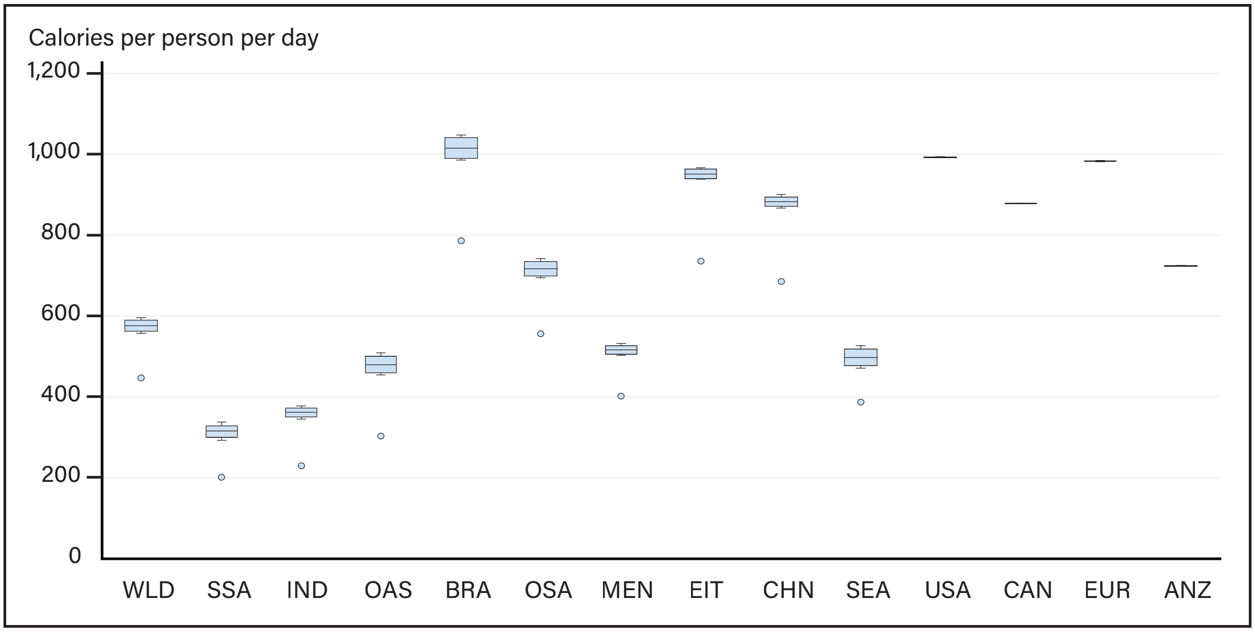
Consumption of animal products by world region is displayed in figure 14a as box and whisker plots.[22] For each region, an outlier dot below each box is per capita animal product consumption in the static diet scenario. The world average on the far left of this figure increases from 450 calories in the static diet scenario to an average of 580 calories per person per day in the income-driven scenarios. The corresponding figures for Sub-Saharan Africa are 200 and 320 calories per person per day. Variation across income-driven scenarios is due to price feedbacks; the highest level of per capita animal product consumption is in the low-population, high agricultural productivity scenario for each region.

Convergence also appears in the model output for total per capita calorie consumption (figure 14b). The world average increases from 2,800 calories in the static diet scenario to an average of 2,990 calories per person per day in the income-driven scenarios. The corresponding figures for Sub-Saharan Africa are 2,470 and 2,700 calories per person per day. FAO projections of per capita calorie consumption in 2050 (Alexandratos and Bruinsma, 2012) were used as a target for the FARM central scenario. The average calorie consumption for developed countries in FAO projections grows from 3,390 calories per person per day in 2015 to 3,490 calories in 2050.

[22] Box and whisker plots summarize a distribution of data points. The median of the distribution is the line at the middle of the box, and outliers are dots outside of the box.

Figure 14a

Per capita calories available for consumption of animal products in 2050 (variation across scenarios)



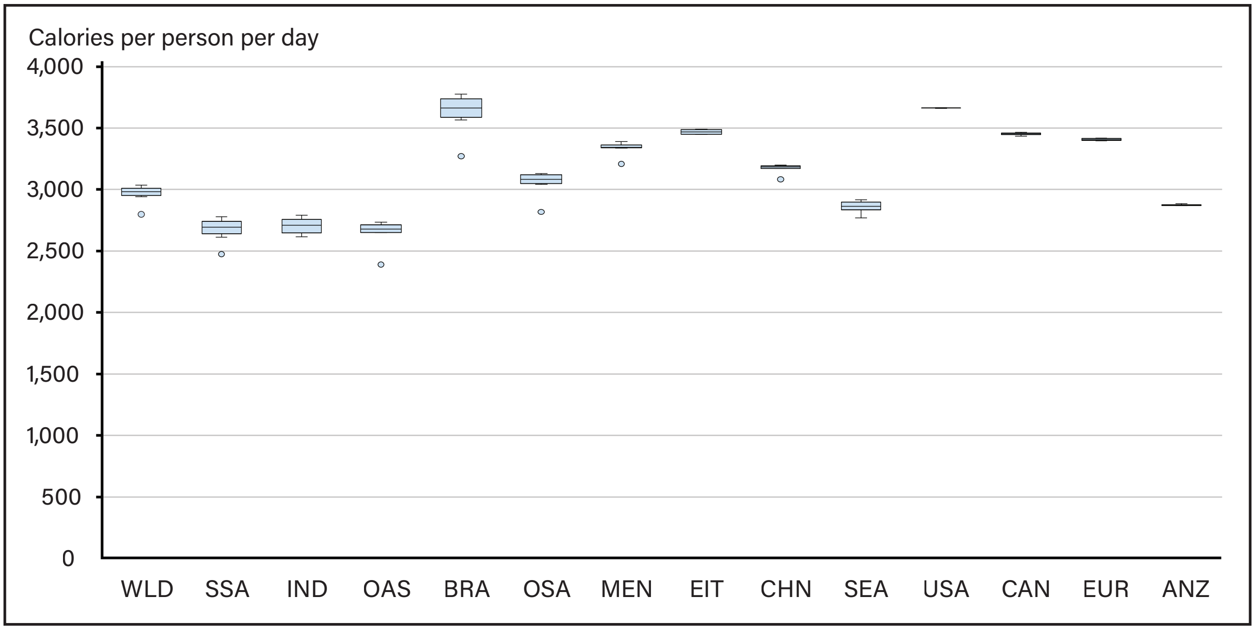
WLD = World. SSA = Sub-Saharan Africa. IND = India. OAS = Other South Asia. BRA = Brazil. OSA = Other South America. MEN = Middle East and North Africa. EIT = Economies in transition. CHN = China. SEA = Southeast and East Asia. USA = United States of America. CAN = Canada. EUR = Europe. ANZ = Australia and New Zealand.

Note: Each box represents a distribution across nine income-driven scenarios, which vary by levels of population growth and agricultural productivity growth. Income-driven scenarios are based on historical patterns of dietary change with growth in per capita income, resulting in partial convergence of animal product consumption toward that of wealthy countries. Variation within each box is due to price feedbacks across scenarios. Wealthy countries (United States, Canada, Europe, Australia, and New Zealand) are modeled with a static diet only, with no price feedback to food consumption. For other regions, an outlier dot below each box is per capita animal product consumption in the static diet scenario (per capita consumption of food calories remains constant at 2011 levels in all world regions).

Source: USDA, Economic Research Service simulations using the Future Agricultural Resources Model.

Figure 14b

Per capita calories available for total food consumption in 2050 (variation across scenarios)



WLD = World. SSA = Sub-Saharan Africa. IND = India. OAS = Other South Asia. BRA = Brazil. OSA = Other South America. MEN = Middle East and North Africa. EIT = Economies in transition. CHN = China. SEA = Southeast and East Asia. USA = United States of America. CAN = Canada. EUR = Europe. ANZ = Australia and New Zealand.

