Global Drivers of Agricultural Supply and Demand

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Abstract

Recent volatility in agricultural commodity prices and projections of world population growth raise concerns about the ability of global agricultural production to meet future demand. This report explores the potential for future agricultural production to 2050, using a model-based analysis that incorporates the key drivers of agricultural production, along with the responses of producers and consumers to changes to those drivers. Model results show that for a percentage change in population, global production and consumption of major field crops respond at nearly the same rate. In response to a change in per capita income, the percentage change in crop consumption is much lower, about one-third the percentage change in income. The model also suggests that the global economy absorbs changes in agricultural productivity growth through compensating responses in yield, cropland area, crop prices, and international trade.

Keywords

Agricultural productivity, food demand, population growth, income growth, land use

Acknowledgments

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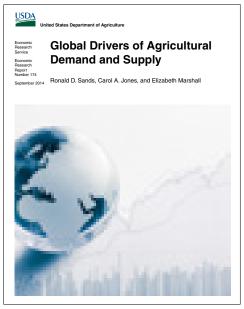
A report summary from the Economic Research Service September 2014



Find the full report at *www.ers.usda.gov/publications/err-economic-research-report/err174*

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What Is the Issue?

Recent volatility in agricultural commodity prices, coupled with projections of world population growth, raise concerns about the ability of global agricultural production to meet future demand. A number of factors are likely to affect the potential for future agricultural production. These include demand drivers such as changes in population and per capita income, as well as supply drivers such as changes in agricultural productivity. The world's population is projected to grow from 7 billion to approximately 9 billion by 2050, and per capita income is projected to grow in nearly all the world's regions. Agricultural productivity has improved rapidly in recent decades, but prospects for future growth are uncertain, especially in light of climate change. ERS examines hypothetical economic and agricultural effects of potential changes in agricultural productivity, population, and per capita income by 2050. These supply-and-demand drivers will determine not only what farmers will produce in the future, where they will produce it, and how affordable it will be, but also how much land and other scarce resources the sector will use.

What Did the Study Find?

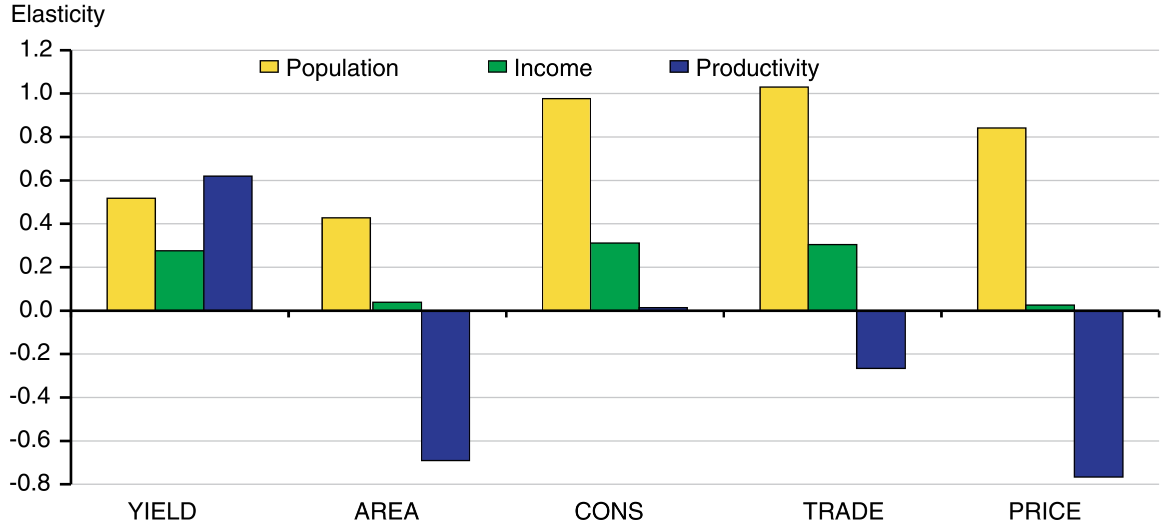
- *Effects of a change in population*. For a 10-percent increase in global population, total crop consumption and production is projected to respond at nearly the same rate. Crop yield, however, increases by only 5 percent for this increase in population, even as increased demand for agricultural commodities pushes prices higher and encourages producers to use more yield-enhancing inputs. Crop area also responds to higher crop prices in this population scenario, with an expected increase in area of 4 percent.

- *Effects of a change in per capita income*. For a 10-percent increase in global per capita income, consumption and production of major crops is projected to increase by approximately 3 percent. Crop yield increases by 3 percent in this scenario, and cropland area increases by less than 1 percent.

- *Effects of a change in agricultural productivity*. A negative shock to global agricultural productivity could come about through a decrease in investments in agricultural research and development over time or through other economic or environmental factors such as climate change. This study did not simulate climate change, but it did consider a 20-percent decline in global productivity by 2050 for major field crops. The primary adjustments to the

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

Elasticities of economic responses to three key drivers



An elasticity is the ratio of percent changes: the percent change in an economic response (e.g., consumption) for each percent change in a driver (e.g., income). When population or income is the driver, economic responses move in the same direction. Yield moves in the same direction as productivity, while cropland area and price move in the opposite direction of productivity. YIELD = average yield of major field crops in tons per hectare. AREA = global area of major field crops. CONS = global consumption = global production. TRADE = global exports = global imports. PRICE = price index of major field crops: wheat, rice, coarse grains, oil seeds, and sugar.

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

change in productivity are in crop yield and cropland area. Through increased use of nonland inputs such as fertilizer and capital equipment, the realized decline in crop yield of 12 percent is less than the initial decline in productivity. To further compensate for the effects of the shock, land area supplied for field crops is projected to increase by 14 percent. At a global level, crop consumption and production are equal, and both decline slightly. World trade volume increases as crop production shifts among world regions. Average prices for field crops increase by 15 percent in this scenario, providing incentives to expand land area and increase use of nonland inputs in agricultural production.

For all scenarios, the percentage change in crop production is approximately the sum of percentage changes in yield and cropland area.

How Was the Study Conducted?

This study was conducted in parallel with a global economic analysis of potential climate impacts organized by the Agricultural Model Intercomparison and Improvement Project (AgMIP). The Future Agricultural Resources Model (FARM) used in this study is 1 of 10 participating models that incorporate global coverage of major field crops and other crop types. FARM is an economic model that simulates agricultural and energy systems for 13 world regions through 2050. Primary data sources include the United Nations (population projections), the Food and Agriculture Organization of the United Nations (agricultural production), the International Energy Agency (energy balances), and the Global Trade Analysis Project at Purdue University (social accounts).

A global reference scenario through year 2050 was constructed using medium-fertility population projections, moderate income growth, and crop productivity data (assuming no climate change impacts) provided by AgMIP to each modeling team. Model output includes consumption and production of agricultural commodities, yield and world prices of major field crops, and land use by crop type. To isolate the sensitivity of model variables to key drivers, a number of additional scenarios were constructed that varied the values of individual drivers one at a time, relative to the reference scenario: low- and high-population scenarios; a low-income scenario; and two low-productivity scenarios.

Global Drivers of Agricultural Demand and Supply

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Introduction

Recent volatility in prices of agricultural commodities and projections of world population growth raise concerns about the ability of global agricultural production to meet future demand. The world's population is projected to grow by approximately 2 billion by 2050. Per capita incomes are projected to grow in nearly all world regions over the same period. Agricultural productivity has improved rapidly in past decades, but prospects for future growth are uncertain, especially in light of climate change. How would the change in population affect the demand for major field crops? How would the increase in per capita incomes affect per capita consumption of crops? How would the global economy absorb a negative shock to agricultural productivity? How sensitive are crop prices to projected changes in population, income, and agricultural productivity?

To help answer these questions, this study uses the Future Agricultural Resources Model (FARM) to simulate agricultural demand, supply, and land use for 13 world regions from 2005 through 2050 (see box "The Future Agricultural Resources Model"). First, researchers construct a global reference scenario through year 2050 using projections on population growth, income growth, and agricultural productivity. This reference scenario represents one potential snapshot of the future, based on a set of moderate but uncertain projections of population, income, and agricultural productivity growth rates. The reference scenario then provides a point of departure for analyses exploring the responsiveness of model outputs to changes in these key drivers of supply and demand varied one at a time. Within each world region, land is allocated to crops, pasture, or forest based on economic returns per hectare of land (1 hectare = 2.47 acres). In each scenario, demand for agricultural products is driven primarily by population and income. Prices of field crops and processed agricultural products adjust to bring agricultural markets into equilibrium.

The Future Agricultural Resources Model

The Future Agricultural Resources Model (FARM) is a global economic model with 13 world regions and operates from 2004 to 2054 in 5-year steps. Model output is usually interpolated to report results in more convenient years, such as 2030 or 2050. Land use can shift among crops, pasture, and forests in response to population growth, changes in agricultural productivity, and environmental policies, such as efforts to mitigate climate change.

The first version of FARM was constructed in the early 1990s by Roy Darwin and others at USDA's Economic Research Service (Darwin et al., 1995). Early versions of the model were used to simulate the impact of a changed climate on global land use, agricultural production, and international trade. Recent versions of FARM add a time dimension to assess alternative climate policies, track energy consumption and greenhouse gas emissions, and provide a balanced representation of world energy and agricultural systems. FARM model development has benefited from participation in the Agricultural Model Intercomparison and Improvement Project (AgMIP) and the Stanford Energy Modeling Forum (EMF). Research in this report uses consensus scenarios from the AgMIP project.

The FARM base year is 2004, which is the base year of a global economic data set distributed by the Global Trade Analysis Project (GTAP) at Purdue University. ERS uses social accounts in GTAP version 7 as the primary economic framework. GTAP 7 provides social accounting matrices for 112 world regions and 57 production sectors. These data are then aggregated to 13 world regions and 38 production sectors for this study. The 38 production sectors retain all GTAP information related to primary agriculture, food processing, energy transformation, energy-intensive industries, and transportation. Participation in AgMIP requires substantial expansion of the agricultural component of FARM.

One of the most important features of FARM is the land-allocation mechanism. For each world region, land competition takes place within agro-ecological zones (AEZs) that differ by growing period and climatic zone. Land is allocated to crops, pasture, and managed forest through a land market in each AEZ.

Economic Framework and Study Design

Table 1 provides a summary of supply-and-demand drivers examined in this study.

Two other important drivers are not covered in this report, but results using the FARM model are published elsewhere:

- Climate and energy policy (demand side). Examples of the *policy dimension* include greenhouse gas cap-and-trade and renewable portfolio standards (Sands et al., 2014a; Sands et al., 2014b). Bioenergy links the energy and agricultural systems, increasing demand for cropland or forest land.

- Climate change (supply side). Agricultural productivity changes over time, due to changing temperature, precipitation, and humidity. Climate impacts vary by world region and crop type. The AgMIP global economic study provides simulations to 2050 driven by several climate and crop process models (Nelson et al., 2014a; Nelson et al., 2014b).

Population over the model time horizon is entered directly into FARM as an exogenous input.[1] Income growth is entered indirectly, by adjusting labor productivity in each world region to approximate income projections from another source.[2] Each production sector in FARM has a set of productivity parameters that can be set directly as annual rates of productivity change. Economic impacts of climate change can also be modeled as changes in productivity parameters for crops, informed by projections from climate models and crop growth models.

FARM includes markets for agricultural products and land to calculate key outputs (see table 2). Because of interactions between markets, most of these output variables are calculated simultaneously.[3]

Table 1

Summary of drivers of agricultural supply and demand in this report

Population (demand side)	Low, medium, and high population projections through 2050.
Income (demand side)	Income growth that contributes to increasing per capita consumption of food over time. Shift in diet toward processed foods and meat.
Agricultural productivity (supply side)	The *technology dimension* as a driver of agricultural production and land use, allowing crop yields to vary, holding agricultural resource use constant.

[1]An exogenous model input or parameter is determined outside the model, and the model has no influence over this input or parameter.

[2] It is common for general equilibrium models to use labor productivity as a parameter to align the path of Gross Domestic Product (GDP) with projections derived from other sources. In FARM, we adjust labor productivity for all production sectors at the same rate within each world region. Here, we align GDP for each world region in FARM with projections from the Shared Socioeconomic Pathways (O'Neill et al., 2014).

[3] See appendix A for more information on FARM.

Table 2

Selected outputs of the Future Agricultural Resources Model

Crop prices (world market price)	Prices are calculated within the economic model to bring world demand and supply into equilibrium for each traded agricultural product.
Crop production (by world region)	Production increases along with world price.
Crop consumption (by world region)	Consumption increases as per capita income increases.
International trade in agricultural products (between world regions)	Trade is calculated as the difference in production and consumption of agricultural products in each world region.
Crop yield (by world region)	Yield depends on assumptions about agricultural productivity and the ability to substitute other inputs (such as fertilizer) for land.
Land used for each agricultural product in each world region	Land is allocated to alternative uses in each land class until rates of return are equalized.

The effect of an increase in population is to increase demand, which raises prices. Producers will respond to higher prices by increasing production, using some combination of increasing cropland and increasing inputs per unit of land. Individual consumers respond to higher prices by shifting consumption to less expensive food types, and, possibly, reducing consumption. Global shifts in trade reflect patterns of consumption that diverge from patterns of production.

Model results depend on model structure and selection of behavioral parameters, such as price and income elasticities of demand; the tradeoff among inputs to agricultural production; and the ability of land to be transformed between various crops, pasture, and forest (see table 3).[4]

The world reference scenario simulated through 2050 for this analysis accounts for projections of population, per capita income, and agricultural productivity. Population projections are from the United Nations medium-fertility scenario (United Nations, 2011). Income projections by world region are from socioeconomic scenarios recently prepared for modeling the impacts of climate change by the international modeling community (O'Neill et al., 2014). In the reference scenario, per capita income grows rapidly in regions such as China, India, and Sub-Saharan Africa. Changes in land productivity through 2050 are provided by the International Food Policy Research Institute (IFPRI).

To determine the responsiveness of model outputs to changes in population, income, and growth in agricultural productivity, inputs are varied one at a time (see table 4). Shaded cells in the table represent deviations from the reference scenario.

World population in the reference scenario grows from nearly 7 billion people in 2004 to approximately 9 billion people in 2050. The low-income scenario represents a 29-percent decline in world average per capita income from the reference scenario in 2050. The reference scenario provides a view of drivers of supply and demand changing over time. Given the uncertainty of these drivers, other scenarios examine alternative specifications and variations in results across scenarios in 2050.

[4] An elasticity is the percentage change in one variable in response to the percentage change in another variable or parameter. For example, the income elasticity of demand is the percentage change in a consumed product in response to a percentage change in income.

Table 3

Behavioral parameters in the Future Agricultural Resources Model

Price elasticity of demand for agricultural products	Rate at which food consumption declines as price increases.
Income elasticity of demand for agricultural products	Rate at which food consumption increases as income increases.
Elasticity of substitution among inputs to production	Tradeoffs among inputs to production such as capital, labor, land, fertilizer, and energy.

Table 4

Overview of scenarios designed to capture economic responses to changes in key drivers: population, per capita income, and agricultural productivity

Chapter	Scenario	Population	Income	Productivity
Agriculture to 2050: A Reference Scenario	Reference	UN-medium	Reference growth	Optimistic
Population	Low population	UN-low	Reference growth	Optimistic
Population	High population	UN-high	Reference growth	Optimistic
Income and Food Conumption Per Person	Low income	UN-medium	Low growth	Optimistic
Agricultural Productivity	Low productivity	UN-medium	Reference growth	20-percent reduction by 2050
Agricultural Productivity	Very low productivity	UN-medium	Reference growth	40-percent reduction by 2050

Note: Scenarios are designed to modify one driver at a time, indicated by the shaded cells. UN=United Nations.

Data Overview

Data for the FARM model base year are primarily from the GTAP version 7 data set. This includes input-output tables and other social accounts measured in U.S. dollars, as well as data on crop production (metric tons) and land use (hectares). These data were aggregated from 112 world regions in the GTAP 7 database to 13 world regions (see table 5).

Figure 1 provides a snapshot of production and consumption across 13 FARM regions for 5 major field crops in the base year, 2004. Production for each field crop is measured in tons, and the aggregate measure is the sum across these five crop types. Production and consumption are equal at the global level but vary across regions. Canada, the United States, Brazil, Australia, and New Zealand are net exporters of field crops; India is mostly self-sufficient with little net trade; and the largest importing regions are Middle East and North Africa, and Southeast and East Asia.

