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Climate-Induced Yield Changes and TFP: How Much R&D Is Necessary To Maintain the Food Supply?

Jayson Beckman, Fengxia Dong, Maros Ivanic, Jonas Jägermeyr, and Nelson Villoria

STRATEGIC PRIORITIES
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Abstract

Increasing agricultural productivity is vital to ensure that global food demand can be met. However, the impact of a changing climate on temperatures and precipitation could potentially influence agricultural productivity by affecting crop yields. This report combines the latest estimates of yield changes from the Agricultural Model Intercomparison and Improvement Project with projections of future productivity changes in the form of total factor productivity (TFP) to gain a better understanding of the future of agricultural production (and thus of food supply). Yield estimates are used from a high greenhouse gas emissions scenario (to show an upper bound, as the impact of climate on yields is the strongest) for corn, rice, soybeans, and wheat. Yield changes are then combined with TFP estimates across four scenarios where research and development (R&D) assumptions determine the rate of TFP growth. Finally, the changes in yields and TFP, in conjunction with changes in populations and incomes, are assessed to shape the projected state of food supply in 2050. The results suggest that with no additional R&D expenditures, climate change would result in a production-consumption gap. When R&D investments are increased by amounts corresponding to the remaining three scenarios, TFP growth is sufficient to mitigate the impacts of climate change and projected population/income growth to maintain production at a level to meet global demand for food.

Keywords: agricultural productivity, Total Factor Productivity, TFP, climate change, crop yields (bushels per acre), corn, soybean, rice, wheat, trade

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Contents

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A report summary from the Economic Research Service *July 2024*

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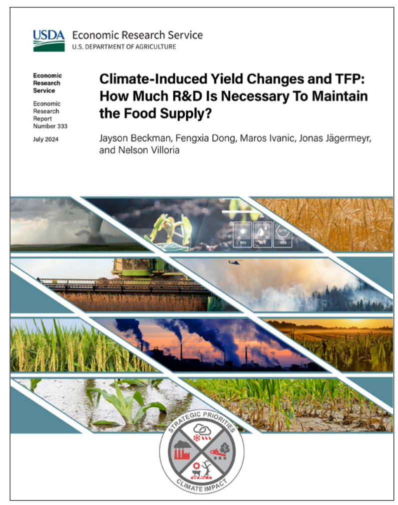


What Is the Issue?

A rising global population—with changing diets and an increasing demand for animal-based products, along with a changing climate—puts pressure on both the existing and future global food supplies. A changing climate could lead to warming temperatures and an increased likelihood of extreme weather events such as droughts and floods, impacting agricultural productivity and crop yields. Reduced crop yields diminish agricultural productivity, affecting not only agricultural quantities but also food prices and ultimately food security. This challenge arises at a time when increasing incomes contribute to an increased demand for food—especially for meat, where crops are a crucial input for animal feed. While increasing agricultural productivity through total factor productivity (TFP)—a measure of the efficiency with which agricultural inputs are combined to produce output—could help mitigate any yield decreases, this comes at a monetary expense in the form of research and development (R&D) needed for achieving it.

What Did the Study Find?

The objective of this study is to further understand the future of the agricultural food supply and demand under climate change. To do so, we first use two pieces of literature to summarize yield and TFP projections to understand the impacts of climate change on the global food supply.

- Most past research shows a climate-induced decline in yields globally for corn only. In contrast, rice, soybeans, and wheat yields all are expected to experience an increase, with wheat particularly benefiting from improved yields in land in higher latitudes. In the United States, research shows declines in yields for corn and soybeans, but increases in wheat by 2050 as a result of climate change.

The global supply of corn, rice, soybeans, and wheat varies by the R&D assumptions and the subsequent changes in TFP.

- Under the scenario of no additional R&D expenditures, global production for all four crops increased. The increase is smallest for corn—5.2 percent compared with more than 22 percent for other crops.
- Wheat production was estimated to increase the most.

Total agricultural production across the four crops is estimated to increase in the United States across all R&D scenarios, but impacts to crops are different.

- U.S. corn production decreases if no additional R&D expenditures are made (beyond 2016 expenditures)—from 385 million metric tons in 2016 to 352 million metric tons in 2050. Production for the other three crops is estimated to increase, although at a slower rate than the global change.

After reviewing the previous research, USDA, ERS researchers used global estimates of population and gross domestic product to project changes in food demand. Half of corn and three-quarters of soybeans were assumed to be used for feed, while rice and wheat were assumed to be directly consumed as food. Combining these demand estimates with supply (from TFP and yields), the production-consumption gap for the four crops was calculated.

- If no additional R&D expenditures are made (beyond 2016 expenditures), then TFP growth would be insufficient to meet global demand for the four crops.
- TFP growth in the other scenarios, which consider various degrees of R&D expenditures, is shown to be able to keep pace with global demand.
- The United States, a major exporter of the four crops, could experience a decrease in the country's production-consumption gap if R&D expenditures are small.

How Was the Study Conducted?