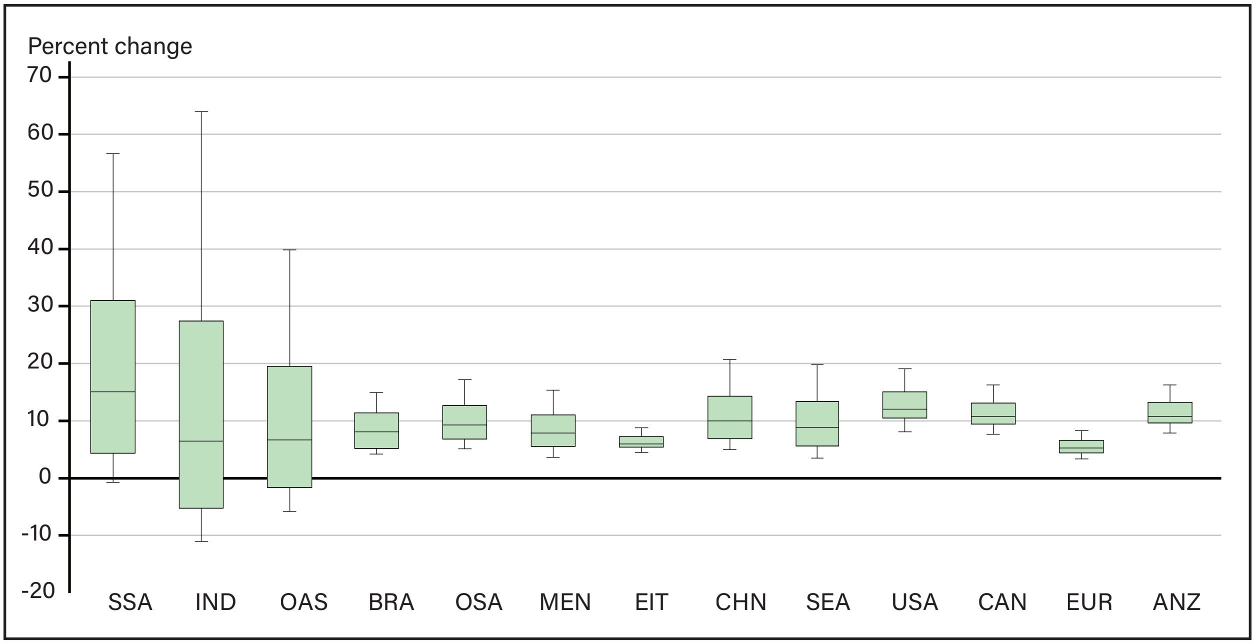
Note: Each box represents a distribution across nine income-driven scenarios, which vary by levels of population growth and agricultural productivity growth. Income-driven scenarios are based on historical patterns of dietary change with growth in per capita income, resulting in partial convergence of food calorie consumption toward that of wealthy countries. Variation within each box is due to price feedbacks across scenarios. Wealthy countries (United States, Canada, Europe, Australia, and New Zealand) are modeled with a static diet only, with no price feedback to food consumption. For other regions, an outlier dot below each box is per capita food consumption in the static diet scenario (per capita consumption of food calories remains constant at 2011 levels in all world regions).

Source: USDA, Economic Research Service simulations using the Future Agricultural Resources Model.

Impact on Food Prices

Food prices vary across scenarios and are plotted for each world region in figure 15. Each box plot contains the percent change, from 2011 to 2050, in a food price index across 10 scenarios. The food price index is relative to a consumer price index in each region (the numeraire in each world region is the consumer price index in that region). For each region, food prices are highest in the scenario with high population growth combined with low productivity growth. Food prices are lowest in the scenario with low population growth combined with high productivity growth. Food prices increase over time in nearly all scenarios—this is a result of assumptions about agricultural productivity growth. More optimistic assumptions imply less of an increase in world average food prices or even a decline in prices.

Figure 15
Change in food prices from 2011 to 2050 across scenarios



SSA = Sub-Saharan Africa. IND = India. OAS = Other South Asia. BRA = Brazil. OSA = Other South America. MEN = Middle East and North Africa. EIT = Economies in transition. CHN = China. SEA = Southeast and East Asia. USA = United States of America. CAN = Canada. EUR = Europe. ANZ = Australia and New Zealand.

Note: The food price index is relative to a consumer price index in each world region. Price variation in each region is across all 10 scenarios listed in table 4. For all regions, food prices are highest in the scenario with high population growth combined with low productivity growth. Food prices are lowest in the scenario with low population growth combined with high productivity growth.

Source: USDA, Economic Research Service simulations using the Future Agricultural Resources Model.

Future Directions

The authors highlighted five areas for further research:

- Data on food loss could be included relatively easily into the modeling framework.
- Data are available to extend model output beyond energy (calories) to protein and other nutrients.
- Opportunities exist to link global analysis of food consumption to U.S. national or subnational models.
- The treatment of agricultural productivity growth remains highly stylized, and historical analysis of yield gaps might improve the realism of agricultural productivity change in CGE models.
- Accounting for energy in rangeland, pasture, and hay would improve model realism.

If data are available for food loss, an extra term can be added to the demand decomposition. This term is "the ratio of food calories available to food calories consumed." FAO food balance sheets provide data as food available for consumption but do not estimate post-retail food loss. However, the Food and Agriculture Organization (2011) provides estimates of food loss at an aggregate level.

$$\textit{Crop calories} = \textit{Population} \times \frac{\textit{Food calories consumed}}{\textit{Person}} \times \frac{\textit{Food calories available}}{\textit{Food calories consumed}} \times \frac{\textit{Crop calories}}{\textit{Food calories available}}$$

Model output by food commodity can be expressed by weight, and food composition tables can be applied to obtain a comprehensive list of nutrient consumption, including macro- and micro-nutrients. Food composition tables have one row for each food commodity and columns for each of the macro- and micro-nutrients. Units are weight of nutrient (grams, milligrams, or micro-grams) per 100 grams of food consumed. Food composition tables from the GENuS model (Smith et al., 2016), with 225 commodities and 23 nutrients, are well suited for calculating nutrient availability in each food consumption scenario.[23]

Global analysis can be paired with U.S. analysis, which allows finer spatial resolution or a more complete set of agricultural commodities. Sands et al. (2017) provided an example of common bioenergy scenarios applied to the FARM and the Regional Environment and Agriculture Programming Model (REAP), a partial-equilibrium model of U.S. agricultural activities maintained at USDA, ERS. The ERS Food Environmental Data System (FEDS) has been used for the analysis of resource requirements of the U.S. diet, including fossil fuels (Canning et al., 2017), natural resources in general (Canning et al., 2020), and freshwater use in the U.S. food supply chain (Rehkamp et al., 2021).

For long-time horizons, agricultural productivity growth becomes important in countries with rapid population and income growth, especially in Sub-Saharan Africa. Adjustment can occur through crop area expansion, changes in food self-sufficiency, yield growth, and government programs to reduce post-harvest food loss. One approach is to consider the gap between current practice and yield potential that avoids limitations from nutrient deficiencies and reductions from weeds, pests, and diseases (van Ittersum et al., 2016).

Food crops used as feed account for only part of the energy requirements for ruminant animals. Accounting for calories provided to ruminant animals by rangeland, pasture, and hay would provide a more complete description of the resource requirements of animal products. Rangeland and pasture use large areas of a limited land resource. Large increases in the production of ruminant meat would require a greater share of feed that competes with food crops (feed grains, silage, oil crops, or hay). FAO's Global Livestock Environmental Assessment Model (GLEAM) quantified many of these relationships (Mottet et al., 2017).

Conclusion

We studied four major drivers influencing the path of global agriculture: population, per capita income, agricultural productivity, and dietary preference to address the following questions:

- How do increasing population and income affect global demand for crops and food products through 2050?
- What is the effect of agricultural productivity growth on food prices and cropland area expansion?
- How do alternative assumptions about population growth affect the size of the world agricultural system in 2050?

[23] Calories (energy) and protein are essential nutrients. Calories are better suited for modeling consumer food demand because they provide more complete coverage of food products and associated land use (e.g., sugar). Model output can always be converted to protein or any other nutrient using food composition tables.

We found that with an income-driven diet and population growth of 39 percent (medium-fertility scenario), available food calories would grow by 44 percent, and crop calories grow by 47 percent from 2011 to 2050. Growth in crop calories reflected income-driven shifts to greater total food calories per person and an increasing share of animal products in food consumption. Food calories and crop calories grew at a slower rate than population in a static diet scenario because developing countries became an increasing share of the world population.

When comparing a high-productivity scenario to a low-productivity scenario, the decline in consumer food prices led to an increase in world crop calorie production of 1.8 percent. Food prices can increase for reasons not covered in this report, such as supply chain disruptions caused by extreme weather events, disease, or war in world breadbaskets. Across scenarios, the largest expansion in cropland occurred with high population growth and low agricultural productivity growth. The largest increase in crop yield occurred with high population growth and high agricultural productivity growth.

Using United Nations projections of world population, production of crop calories grew by 33 percent (low population growth), 47 percent (medium population growth), and 61 percent (high population growth) from 2011 to 2050. Population scenarios addressed uncertainty in future population, such as deaths from the Coronavirus (COVID-19) pandemic.

This report analyzed the challenge of feeding 9.7 billion people (medium population growth scenario) by 2050, with rising incomes. In the general equilibrium framework used here, prices mediate interactions between the agricultural supply and demand systems. For example, an increase in agricultural productivity reduces the cost of food production, which feeds back to an increased demand for food.