The world's 13 billion hectares of land cannot be easily partitioned into categories such as agriculture, forest, pasture, and other uses. For example, some forested land is also used for grazing. Figure 2 provides an overall picture of global land use in seven land-use categories provided by GTAP. India is unique for having a high share of total land as cropland. Built-up land is a small share of total land use across all regions.[5]

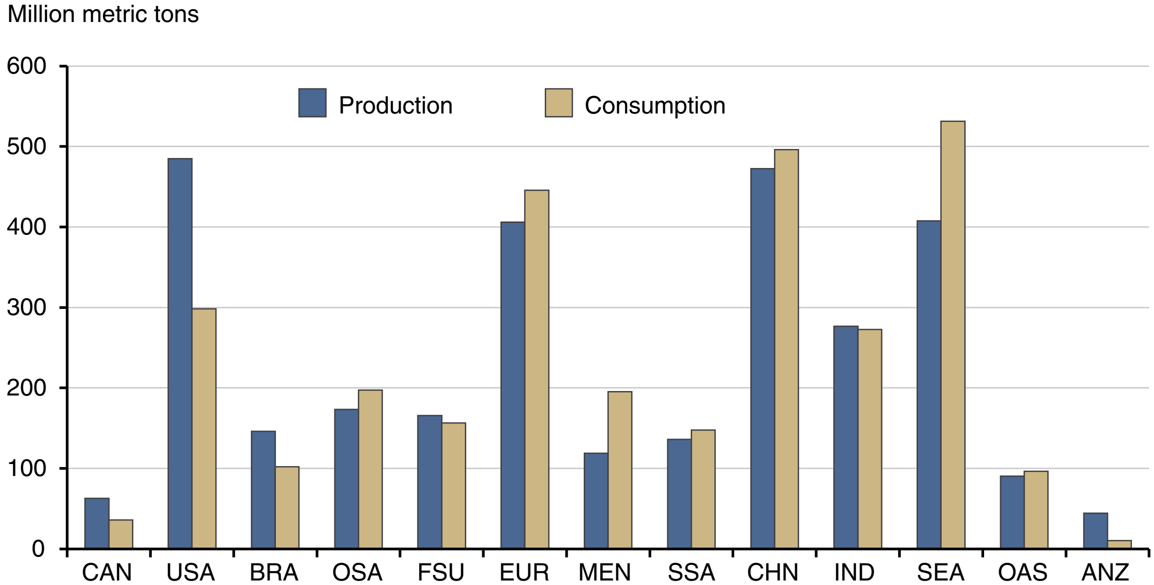
Table 5
Thirteen world regions in FARM

Symbol	Description
CAN	Canada
USA	United States
BRA	Brazil
OSA	South and Central America countries other than Brazil
FSU	Former Soviet Union
EUR	Europe (excluding Turkey)
MEN	Middle East and North Africa (including Turkey)
SSA	Sub-Saharan Africa
CHN	China
IND	India
SEA	Southeast and East Asia countries other than China
OAS	South Asian countries other than India
ANZ	Australia, New Zealand, and Oceania

FARM = Future Agricultural Resources Model.

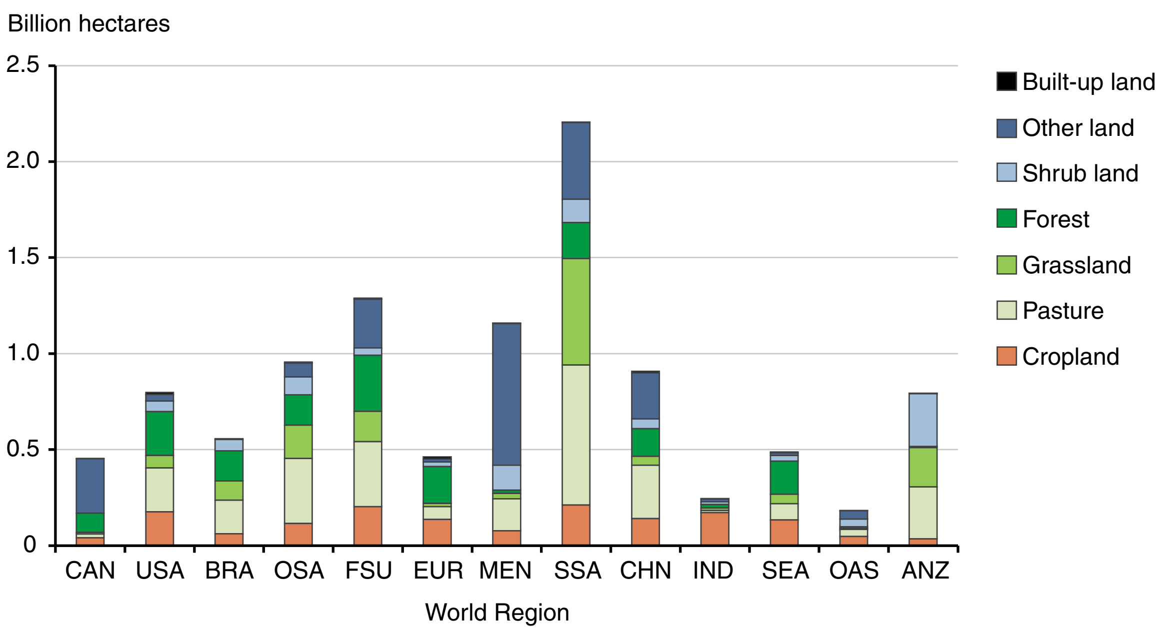
[5] Land-use definitions vary across sources, especially for forest land. See the Food and Agriculture Organization (FAO) of the United Nations (2010) for alternative estimates of world forest land. Nickerson et al. (2011) provide a more detailed set of land-use types for the United States. Total cropland compares reasonably well, but some cropland is idle or used for pasture in the United States.

Figure 1
Production and consumption of five major field crops in 2004



Note: See table 5 for abbreviations of region names. The five crop types are rice, wheat, coarse grains, oil seeds, and sugar. Measures of aggregate production and consumption are the total weight in tons across these five crop types.
Source: USDA, Economic Research Service using the GTAP 7 database.

Figure 2
Benchmark land use by world region in 2004



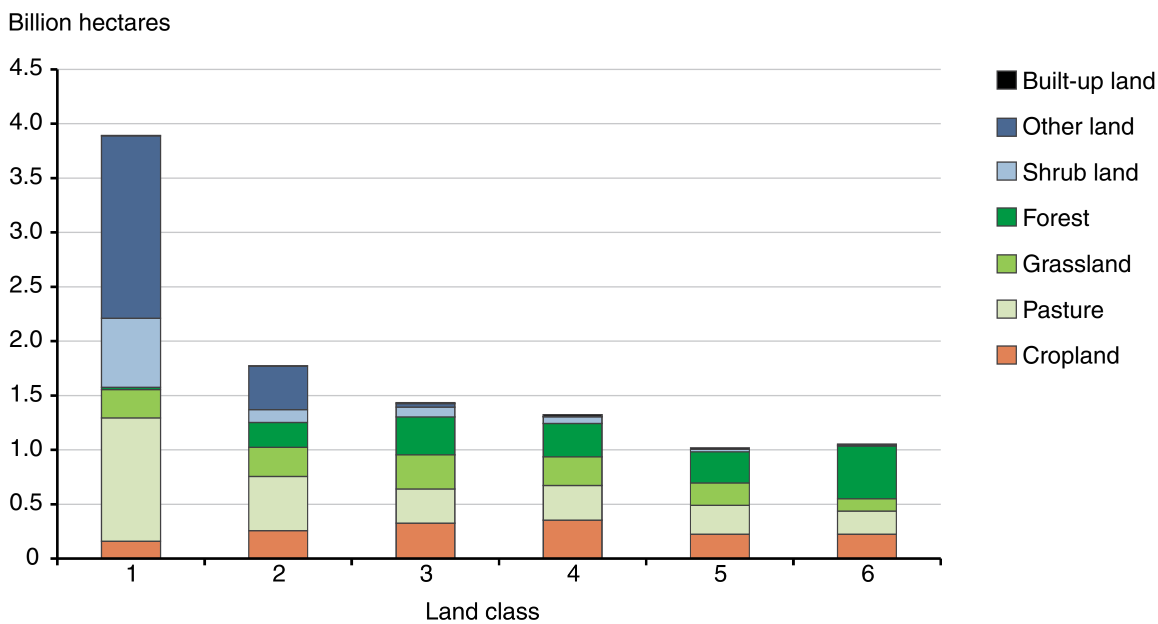
Note: See table 5 for abbreviations of region names.
Source: USDA, Economic Research Service using the GTAP 7 database.

Global land area is also reported in GTAP by land class and land-use type (see fig. 3).[6] FARM uses six land classes that partition land by length of growing period (LGP). Across all land classes, total area for global cropland is approximately 1.5 billion hectares. Land Class 1 is the largest in area but contains the smallest amount of cropland. All land classes have a significant amount of cropland, but Land Classes 3 and 4 contain the most. There is no clear pattern relating crop yield to land class, as this varies by crop, level of irrigation, and world region. Within each FARM region and model time step, land from each land class is allocated to individual crops and other land uses.

The agricultural component of FARM allocates land across crops, pasture, and forest. Crops are partitioned into eight crops or crop types. The five major field crops include wheat, coarse grains, rice, oil seeds, and sugar. The three other crop types are fruits and vegetables, plant-based fibers, and other crops. Other agricultural activities in FARM are meat and dairy production, forestry, and fisheries.

Overall projections of world population through 2050 mask a variety of growth patterns among individual countries (see fig. 4). India is projected to surpass China as the most populous country around 2020, but Sub-Saharan Africa is expected to surpass India by 2040. The populations of India, China, and Brazil are all expected to peak and decline in the 21st century whereas the U.S. population will increase slowly but continuously.

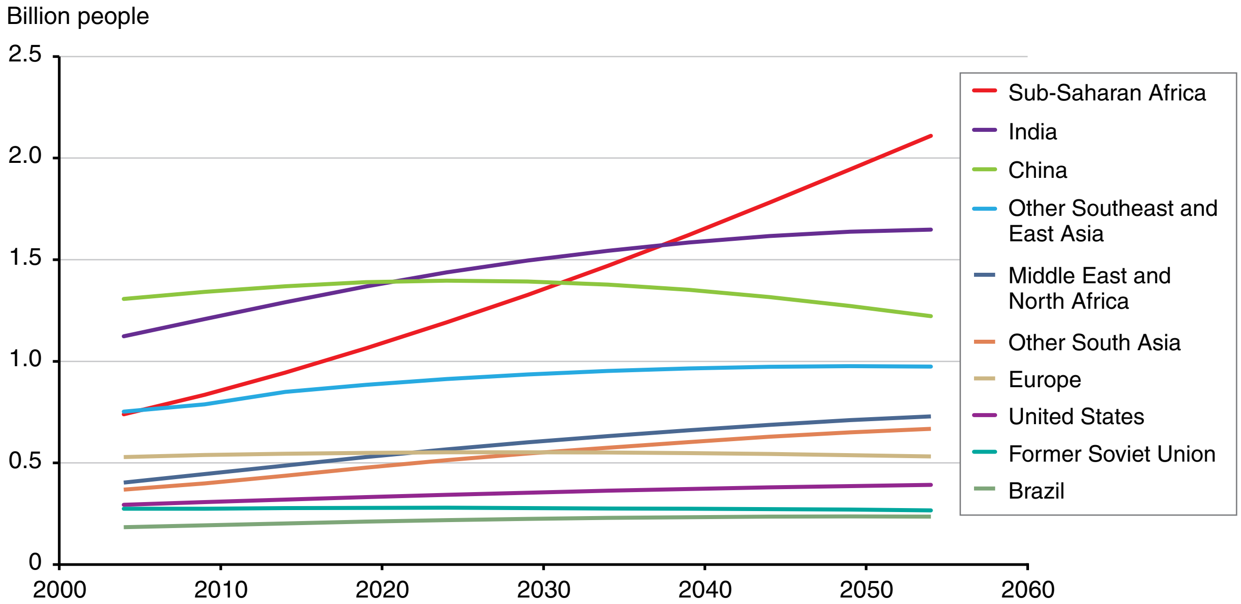
Figure 3
Benchmark global land use by land class in 2004



Note: Land classes correspond to length of growing period: Land Class 1, 0 to 59 days; Land Class 2, 60 to 119 days; Land Class 3, 120 to 179 days; Land Class 4, 180 to 239 days; Land Class 5, 240 to 299 days; Land Class 6, over 300 days.
Source: USDA, Economic Research Service using the GTAP 7 database.

[6] Land use in GTAP is partitioned into 18 agro-ecological zones (AEZs). We aggregated GTAP AEZs into six land classes based on length of growing period (LGP), with approximately 60 days separating the midpoint of each land class. Land Class 1 has an LGP of 0 to 59 days, while Land Class 6 has an LGP greater than 300 days. The six land classes divide the world into areas of progressively increasing humidity: arid; dry semi-arid; moist semi-arid; sub-humid; humid; and humid with year-round growing season (Monfreda et al., 2009, p. 42).

Figure 4
Population projections for selected FARM regions (UN medium-fertility scenario)



FARM = Future Agricultural Resources Model. UN = United Nations.
Source: USDA, Economic Research Service using data from United Nations Population Division, World Population Prospects: 2010 Revision.

Agriculture to 2050: A Reference Scenario

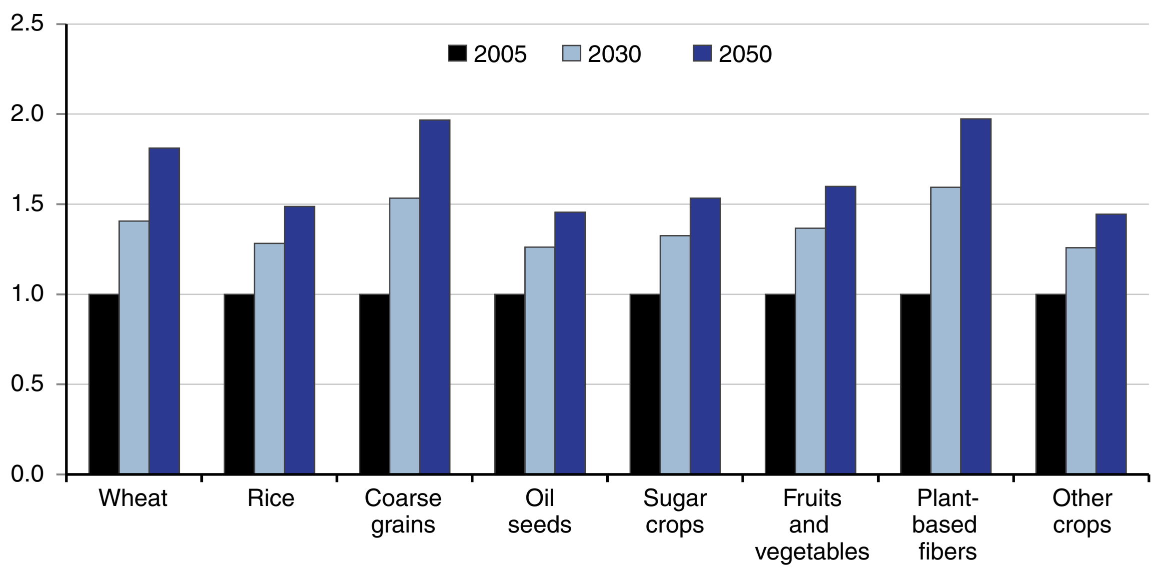
The global reference scenario provides a point of comparison for analysis. First, however, it is important to understand the way agricultural productivity changes over time in the reference scenario. This begins with an exogenous productivity index for each of eight crop types that increase over time (see fig. 5a). This index is considered to be land augmenting: less land is needed per unit of product, but requirements for other inputs per unit of product are not affected.[7] Average annual percentage growth rates range from 0.93 to 1.88 percent across crop groups, between 2005 and 2030.[8] Growth rates decline across all crop groups from 2030 to 2050.

If the ratio of each input to unit of product were fixed in each year, then figure 5a would show the yield of each crop type. However, the ratios of all inputs to unit of product respond to prices to achieve equilibrium between demand and supply for each crop type. In particular, equilibrium yield will increase if crop prices increase relative to prices of inputs such as fertilizer, land, labor, and capital equipment.

Figure 5a

Land-augmenting agricultural productivity index (2005 = 1)

Reference scenario model input (exogenous drivers)



Note: These productivity indexes are ratios of productivity in 2050 or 2030 to productivity in 2005 (they are not annual percentage growth rates).

Source: USDA, Economic Research Service using data from International Food Policy Research Institute.

[7] Exogenous productivity drivers in figure 5a are from the IMPACT model maintained by the International Food Policy Research Institute. IMPACT values are based on expert opinion about potential biological yield gains for crops in individual countries and on historical yield gains and expectations about future private and public sector research and extension efforts. These estimates do not include crop model-based climate change effects or economic model yield responses to changes in input or output prices (Nelson et al., 2014a).

[8] Annual percentage growth rates based on figure 5a are lower than historical growth rates of world cereal yield, which averaged 2.0 percent per year from 1961 through 2009 (Fuglie, 2012).

Global average yield by crop type in the FARM reference scenario increases in all eight crop groups over time (fig. 5b). Average annual percentage growth rates range from 0.84 to 2.18 percent across crop groups, between 2005 and 2030. Most of the increase is due to assumptions about land-augmenting crop productivity (see fig. 5a), but some of the increase is price induced.

Prices in FARM adjust so that world markets clear for all crops (fig. 6).[9] Price increases are modest, due to the large increases in land-augmenting agricultural productivity. In general, if yield in figure 5b is greater than the corresponding land-augmenting productivity index in figure 5a, crop prices increase over time (fig. 6).