To assess the potential impact of climate change on food supply and demand, yield change estimates were determined for corn, rice, soybeans, and wheat, referred to as the Global Gridded Crop Model Intercomparison yields, as provided by Jägermeyr et al. (2021). These estimates were based on climate projections from global climate models and global gridded crop models. Estimates were used from a climate change scenario of Representative Concentration Pathways, a characterization of how greenhouse gases will change in the future (RCP) 8.5, and from Shared Socioeconomic Pathways, which projected socioeconomic global changes (SSP) 5. This scenario projects high greenhouse gas emissions. The yield changes were combined with TFP estimates across four scenarios (data are from Fuglie et al., 2022), where R&D assumptions determine the rate of TFP growth. While many climate projections extend until 2100, the focus of this report is on 2050, as projection accuracy diminishes over longer timeframes. Following Beckman et al. (2023), averages around the timeframe of interest are provided. These averages helped smooth out any spikes in a given year that might have resulted from weather-related variations rather than climate-related changes. Data for 2048–52 were used for the average of 2050, and data for 1983 (the beginning of yield estimates) through 2016 served as the baseline (TFP projections start at 2016). How these food supply changes could impact agriculture was examined by considering how food demand might change by 2050 through changes in population and consumption.

Climate-Induced Yield Changes and TFP: How Much R&D Is Necessary To Maintain the Food Supply?

Introduction

Agricultural production has generally supplied the world with the food needed to feed the population (although famine and hunger are persistent in some areas and periodic in others, often due to climatic disturbances such as drought and flooding). A key driver behind this phenomenon is the continuous increase in agricultural outputs facilitated by the growth in total input use and improvements in total factor productivity (TFP). TFP measures the efficiency with which agricultural inputs (such as land, labor, capital, and material resources) are combined to produce output. According to data from Morgan et al. (2022), TFP in global agriculture consistently increased by a minimum of 2 percent annually from the 1960s until 2010, when the rate dropped below 2 percent to an average of 1.93 percent per year.

The Green Revolution represents a notable period (from around the 1940s to the 1960s) of heightened agricultural productivity, marked by grain yields increasing at a rate greater than human population growth (Ortez, 2022).[1] [2] Higher agricultural productivity implies that less land and fewer inputs (such as labor) are needed to produce the food the world needs (Ritchie et al., 2022). But an increasing global population (the United Nations states that it could reach 11 billion people by 2100 (Adam, 2021)) and a changing climate threaten to put pressure on the current and future food supply (Schmidhuber & Tubiello, 2007), highlighting the important role of agricultural productivity in sustaining agricultural production.

The success of the Green Revolution in increasing agricultural productivity can be attributed to various factors, prominently including yield improvements. Tillman (1999) noted that the careful selection of crop plant varieties tailored to local growing conditions can result in higher-yielding strains of crops and the ability to grow crops in many different regions of the world. Fuglie (2018) noted that the global diffusion of semi-dwarf varieties of rice and wheat during the Green Revolution led to varieties that had a greater yield response to fertilizer. As a result, Gollin et al. (2021) estimated that high-yielding crop varieties increased yields from 1965 to 2010 by 44 percent. However, it has been acknowledged that the rate of yield increase could decline as the most accessible and substantial gains from crop breeding programs have already been realized (Ruttan, 1999). Moreover, future agricultural productivity can be affected by changes in yields resulting from a changing climate. Relating climate change back to overall changes in TFP, Ortiz-Bobea et al. (2021) indicated that climate change has reduced the growth in global agricultural TFP by 21 percent from 1961 to 2016, with more severe impacts in warmer regions such as Africa and Latin America and the Caribbean.

The connection between climate and yields is important, as Ray et al. (2015) estimated that climate variation accounts for a third of global crop yield variability. Estimates from the Global Gridded Crop Model Intercomparison (GGCMI) indicate that shifts in yields due to climate change could happen sooner (within the next 20 years) than previously projected (Jägermeyr et al., 2021). Numerous studies (e.g., Challinor et

[1] As a reviewer points out, the increases in yields do not happen in a vacuum, but rather, there is usually some underlying factor related to TFP, such as technological change, technical efficiency, scale-and-mix efficiency, or favorable environmental factors.

[2] Since the Green Revolution, the next instance of increased yields has been deemed the "biorevolution" (Buttel et al., 1985), the Gene Revolution (Hamdan et al., 2022), or something akin to acknowledging that biotechnology has improved yields, especially in Argentina, Brazil, and the United States, countries that use biotechnology in crop production.

al., 2014; Porter et al., 2019; Zhao et al., 2017) concluded that rising temperatures will negatively affect global crop yields, with the impacts expected to differ across commodities. For example, Zhao et al. (2017) estimated that a +2 degree Celsius increase in global mean temperature from 2029 to 2058 would lead to a 3.3-percent reduction in global rice yields, 3.6 percent in soybeans, 6.9 percent in wheat, and 8.6 percent in corn. In addition, Proctor et al. (2022) noted that many climate models might be underestimating the potential yield decline. These models often focus on precipitation without accounting for soil moisture and neglect factors such as evaporation, infiltration, and runoff.

Fuglie and Echeverria (2023) discussed the link between yields and TFP, noting that changes in yield while holding inputs fixed can be considered a direct measure of TFP. The authors highlighted two effects of technical change: (1) a pure productivity effect, representing a shift in the production function, and (2) a competitiveness effect, where new technology increases the marginal product of other inputs, inducing farmers to use technology more, thereby further increasing output. Measures of TFP capture the pure productivity effect of technological change. Technologies that increase crop yield or reduce the inputs required to produce a given yield (leading to a decrease in the unit cost of output) contribute to an increase in TFP. This study aims to investigate how TFP can help mitigate climate-induced yield changes. To refine the focus on this issue, the authors deliberately omitted the competitiveness effect in this study and concentrated solely on the pure productivity effect.