Figure 8 provides a comparison of the FARM central scenario to historical food calories between 2011 (FARM base year) and 2019. FAO data on food calories in 2019 is slightly higher than the FARM simulations. This indicates that food consumption continues to respond strongly to increases in per capita income.

This report did not address climate change, but climate change impacts on agriculture can be modeled as changes in agricultural productivity relative to baseline productivity growth (Nelson et al., 2014). Lower agricultural productivity growth implies the need for greater cropland area and higher food prices.

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Appendix A: FARM Background

The Future Agricultural Resources Model (FARM) is designed to simulate six major drivers of world agricultural and energy systems to at least 2050: population growth, growth in per capita income, agricultural productivity, dietary preference, climate change mitigation, and climate change impacts on agriculture. Authors focused on the first four drivers in this report, including a link between per capita income and food consumption. This appendix provides updated model documentation.

The FARM is a recursive-dynamic CGE model—essentially a sequence of static equilibria with capital stocks updated between time steps but lacking foresight of future economic variables.[24] Land use can shift among crops, pasture, and managed forests in response to population growth and changes in income, with behavioral responses determined by price and income elasticities (Sands et al., 2014 and 2017). Crop yield is endogenous, even with underlying productivity trends that are exogenous to the model. The model can substitute other inputs for land if land becomes expensive.

The global economic model used for this study requires three key data sets: a global social accounting matrix (SAM) from GTAP, food balance sheets from the Food and Agriculture Organization (FAO) of the United Nations, and tables for converting food consumption by weight to calories. A SAM defines the economic structure and scale for a model, including the number of production sectors, the number of world regions, and the primary factors of production (land, labor, and capital).[25] A SAM is entirely in monetary units, built around an input-output table. Tax and transportation margins are associated with each production activity. Transportation margins generally imply additional energy costs to move goods to market; however, data on energy consumption in agriculture is not always available.

A SAM lacks quantity information, and additional data are needed to recover quantities for food and energy commodities. FAO food balance sheets provide the quantitative link between food consumption and derived demand for primary crops (FAO, 2001). The SAM used to benchmark the FARM is a hybrid between economic data provided by GTAP and quantity data from FAO food balances. Food composition tables provide the link between kilograms (kg) of food consumed and various nutrients. For this study, authors only used the conversion factors for kilograms (kg) of food to kilocalories (kcal).[26] The primary challenge is matching monetary flows in the benchmark SAM with energy flows (joules), agricultural commodities (calories), or land (hectares).

The GTAP data distribution has the same number of production activities as products for consumption. However, it is convenient to maintain a distinction between produced commodities and production activities, allowing for the possibility of joint products or multiple activities producing the same product. For example, the FARM considers oil and gas as joint products from a combined oil and gas production activity. The FARM also considers milk and ruminant meat as joint products of a ruminant animal production activity.

Further data processing expands the number of production sectors. The single electricity production sector in GTAP is expanded to include nine electricity generating technologies; household transportation is removed

[24] There are two important differences between recursive-dynamic models and perfect foresight models. First, recursive-dynamic models can handle a greater number of production sectors and world regions because time steps are solved in sequence. Perfect foresight models solve all time steps simultaneously, along with added complexity to endogenize investment. The trade-off is sectoral and geographical detail vs. complexity of investment structure.

[25] See Aguiar (2016, figure 2) for an overview of the Global Trade Analysis Project database structure. Although this is not presented in the format of a social accounting matrix (SAM), it has all the necessary elements. Background on computable general equilibrium models and social accounts is found in Dervis et al., 1982. Miller and Blair (2009) provide more detail on SAM construction and other uses for SAMs.

[26] Extensions to this study could include other macro-nutrients (e.g., protein and fat) and micro-nutrients (e.g., zinc and iron).

from final demand to create a new transportation services sector; and household energy consumption is also removed from final demand to create a new energy services sector. Dedicated biomass production is introduced as a new field crop, which is then combusted in a bioelectricity activity. Biomass, therefore, becomes a link between agricultural and energy systems.

Understanding the difference between final (food) calories available for consumption and primary (crop) calorie production is fundamental to the analysis in this report. Final calories are those that can be consumed as food. Primary (crop) calories are produced from the land before processing into animal products or other products. Crop calories are greater than food calories due primarily to losses as feed is converted to meat, dairy products, and eggs. Some losses also occur during conversion to other food products. A further distinction is between crop calories produced and crop calories used domestically. At the country level, they differ due to international trade. Domestic crop use includes seed, animal feed, food processing, and crops consumed directly as food. At the world level, international trade nets to zero, and supply of crop calories equals the use of crop calories. The primary challenge for modelers is combining information from social accounting matrices and food balance sheets to form a hybrid model that tracks monetary values and food quantities.

Consumer Demand

The consumer demand system in the FARM has two stages:

- Linear Expenditure System (LES) for the first stage.
- Constant Elasticity of Substitution (CES) for the second stage.

The most important requirement for the first stage is that food consumption not scale directly with per capita income. This excludes Cobb-Douglas and CES demand systems, which would violate Engel's Law.[27] The LES is derived from a shifted Cobb-Douglas utility function, with an extra shift parameter.[28]

Demand for an individual commodity in the Linear Expenditure System is given by

$$x_i\,(p\,,\,m) = \gamma_i + \frac{1}{p_i}\,\beta_i\,(m - \textstyle\sum_k p_k \gamma_k) \tag{1}$$

where p_i is the price of good i; p is a vector of prices, m is total expenditure; and γ_i is the quantity of good i that is purchased regardless of price, sometimes called a "subsistence quantity." The β_i parameters are value shares of income m remaining after minimum quantities of each commodity have been purchased. Income and price elasticities are not parameters of the demand system, but they can be calculated from parameters β and γ. The income elasticity of demand is calculated from (1) by differentiating with respect to income.

$$\varepsilon_{im} = \frac{\beta_i m}{p_i x_i} = \frac{\beta_i}{s_i} \tag{2}$$

where s_i is the value share of commodity i in total expenditure m. Base-year calibration requires setting the β and γ parameters so that base-year data is replicated from GTAP, including value shares for each commodity in total expenditure m. A convenient method of calibration is to set the base-year ratio $\frac{\gamma_i}{x_i}$, and then β_i

[27] Engel's Law can be stated as "the poorer a family is, the larger the budget share it spends on nourishment" (Chai and Moreta, 2010).

[28] Lanz and Rutherford (2016) is a standard reference for computable general equilibrium (CGE) models using Global Trade Analysis Project (GTAP) data. Valin et al. (2014) provided examples of consumer demand systems for agricultural products in CGE and partial-equilibrium models.

parameters are calculated to match GTAP value shares. The ratio $\frac{\gamma_i}{x_i}$ must be in the interval [0,1] and can be used to indirectly set income elasticities, especially for agricultural products. Note that income and price elasticities cannot be set independently in the LES: once the $\frac{\gamma_i}{x_i}$ ratio is set, then income and own-price elasticities are already determined. Levels of the ratio $\frac{\gamma_i}{x_i}$ close to 1 imply low income and own-price elasticities. The own- and cross-price elasticities of demand are calculated from equation (1) by differentiating with respect to prices.

$$\varepsilon_{ii} = -1 + \frac{(1-\beta_i)\,\gamma_i}{x_i} \tag{3}$$

$$\varepsilon_{ij} = -1 + \frac{(1-\beta_i)\,p_j\gamma_j}{p_i x_i} \tag{4}$$

The second stage is a CES production function that combines individual commodities into a composite commodity. This provides limited flexibility for setting price elasticities for individual commodities with an additional parameter, the elasticity of substitution in the CES nest.

Let G represent "grains" as a first-stage composite of second-stage commodities wheat (w), rice (r), and maize (m). After taking partial derivatives and some algebra, own-price elasticities (5) and cross-price elasticities (6) were obtained:

$$\varepsilon_{ww} = \varepsilon_{GG}^{LES}\frac{s_w}{s_{wrm}} + \varepsilon_{ww}^{CES} = \left[-1 + \frac{(1-\beta_G)\gamma_G}{x_G}\right]\frac{s_w}{s_{wrm}} + \sigma\left(\frac{s_w}{s_{wrm}} - 1\right) \tag{5}$$

where σ is the elasticity of substitution in the CES nest and is always non-negative; s_r is the value share of rice in total expenditure; and s_{wrm} is the is the value share of wheat, rice, and maize combined.

$$\varepsilon_{wr} = \varepsilon_{GG}^{LES}\frac{s_r}{s_{wrm}} + \varepsilon_{wr}^{CES} = \left[-1 + \frac{(1-\beta_G)\gamma_G}{x_G}\right]\frac{s_r}{s_{wrm}} + \sigma\frac{s_r}{s_{wrm}} \tag{6}$$

The own-price elasticity of demand is always negative. The cross-price elasticity can be positive or negative, depending on model parameters and value shares.