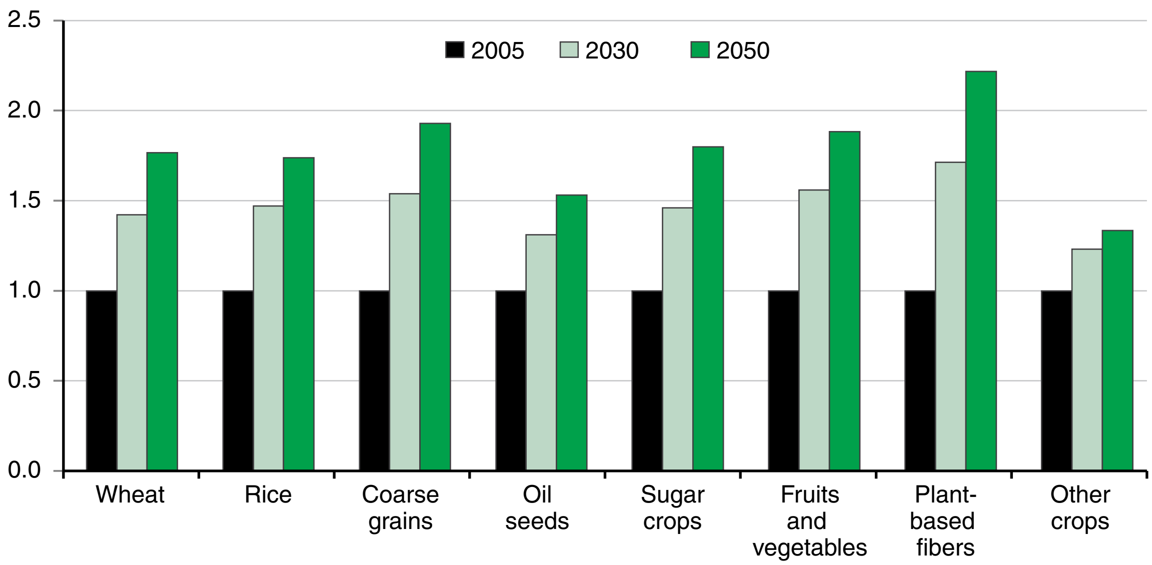
For each agricultural commodity, demand equals supply at the global level. Trade allows for differences in demand and supply at the regional level:

exports + (population × per-capita consumption) = (harvested area × yield) + imports

Figure 7a shows the increase in world demand for five major crops across 45 years in the FARM reference scenario. The increase in demand for each crop is partitioned into two explanatory factors: population growth and income growth. These changes in crop demand are large: increases range from 68 percent for wheat to 102 percent for sugar, with an average increase of 77 percent for the five crop types added together. Of this 77-percent increase, 50 percent is attributed to population growth and the remaining 27 percent to increasing incomes.

Figure 5b
World average yield index of major crop groups (2005 = 1)

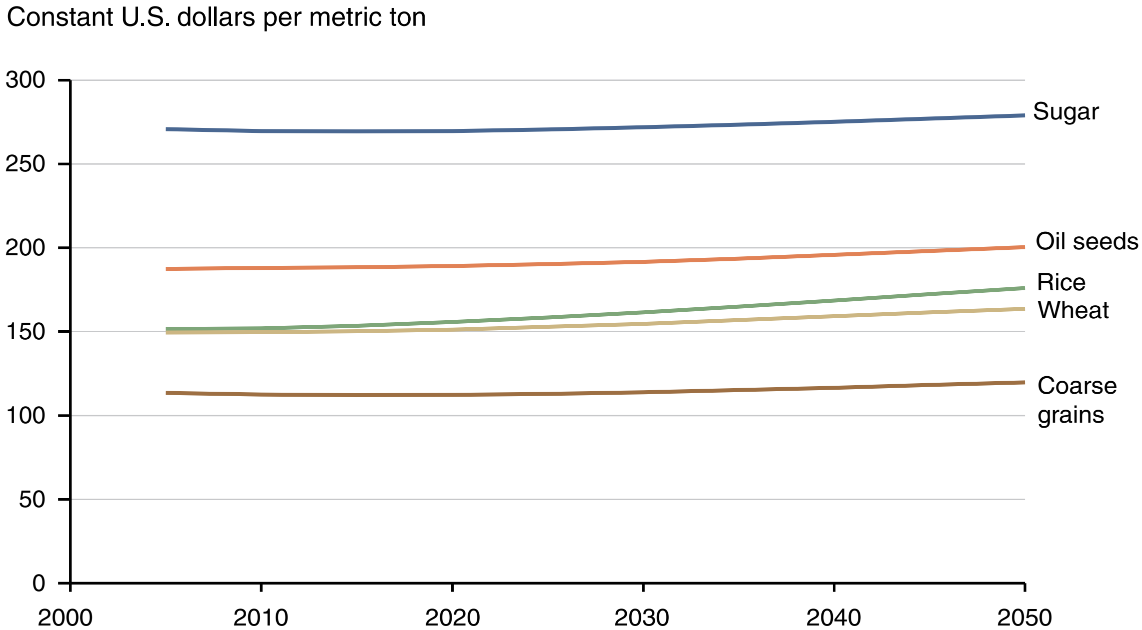
Reference scenario model output (combining exogenous and endogenous effects)



Note: These yield indexes are ratios of crop yield in 2050 or 2030 to crop yield in 2005 (they are not annual percentage growth rates).
Source: USDA, Economic Research Service using Future Agricultural Resources Model reference scenario.

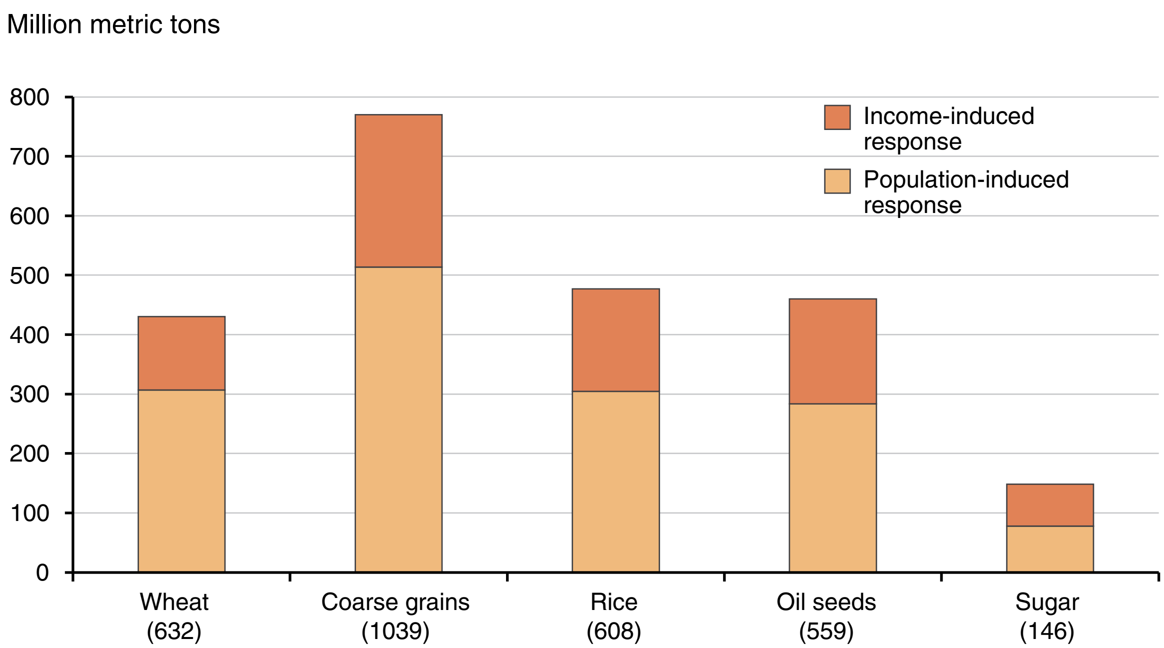
[9] Prices are adjusted for inflation.

Figure 6
World average prices for major crops, reference scenario



Sources: USDA, Economic Research Service using GTAP 7 database; Future Agricultural Resources Model reference scenario.

Figure 7a
Components of change in world crop demand (2004-49), reference scenario



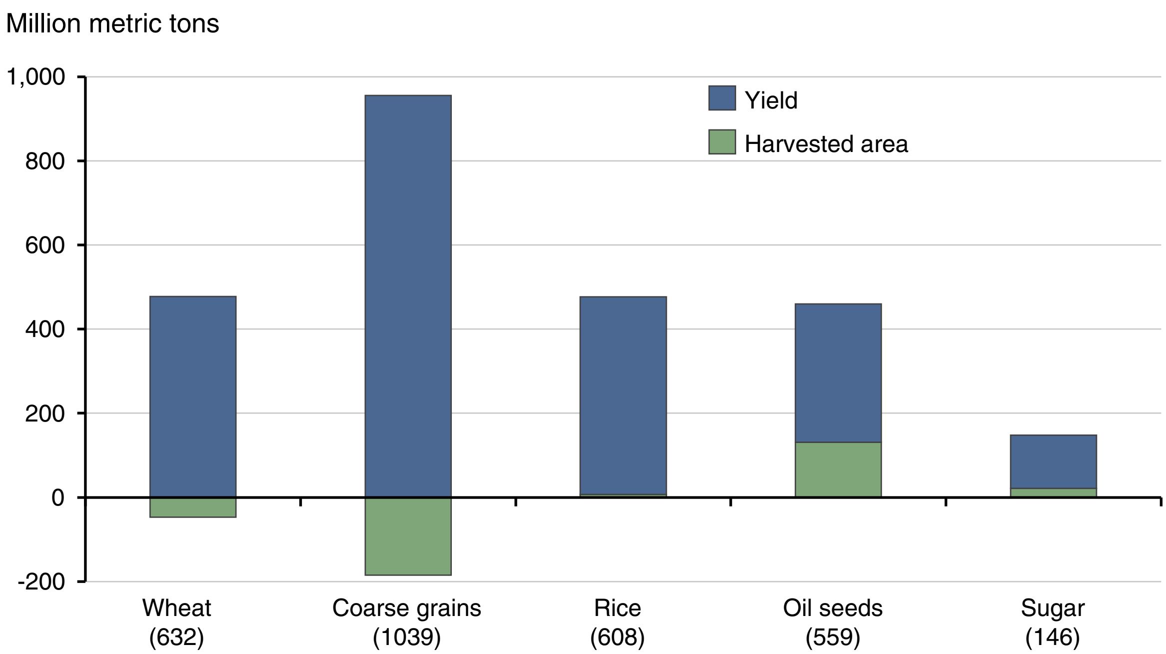
Note: Numbers in parentheses are 2004 world production levels in million metric tons.
Sources: USDA, Economic Research Service using GTAP 7 database; Future Agricultural Resources Model reference scenario.

Valin et al. (2014) provide a comparison of food demand through 2050 across 10 global economic models in AgMIP, along with a comparison to FAO projections to 2050 (Alexandratos and Bruinsma, 2012). Food demand in metric tons is reported for ruminant meat, nonruminant meat, dairy products, and crops consumed directly. FAO uses income projections for 2050 that are lower than income projections used by AgMIP models, contributing to projections of food demand that are generally lower than the AgMIP average.

Differences over time in food demand across AgMIP models primarily reflect different functional forms and parameterization of the response of per capita food consumption to rising incomes, especially for developing countries. Projections from the FARM model are near the AgMIP average for consumption of meat and dairy products but above the AgMIP average for crops consumed directly. Figure 7a reports total consumption of crops, including crops used indirectly for meat and dairy products.

Figure 7b provides a decomposition of the supply side into changes in yield and harvested area for select crops.[10] At the global level, a change in demand must equal the corresponding change in supply. Prices adjust within FARM to enforce the equality between world supply and demand for each commodity. Most of the increase in world food supply is due to increases in yield. The change in

Figure 7b
Components of change in world crop supply (2004-49), reference scenario



Note: Numbers in parentheses are 2004 world production levels in million metric tons.
Sources: USDA, Economic Research Service using GTAP 7 database; Future Agricultural Resources Model reference scenario.

[10] The decomposition method used here is the logarithmic mean Divisia index (LMDI). See Ang (2005) for a guide on using this method to decompose a change in a multiplicative relationship into additive components.

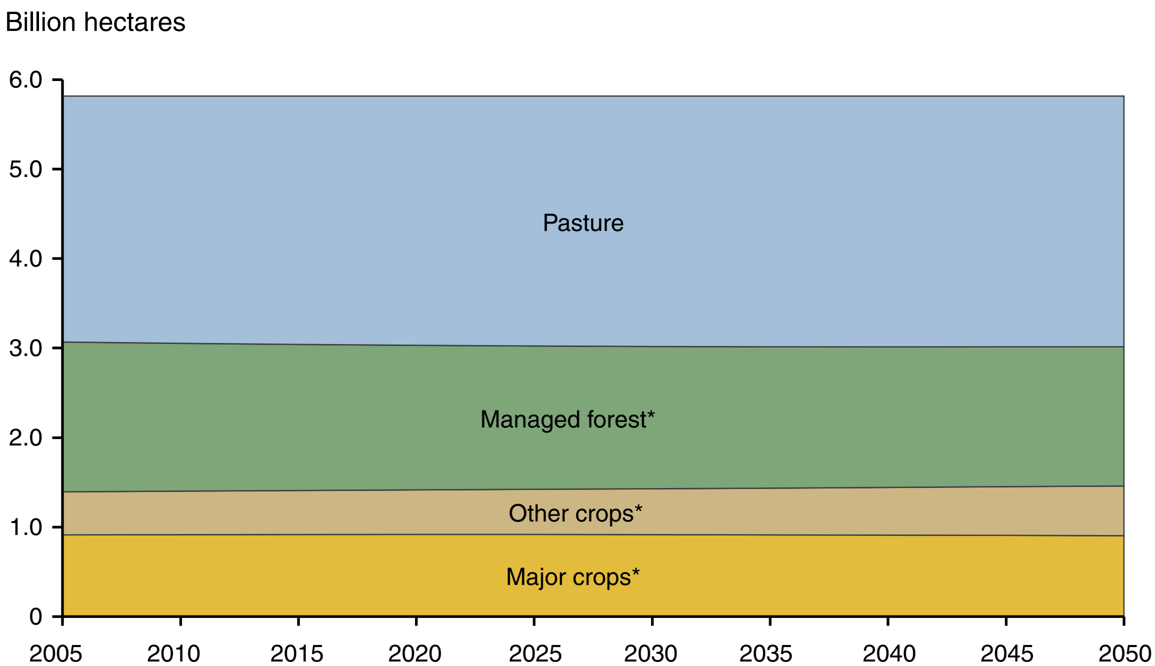
harvested area is relatively small for each crop in this reference scenario.[11] The net change in total harvested area is slightly negative.

As shown in figure 8, the main feature of the reference scenario pattern of land use is that total world cropland (five crops plus three crop types) is stable over time, primarily because of optimistic assumptions of agricultural productivity growth (fig. 5a). The total of cropland, pasture, and forest land is constrained to be constant over time.[12]

In a future that resembles the one constructed under the reference scenario, the increased demand for agricultural products associated with greater incomes and a larger population can be met without significant increases in cropland area or product prices. The increases in agricultural productivity assumed by the reference scenario are sufficient to keep up with growing demand for agricultural products. That future is uncertain, however, and the results are sensitive to the assumptions used to construct the reference scenario.

Figure 8

World agricultural land-use simulation, reference scenario



* The five major field crops are rice, wheat, coarse grains, oil seeds, and sugar. The three other crop types are fruits and vegetables, plant fibers, and other crops. Managed forest is accessible forest land.

Sources: USDA, Economic Research Service using GTAP 7 database; Future Agricultural Resources Model reference scenario.

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[11] The FARM model base year is 2004 and is solved every 5 years until 2054. Most charts with FARM output are interpolated to show results from 2005 through 2050. However, the LMDI decomposition holds only at model time steps, and here we report the change from 2004 through 2049.

[12] We do not simulate expansion of managed land into unmanaged forest. Schmitz et al. (2014) provide a comparison of land use across 10 economic models participating in the AgMIP global economic study. Expansion of cropland is constrained in models with land competition among crops, pasture, and forest, such as FARM.