Yield Changes

To assess how climate might affect crop yields in the future, data from Jägermeyr et al. (2021) were used to provide estimates of yields for corn, rice, soybeans, and wheat until 2099 (referred to as the GGCMI yields) based on climate models used by the Coupled Model Intercomparison Project Phase 6 (CMIP6).[3] These data are based on estimates from 5 global climate models (GCMs) and 12 global gridded crop models (GGCMs),[4] considering 2 different climate scenarios: (1) Representative Concentration Pathway (RCP) 2.6 and Shared Socioeconomic Pathway (SSP) 1, which reflect optimistic climate mitigation policies; and (2) RCP 8.5 and SSP 5, a scenario projecting high emissions (see box, "Yield Aggregations," for information on how to obtain these shocks). As each climate model runs its unique response of Earth's atmosphere to greenhouse gas emission (GHG) scenarios through 2100, estimates may vary across models based on individual assumptions on future GHG emissions. The crop models simulate how crops grow and respond to climate model inputs, including temperature, rainfall, and atmospheric carbon dioxide,[5] with each crop species' behavior grounded in biological responses observed in indoor and outdoor lab experiments. Given that this study focuses on how TFP can help mitigate climate-induced yield changes, the estimates from RCP 8.5 and SSP 5 are exclusively considered (see EPA (2022) for information on RCPs and Riahi et al. (2017) for information on SSPs). The analysis in this report highlights the trends in projected yield change over time, especially for the major producers of these commodities.

[3] The models used in Jägermeyr et al. (2021) note that improvements from the GCMs result in better representations of extreme events.

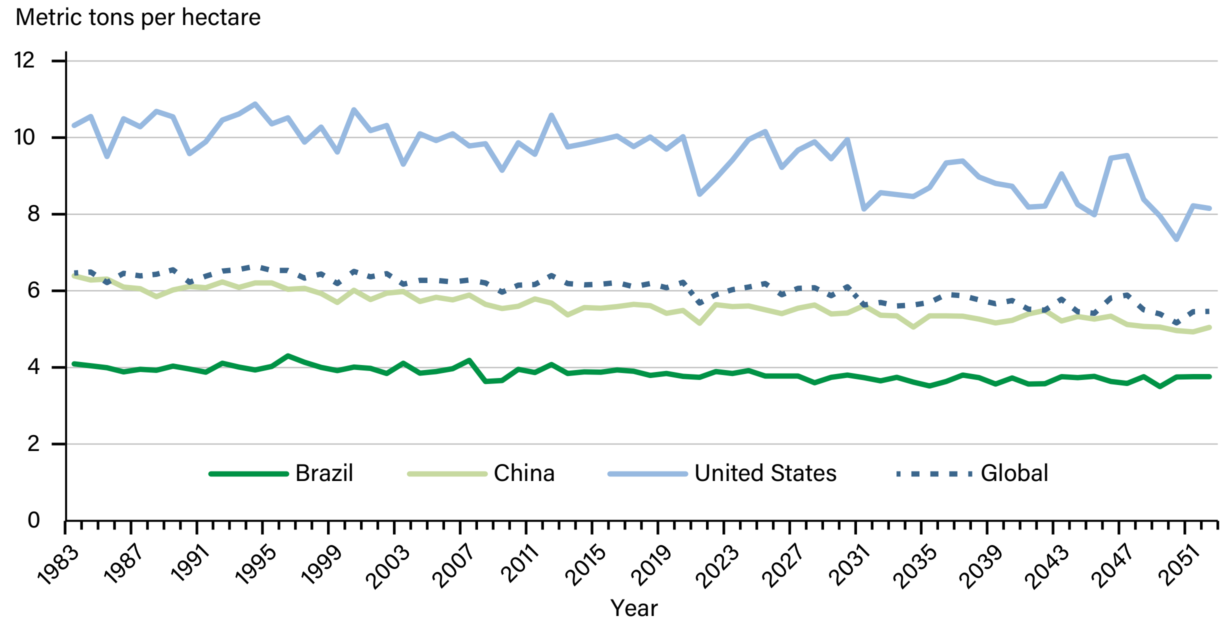
[4] Although there is the possibility of 60 estimates for each crop in each region, not all models have an estimate covering each possibility. However, most country/crop combinations have at least 40 estimates.

[5] Plants use carbon dioxide to grow as part of the photosynthesis process; thus, changes in atmospheric carbon dioxide can affect plants (this is noted as CO_2 fertilization). Taylor and Schlenker (2003) found that increased carbon dioxide (also known as the carbon dioxide fertilization effect) led to past yield gains. But Sneed (2018) surveyed experts, and their opinions were mixed—although a general conclusion was that increased carbon dioxide was beneficial to yields, but the effect gets saturated at some level and can turn harmful. The crop yields from Jägermeyr et al. (2021) did consider carbon dioxide fertilization, noting that the average effects in their data were in line with field experiments. Those studies mentioned earlier (Challinor etal., 2014; Porter et al., 2019; Zhao et al., 2017) exclude any changes in atmospheric CO_2 concentration.