First-stage commodity groups, which provide a way to group agricultural commodities, are shown as the final seven columns in table A.1. Each row of this table is assigned to one of the first-stage groups. Most of the commodities are food commodities: the exceptions are plant fibers, forestry, wool, and hay (included in "other crops"). However, all commodities in table A.1 influence the demand for land.

Table A.1

Agricultural production sectors and first-stage mapping for demand system

Group	Subgroup	Product	Grains	Veg. oils	Sugar	Veg. and fruit	Other crops	Animal products	Forest products
Primary agriculture	Crops	Wheat	X						
		Paddy rice	X						
		Other grains	X						
		Oilseeds		X					
		Sugar (cane and beet)			X				
		Vegetables and fruit				X			
		Plant fibers					X		
		Other crops					X		
	Fisheries	Fish						X	
	Forestry	Forestry							X
	Ruminant	Cattle and other ruminants						X	
		Raw milk						X	
		Wool						X	
	Non-ruminant	Other animal products						X	
Food processing		Vegetable oils		X					
		Processed rice	X						
		Sugar			X				
		Beverages and tobacco products					X		
		Other food					X		
		Meat from cattle and other ruminants						X	
		Dairy products						X	
		Other meat products						X	

Veg. = vegetables.

Source: USDA, Economic Research Service, based on Future Agricultural Resources Model.

Agricultural products are often consumed after processing into vegetable oils, sweeteners, dairy products, meat products, and other food products. Many of these products are not consumed directly at home but are purchased along with services as food away from home.

Relationship Between FAO Food Balance Sheets and Input-Output Tables

An understanding of the difference between final (food) calories available for consumption and primary (crop) calorie production is necessary to interpret the analysis that follows. Final calories are those that can be consumed as food, covering all food products. Primary (crop) calories are produced from the land before processing into animal products or other food products. Crop calories are greater than food calories, primarily due to losses as feed is converted to meat, dairy products, and eggs. Losses can also occur as crops are converted to nonanimal food products. At the country level, crop calories produced may be different than crop calories used due to international trade or changes in stocks.

Food Balance Sheets published by the Food and Agriculture Organization (FAO) of the United Nations are the primary data source for historical food consumption by food type and country. In each food balance sheet for each food commodity, domestic supply equals domestic use, measured in tons. Domestic supply is the quantity of food produced (PROD), plus imports (IMP), less exports (EXP), adjusted for change in crop storage (STOCK). Domestic use includes crops used for seed, animal feed, processed food, non-food uses, and waste during storage and transportation. The remainder is food available for consumption (FOOD), which is greater than food consumed due to waste at home or in restaurants. FAO food balance sheets do not provide estimates of food waste at home or in restaurants but do estimate waste during storage and transportation. Except for statistical error, domestic supply should equal domestic use in each country.

Table A.2 displays the first four commodities listed in an FAO food balance sheet from the United States in 2013. Large quantities of maize in the United States are used for animal feed and ethanol production. The core of a social accounting matrix is an input-output table for each country or world region. An input-output table is constructed from a "use table" and a "make table" in monetary units (Miller and Blair, 2009). The use table has commodities as rows and activities as columns and shows the monetary value for each input to a given production activity. A make table has activities as rows and commodities as columns and shows which commodities are produced by each production activity. If each activity produces only one commodity, then the make table is diagonal. A food balance sheet is essentially a "use table" in physical units instead of monetary units, with food commodities as rows and activities as columns.

Table A.2
Standard Food Balance Sheet structure (thousand metric tons), in the United States, 2013

	PROD	+ IMP	+ STOCK	- EXP	- FEED	- SEED	- WASTE	- PROC	- OTHER	= FOOD
Wheat	57,967	5,491	5,284	34,691	6,196	2,096	0	0	16	25,742
Rice	5,745	923	-27	3,522	0	109	200	464	142	2,203
Barley	4,683	864	16	696	1,440	107	0	3,161	0	160
Maize	353,699	3,595	-39,863	24,655	128,024	582	0	23,230	137,023	3,917

+ = plus. - = minus. PROD = production. IMP = imports. STOCK = change in crop storage. EXP = exports. WASTE = waste during storage and transportation. PROC = processing into other food products. OTHER = nonfood uses such as maize for ethanol. FOOD = food available for consumption.

Source: USDA, Economic Research Service using food balance sheets from the Food and Agriculture Organization of the United Nations.

Hybrid Units

The benchmark SAM for a CGE model is in monetary units, but monetary values might be inconsistent with quantity information obtained elsewhere. This problem has long been apparent in applications of CGE models to energy and climate policy, where monetary values of energy commodities were not consistent with energy balance tables from the International Energy Agency. The solution was to reconstruct the SAM so that energy commodities obey the law of one price (net of tax, transport, and distribution margins). If one knew the price of an energy commodity, in dollars per gigajoule, one could always back out its quantity from a monetary value. In the early 1990s, individual modeling teams devised their own solution for merging energy balances with input-output tables, but the GTAP group later provided a solution built directly into the GTAP data set. This type of SAM reconstruction is similar in concept to a hybrid input-output table, which has hybrid units of dollars and joules (Miller and Blair, 2009). The goal was to maintain energy conservation in the model, capturing direct energy consumption in a production process, as well as indirect energy consumption through other inputs.

The same challenge exists with respect to agricultural products. Ideally, the SAM would be reconstructed with physical units for agricultural products (metric tons), energy units for energy carriers (joules), and real U.S. dollars for all other commodities. Food balance sheets are used for agriculture in the same way that energy balance tables were used for energy. In principle, CGE models should be able to reproduce FAO food balance sheets since the full value chain is modeled.

Since food balance sheets use units of metric tons, that is a good choice for units of agricultural products in a hybrid input-output structure. One way to proceed is to replace agricultural rows in a country's input-output table with quantities from food balance sheets and recalculate the monetary values for each entry as if one price prevailed across all users of this agricultural commodity. However, some complications must be addressed: the price of imported goods may be very different from domestically produced goods; joint products (e.g., beef and dairy); maintaining plausible feed-to-meat conversion efficiencies; and the SAM must remain in monetary and physical balance.

Once food demand is known in tons, it can be divided by population and 365 to obtain grams per person per day. Food conversion tables can then be directly applied to obtain calories per person per day, grams of carbohydrates, protein, and fat, and milligrams of other nutrients.

Tracking Calories

To track calories in the FARM:

- Convert units for commodities in FAO food balances to calories;
- Aggregate 98 FAO food categories into 14 GTAP food categories;
- Replace monetary values with food quantities (calories) for each food commodity row in the benchmark SAM;
- Calculate the average price for each food commodity and multiply by quantity to derive new monetary values; and
- Rebalance SAM.[29]

[29] The rebalancing process is limited: payments to owners of capital are adjusted for each production process to maintain the same cost of production. This avoids any economy-wide statistical adjustment and maintains the original balance of the Global Trade Analysis Project (GTAP) social accounting matrix.

FAO food balance tables provide national food consumption levels in calories for 98 commodities. These were mapped to 14 GTAP food production sectors, which are the 14 rows in table A.3 with calories as units. Some of these are primary agricultural sectors, and some are secondary (food processing). FAO food balances also provide information on calories used as feed and as inputs to other production processes. Some calories end up as biofuels (e.g., corn to ethanol).

A hybrid input-output table is then constructed by replacing monetary values with calories in 14 rows of table A.3. All calorie accounting is done within these rows, either as an input to another production process or as consumer demand. To avoid double counting between primary agriculture and processed products, all calorie accounting occurs in these rows with calories as units. The input-output table is then rebalanced so that these 14 rows can be expressed either as monetary values or as calories. The hybrid input-output table becomes part of the benchmark SAM for each world region. Even though the SAM is entirely in monetary values, physical quantities (calories) that match FAO food balances can be recovered by applying prices. Some challenges remain, such as the energy content of hay or other forage crops has not been accounted for, and exports and imports may trade at prices that differ from domestic production.