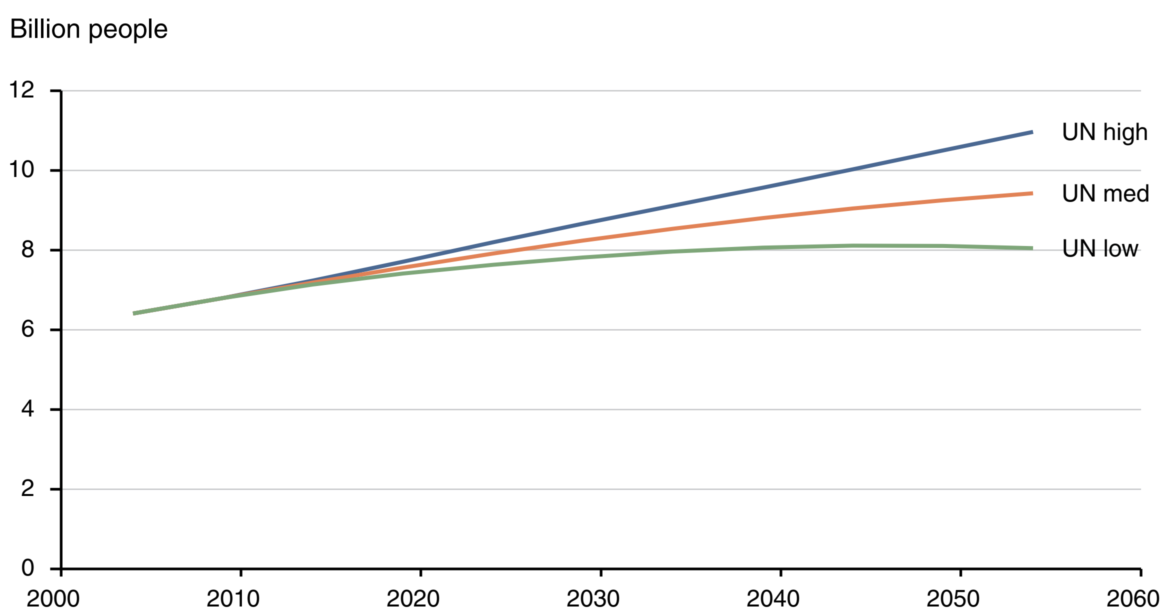
Population

Scenarios in this section keep income and productivity projections the same as in the reference scenario but allow population to follow either a low or a high path. As population increases, demand for agricultural products increases in nearly equal proportions, even without an increase in per capita income.

In 2011, the United Nations released world population projections from 2010 through 2100 (United Nations, 2011). Uncertainty is characterized using low, medium, and high assumptions about fertility. World population in the medium-fertility scenario is 9.3 billion in 2050, up from 6.9 billion in 2010 (fig. 9). World population in the low scenario is 8.1 billion people in 2050 (13 percent lower than the medium scenario).

In 2050, world population is 10.6 billion in the high scenario, 14 percent greater than in the medium scenario. Production is the same as consumption at the world level, and the two increase at nearly the same rate as population (fig. 10). Yield and area harvested both increase as average crop prices increase with increased demand, thereby supporting the increased production of field crops, with the percentage increase in production approximately equal to the sum of percentage increases in yield and area.[13]

Figure 9
World population projections to 2050



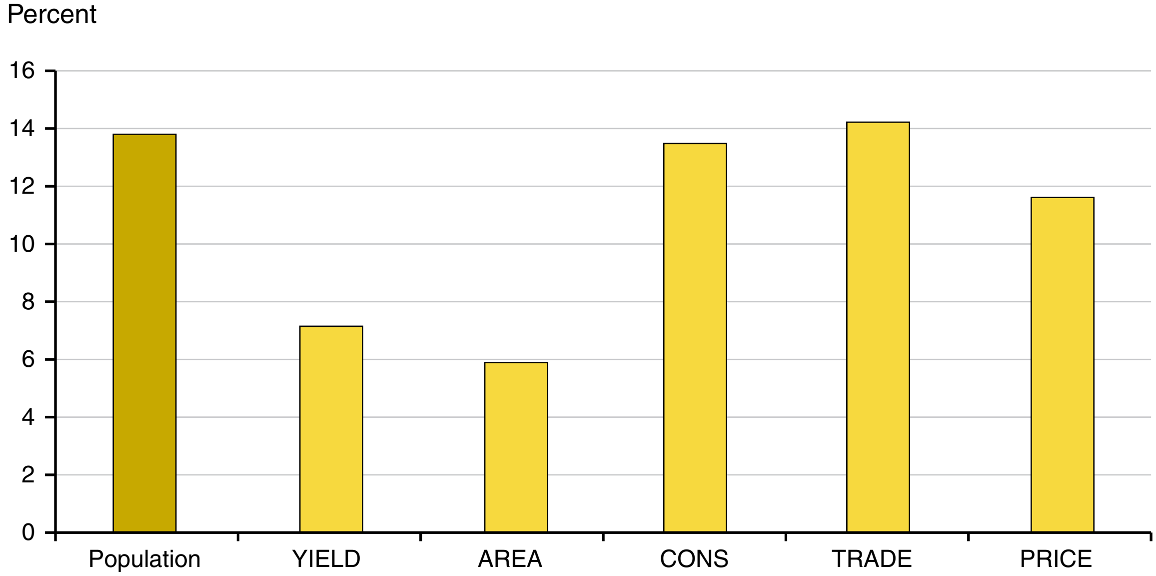
UN=United Nations.
Source: USDA, Economic Research Service using data from United Nations Population Division, World Population Prospects: The 2010 Revision.

[13] This type of figure appears near the beginning of this chapter and the following two chapters. The first column is the percentage change in one driver (other drivers held constant), with economic responses in the other columns.

Figure 10

Economic responses to an increase in world population in 2050

High population scenario relative to medium population scenario



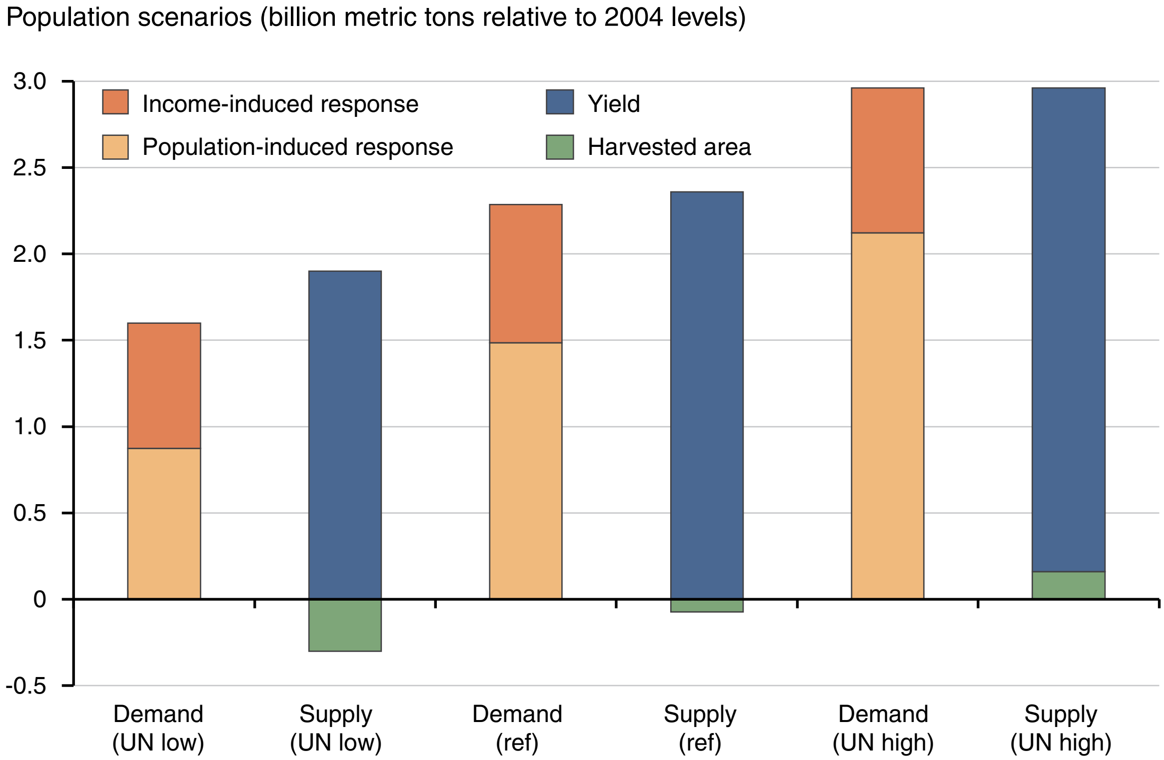
Note: Economic responses cover five major field crop types: rice, wheat, coarse grains, oil seeds, and sugar. The driver is world population. YIELD = average yield of major field crops in tons per hectare. AREA = global area of major field crops. CONS = global consumption = global production. TRADE = global exports = global imports. PRICE = price index across the major field crops.

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

Figure 11 provides a decomposition of changes in crop demand and supply into changes in two demand components (population and income) and two supply components (yield and harvested area). Data in the figure reflect global supply and demand, with imports equal to exports. If the figure instead included data pertaining to an individual country or world region, the data would reflect changes in exports and imports.

Increasing population drives an increase in crop demand across low-, medium (reference)-, and high-population scenarios, with a combination of yield increase and land-use change on the supply side. Global land-use declines (relative to the reference population growth scenario) in the low-population scenario for five major field crops. Global cropland changes very little in the reference scenario but increases in the high-population scenario.

Figure 11
Components of change in world crop demand and supply, 2004-49



Notes: This figure shows demand and supply for the sum of five major field crops: rice, wheat, coarse grains, oil seeds, and sugar. Changes in demand and supply are the total change over a 45-year horizon. Production levels in 2004 are 3.0 billion metric tons in all scenarios; therefore, production in the high-population scenario is approximately double production in 2004. Components for the reference scenario equal the sum of columns from figures 7a and b.
UN = United Nations.
Sources: USDA, Economic Research Service using GTAP 7 database; Future Agricultural Resources Model reference scenario.

Income and Food Consumption Per Person

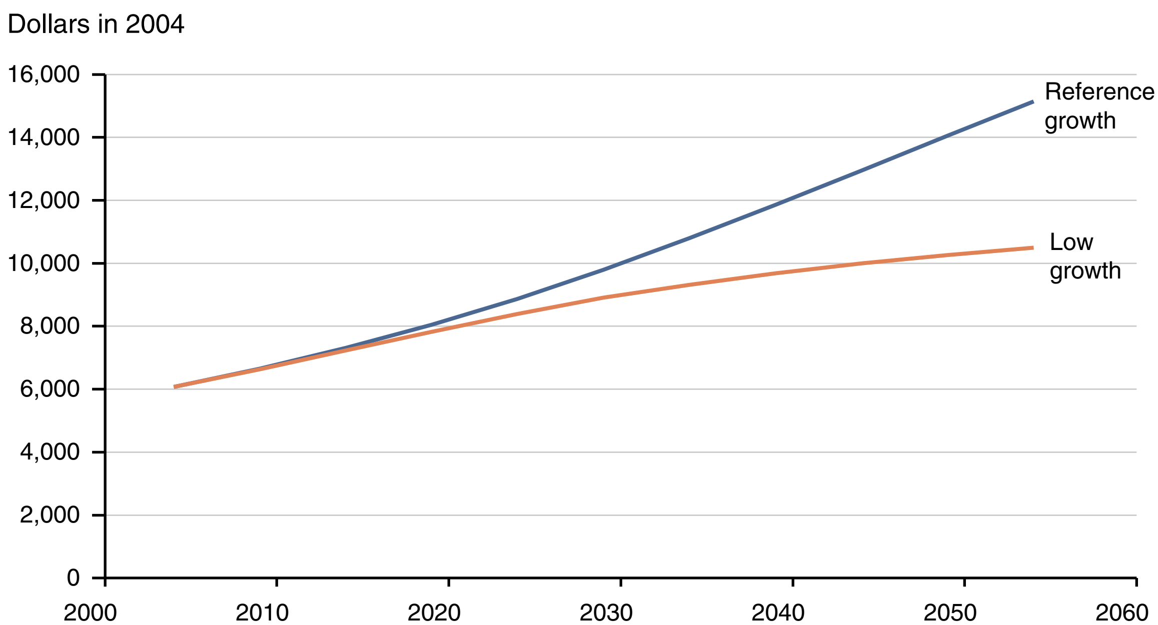
This section presents a scenario with lower income growth over time relative to the reference scenario. For example, income growth may be lower if educational attainment and access to public health care is lower than in the reference scenario. By 2050, per capita Gross Domestic Product (GDP) is 29 percent less in the low-growth scenario than in the reference scenario (fig. 12). Per capita GDP still grows over time in the low-growth scenario, just not as fast as in the reference scenario.

In the low-growth scenario, population and crop productivity growth rates are the same as those in the reference scenario, but GDP grows more slowly in all world regions.[14] Economic responses to this change are shown in figure 13, with the low-growth scenario relative to the reference scenario.

Lower per capita income growth leads to decreased demand for animal protein, which leads to decreased demand for crops used as animal feed. However, the decrease in consumption of field crops is much smaller, on a percentage basis, than the decrease in per capita income. This pattern of decreased consumption of animal products along with declining per capita income is apparent in historical food consumption across countries of varying per capita income.[15] As in figure 10,

Figure 12

Projections of world average real GDP per capita

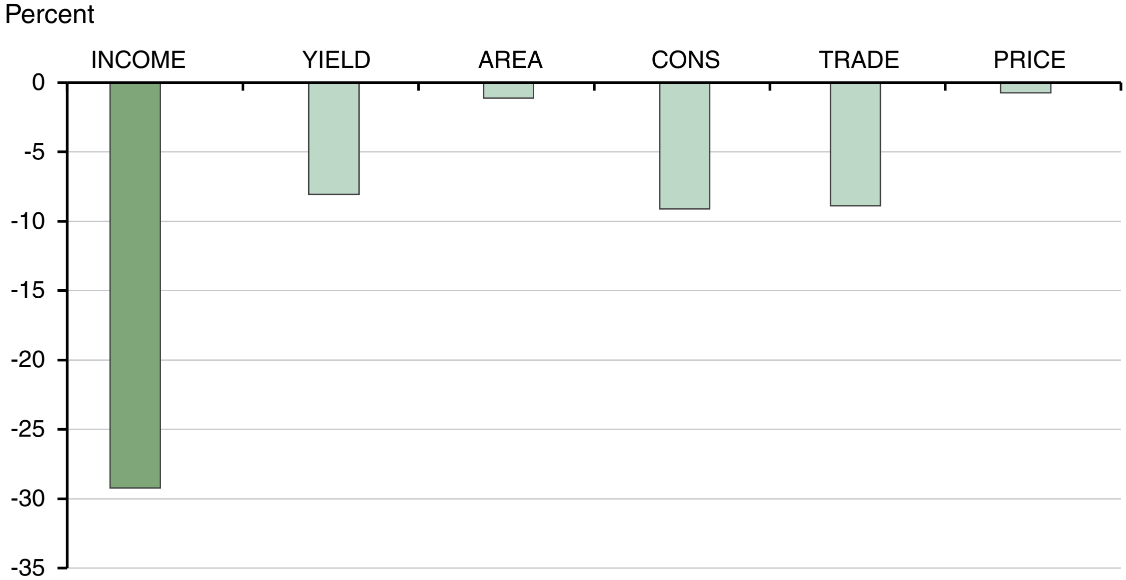


GDP = Gross Domestic Product.
Source: USDA, Economic Research Service projections derived from Shared Socioeconomic Pathways SSP2 and SSP3.

[14] GDP growth rates are from two of five Shared Socioeconomic Pathways (SSPs): SSP2 for reference growth and SSP3 for low growth. O'Neill et al. (2014) provide an overview of, and motivation for, SSPs. The SSP data are available at https://secure.iiasa.ac.at/web-apps/ene/SspDb. Income pathways from SSP2 and SSP3 are used here for easy comparison with other model results assessed in the AgMIP global economic modeling study (Nelson et al., 2014a).

[15] See box "Food Balance Sheets" for background and historical variation of per capita consumption of animal products for India, China, Brazil, and the United States.

Figure 13
Economic responses to a decrease in world income in 2050
Low-growth scenario relative to reference scenario



Note: Economic responses cover five major field crop types: rice, wheat, coarse grains, oil seeds, and sugar. The driver is per capita income. YIELD = average yield of major field crops in tons per hectare. AREA = global area of major field crops. CONS = global consumption = global production. TRADE = global exports = global imports. PRICE = price index across the major field crops.
Source: USDA, Economic Research Service using Future Agricultural Resources Model scenarios.

the percentage change in production is approximately the sum of percentage changes in yield and harvested area.

Box figure 2 displays world average per capita consumption of three food categories over time. Global per capita consumption increased in all three food categories from 1961 through 2007, reflecting world economic growth. It is quite possible for per capita consumption of crops to peak and decline in the future, as consumption patterns in developing countries shift toward patterns in wealthy countries such as the United States.

Food Balance Sheets

Food balance sheets describe the total supply and use of various categories of food in a country for a given year. Food balance sheets for groups of countries can be constructed by summing sheets of individual countries for each food category.[1] Supply is equal to the quantity of food produced, plus imports, adjusted for any change in stocks. Use includes crops or food consumed by households, used for seed, processed for food and nonfood use, and exports. Except for statistical error, total supply should equal total use.

The Food and Agriculture Organization (FAO) of the United Nations is the primary source of food balance sheets, with detailed coverage of food commodities (FAO, 2001). FAO provides food balance sheets on an annual basis beginning in 1961. FAO food balance sheets group commodities 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. For this study, commodities are combined to match the crops and crop types in the Global Trade Analysis Project (GTAP) database.

The basic unit used in FAO food balance sheets is metric tons per year. The quantity of final consumption by households is then converted to kilograms per person per year using that country's population. Finally, household consumption is converted to units of kilocalories per person per day. This unit enables one to sum calories across commodities and compare diets across countries and over time.

Note that there can be confusion between large calories and small calories, where 1 large calorie equals 1,000 small calories. The calories used in nutrition labels at grocery stores are large calories. FAO food balances use small calories, but they are always displayed as kilocalories (kcal). Therefore, 1 kcal is the same as 1 large calorie familiar to consumers.