Corn Yield Changes

The GGCMI ensemble mean, representing the average yield across the 12 crop models and 5 climate models, indicates that climate change could impact corn yields in the future. The global average for corn yield falls below the 6.3 metric tons per hectare (metric tons/ha) average observed from 1983–2016. The estimated global average for 2050 is 5.4 metric tons/ha, reflecting a 14.8-percent decrease from the baseline. It is important to note that the GGCMI results isolate the impacts of changing climate conditions on productivity but do not incorporate other potential sources of productivity change, which is addressed in the TFP section of this report. Jägermeyr et al. (2021) attributed this yield decline to adverse impacts in low-latitude regions, where climate projections exceed the optimal temperature thresholds for corn.

Figure 1
Estimated corn yields from GGCMI, 1983–2052



GGCMI = Global Gridded Crop Model Intercomparison.

Note: The estimated yield is the model ensemble mean across the 12 climate models and 5 crop models.

Source: USDA, Economic Research Service using data from Jägermeyr et al. (2023).

Yield Aggregations

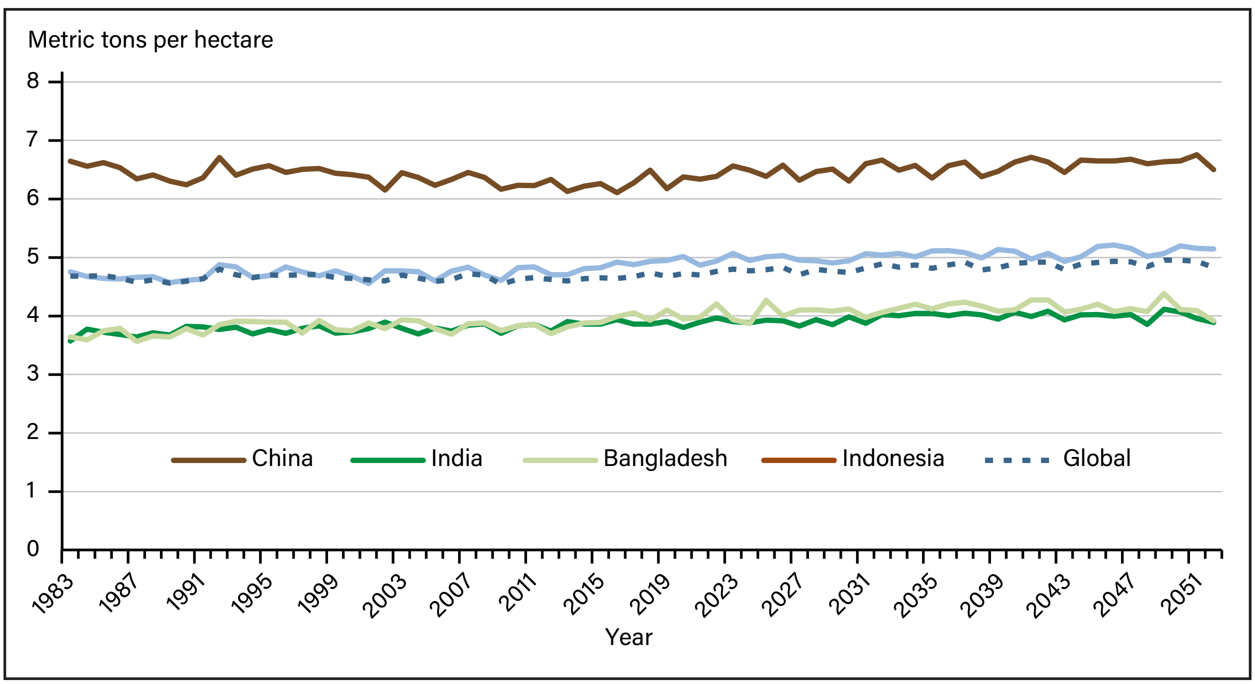
The Global Gridded Crop Model Intercomparison (GGCMI) project focuses on assessing climate change impacts, but the models do not consider the potential adaption of farmers to climate change. The baseline for these models spans from 1983–2013, with yields projected based on actual yields and climate conditions during that period. To align with total factor productivity (TFP) data, this study extended the baseline to 2016. The data are presented in the form of yield indices, each tracking the yield trajectory of individual crops in a 30 arc-minute grid cell as projected by each model. To provide estimates for this report at the country and global levels, a tool called the GGCMI-AgMIP Yield Data Aggregator Tool (Jägermeyr et al., 2023) was constructed. This tool not only provides the yield estimates across various crops and models but also allows users to aggregate the data based on agroecological zones (AEZs). AEZs classify land according to shared climate, precipitation, and moisture conditions (Avetisyan et al., 2010). Users can also aggregate the data to the country level or based on custom-defined criteria.

In 2021, the major corn producers (based on land allocation) were China (43.3 million hectares), the United States (34.5 million hectares), and Brazil (21.8 million hectares), and collectively accounted for 48 percent of the global corn cultivation area. Figure 1 presents the GGCMI estimates for corn yield changes in these three countries. It is noteworthy that U.S. corn yields are much larger than those of Brazil and China. According to USDA, Foreign Agricultural Service (FAS) (2023), U.S. yields in 2021 reached 11.1 metric tons/ha, while Brazil and China yields recorded 5.3 metric tons/ha and 6.3 metric tons/ha, respectively. But climate change is estimated to impact U.S. corn yields more severely than those of Brazil and China (figure 1). The data indicate that U.S. corn yields decrease by 26.1 percent in 2050 relative to the baseline (see appendix A for more detailed information on changes to the United States by AEZ). For Brazil, the change in corn yields for 2050 is -6.7 percent, while for China, it is -17.9 percent. Note that the GGCMI yields indicate that not all countries would be negatively impacted by corn yields due to climate change. However, those countries showing increases in yields tend to have a relatively small share of global land dedicated to corn.