Table A.3
Calorie map between production sectors

Subgroup	Symbol	Feed	VOL	PCR	SGR	B_T	CMT	MIL	OMT	LUM PPP	Other	Consumer demand
Crops	WHT	Cal.				Cal.						Cal.
	PDR	Cal.		Cal.								Cal.
	GRO	Cal.									Cal.	Cal.
	OSD	Cal.	Cal.								Cal.	Cal.
	C_B	Cal.			Cal.							(Cal.)
	V_F					Cal.						Cal.
	PFB											$
	OCR	$										$
Fisheries	FSH											Cal.
Forestry	FRS									$		–
Ruminant	CTL						Cal.					(Cal.)
	RMK							Cal.				(Cal.)
	WOL											$
Non-ruminant	OAP								Cal.			Cal.
Food processing	VOL											Cal.
	PCR											$
	SGR											Cal.
	B_T											Cal.
	CMT											$
	MIL											$
	OMT											Cal.
	OFD											$
Forest products	LUM											$
	PPP											$

Cal. = calories. $ = U.S. dollars.

Primary agriculture: WHT = wheat. PDR = rice. GRO = other grains. OSD = oilseeds. C_B = cane and beet sugar. V_F = vegetables and fruit. PFB = plant-based fibers. FSH = fish. FRS = forestry. CTL = cattle. RMK = raw milk. WOL = wool. OAP = other animal products.

Processed agricultural products: VOL = vegetable oils. PCR = processed rice. SGR = sugar. B_T = beverages and tobacco. CMT = cattle meat. MIL = milk. OMT = other meat. OFD = other food. Lumber (LUM) and pulp and paper (PPP) are included because they influence the demand for land and the amount of land available for crops.

Note: Primary agricultural products (the first 14 rows) provide inputs to food processing activities (columns). For example, oilseeds are inputs to vegetable oils; cane sugar is an input to processed sugar. To avoid double counting between primary agriculture and processed products, all calorie accounting occurs in the 14 rows with calories as units.

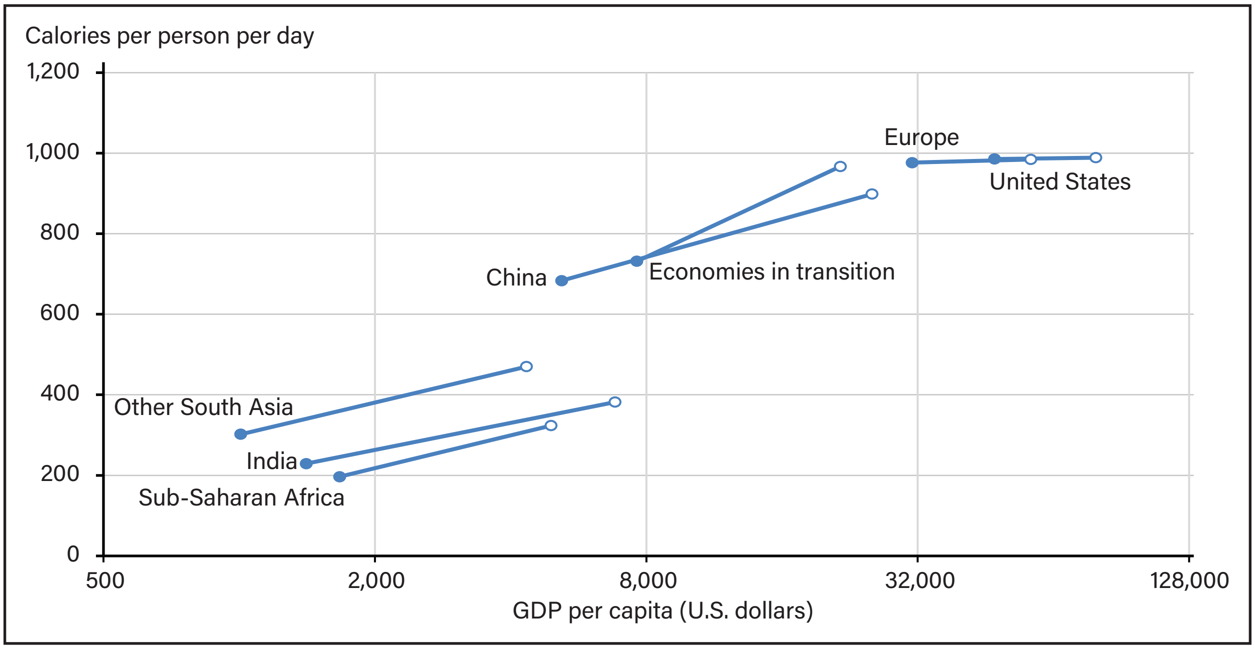
Source: USDA, Economic Research Service using data from the Future Agricultural Resources Model and food balance sheets from the Food and Agriculture Organization of the United Nations.

Calibration of Income Response

To keep future per capita calorie consumption within reasonable bounds, authors relied on Alexandratos and Bruinsma (2012) for projections to 2050. Combined with income projections from the Shared Socioeconomic Pathways (Dellink et al., 2017), beginning and ending combinations of income and calorie consumption for each world region in FARM can be plotted. This plot is shown in figure A.1 for animal products. From this, a long-run income elasticity for animal products (or any other food category) can be calculated for each region.

The slopes of the line segments in figure A.1 correspond to average income elasticities. At higher income levels, as in Europe or the United States, the income elasticity for calories of animal products approaches zero (i.e., the line segments for Europe and the United States are nearly flat).

Figure A.1
Long-run income response of animal product consumption to per capita income



GDP = Gross Domestic Product.

Note: The left endpoint of each line segment represents 2011; the right endpoint represents 2050.

Source: USDA, Economic Research Service using data from the Future Agricultural Resources Model.

To provide a plausible transition of food consumption to 2050, especially with rapidly growing per capita incomes, income and price elasticities decline over time. This implies that underlying β and γ parameters must also change over time.

For calibration of an income response, the most important elasticity is the first stage (LES) income elasticity. The LES does not have the flexibility to calibrate income and price elasticities independently; once income elasticities are set, price elasticities are pre-determined. The following equation can be derived from (1) and (2) and is useful for calibrating LES demand to beginning and ending income elasticities.

$$\frac{\gamma_i}{x_i} = 1 - \varepsilon_{im} \frac{sup}{m} \qquad (7)$$

where "supernumerary income" is defined as

$$sup = m - \sum_k p_k \gamma_k \qquad (8)$$

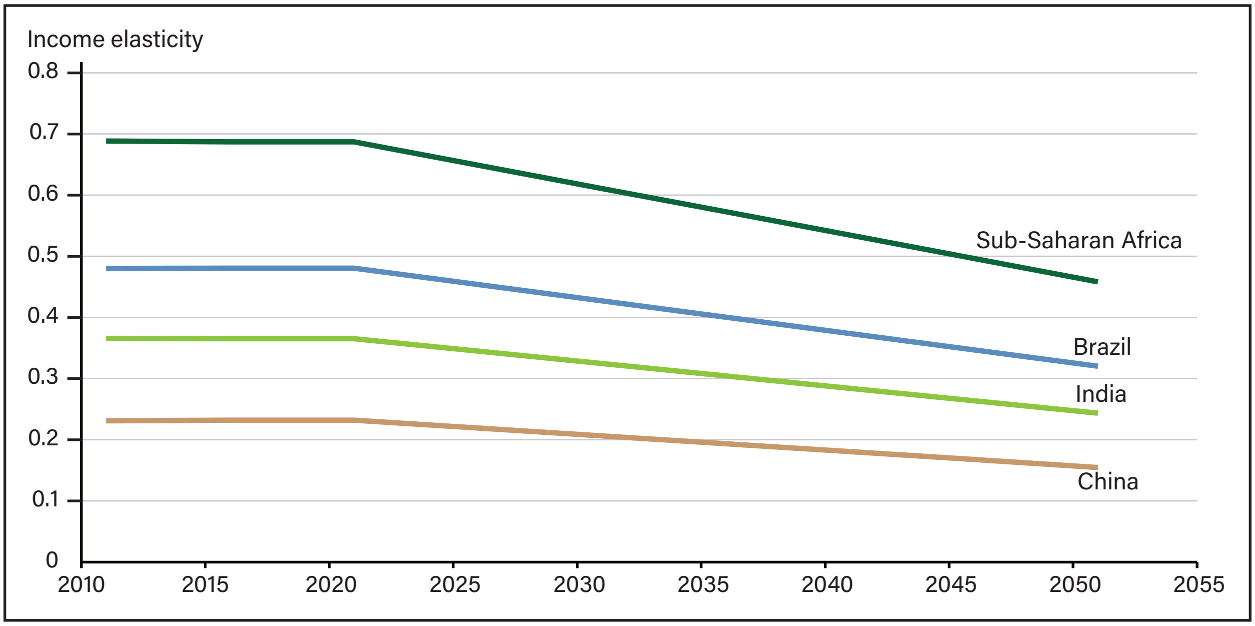
This provides guidance for setting the base-year ratio γ_i / x_i. Since *sup* is a function of γ_i, equation (7) is solved iteratively for base-year γ_i, updating *sup* during each iteration using model output. For any given income elasticity, parameter γ_i can be used to calibrate the beginning income response.