Box figure 1 provides a cross-country comparison of food consumption in three broad categories: crops consumed directly, crops consumed indirectly as processed crops, and animal products. The food categories are aggregates of detailed food types in food balance sheets constructed by FAO. Direct crop consumption consists primarily of cereals but also includes starchy roots, food legumes, fruits, and vegetables. Processed crops include vegetable oils from oil crops, sweeteners from sugar crops, and alcoholic beverages. Animal products include meat, milk, butter, eggs, and animal fats.

Per capita consumption of total calories varies widely across countries, with the United States well above the world average and India below. The type of calories consumed also varies, for example, with very low per capita consumption of animal products in India relative to other countries with a comparable standard of living. Primary calories include all food or feed crops, while secondary calories include processed crops or animal products. More than one primary calorie is required to produce each calorie of processed crop or animal product, with more primary calories needed for animal products than for processed crops. The implication is that per capita consumption of total primary calories increases along with the quantity of animal products. Residents of wealthier countries generally consume more total calories and more animal products than residents of other countries. Even without population growth, total demand for crops would increase as China and India become wealthier and animal products become a larger share of total calories. However, income-related growth in per capita consumption of

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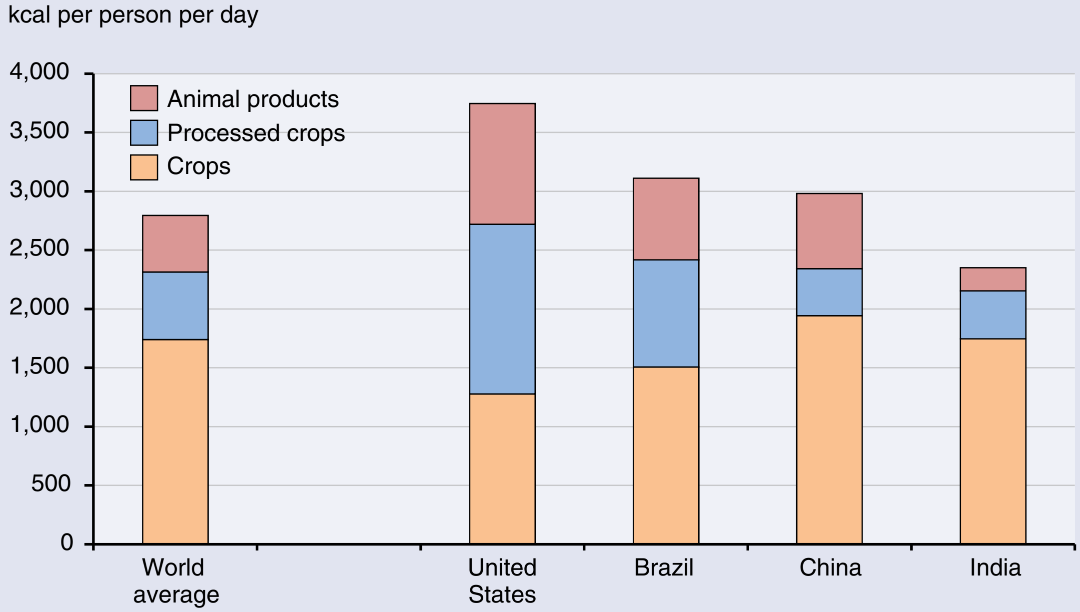
[1] Sums include trade between countries within each grouping of countries.

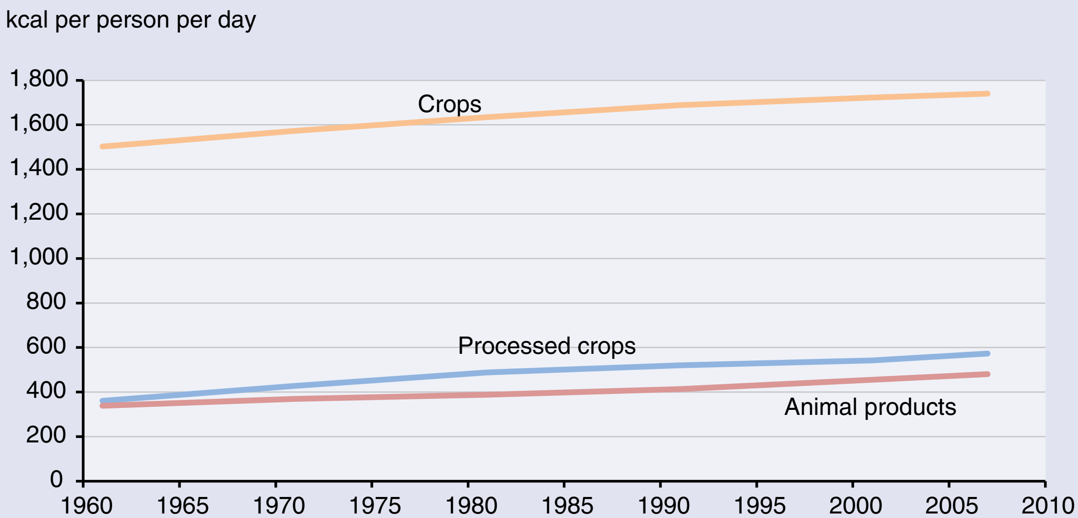
animal products may be less in India than in other countries due to dietary restrictions associated with religious beliefs.

Box figure 1
Per capita food consumption in select countries in 2007



Note: “crops” includes all crops, not just the five major field crop types.
Source: USDA, Economic Research Service using data from Food and Agriculture Organization of the United Nations food balance sheets.

Box figure 2
Increasing per capita food consumption over time (world average)



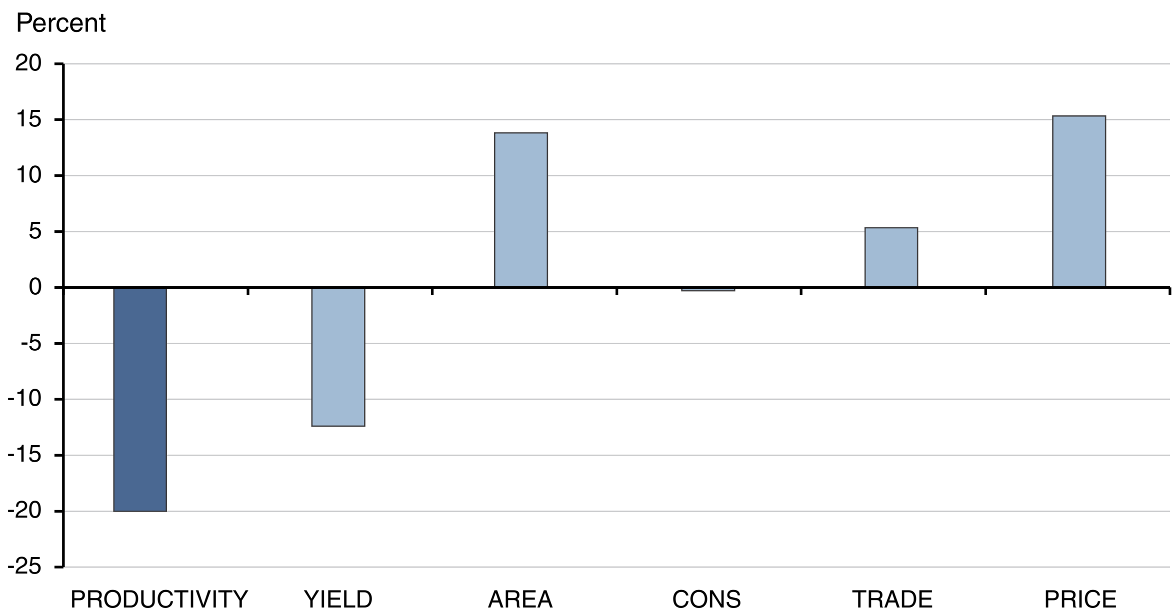
Note: “crops” includes all crops, not just the five major field crop types.
Source: USDA, Economic Research Service using data from Food and Agriculture Organization of the United Nations food balance sheets.

Agricultural Productivity

Scenarios in this section keep population and income the same as in the reference scenario but examine the effects of lower growth in agricultural productivity. These scenarios reflect considerable uncertainty about the future growth in agricultural productivity in the face of global climate change, unpredictable public and private investment decisions concerning agricultural research and development (R&D), and myriad other factors that could affect productivity trends. Two low-productivity scenarios were constructed: one with a 20-percent decline in land-augmenting productivity relative to the reference scenario by 2050 and another with a 40-percent decline. Agricultural productivity still increases through 2050 in the 20-percent low-productivity scenario, just not as fast as in the reference scenario. When comparing productivity levels in 2050, the low-productivity scenarios appear as a negative productivity shock relative to the reference scenario.

Figure 14 shows how the global economy absorbs the hypothetical decline in productivity growth in 2050. Actual yield does not fall as much as land productivity because other inputs increase as crop prices increase. The productivity shock is largely absorbed both through intensification of agricultural production and through an increase in harvested area. Production and consumption decline slightly as consumers adjust spending patterns in response to higher prices of food. Again, as in figures 10 and 13, the percentage change in production is approximately the same as the sum of percentage changes in yield (in this case, negative) and area harvested.

Figure 14
Economic responses to a 20-percent decline in agricultural productivity in 2050*



* The 20-percent decline was selected because it is close to the average productivity decline in Nelson et al. (2014b), a modeling study of potential climate impacts on world agriculture.

Note: Responses cover five major crop types: rice, wheat, coarse grains, oil seeds, and sugar. The driver is a change in productivity (PRODUCTIVITY), the change in yield holding nonland inputs to production constant. YIELD = average yield in tons per hectare, allowing increases in nonland inputs to production. AREA = global area of major field crops. CONS = global consumption = global production. TRADE = global exports = global imports. PRICE = price index across the major field crops.

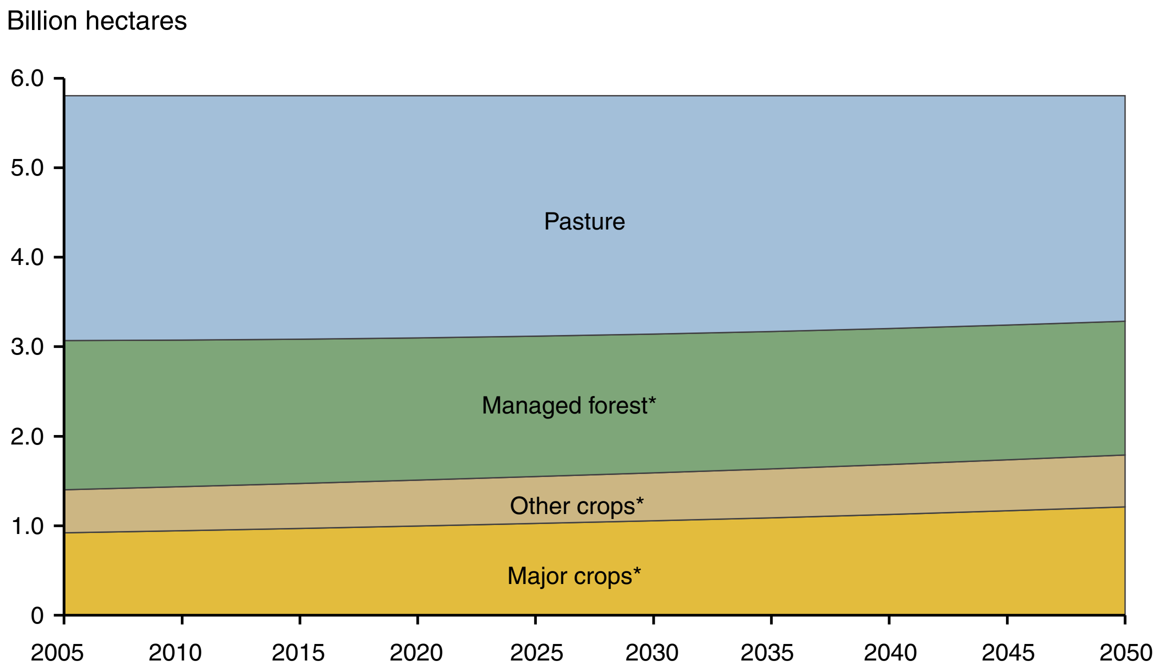
Source: USDA, Economic Research Service using Future Agricultural Resources Model scenarios.

Earlier in this study, the reference scenario was developed using exogenous drivers for land-augmenting productivity provided by AgMIP (see fig. 5a). Land use for crops remains stable through 2050 with the reference scenario's productivity assumptions (see fig. 8), which are lower than historical productivity growth rates. However, more land is used for crops in the low-productivity scenarios. Figure 15 shows the increase in cropland from 2005 through 2050 in the very low productivity scenario, with a corresponding decrease in pasture and managed forest.[16] World cropland grows 28 percent during the period, from 1.40 billion hectares to 1.79 billion hectares.

The most striking difference between the low-productivity and very-low-productivity scenarios is the change in average price for major crops. The price increase is 16 percent in the low-productivity scenario but 99 percent in the very-low-productivity scenario.

The sources of agricultural output growth can be partitioned into increases in land in production and changes in crop yield. Yield growth (output per unit of land) represents—in a single indicator—multiple sources of production growth. One source is farmer intensification of inputs, such as irrigation, fertilizer, and capital equipment per unit of land in response to price signals. Another source is increases in total factor productivity (TFP), which reflects improved technologies and improved

Figure 15
World agricultural land-use simulation—very-low-productivity scenario (40 percent less than reference scenario)



* The five major field crops are rice, wheat, coarse grains, oil seeds, and sugar. The three other crop types are fruits and vegetables, plant fibers, and other crops. Managed forest is accessible forest land.
Sources: USDA, Economic Research Service using GTAP 7 database; Future Agricultural Resources Model scenario.

[16] A 20-percent decline in productivity is approximately the world average decline by 2050 in AgMIP climate impact scenarios (Nelson et al., 2014a; Nelson et al., 2014b). The 40-percent productivity decline scenario was selected as an extreme case.

management resulting from long-term R&D investments. [17] Agricultural productivity has improved rapidly in past decades, but prospects for future growth are uncertain, especially in the context of climate change (see box "Climate Change as an Emerging Driver").

Growth in agricultural output relative to total agricultural land area (total yield) has paralleled the trends in output growth, remaining fairly steady at an average of about 2.1 percent per year from 1961 through 2007. Increases in yield are attributed to a combination of new high-yielding, fertilizer-responsive seed varieties, in conjunction with major increases in fertilizer use and the expansion of irrigation or better water control within irrigated systems (Heisey and Norton, 2007). However, the relative contributions of input intensification and TFP growth have reversed over time, as the annual growth in TFP rose from 0.2 percent in the 1960s to about 1.7 percent since 1990, and the growth in inputs per unit of land fell commensurately.

Climate Change as an Emerging Driver

Land-use change has traditionally been explored from the perspective of changing economic and social conditions within a constant biophysical regime. In recent decades, however, concerns regarding fundamental changes in climate systems have resulted in increased attention to the relationship between climate change and land use.[1]

A large body of research has explored land-use change as a contributing factor in climate change by inventorying the carbon sequestration capacity of different land uses and estimating how movement of land from forest to agriculture, for instance, changes terrestrial carbon storage capacity and atmospheric carbon concentration. An exploration of how crop production and land use might respond to climate change, however, has been constrained by limited availability of robust future climate projections and uncertainty about how such climate projections translate into the more short-term regional weather patterns that strongly influence how land-use decisions are made. The emergence of an ensemble of climate projections from both the fourth and fifth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) has loosened that limitation somewhat. Based on a common set of emissions scenarios, all of the IPCC climate projections estimate an increase in global mean surface air temperature, with the largest temperature increases over land and at northern latitudes (IPCC, 2007 and 2013). While there is considerable variability among the projections in the details of regional

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[1] The role of climate change in global economic models of agriculture is the current topic of study in the Agricultural Model Inter-comparability and Improvement Project (AgMIP). Background on AgMIP can be found at www.agmip.org

[17] Productivity can be characterized using measures of total-factor productivity (TFP) or partial-factor productivity (PFP). TFP is an index that measures output per unit of all inputs and measures the extent to which fewer resources are required to produce a given level of output. As such, TFP can be interpreted as a signal of technical change or improved efficiency in the use of inputs. An alternative productivity index, partial-factor productivity (PFP), measures output per unit of a particular input. For example, yield growth (output per unit of land) is a partial productivity measure. However, both TFP and PFP are imperfect measures of innovation because they also reflect economies of scale, as well as changes over time in key environmental conditions affecting yields: local growing conditions (length of growing season and precipitation), soil quality, and the availability of water for irrigation.

Climate Change as an Emerging Driver—continued

precipitation, they generally project increased precipitation in tropical areas that experience large precipitation events, such as monsoon regions, over the tropical Pacific, and at high latitudes. Precipitation is generally projected to decrease in subtropical dry regions, with dry midlatitude regions projected to get drier, and wet midlatitude regions likely to get wetter by the end of the century (IPCC, 2013).

Globally variable changes in temperature, precipitation, length of growing season, and incidence of extreme weather events will have region- and crop-specific impacts on agricultural productivity and yields. The IPCC (2007) broadly projects positive yield impacts for 1-3º C temperature change within temperate regions, but several studies of climate change impacts within the United States have projected mixed impacts of climate change on crop yields in the short term (Reilly et al., 2003; McCarl, 2008; Beach et al., 2010; Malcolm et al., 2012). The results of such studies are highly sensitive to whether and how the yield-enhancing effects of atmospheric carbon dioxide are considered in the analysis (Reilly et al., 2007; Cline, 2007).