Rice Yield Changes

Globally, rice ranked as the third-most-produced grain in 2021, totaling 514 million metric tons, following corn (1,216 million metric tons) and wheat (779 million metric tons). Oilseed production surpasses rice at 607 million metric tons. Figure 2 presents the data on rice yields, revealing a less-variable global yield compared with corn. The trajectory of future global corn yields was between 5 to 7 metric tons/ha, while rice yields stayed within 4.5 to 5 metric tons/ha. The coefficient of variation (CV), a measure of data dispersion around the mean, further indicates that corn yields are more variable, with a 6.0-percent CV for corn compared with the more stable 2.4-percent CV for rice. Although there were increases in climate-induced yield changes for rice up until 2050, the GGCMI estimates suggest that yields will decrease from their peak of 4.94 metric tons/ha after 2074. This trend is also pointed out by Jägermeyr et al. (2021), who noted a decline in rice (and soybeans) toward the end of the century.

Figure 2
Estimated rice yields from GGCMI, 1983–2052



GGCMI = Global Gridded Crop Model Intercomparison.

Source: USDA, Economic Research Service using data from Jägermeyr et al. (2023).

Rice is directly consumed as food and tends to be consumed in developing countries, leading it to be called the most important food crop of the developing world (Zeigler, 2017).[6] The leading rice producers in 2021 included China (149 million metric tons), India (129 million metric tons), Bangladesh (36 million metric tons), and Indonesia (34 million metric tons). They accounted for 60 percent of the total global rice cultivation area and 67.8 percent of rice production as of 2021. While the United States is a significant global exporter, it does not rank among the largest producers, contributing 6 million metric tons. Similar to the pattern observed with U.S. corn, the largest producer (China) boasts yields surpassing the global average (figure 2). Despite India dedicating more land to rice, its yields are nearly half those achieved by China. One reason for this is that China uses fertilizers in much greater amounts in rice production than the other featured producers.[7] The yield changes from the GGCMI reveal that similar to corn in the United States, China maintains the highest rice yields, with yields gradually approaching the world average. Specifically, the change in China's rice yields was 3.7 percent, while the global change was 5.4 percent. Notably, yields for the other major producers also experienced increases: 5.1 percent for India, 7.7 percent for Bangladesh, and 7.7 percent for Indonesia. Although Jägermeyr et al. (2021) did not focus on specific evidence by country (country-level aggregations provided in figures S5 and S6), they highlighted that rice was the only commodity experiencing a yield increase in the Tropics (see appendix B for U.S. results).