A similar process is used to calibrate the model to a target end-year income elasticity. Depending on the diet scenario, the per capita growth of x_i is specified in advance so the ending x_i is known. Ratio *sup/m* can be approximated using output from previous model runs, providing enough information to iteratively solve for end-year γ_i. The β_i are calculated using equation (2).[30]

End-year (2050) income elasticities for animal products are calculated from data in figure A.1. This ensures calibration to FAO projections of food consumption in 2050. The ratio of 2020 income elasticities to 2050 income elasticities is arbitrarily set to 1.5, which can be seen in the calibrated elasticities in figure A.2. This ratio of income elasticities does not affect model output in 2050 but does affect the time path from 2020 to 2050.

Figure A.2

Calibrated income elasticities for animal products in selected regions in the FARM, 2011–50



Note: Elasticities in developing countries fall over time as income increases, beginning in the third model time step (2021).

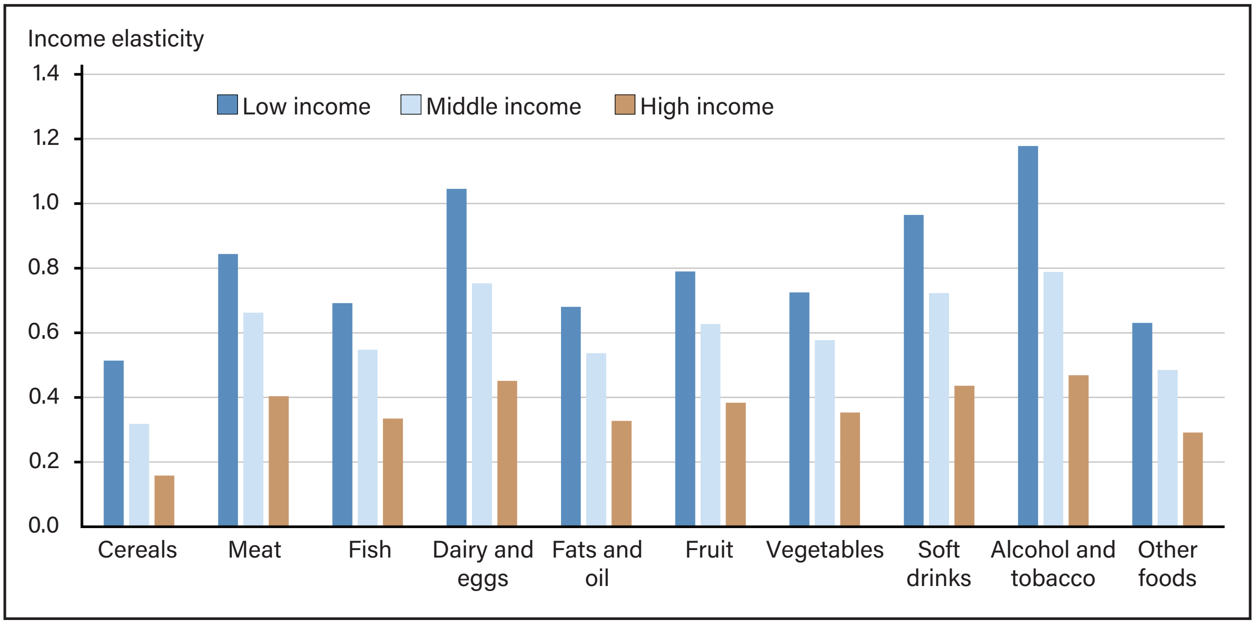
Source: USDA, Economic Research Service using data from the Future Agricultural Resources Model.

A point of comparison is a set of income elasticities estimated from 2011 ICP data (figure A.3), with economies grouped into low, medium, and high income. These elasticities are for 2011 only and roughly correspond to beginning elasticities in the FARM. The pattern of higher income elasticities in low-income economies is consistent across all the food categories. Overall, the base-year income elasticities in the FARM are lower than the 2011 ICP estimates. In particular, the high-income elasticity for animal products in figure A.3 does not reflect saturation in wealthy economies such as the United States or Europe. This is due in part to the wide range of economies considered high income: all economies with per capita income greater than 45 percent of the United States. The United States and Europe are at the high end of this range.

[30] When elasticities approach zero, the demand system approaches Leontief (fixed coefficient), which is a special case of the Linear Expenditure System. The share of supernumerary income goes to zero, and commodity demand equals the subsistence quantity. A feature of computable general equilibrium models is that demand systems satisfy curvature conditions globally, which restricts the functional forms available. Empirical work generally uses more flexible functional forms, which creates a challenge to compare parameters between functional forms.

Figure A.3

Income elasticities for food subgroups, 2011 International Comparison Program



Note: Low-income economies are defined as having per capita incomes less than 15 percent of the per capita income in the United States. Middle-income economies are those with incomes between 15 and 45 percent, and high-income economies are those with greater than 45 percent of U.S. per capita income.

Source: USDA, Economic Research Service calculations based on International Comparison Program 2011.

It would be convenient to simply substitute income elasticities derived from ICP data into the FARM model. This approach could be useful for short-time horizons but can generate implausibly high levels of per capita calorie consumption in simulations to 2050. For example, if per capita income increases by 200 percent in China (figure 7), and an income elasticity of 0.6 (from figure A.3) is applied to animal products, then animal product consumption would be expected to grow by 120 percent from 750 to 1,650 calories per person per day (compared to figure 1). This is about 50 percent greater than U.S. daily animal product consumption in 2019.

CGE Framework

New tools and data have become available since the first version of the FARM was constructed, most notably the GTAP dataset (Hertel, 1997) and tools for using GTAP data in the General Algebraic Modeling System (GAMS) programming language (Lanz and Rutherford, 2016). Therefore, the development of the new FARM model did not start from scratch; the starting point was code in GAMS provided by Lanz and Rutherford (2016). This software provides a comparative static global CGE model fully compatible with GTAP 8 social accounts and bilateral trade between world regions. The software also provides utilities for converting GTAP data into the GAMS programming environment.

The FARM has been extended in many ways beyond the model in Lanz and Rutherford (2016):

- Converted from a comparative-static to a recursive-dynamic framework with 5-year time steps;
- Converted the consumer demand system from constant-elasticity-of-substitution to the Linear Expenditure System;
- Allowed for joint products in production functions;

- Introduced land classes for agricultural and forestry production; and,
- Introduced electricity generating technologies.

The FARM is solved using the PATH solver in GAMS, with each model equation paired with a model variable. Most model equations are one of three types: market clearing, zero-profit (efficiency) conditions, and income balance. Market-clearing equations are paired with market prices, zero-profit conditions are paired with production quantities, and income balance equations are paired with expenditure by a representative agent (table A.4).

Table A.4
Matched variables and equations in the Future Agricultural Resources Model

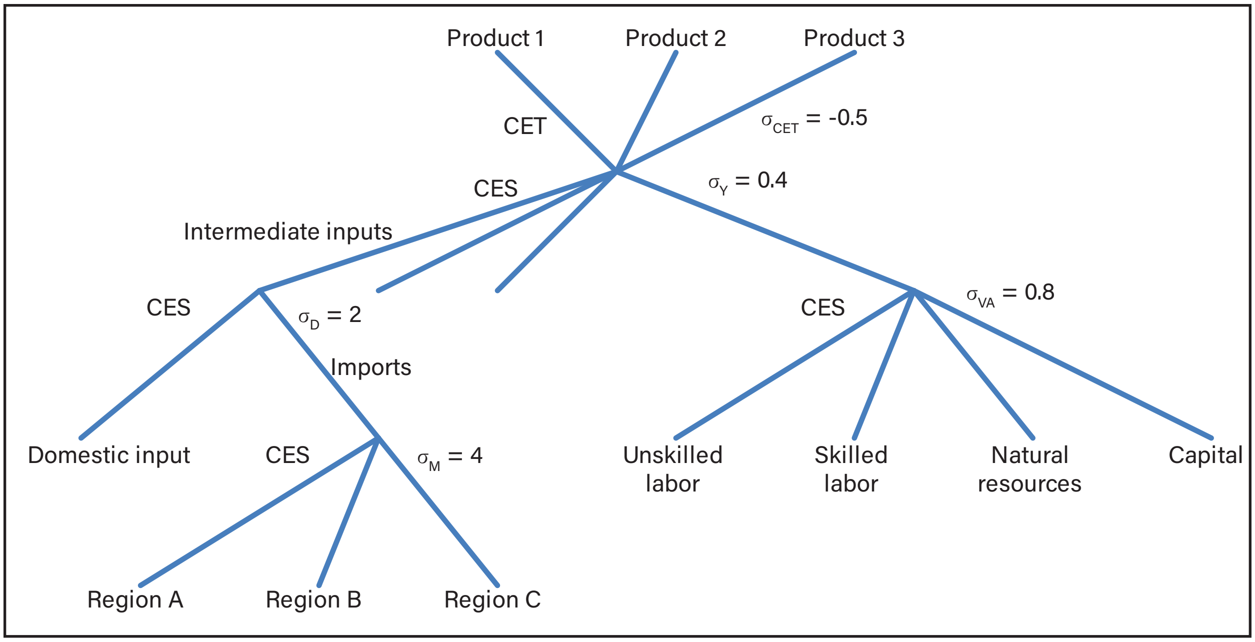
Variables (unknowns)	Equations
Prices of produced commodities (by region of production)	Market clearing (domestic supply equals domestic demand plus foreign demand)
Rentals of primary factors (capital, labor, natural resources) in each region	Market clearing
Land rents by land class (in each region)	Market clearing
Scale of production (by region and commodity)	Zero-profit conditions (price received equals total cost of production)
Expenditure of representative agent (in each region)	Income balance

Source: USDA, Economic Research Service based on the Future Agricultural Resources Model.