Even in the short term, however, climate change is expected to have a much more negative impact on agricultural yields in developing countries (Parry et al., 2004; Fischer et al., 2005; Hertel et al., 2010). Productivity may be more negatively affected because many developing countries are already at the upper end of their temperature ranges, and precipitation is not expected to increase as it is in many temperate regions (Easterling et al., 2007; Mertz et al., 2009). Evidence suggests climate change has already slowed the growth in crop yields over recent decades in India (e.g., Auffhammer et al., 2006) and globally (Lobell et al., 2011). Regardless of short-term effects, many researchers project that as continuing temperature increases exceed critical thresholds in the mid-to-late century, crop yields will eventually decline both within the United States and worldwide (Parry et al., 2004; Schlenker et al., 2005; Schlenker and Roberts, 2009; IPCC, 2007; Burke et al., 2011). Though such studies often focus on the direct yield impacts of climate conditions on crop growth, agricultural productivity will be further affected by climate change impacts on ecosystem services that agriculture relies on, such as pollination, pest pressures, water supplies, and flood control.

Altered growing conditions are likely to have significant impacts on patterns of relative productivity of managed systems in the provision of food, feed, fiber, and fuel products worldwide. Such significant changes in economic opportunity often lead to land-use change, as decisionmakers adjust their land-use decisions to take advantage of new opportunities or to minimize the effects of new constraints (Lambin et al., 2001). Climate adaptation—or the human response to the changing constraints and opportunities associated with climate change—has been identified as a potentially significant driver of future patterns of land use worldwide, particularly with respect to changes in agricultural land use. Changing patterns of land use as an adaptation strategy will be constrained by the regional availability of land suited for agriculture. The estimated impacts of climate change on the global availability of suitable land for agriculture are mixed and sensitive to the climate scenarios used (Zhang and Cai, 2011). In general, however, studies estimate that arable land increases at the higher latitudes, including Canada, Russia, Northern United States, and Southern Argentina, and decreases in Western Africa, Central America, Western Asia, the South-Central United States, and Northern South America (Ramankutty et al., 2002; Zhang and Cai, 2011).

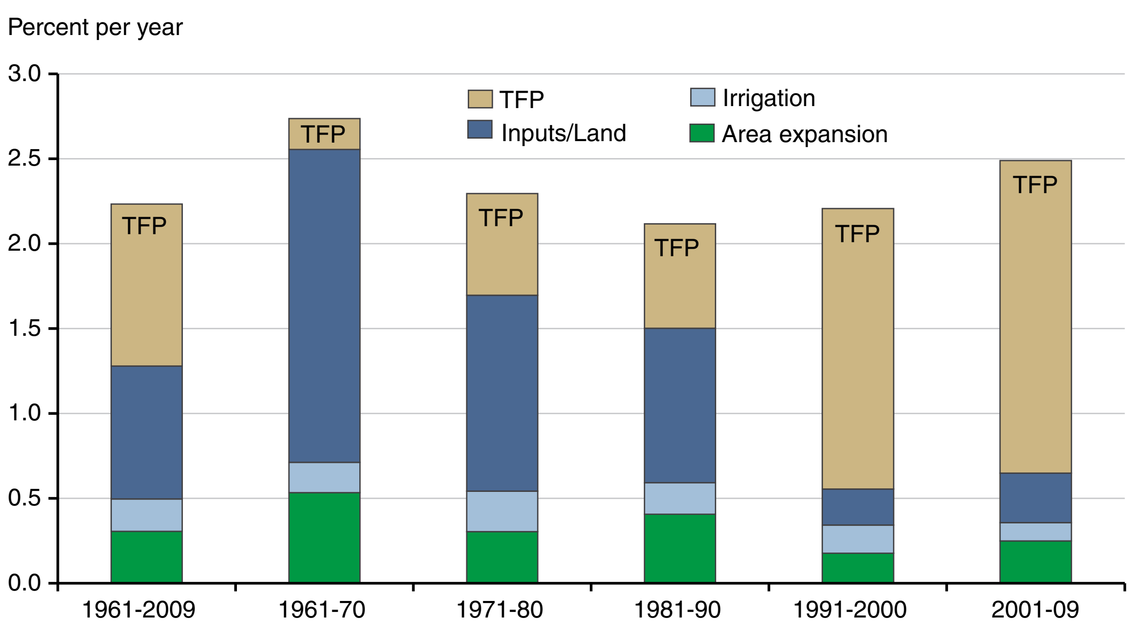
The pattern in yield growth has varied across commodities. For example, the cereal yield growth rate has shown signs of slowing after 1990: global cereal yield increased by about 2.5 percent per year in the 1970s and 1980s but by only 1.3 percent per year during 1991-2009 (Fuglie, 2012). However, the pattern for cereals does not appear to be representative of agriculture as a whole. It has been offset by productivity improvements elsewhere—rising yield growth in other commodities and greater intensification of land use—to keep total output per hectare of agricultural land rising at historical rates.

Historical Growth in Agricultural Production: Decomposition of Source

Global agricultural production has increased more than 150 percent over the past five decades (Fuglie, 2012). The rate of output growth has remained remarkably consistent over the past 50 years—averaging 2.7 percent per year in the 1960s and between 2.1 and 2.5 percent per year every decade since (fig. 16). Over this period, the high rate of growth in production levels occurred primarily through yield growth rather than cropland expansion. However, the sources of yield growth have shifted from intensification of inputs per unit of land to growth in TFP.

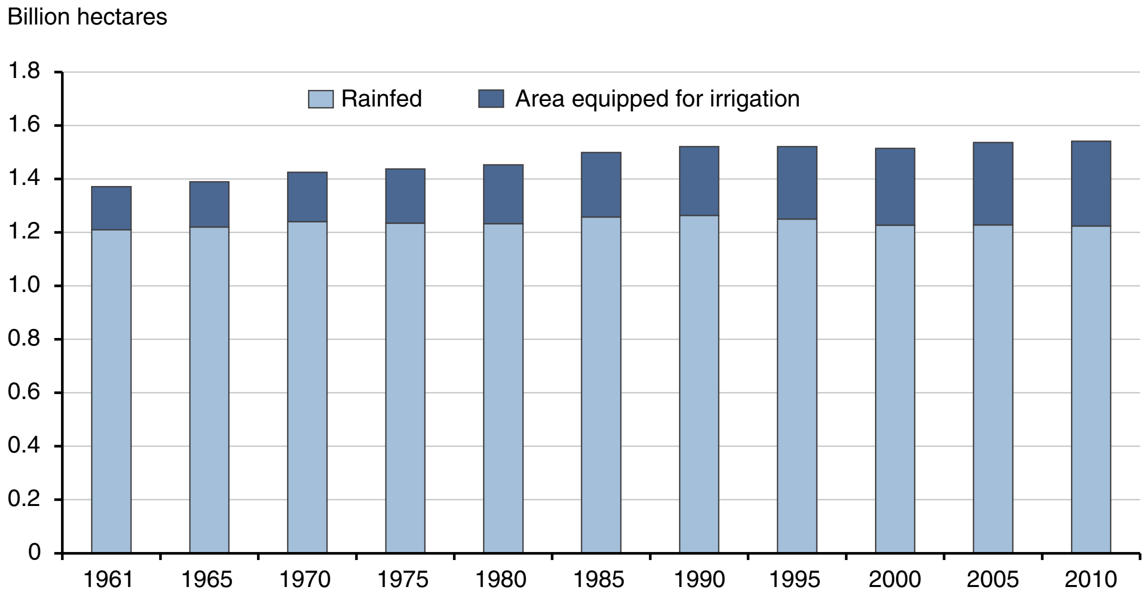
From 1961 through 2009, the world's cultivated area grew by 12 percent. At the same time, global irrigated area doubled, accounting for most of the net increase in cultivated land (fig. 17). Most of the area expansion occurred by 1990. However, the conversion of lands from rainfed to irrigated has continued throughout the period, such that agriculture uses 70 percent of water withdrawn from aquifers, streams, and lakes (FAO, 2011).

Figure 16
Sources of global agricultural growth



TFP = Total factor productivity.
Source: USDA, Economic Research Service using data from Fuglie (2012), p. 350.

Figure 17
Evolution of world cropland under irrigated and rainfed croppings



Sources: USDA, Economic Research Service using data from the Food and Agriculture Organization of the United Nations (2011, 2014).

Analysis Across Drivers

In this study, the sensitivity of model output is observed for changes in reference scenario assumptions on population, income, and agricultural productivity. Figures 10, 13, and 14 depict the response of model output variables to changes in each of these drivers. These changes are presented in table 6 for easy comparison. These results were obtained by varying each driver one at a time, holding the other drivers constant.

With population as a driver, the percentage increases in crop consumption (13.5 percent), production (13.5 percent), and trade volume (14.2 percent) scale at nearly the same percentage rate as population (13.8 percent). This increase in global production is obtained with increases in yield (7.1 percent) and area (5.9 percent). With income as a driver, the percentage change in all economic responses is smaller than the percentage change in income (-29.2 percent). In particular, crop consumption falls at a smaller percentage rate (-9.1 percent) than income. With a decline in agricultural productivity, intensification of agricultural production limits the decline in yield (12.4 percent) to be significantly less than the decline in productivity (20.0 percent). However, to keep the decline in global crop production small, harvested area increases (13.8 percent).[18]

Percentage changes from table 6 can be converted to elasticities: the percentage change in an economic response divided by the percentage change in one of the drivers. For example, the elasticity of global crop consumption (13.5 percent) with respect to world population (13.8 percent) is 0.98, or nearly one-to-one. Figure 18 presents elasticities of five economic responses with respect to three drivers, allowing a direct comparison across drivers for each economic response. While the scenarios in these estimates are based on often-modelled declines relative to the reference scenario, elasticities are presented as responses to an increase in each driver for easy comparison. For example, the figure shows how an *increase* in productivity would affect economic indicators: yield increases, harvested area declines, and average price falls.

Table 6

Economic responses to changes in agricultural drivers

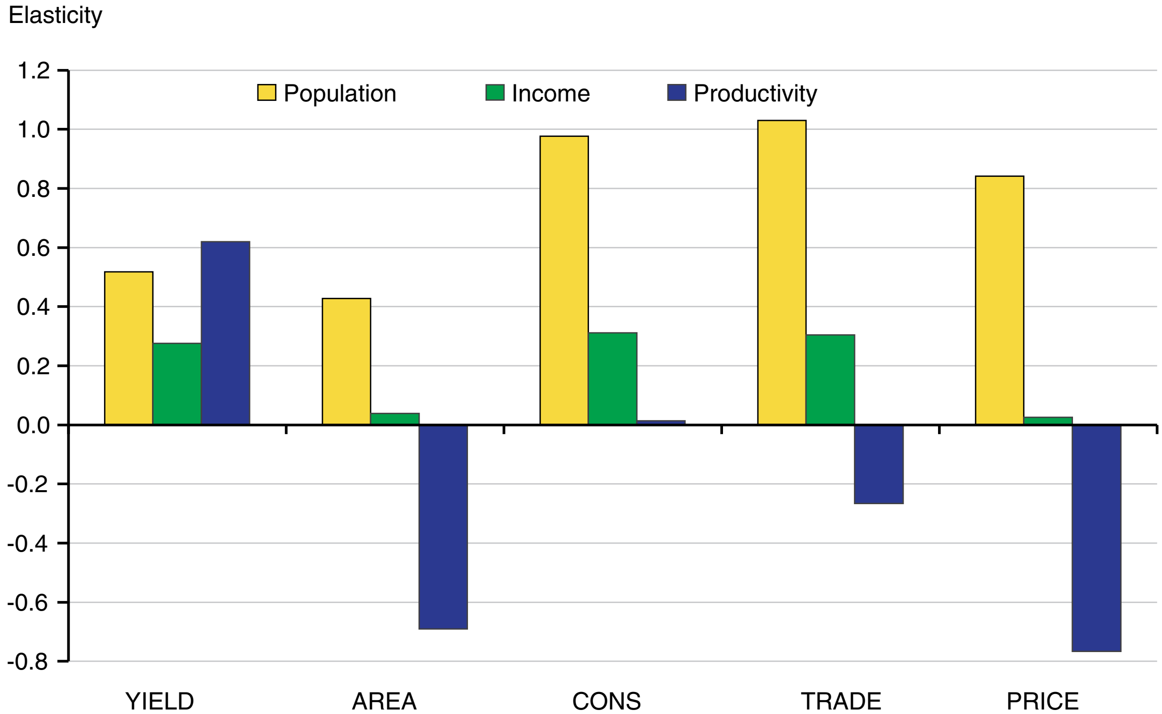
Percent change from reference scenario	DRIVER	YIELD	AREA	CONS	TRADE	PRICE
				Percent		
+13.8	POPULATION	7.1	5.9	13.5	14.2	11.6
-29.2	INCOME	-8.1	-1.1	-9.1	-8.9	-0.7
-20.0	PRODUCTIVITY	-12.4	13.8	-0.3	5.3	15.3

YIELD = average yield of major field crops in tons per hectare. AREA = global area of major field crops. CONS = global consumption = global production. TRADE = global exports = global imports. PRICE = price index of major field crops: rice, wheat, coarse grains, oil seeds, and sugar.

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

[18] For small changes in harvested area, the percentage change in production is approximately equal to the percentage change in yield plus the percentage change in area. For larger changes in harvested area, cropland expands into less productive land and the approximation is less accurate.

Figure 18
Elasticities of economic responses to three key drivers



An elasticity is the ratio of percent changes: the percent change in an economic response (e.g., consumption) for each percent change in a driver (e.g., income). When population or income is the driver, economic responses move in the same direction. Yield moves in the same direction as productivity, while cropland area and price move in the opposite direction of productivity. YIELD = average yield of major field crops in tons per hectare. AREA = global area of major field crops. CONS = global consumption = global production. TRADE = global exports = global imports. PRICE = price index of major field crops: wheat, rice, coarse grains, oil seeds, and sugar.

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

The elasticities of crop yield with respect to all three drivers is less than one, with similar responses from population and productivity and less of a response from income. Harvested area responds positively to population and negatively to productivity increases. If both population and productivity increase at the same time, as is assumed in the reference scenario, the combined effects on area may cancel. Global crop consumption, production, and world trade volume respond in a nearly one-to-one ratio with population but with a much smaller response to income. Crop prices move in the same direction as population, but in the opposite direction of productivity. As with area, if population and productivity increase at the same time, their effects on price may offset each other.

Summary and Future Direction

This study describes economic responses to three drivers of agricultural supply and demand: population, per capita income, and agricultural productivity. Responses to these drivers provide an enhanced understanding of global land use and agricultural markets over time, whether in a conceptual model or a formal computational model such as FARM. A conceptual model developed by Hertel (2011) provides qualitative insights on drivers of agricultural demand, supply, and land use in a simple partial-equilibrium framework with a single agricultural product and single region. This study examines numerical relationships between drivers and a set of global economic responses: crop yield, harvested area, consumption, production, trade volume, and average prices.

The analysis started with a reference scenario to 2050 with sufficient gains in agricultural productivity over time to maintain stable cropland area and crop prices. However, productivity growth could be lower depending on the level of future agricultural research or climate change. The reference scenario used the medium-fertility population scenario of the United Nations, which includes significant population growth. If agricultural productivity growth is less than in the reference scenario, or if population growth is greater than in the reference scenario, crop prices increase to provide incentives for an increase in cropland area. The increase in cropland area is limited due to competition for land among crops, pasture, and forest.

The reference scenario in this report is the same as contributed by the FARM modeling team to AgMIP. The global economic modeling group of AgMIP recently published a collection of papers in *Agricultural Economics* that compares results from FARM with nine other global agricultural models and identifies areas for further model improvement. This special issue includes an overview paper (Von Lampe et al., 2014), a methodology paper (Robinson et al., 2014), a food demand paper (Valin et al., 2014), and a land-use paper (Schmitz et al., 2014).

On the demand side, the AgMIP global economic modeling group will continue to examine food demand as it responds to rising per capita income. Each of the global modeling teams adjusted income elasticities over time but would prefer an alternative food demand structure that endogenously makes this adjustment in income elasticities. Further analysis is planned for livestock, especially tracking the efficiency of feed-to-meat conversion. Environmental policies that promote biofuels are a relatively recent demand driver for crops and land.

More research is needed on the supply side, especially with respect to agricultural productivity in the context of climate change. Initial analyses using the AgMIP global economic models are published in Nelson et al. (2014a and 2014b). Other topics that require further attention include integration with process-based crop models, the treatment of water, and extreme events such as a multiyear drought. This study covers global results, but figure 18 shows that international trade can provide an important economic adjustment to supply and demand shocks. This finding suggests that regional analysis may provide interesting response patterns to complement global results.