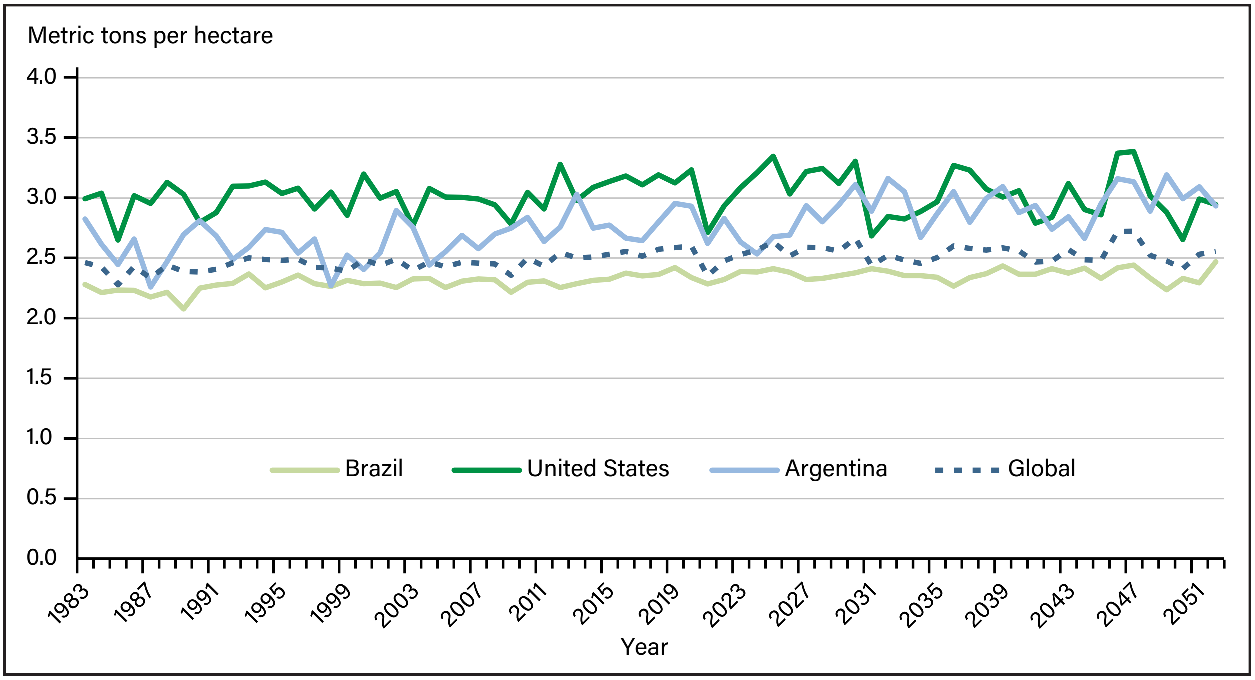
Soybean Yield Changes

Soybeans rank as the most globally produced oilseed. In 2021, they accounted for 358 million metric tons of the 607 million metric tons of total oilseed production (FAS, 2023). Soybeans are extensively traded in both the actual crop and the processed forms, such as soybean meal and oil (USDA, Economic Research Service (ERS), 2023). Figure 3 illustrates the projected changes in future soybean yields. The global change up to 2050 was 2.1 percent. Note that similar to rice, soybean yields exhibit a decline by the end of the century; however, we only considered changes to 2050. The coefficient of variation (CV) for the global changes up to 2050 was 3.35 percent, aligning more closely with the variability observed in rice than that in corn.

[6] Corn, oilseeds, and wheat are not directly consumed by humans in large amounts but are instead used as input for various food products.

[7] In 2013, China used 1,260 kilograms per hectare (kg/ha) of fertilizers on rice, while India used 563 kg/ha, Bangladesh used 136 kg/ha, and Indonesia used 348 kg/ha (Naher et al., 2019).

Figure 3
Estimated soybean yields from GGCMI, 1983–2052



GGCMI = Global Gridded Crop Model Intercomparison.
Source: USDA, Economic Research Service using data from Jägermeyr et al. (2023).

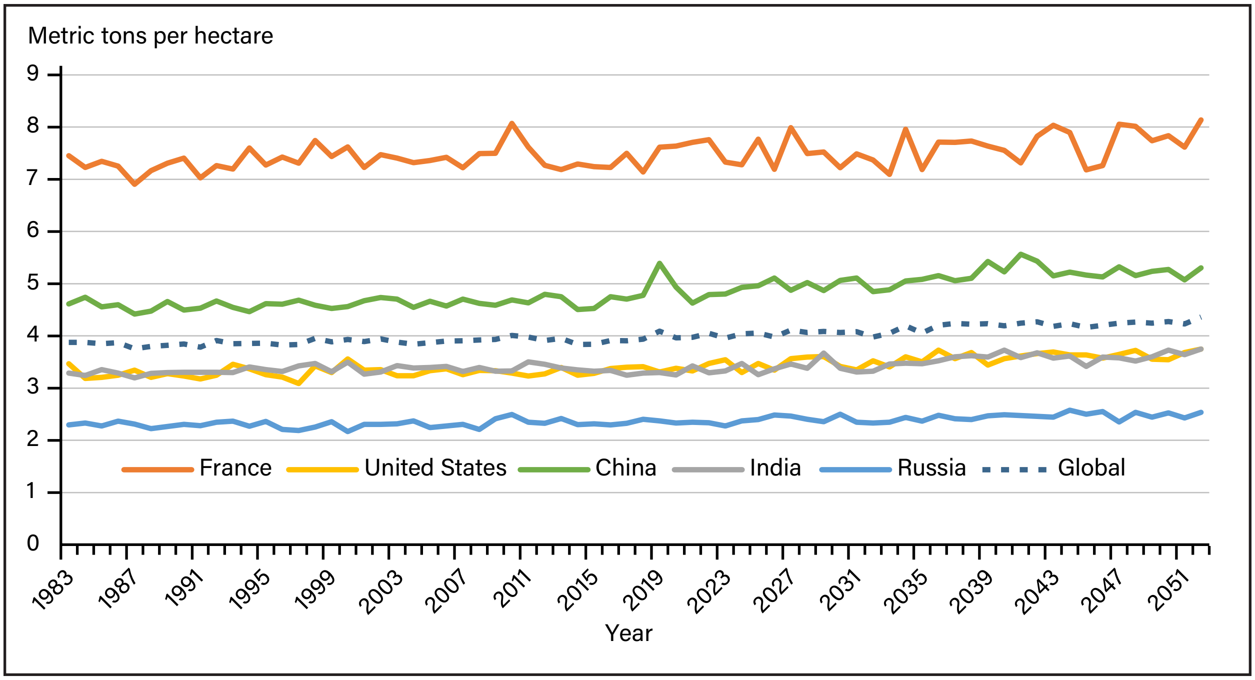
In 2021, the major producers in terms of land allocated to soybeans were Brazil (41.5 million hectares), the United States (34.9 million hectares), and Argentina (15.9 million hectares). Together, these countries accounted for 70 percent of the global land allocated to soybean cultivation. However, their contribution to production was even more substantial at 82.4 percent, achieving much higher yields compared with other major soybean-producing countries, such as India and China. The United States has historically had the highest soybean yields, recording actual yields of 3.5 metric tons per hectare (metric tons/ha) in 2021. In comparison, Argentina and Brazil reported yields of 2.8 metric tons/ha and 3.1 metric tons/ha, respectively, that same year. Only Turkey, a much smaller producer, surpassed the United States in yields at 3.9 metric tons/ha in 2021 (FAS, 2023). Yields were expected to increase 2.3 percent for Brazil and 12.6 percent for Argentina from 2014–52. However, yields for the United States were forecast to decrease by 3.7 percent over the same period. This change is in line with Beckman et al. (2023), who estimated a 3.0-percent decrease in U.S. soybean yields from 2016 to 2036[8] (see appendix for more specific U.S. results).