Production

Each production sector is modeled as a nested CES production function as shown in figure A.4. The top CES nest is an aggregate of intermediate inputs and nested value added. Each intermediate input is distinguished by source—from domestic production or imports from other world regions.

Figure A.4
Generic production structure in the Future Agricultural Resources Model



CES = constant elasticity of substitution. CET = constant elasticity of transformation.

Note: Authors adopted the GTAP convention for Armington trade elasticities that σ_M is twice σ_D (Hertel and van der Mensbrugghe, 2019). Instead of allowing these elasticities to vary by commodity, they are kept constant at σ_M = 4 and σ_D = 2. This is within the range of GTAP elasticities and those in Ahmed et al. (2021).

Source: USDA, Economic Research Service based on the Future Agricultural Resources Model.

Output from each production activity passes through a constant-elasticity-of-transformation (CET) function before it can be consumed or exported. A CET function has the same functional form as a CES production or cost function but with an elasticity less than or equal to zero. Most production activities have only one product, but there are exceptions such as oil and natural gas as joint products from a single production activity. More complex production structures can be created by combining two or more generic production structures connected by an intermediate product.

Technical Change

The authors used technical change parameters to construct a plausible global reference scenario for energy, agriculture, and land use through 2050. All technical change parameters were input specific and are considered as input augmenting. For example, labor productivity parameters were used to produce GDP pathways for each region that closely approximate target pathways from Shared Socioeconomic Pathways (SSPs). These parameters vary over four dimensions: model time step, input to production, production sector, and world region. Productivity improvements are reflected in input-output ratios that decline over time.

The efficiency of energy use by production sector is set exogenously to provide plausible scenarios of energy consumption by energy carrier: coal, refined petroleum, natural gas, and electricity. Capital-augmenting technical change is set to zero for all production sectors and regions, with two exceptions: electricity from wind and electricity from solar. Technical change is captured through all inputs other than capital.

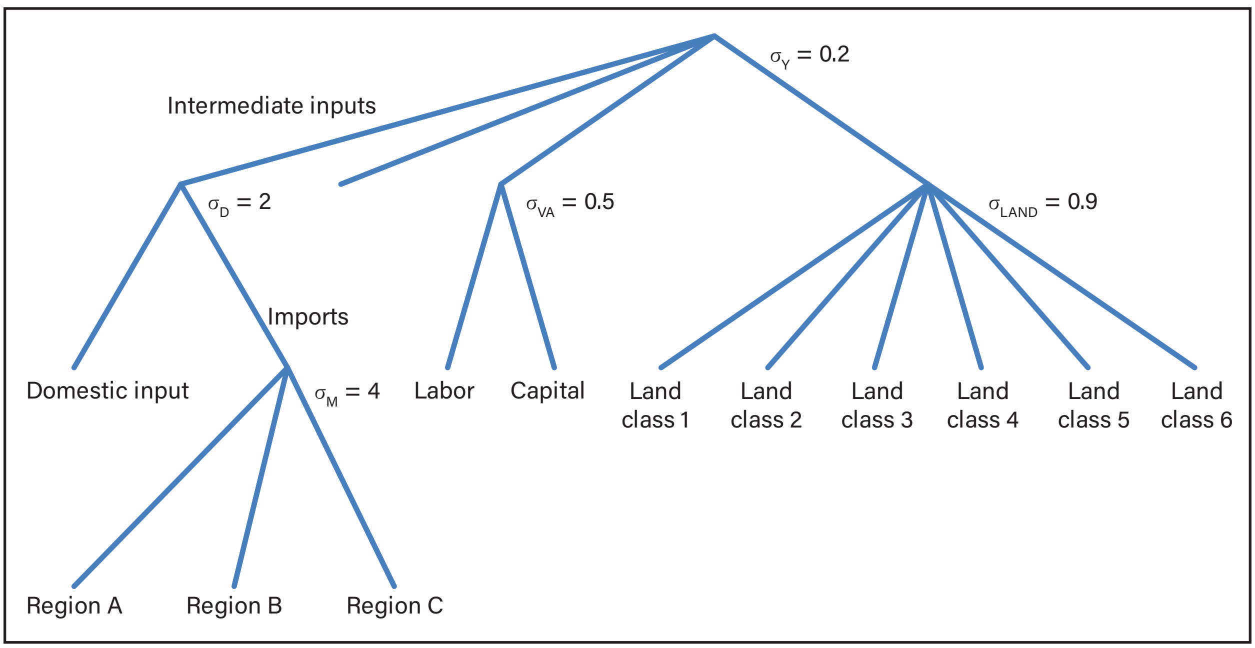
Each land-using production function (e.g., wheat, rice, coarse grains) has a technical coefficient associated with land that varies over time. Crop yield is also influenced in FARM by changes in prices of agricultural products and the substitution of nonland inputs for land. Therefore, simulated crop yield in the FARM is a combination of exogenous technical change and price-induced effects.

Land as an Input to Production

Land use can shift among crops, pasture, and managed forests in response to population growth and changes in income, with behavioral responses determined by price and income elasticities. The GTAP 9 database distributed by Purdue University includes supplemental data on physical quantities from FAO. The base year is 2011, and the GTAP dataset includes a global social accounting matrix with economic values, land cover for aggregate land types, harvested area for eight crop types, and production quantities for five types of field crops. Further, the GTAP dataset provides land use by 18 agro-ecological zones (AEZs). See Monfreda et al. (2009) for background on the construction of AEZs for GTAP. Lee et al. (2009) provided a description of the land-use database provided by GTAP. FARM operates with up to 18 land classes in each region, which correspond to 18 AEZs provided in GTAP land-use data.

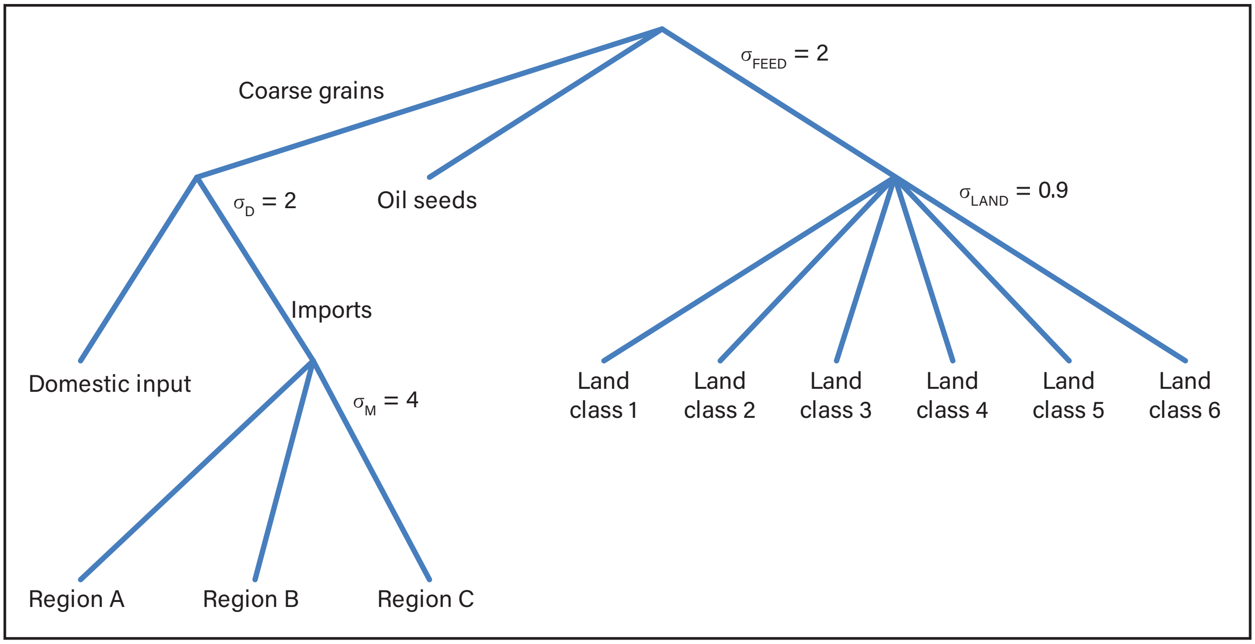
The FARM production structure with land as an input is shown in figure A.5. Each land class allocates land to 1 of 11 land-using production sectors: 5 field crops, 1 energy crop, 3 other crop types, pasture for ruminant animals, and managed forests. Within each land-using production sector, land from land classes is combined into a land aggregate in a CES nest. Other nesting structures bring intermediate inputs and value added into the production function. Input groups compete within the top-level CES nest. The nesting structure for animal feed is shown in figure A.6, which is a special case of figure A.5. Feed for ruminant animals is a combination of pasture and crops.