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Appendix A. FARM Documentation

Introduction

The Future Agricultural Resources Model (FARM) is a global computable general equilibrium (CGE) economic model with 13 world regions that operates in 5-year steps from 2004 to 2054. Land use can shift among crops, pasture, and forests in response to population growth, changes in agricultural productivity, and policies such as a renewable portfolio standard or greenhouse gas cap-and-trade. See Hertel et al. (2009a) for a comprehensive overview of modeling land use in CGE models.

The first version of FARM was constructed in the early 1990s by Roy Darwin and others at USDA's Economic Research Service (ERS) (Darwin et al., 1995). By partitioning land into land classes, this model provided a unique capability among CGE models to simulate land use on a global scale. Early versions of the FARM model were used to simulate the impact of a changed climate on global land use, agricultural production, and international trade.

Planning for a new version of FARM began in 2009, with model construction in 2010 through 2012. The new FARM model adds a time dimension for analysis of alternative climate policies, tracks energy consumption and greenhouse gas emissions, and provides a balanced representation of world energy and agricultural systems. FARM model development has benefited from participation in the Stanford Energy Modeling Forum (EMF) and the Agricultural Model Intercomparison and Improvement Project (AgMIP). Participation in AgMIP required substantial expansion of the agricultural component of FARM. Bio-electricity using switchgrass provides a link between the energy and agricultural systems.[19]

The FARM base year is 2004, which is the base year of a global economic data set distributed by the Global Trade Analysis Project (GTAP) at Purdue University. This study uses social accounts in GTAP version 7 as the primary economic framework. GTAP 7 provides social accounting matrices for 112 world regions and 57 production sectors. These data are then aggregated to 13 world regions and 38 production sectors. The 38 production sectors retain all GTAP information related to primary agriculture, food processing, energy transformation, energy-intensive industries, and transportation.

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 from final demand to create a new transportation services sector; household energy consumption is also removed from final demand to create a new energy services sector.

Several other global CGE models contain agricultural and land-use structures comparable to FARM. The primary strength of FARM is a balanced approach to the energy and agriculture systems within a CGE framework for energy and climate policy simulations. The GTAP project offers a variety of general equilibrium models that have advanced in complexity over time. GTAP-E was one of the earlier extensions of the basic GTAP model, with a focus on energy-economy-environment-trade connections (Burniax and Truong, 2002). The GTAP-AEZ model (Hertel et al., 2009b) is a CGE model with land allocation decisions and equilibrium market feedbacks under specific climate change policy shocks. Land competition is concentrated within agro-ecological zones (AEZs) that differ by growing period and climatic zone. The GTAP-AEZ-GHG model (Golub et al., 2009) is

[19] Recent Energy Modeling Forum applications of FARM can be found in Sands et al. (2014a, 2014b).

a CGE model that integrates various types of land, related greenhouse gas emissions, and carbon sequestration sources into the GTAP-AEZ model. LEITAP extends the GTAP-E model by separating energy inputs from nonenergy inputs to examine biofuel production (Woltjer et al., 2007). The Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) model includes energy-demand specifications, new energy technologies, and a basic climate model that links greenhouse gas emissions with the carbon cycle, radiative forcing, and temperature changes (Van Der Mensbrugghe, 2008).

Production Activities

GTAP data sets are updated every 3 or 4 years, providing greater coverage of individual countries and a new base year at each update. However, the number of production sectors remains at 57 at each update. From those 57 sectors, we have retained all GTAP detail for primary (table A.1 (a)) and processed agricultural products (table A.1 (b)). Primary agricultural products include five major field crops, three other crop types, products of ruminant animals, products of nonruminant animals, fishing, and forestry.

Agricultural products are mostly 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.

The energy side of FARM retains all GTAP detail in energy carriers (table A.1 (c)) and energy-intensive industries (table A.1 (d)). Recent GTAP data sets are constructed to maintain consistency between energy values in the GTAP data set and energy quantities from energy balances distributed by the International Energy Agency (IEA). This provides energy values consistent with the law of one price for each energy carrier: within each world region, all consumers of energy pay the same price

Table A.1 (a)
Primary agricultural products in the Future Agricultural Resources Model

GTAP symbol	Description
wht	Wheat
pdr	Paddy rice
gro	Other grains
osd	Oil seeds
c_b	Sugar (cane and beet)
v_f	Vegetables and fruits
pfb	Plant-based fibers
ocr	Other crops
ctl	Cattle and other ruminants
rmk	Raw milk
oap	Other animal products
fsh	Fish
frs	Forestry

Table A.1 (b)

Food processing activities in the Future Agricultural Resources Model

GTAP symbol	Description
vol	Vegetable oils
pcr	Processed rice
sgr	Sugar
b_t	Beverages and tobacco products
ofd	Other food
cmt	Meat from cattle and other ruminants
mil	Dairy products
omt	Other meat products

Table A.1 (c)

Energy production sectors in the Future Agricultural Resources Model

GTAP symbol	Description
ecoa	Coal
eoil	Crude oil
egas	Natural gas
ec_p	Refined coal and petroleum products
eely	Electricity

Table A.1 (d)

Energy-intensive industries in the Future Agricultural Resources Model

GTAP symbol	Description
lum	Wood products
ppp	Paper and pulp
crp	Chemicals, rubber, and plastic
nmm	Nonmetallic minerals
i_s	Iron and steel
nfm	Nonferrous metals

net of tax and transport margins. The GTAP data distribution includes supplemental energy quantity data aggregated from detailed IEA energy balances, which provide sufficient energy information for calculating carbon dioxide emissions from energy combustion.

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

Dedicated biomass production is introduced as a new field crop, which is then combusted in a bio-electricity activity. Biomass therefore becomes a link between agricultural and energy systems.

CGE Framework

New tools and data have become available since the first version of FARM was constructed in the early 1990s, most notably the GTAP data set (Hertel, 1997) and tools for using GTAP data in the General Algebraic Modeling System (GAMS) programming language (Rutherford, 2010). Therefore, development of the new FARM model did not start from scratch: the starting point was code in GAMS provided by Rutherford (2010). This software provides a comparative-static global CGE model fully compatible with GTAP 7 social accounts and bilateral trade between world regions. The software also provides utilities for converting GTAP 7 data into the GAMS programming environment.

The FARM model is solved using the PATH solver in GAMS, with each model equation paired with a model variable (see table A.2). 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.

Demand

An economic simulation of per-capita food consumption relies on behavioral parameters, especially income and price elasticities. A study by ERS (Muhammad et al., 2011) addresses the question: How is an additional dollar of income split among various food commodities? The authors of this study estimated income and price elasticities using data from the International Comparison Program (ICP) of the World Bank. These data clearly show a declining share of food in an extra dollar of total expenditure across countries ranked from low to high per capita income. Further, cereals are a declining share of marginal food expenditure as per capita income increases. This study provides

Table A.2
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

empirical support for income elasticities that can be used in economic models such as FARM.

Consumer demand for individual commodities is calculated using the Linear Expenditure System (LES). Equations (A.1) and (A.2) are based on Sydsaeter et al. (2010). The LES is derived from a shifted Cobb-Douglas utility function.

$$u(\mathbf{x}) = \prod_{i=1}^{n} (x_i - \gamma_i)^{\beta_i} \qquad \beta_i > 0 \qquad \sum_i \beta_i = 1 \tag{A.1}$$

Demand for an individual commodity is given by

$$x_i(\mathbf{p}, m) = \gamma_i + \frac{1}{p_i}\beta_i\left(m - \sum_i p_i\gamma_i\right) \tag{A.2}$$

The beta parameters are value shares of income remaining after minimum quantities of each commodity have been purchased. Income elasticities of demand and own-price elasticities of demand can be calculated from Equation (A.2) by differentiating with respect to income (A.3) and prices (A.4), respectively.

$$\varepsilon_{im} = \frac{\beta_i m}{p_i x_i} = \frac{\beta_i}{S_i} \tag{A.3}$$

$$\varepsilon_{ii} = -\frac{\beta_i}{p_i x_i}\left(p_i\gamma_i + m - \sum_k p_k\gamma_k\right) \tag{A.4}$$

Base-year calibration requires setting the gamma and beta parameters in (A.2) so that FARM replicates base-year data from GTAP, including value shares for each commodity in total expenditure *m*. A convenient method of calibration is to set the ratio γ_i / x_i , and then β_i parameters are calculated to match GTAP value shares. The ratio γ_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 Linear Expenditure System: once the ratio γ_i / x_i is set, then income and own-price elasticities are already determined. Levels of the ratio γ_i / x_i close to 1 imply low income and own-price elasticities.

Over the timeframe of FARM simulations, per capita income grows very fast in regions such as China and India. Given the evidence of declining income shares of food products as per capita income increases, we allow income and price elasticities to decrease over time by allowing the gamma and beta parameters to change over time. The ratio γ_i / x_0 varies over time, and we specify this ratio for the base-year of 2004 and the final simulation year of 2054. We also allow the beta parameters for agricultural products to decrease over time by setting an annual percentage rate of decline.

Supply

Each production sector is modeled as a nested constant-elasticity-of-substitution (CES) production function as shown in figure A.1. 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. CES substitution elasticities increase from the top of the CES tree to the bottom ($\sigma_Y < \sigma_D < \sigma_M$ and $\sigma_Y < \sigma_{VA}$).

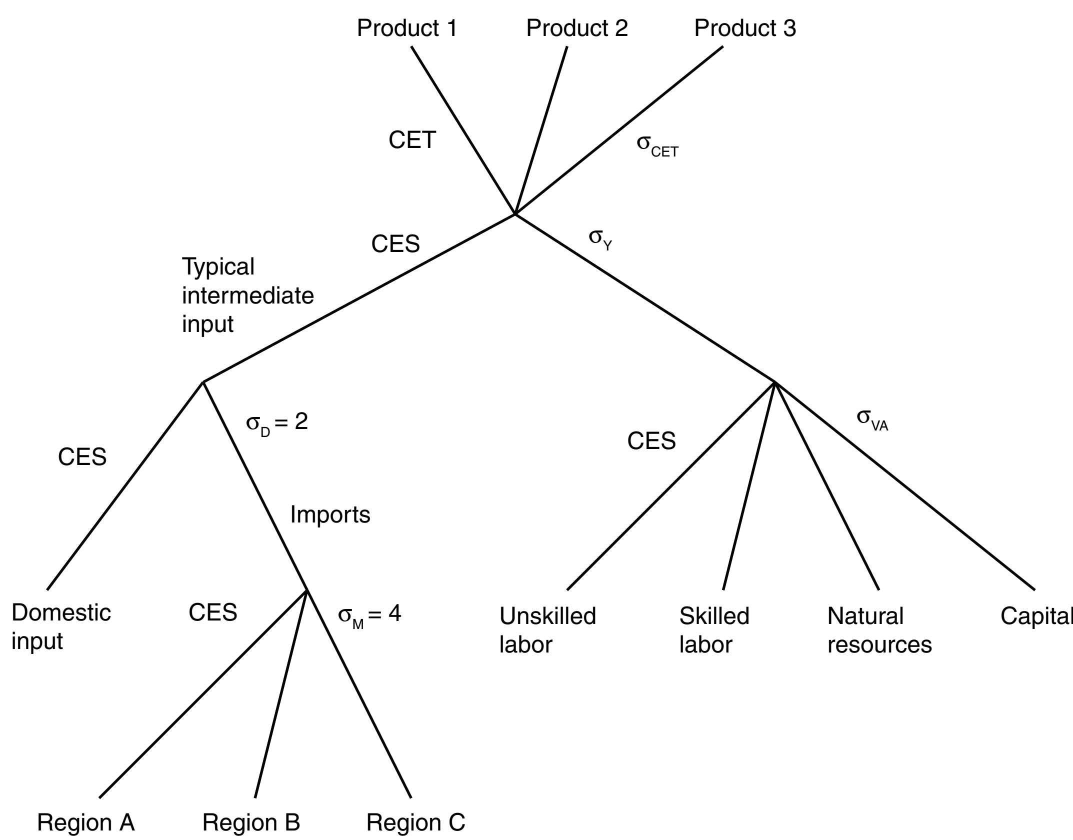
Output from each production activity passes through a constant-elasticity-of-transformation (CET) function before it can be consumed or exported. A CET function has the same functional form as a CES production or cost function but with an elasticity less than or equal to zero. Most production activities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

Four elasticities determine the rates of substitution in each production function: σ_Y is the substitution elasticity in the top nest; σ_{VA} is the elasticity in the value-added nest; σ_D is the substitution elasticity between domestic production and aggregate imports; σ_M is the elasticity across imports. This nesting structure embodies the Armington assumption, where products are distinguished by country of origin (Armington, 1969).

More complex production structures can be created by combining two or more generic production structures connected by an intermediate product. A good example is electricity generation, where the outputs of each generating technology are combined into a CES nest (fig. A.2). Each electricity

Figure A.1

Generic production structure in the Future Agricultural Resources Model (FARM)

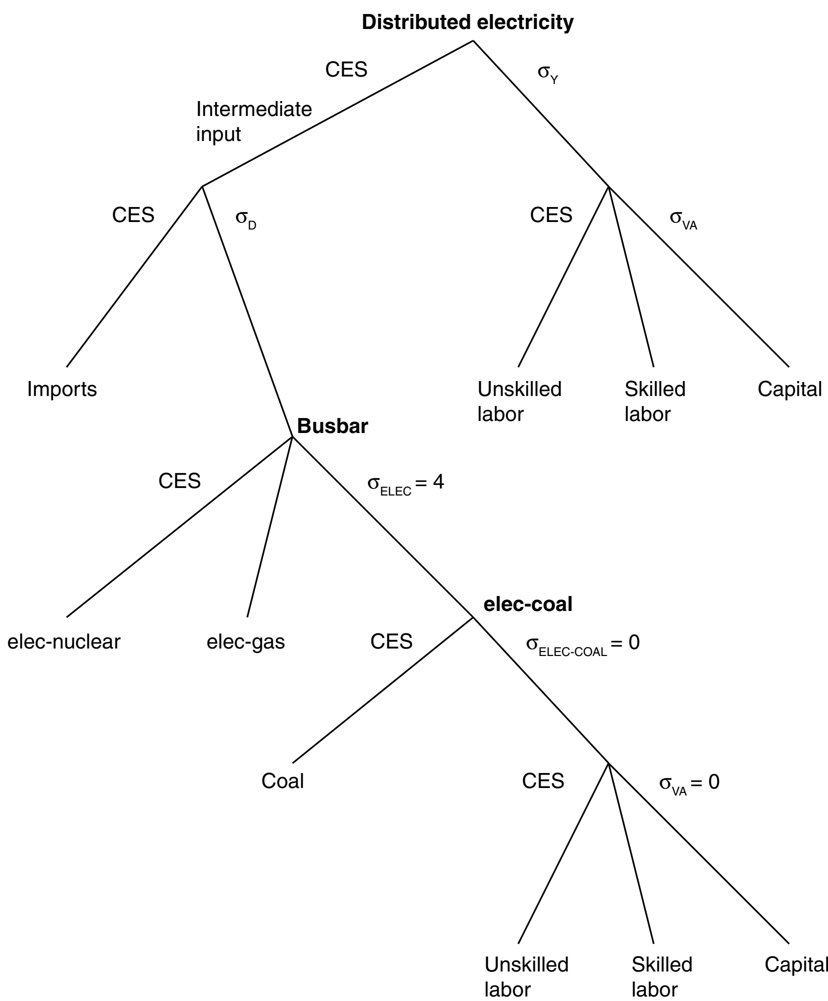


FARM = Future Agricultural Resource Model. CES = constant elasticity of substitution.
Source: USDA, Economic Research Service.

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 of the 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.2 combines three production activities, where each activity is a special case of the generic production structure of figure A.1.

The FARM model has been extended in many ways beyond the model in Rutherford (2010): conversion from comparative-static to a dynamic-recursive framework with 5-year steps; conversion of the consumer demand system from CES to the Linear Expenditure System (LES); allowing for joint

Figure A.2
Electricity generation and distribution in the Future Agricultural Resources Model (FARM)



FARM = Future Agricultural Resources Model. CES = constant elasticity of substitution.
Source: USDA, Economic Research Service.

products in production functions; introduction of land classes for agricultural and forestry production; and introduction of electricity-generating technologies.

Technical Change

We use technical change parameters to construct a plausible global reference scenario for energy, agriculture, and land use through 2050. All technical change parameters are input-specific and are considered as input augmenting. For example, labor productivity parameters are used to produce Gross Domestic Product (GDP) pathways for each region that closely approximate target pathways from Shared Socio-economic Pathways (SSPs). These parameters vary over four dimensions: model time step, input to production, production sector, and world region.

Land-augmenting technical change parameters are taken directly from the AgMIP reference scenario. Capital-augmenting technical change is set to zero for all production sectors and regions, with two exceptions: electricity from wind and electricity from solar. The efficiency of energy use by production sectors is set exogenously to provide plausible scenarios of energy consumption by energy carrier: coal, refined petroleum, natural gas, and electricity.