Wheat Yield Changes

Figure 4 presents the global yield changes for wheat, with a noteworthy observation that yields are estimated to increase up to 2050 (see box, "Wheat Estimates by GCM"). Globally, this increase was forecast to be 10.2 percent. Jägermeyr et al. (2021) attributed this increase to a strong response to CO_2 fertilization and the impact of climate change, which results in higher yields in high-latitude regions such as the northern United States and Canada.

[8] However, Beckman et al. (2023) estimated an increase in U.S. corn yields, which is not in line with the yields estimated from GGCMI.

Figure 4
Estimated wheat yields from GGCMI, 1983–2052



GGCMI = Global Gridded Crop Model Intercomparison.

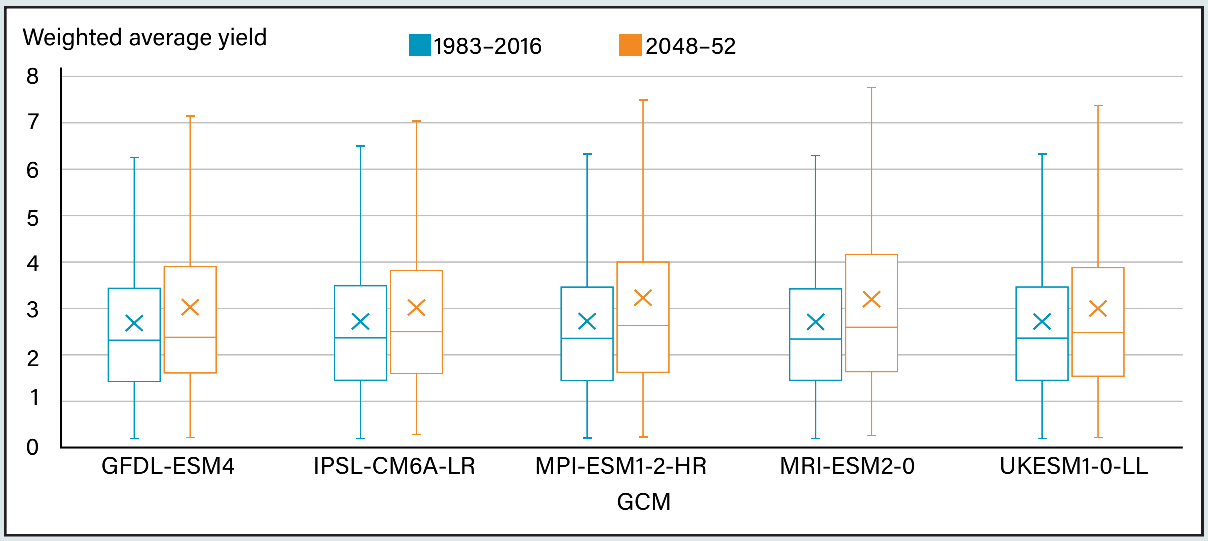
Source: USDA, Economic Research Service using data from Jägermeyr et al. (2023).

Wheat Estimates by GCM

The Global Gridded Crop Models Intercomparison dataset (GGCMs) is an ensemble of 12 crop models that utilize inputs from 5 global climate models (GCMs) to generate yield estimates. The simulations of yields occur under harmonized simulation protocols similar to those used by the climate change modeling community (Jägermeyr et al., 2021). Despite the harmonized protocols, each crop model is independent from the others and subject to its own uncertainty sources, especially regarding CO_2 fertilization (Müller et al., 2021). As noted in Jägermeyr et al. (2021) and following best practices in the climate modeling community (Wallach et al, 2016), it is best to use the average of these estimates, or ensemble mean, as the ensemble prediction of yield changes rather than considering each of the 60 possibilities from the combination of GGCMs and GCMs. Because our focus in this USDA, ERS 2024 report is on modeling the effects of the best prediction by the model ensemble, we do not undertake any model-level analysis. Indepth explorations of model-level uncertainty are provided by Müller et al. (2021). A discussion of the desirability of using ensemble-generated statistics is provided by Wallach et al., 2016. Box figure 1 presents a box plot for wheat yields as estimated by GCMs, comparing estimates from the baseline to the future. As the box figure 1 shows, the models predict similar estimates for wheat yields during the 1983–2016 time period. This alignment is expected given that GGCMs calibrate around identical historical yields up to 2013 (recall that 1983–2013 serves as the model's baseline), and the subsequent years (2014–2016) provide limited time for significant variation. However, variations in future yields exist across GCMs (2048–52). This is illustrated by both the average (depicted as an "x") and the horizontal bar in the middle of the box, representing the median. The box itself represents the quartiles of the data; its bottom denotes the lower quartile value, indicating where the first 25 percent of the data falls, while the top represents the upper quartile value. The box itself represents where the middle 50 percent of the data lies, and the vertical lines outside the box indicate points that fall beyond this range.

Box figure 1

Box plot for wheat yields by global circulation model (GCM) and years



Note: The x-axis refers to each of the GCMs used by Global Gridded Crop Model Intercomparison (GGCMI).