Figure A.5
Production structure for crops and forestry



Source: USDA, Economic Research Service based on the Future Agricultural Resources Model.

Figure A.6
Feed production structure for ruminant animals



Source: USDA, Economic Research Service based on the Future Agricultural Resources Model.

Hertel et al. (2009a) provided a discussion of land use in CGE models using GTAP data. The most common approach is to allocate total land in each land class to its uses using a CET function. The main drawback of this approach is that land quantities are not preserved: the quantity of land going into a CET nest does not equal the sum of land quantities allocated to production sectors. Land values are preserved, but not land quantities.

This presents a dilemma for CGE modelers, especially for analysis where land use is an important output. For example, carbon emissions from land-use change are an important component of global greenhouse gas emissions. In the FARM model, authors considered each land class a primary factor of production with a market clearing condition. Market clearing assures that land quantities are preserved. Each land class has its own land market, where the rental per hectare of land within each class is the same regardless of land use. This condition was imposed on the data when calibrating to benchmark data in the base year.

The assumption of equal land rents can be justified by the land allocation theory in Sands and Leimbach (2003). This has been used successfully in a partial equilibrium framework where the yield for each land use, within a land class, is described by a joint probability distribution and includes a correlation coefficient for yield between land uses. If the land use with the highest profit rate is always selected, then the share of land allocated to each land use can be calculated. The average land rent is the same across land uses within a land class, regardless of the share of land going to each land use.

Hertel et al. (2009b) stated the conditions where a single crop production function with land inputs from several land classes is equivalent to having a production function for each crop × land class combination. One of the conditions is that land rents for a given crop are proportional to yield across land classes. This follows from the price received per unit of output is the same regardless of land class; and the cost per unit of output for non-land inputs is the same regardless of land class. Then the expenditure on land per unit of output is the same across land classes. If land rents are proportional to yield, then low yields are offset by low land rents, and high yields are matched with high land rents.

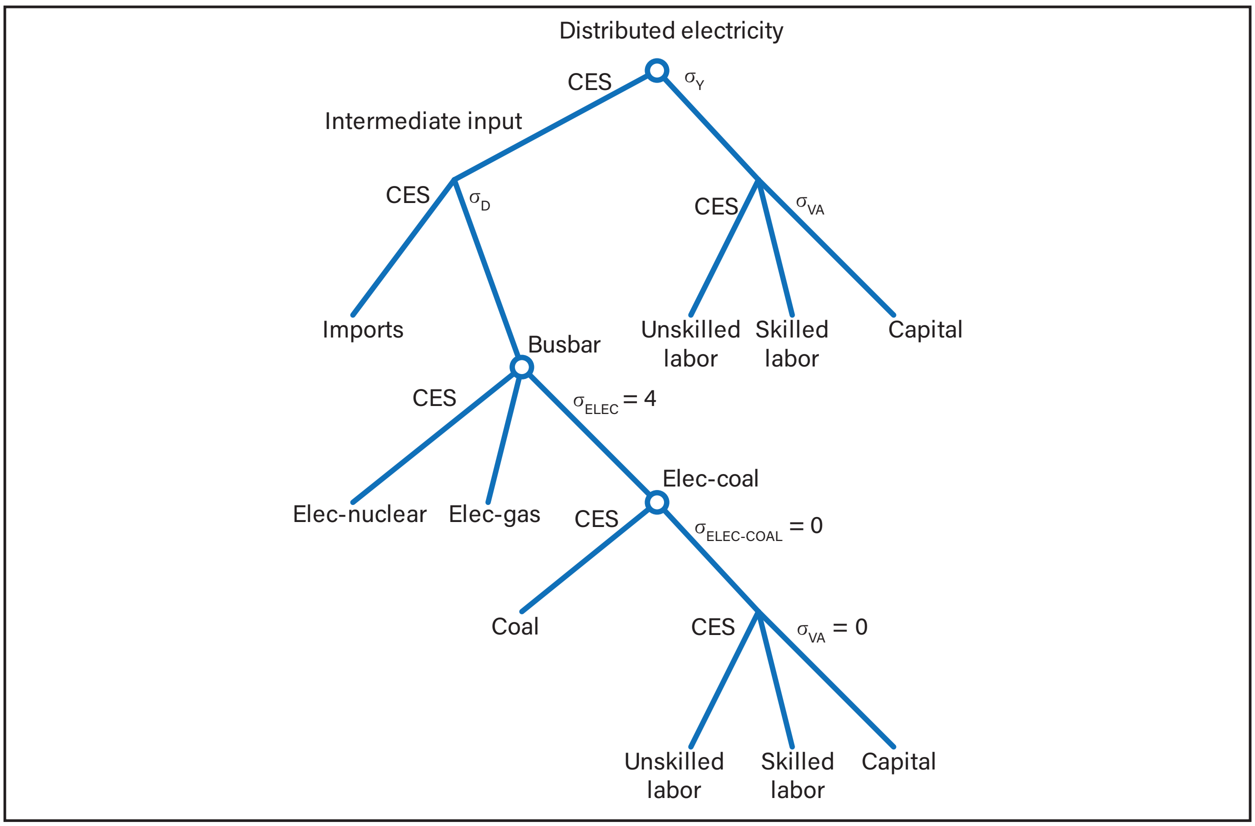
In summary, two efficiency conditions were imposed algebraically on the input dataset. The first is that average land rents within a land class are equal across land uses. The second is that land rents across land classes for a given land use are proportional to yield.

For CGE models that use the GTAP data set, land use by agro-ecological zone (AEZ) is common. Going to smaller geographical units is not easy but is done in partial equilibrium models such as the Global Change Analysis Model (GCAM) and the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). This is an area where CGE models can be improved, perhaps using data collected by partial equilibrium modeling teams. The GCAM and IMPACT models use watersheds for geographical units, which can be scaled to any desired level of detail.

Electricity Generation

Electricity generation is a good example of combining generic production structures, where outputs of each generating technology are combined into a CES nest (figure A.7). Each electricity generation technology is a fixed-coefficient nest of fuel, other intermediate inputs, and value added. The electricity generated by each technology is consumed by a "busbar" technology, which is simply a CES nest that combines output from all electricity generating technologies. All output from "busbar" is consumed as an intermediate product to "distributed electricity" with the capital and labor needed to transmit electricity from the generating plant to industrial, commercial, and residential customers. The electricity structure in figure A.7 combines three production activities, where each activity is a special case of the generic production structure of figure A.4.

Figure A.7
Electricity generation and distribution in Future Agricultural Resources Model



CES = constant elasticity of substitution.

Source: USDA, Economic Research Service based on the Future Agricultural Resources Model.

Appendix B: Marginal Expenditure Shares

Figures 4 and 5 provide marginal expenditure shares for broad categories of consumer expenditure and food products, respectively. If expenditure shares for good *i* are given by

$$w_i = \frac{E_i}{E} = \alpha_i + \beta_i lnE + \varepsilon_i \quad (1)$$

$$\sum_i \alpha_i = 1 \quad (2)$$

$$\sum_i \beta_i = 0 \quad (3)$$

where E_i is expenditure on good i, E is total expenditure, α_i and β_i are parameters to be estimated, and ε_i is a residual.

Then marginal expenditure shares are calculated as

$$\frac{dE_i}{dE} = w_i + \beta_i \quad (4)$$

Note that expenditure shares and marginal shares sum to 1. This is a simplified version of the consumer demand model in Muhammad et al. (2011), including only the income term and excluding price terms.