Each nest in a constant-elasticity-of-substitution production function can be written as,

$$q(\mathbf{x}) = a_0 \left[\sum_{i=1}^{N} (\alpha_i x_i)^{\rho} \right]^{1/\rho} \tag{A.5}$$

Where output q is a function of inputs **x** and technical coefficients a_0 through a_N, and N is the number of inputs to production. Rho is a parameter that determines the elasticity of substitution according to

$$\sigma = 1/(1-\rho) \tag{A.6}$$

The dual CES cost function for a nest is

$$g(\mathbf{p}) = \frac{1}{a_0} \left[\sum_{i=1}^{N} \left(\frac{p_i}{\alpha_i} \right)^{r} \right]^{1/r} \tag{A.7}$$

where $\sigma = 1/(1-\rho)$ and p_i is an element of the price vector **p**. (A.8)

All of the alpha parameters in the CES production function can be specified to have an independent growth rate during each 5-year step. This is similar to the Autonomous Energy Efficiency Improvement (AEEI) parameter used in some energy models; but in FARM, exogenous rates of technical change can be specified for any input to production. For example, the labor productivity parameter is used primarily for calibrating FARM to a GDP growth path. The energy productivity parameters are then used to adjust energy consumption. An increase in the alpha parameter represents increasing technical efficiency. Equation (A.9) describes the evolution of alpha parameters through 5-year steps.

$$\alpha_{ij}(T) = \overline{\alpha}_{ij} \prod_{S=1}^{T} (1 + g_{ij}(S))^{NSTEP} \tag{A.9}$$

T is an integer that represents the model time step, where T=1 during the base year of 2004. Since the model runs in 5-year steps, T=2 represents 2009. If t is the number of years since 2004, then

$$t = T \times NSTEP$$

The flexibility provided by non-neutral technical change is used extensively for calibrating a reference scenario in FARM.

Technical change is neutral if all of the alpha parameters from Equation (A.9) change at the same rate. This can also be accomplished by changing only the a_0 parameter and leaving the other a parameters constant.

$$\alpha_{0j}(T) = \overline{\alpha}_{0j} \prod_{S=1}^{T} (1 + g_{0j}(S)^{\ NSTEP} \tag{A.10}$$

Agricultural Productivity

Each land-using production function (e.g., wheat, rice, coarse grains) has a technical coefficient associated with each land class that varies over time. A reference scenario was constructed for this report using exogenous changes in yield through 2050 provided through the AgMIP project by the International Food Policy Research Institute (IFPRI). These changes in yield were applied only to the land input, as land-augmenting technical change. Crop yield is also influenced in FARM by changes in prices of agricultural products and inputs to agricultural production. Therefore, simulated crop yield in FARM is a combination of exogenous and price-induced effects.

IFPRI has constructed yield projections through 2050 for a reference scenario and eight climate impact scenarios. These scenarios of yield growth are used by 10 global economic modeling teams in AgMIP project, including FARM. The climate impact scenarios are based on output from two climate models and several crop growth models.

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 7 database distributed by Purdue University includes supplemental data on physical quantities from the Food and Agriculture Organization (FAO). The base year is 2004, and the GTAP data set 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 data set provides land use by 18 agro-ecological zones (AEZs). See Monfreda et al. (2009) for background on construction of AEZs for GTAP. Lee et al. (2009) provide a description of the land use database provided by GTAP. FARM operates with 6 land classes in each region, which are aggregates of the 18 AEZs provided in GTAP land-use data. The six land classes represent area partitioned by length of growing season, which is a function of temperature and water supply.

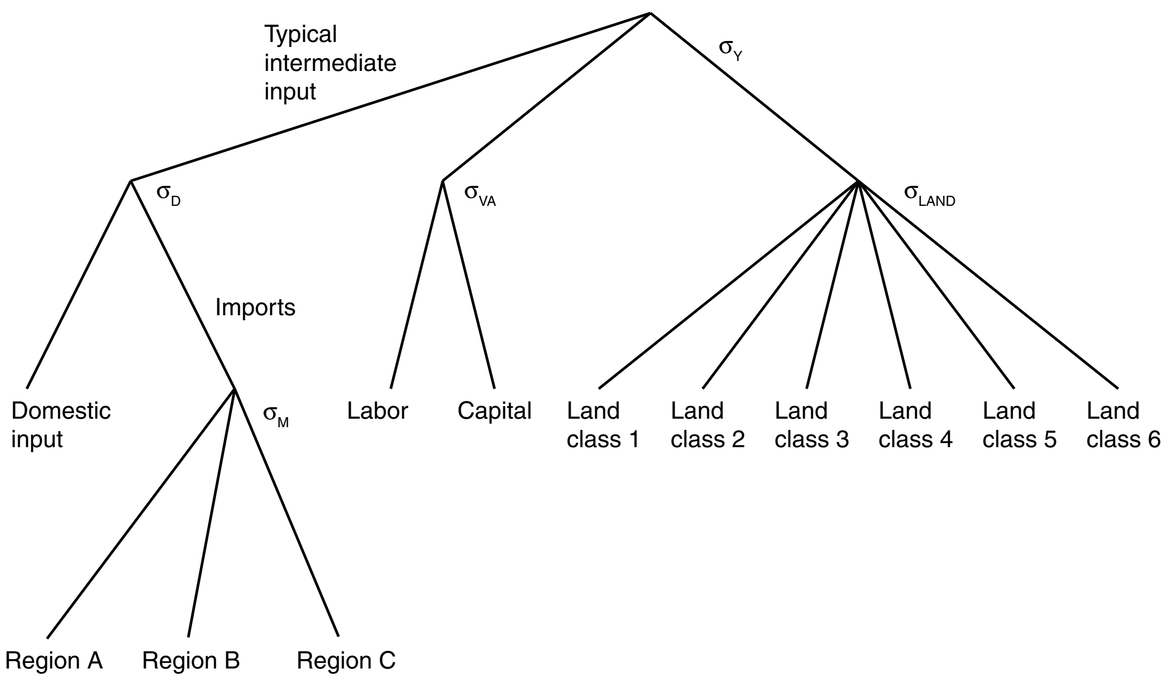
The FARM production structure with land as an input is shown in figure A.3. Each of 6 land classes allocates land to 1 of 10 land-using production sectors: 5 field crops, 3 other crop types, pasture for ruminant animals, and managed forests. Within each land-using production sector, land from six land 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.

Hertel et al. (2009a) provide a discussion of land use in CGE models using GTAP land-use data. The most common approach is to have land allocated from each land class by 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 quantities of land allocated to production sectors. Land values are preserved, but land quantities are not.[20]

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. For this FARM application, we consider each land class as a mobile primary factor with a market-clearing condition. Market clearing assures that land quantities are preserved. σ_{LAND} is less than one to limit movement of land between land classes.

The nesting structure for animal feed is shown in figure A.4, which is a special case of figure A.3. Feed for ruminant animals is a combination of pasture and crops.

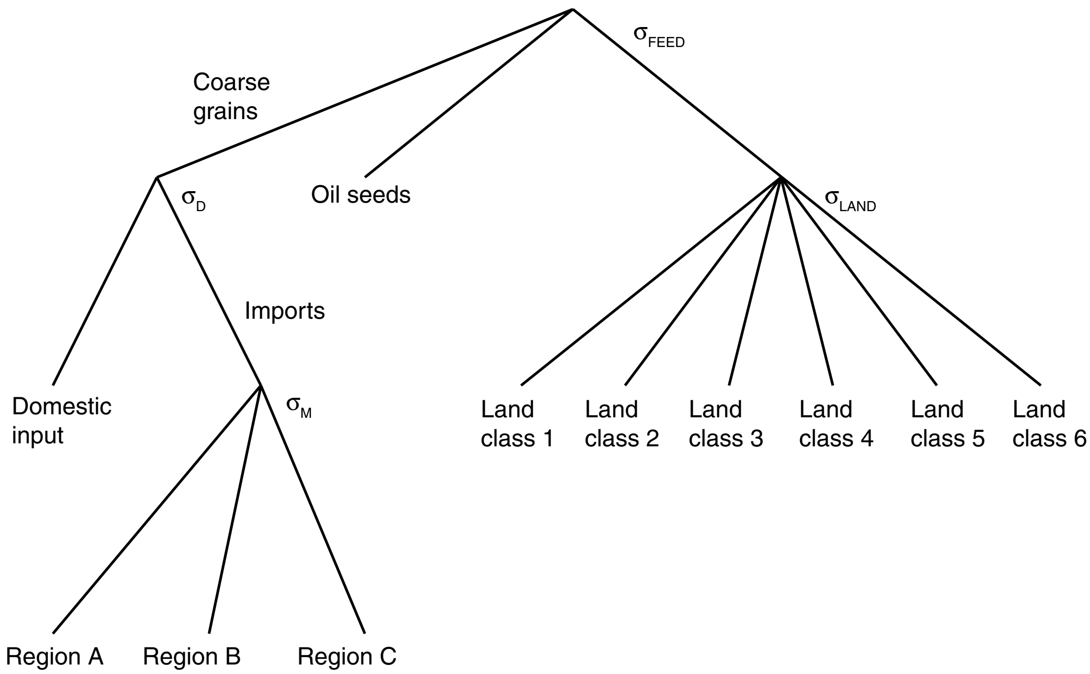
Figure A.3
Production structure for crops and forestry



Source: USDA, Economic Research Service.

[20] An alternative land allocation structure that preserves land quantities is described in Sands and Leimbach (2003). This has been used successfully in a partial equilibrium framework.

Figure A.4
Feed production structure for ruminant animals



Source: USDA, Economic Research Service.

Substitution elasticities in FARM

Four types of substitution elasticities are used in the FARM generic production structure. These elasticities are listed in table A.3 for primary and secondary agricultural products. Primary agriculture consists of eight crops or crop types, ruminant animals, non-ruminant animals, and dairy. Secondary agriculture consists of crops or animal products processed for final consumption. These elasticities are constant over time and across world regions.

σ_M is an Armington elasticity that determines the substitutability of the same type of product imported from other world regions. σ_D is an Armington elasticity that distinguishes domestic products from the Armington import aggregate. The GTAP 7 database includes suggested values for σ_M and σ_D, which vary by product. These elasticities are all greater than 1, with some much greater than 1. For FARM, we have set these elasticities to be the same across products but within the range of elasticities suggested by GTAP.

For primary agriculture, we have split the value-added nest into two parts: one nest for labor and capital and the other nest for land inputs (fig. A.3). For this reason, values of σ_{VA} in FARM are not directly comparable to suggested values in the GTAP data set. σ_{LAND} equals 0.4 in all production structures that use land. σ_Y then becomes the parameter that determines substitution between land and other inputs. In the ruminant feed production structure (fig. A.4), σ_{FEED} is set to 1.5 to allow substitution between pasture and feed crops.

Table A.3
Substitution elasticities in the Future Agricultural Resources Model (FARM)

	sigma(Y)	sigma(VA)	sigma(D)	sigma(M)
Paddy rice	0.20	0.80	2.00	4.00
Wheat	0.20	0.80	2.00	4.00
Other grains	0.20	0.80	2.00	4.00
Vegetables, fruits, nuts	0.20	0.80	2.00	4.00
Oil seeds	0.20	0.80	2.00	4.00
Sugarcane, sugar beet	0.20	0.80	2.00	4.00
Plant-based fibers	0.20	0.80	2.00	4.00
Other crops	0.20	0.80	2.00	4.00
Cattle, sheep, goats	0.80	0.40	2.00	4.00
Nonruminant animals	0.80	0.40	2.00	4.00
Raw milk	0.80	0.40	2.00	4.00
Bovine meat products	0.00	0.40	2.00	4.00
Other meat products	0.00	0.40	2.00	4.00
Vegetable oils and fats	0.00	0.40	2.00	4.00
Dairy products	0.00	0.40	2.00	4.00
Processed rice	0.00	0.40	2.00	4.00
Sugar	0.00	0.40	2.00	4.00
Other food products	0.00	0.40	2.00	4.00
Beverages and tobacco	0.00	0.40	2.00	4.00

Income and own-price elasticities of demand in FARM

Income and own-price elasticities for consumers are derived from the Linear Expenditure System (LES) and are set indirectly through LES parameters. Unlike substitution elasticities, income and own-price elasticities vary by world region and over time. Income elasticities and own-price elasticities for the fourth model time step (year 2019) are shown in tables A.4 and A.5, respectively.

Income elasticities for all agricultural products are very low in developed countries such as the United States. Income elasticities for developing countries are greater but converge over time toward elasticities in the United States. These elasticities are set using modeler's judgment to be qualitatively consistent with Muhammad et al. (2011).[21]

Once income elasticities are set in the LES, no degrees of freedom remain and own-price elasticities of demand follow immediately (table A.5). If the value share of consumption is small for a commodity, then the own-price elasticity of demand is close to the income elasticity of demand in absolute value.[22]

[21] The GTAP project provides a set of target income elasticities that are much higher for meat and processed food, even for the United States.

[22] GTAP also has a set of target price elasticities by commodity and world region. However, some combinations of GTAP income and own-price elasticities are impossible using the Linear Expenditure System.

Table A.4

Income elasticities of demand in the Future Agricultural Resources Model, 2019

	USA	Brazil	Former Soviet Union	India	China
Paddy rice	0.00	0.00	0.00	0.21	0.32
Wheat	0.00	0.27	0.30	0.30	0.40
Other grains	0.00	0.26	0.28	0.25	0.40
Vegetables, fruits, nuts	0.16	0.26	0.29	0.24	0.32
Oil seeds	0.15	0.27	0.29	0.24	0.00
Sugarcane, sugar beet	0.00	0.00	0.31	0.23	0.00
Plant-based fibers	0.15	0.26	0.31	0.25	0.00
Other crops	0.16	0.27	0.00	0.24	0.00
Cattle, sheep, goats	0.15	0.27	0.30	0.00	0.42
Nonruminant animals	0.15	0.27	0.30	0.29	0.41
Raw milk	0.15	0.35	0.30	0.27	0.00
Bovine meat products	0.16	0.32	0.41	0.51	0.30
Other meat products	0.15	0.31	0.40	0.00	0.26
Vegetable oils and fats	0.16	0.30	0.43	0.34	0.24
Dairy products	0.16	0.32	0.39	0.45	0.29
Processed rice	0.16	0.32	0.40	0.41	0.22
Sugar	0.16	0.37	0.42	0.32	0.25
Other food products	0.16	0.34	0.40	0.41	0.26
Beverages and tobacco	0.22	0.40	0.40	0.45	0.30

Table A.5

Own-price elasticities of demand in the Future Agricultural Resources Model, 2019

	USA	Brazil	Former Soviet Union	India	China
Paddy rice	0.00	0.00	0.00	-0.16	-0.29
Wheat	0.00	-0.24	-0.24	-0.22	-0.36
Other grains	0.00	-0.24	-0.23	-0.18	-0.36
Vegetables, fruits, nuts	-0.14	-0.23	-0.23	-0.18	-0.29
Oil seeds	-0.14	-0.24	-0.23	-0.18	0.00
Sugarcane, sugar beet	0.00	0.00	-0.25	-0.17	0.00
Plant-based fibers	-0.14	-0.24	-0.25	-0.18	0.00
Other crops	-0.14	-0.24	0.00	-0.18	0.00
Cattle, sheep, goats	-0.14	-0.24	-0.24	0.00	-0.38
Nonruminant animals	-0.14	-0.25	-0.24	-0.21	-0.37
Raw milk	-0.14	-0.31	-0.24	-0.20	0.00
Bovine meat products	-0.14	-0.29	-0.33	-0.37	-0.27
Other meat products	-0.14	-0.28	-0.32	0.00	-0.24
Vegetable oils and fats	-0.15	-0.27	-0.34	-0.25	-0.22
Dairy products	-0.15	-0.29	-0.31	-0.33	-0.26
Processed rice	-0.15	-0.29	-0.32	-0.30	-0.20
Sugar	-0.15	-0.34	-0.34	-0.23	-0.22
Other food products	-0.15	-0.30	-0.32	-0.30	-0.23
Beverages and tobacco	-0.20	-0.36	-0.32	-0.33	-0.27

Appendix B. Decomposition Methodology

A change in a multiplicative relationship can be decomposed into additive components using logarithms. In this case, the change is over time, but the decomposition can also be calculated between two scenarios at a point in time. We use the logarithmic mean Divisia index (LMDI) as described by Ang (2005) to decompose changes in supply and demand of agricultural products into explanatory components. For each agricultural product, supply equals area times yield, and demand equals population times per capita consumption. The demand component for per capita consumption is renamed "income" in this report.

$$Supply = Area \times Yield$$

$$\Delta Supply = S^T - S^0 = \Delta S_{area} + \Delta S_{yield} \tag{B.1}$$

where

$$\Delta S_{area} = \frac{S^T - S^0}{\log S^T - \log S^0} \log\left(\frac{Area^T}{Area^0}\right) \tag{B.2}$$

$$\Delta S_{yield} = \frac{S^T - S^0}{\log S^T - \log S^0} \log\left(\frac{Yield^T}{Yield^0}\right) \tag{B.3}$$

$$Demand = Population \times Consumption\ (per\text{-}capita)$$

$$\Delta Demand = D^T - D^0 = \Delta D_{population} + \Delta D_{income} \tag{B.4}$$

where

$$\Delta D_{population} = \frac{D^T - D^0}{\log D^T - \log D^0} \log\left(\frac{Pop^T}{Pop^0}\right) \tag{B.5}$$

$$\Delta D_{income} = \frac{D^T - D^0}{\log D^T - \log D^0} \log\left(\frac{Cons^T}{Cons^0}\right) \tag{B.6}$$