GFDL-ESM4 = Geophysical Fluid Dynamics Laboratory Earth System Model generation 4; IPSL-CM6A-LR = Institut Pierre-Simon Laplace Coupled Model phase 6-low horizontal resolution; MPI-ESM1-2-HR = Max Planck Institute Earth System Model version 1.2-higher resolution; MRI-ESM2.0 = Meteorological Research Institute Earth System Model version 2.0; UKESM1-0-LL = United Kingdom Earth Station Model-version 1.0-longitude/latitude.

Source: USDA, Economic Research Service using data from Jägermeyr et al. (2023).

Major global wheat producers in 2021 include China, with a production of 137.0 million metric tons, India with 109.6 million metric tons, Russia with 75.2 million metric tons, the United States with 44.8 million metric tons, and France at 33.2 million metric tons. The yields for these countries are shown in figure 4. Note that France starts with the highest yields and maintains significantly higher yields than other major producers. The United States has lower yields than the global average, which could be explained by hot-dry-windy events impacting historical yields (and, hence, future yield estimates) (Zhao et al., 2022).

Total Factor Productivity

Total factor productivity (TFP) measures the efficiency with which agricultural inputs (such as land, labor, capital, and material resources) are combined to produce output. It is generally regarded as a measure of overall agricultural productivity (see box, "International Comparisons of Agricultural Total Factor Productivity in Global Agriculture"). TFP growth is usually achieved through advancements in technologies, improved farming practices, specialization in commodities and farming systems that optimize local resources, and various strategies aimed at enhancing the efficiency of agricultural commodity production (Fuglie et al., 2024). Although TFP growth can help farmers produce more products with the same or fewer resources, TFP is highly dependent on investments in research and development (R&D) (Fuglie, 2018). R&D investments can originate from diverse sources, including public entities such as Government agencies and universities, private businesses, and nongovernmental, nonprofit agricultural research centers like the Consortium of International Agricultural Research Centers (CGIAR) (Fuglie, 2018). While the CGIAR consortium represents a relatively small fraction of total R&D expenditures (less than 1.5 percent of global public spending), its contributions have played a significant role in enhancing productivity, particularly in developing countries (Alston et al., 2006).

International Comparisons of Agricultural Total Factor Productivity in Global Agriculture

The USDA, Economic Research Service (ERS) International Agricultural Productivity data product measures agricultural TFP (total factor productivity) as an index (with a base year of 2015 = 100) for each county and region. Since each country's TFP is set to 100 in the year 2015, international comparisons of TFP are only feasible for the rate of TFP growth; the indices themselves do not facilitate comparisons of TFP levels across countries. To measure the rate of TFP growth (and the values of the annual index), USDA, ERS employs a two-step process. First, it calculates the rates of growth in total agricultural outputs and total agricultural inputs. Subsequently, the rate of TFP growth is derived as the difference between the growth rates of total output and total input.

Agricultural output is the aggregation of 199 agricultural commodities, including 160 crops, 31 animal products, and 8 aquaculture products. On the other hand, agricultural inputs comprise quantities of land, labor, capital, and intermediate inputs employed in production. Input quantities are aggregated into a composite input index using a cost-accounting procedure. The growth rate in total inputs is determined as the weighted average of the growth in each factor input, where the weights are factor cost shares. Factor shares for agricultural land, labor, capital, and intermediate inputs are compiled for each country and region from multiple sources (Fuglie, 2015).

This methodology facilitates the decomposition of output growth into two components: (1) the share of new output coming from changes in the quantities of the various inputs (or a combination of inputs) and (2) the share coming from increases in TFP.

It has been pointed out by many (Alston et al., 2011; Baldos & Hertel, 2018; Fuglie, 2018) that the growth rate in R&D expenditures, especially from public sources, has decelerated since the Green Revolution. Baldos and Hertel (2018) provided evidence of this slowdown in public R&D in the United States. However, as highlighted by them and others (Fuglie, 2018; Pardey et al., 2016), there has been a notable shift in global R&D expenditures toward middle-income countries, particularly China. Fuglie et al. (2024) documented a slowdown in global agricultural TFP growth to 1.1 percent per year from 2011 to 2020. This compares to a growth of nearly 2.0 percent per year on average from 2001 to 2010. A slowdown this notable implies that producers might need to use more land and/or other inputs to maintain sufficient food production if the change in global population is greater than TFP growth (Morgan et al., 2022).

To assess whether TFP can help sustain agricultural production to meet global food demands, information from Fuglie et al. (2022) was used to examine the link between R&D investment and future TFP. In that report, Fuglie and co-authors presented eight scenarios that project potential future R&D expenditures, which were then used to estimate the change in TFP. The scenarios that considered environmental policies were not used for this USDA, ERS 2024 report. Table 1 presents the scenarios considered in this study: Scenario 1 (S1) involves no R&D growth; Scenario 2 (S2) assumes balanced, moderate growth across all R&D sources; Scenario 3 (S3) assumes high growth in R&D for the least-developed countries (LDC); and Scenario 4 (S4) assumes high growth in R&D for high-developed countries and balanced growth for LDCs.

The change in TFP, as derived from Fuglie et al. (2022), was based on R&D expenditures from various sources: public R&D (values represented by LDC, E & C Euro, and Other Developed in table 1); R&D from CGIAR; and private R&D. Given that expenditures in R&D take some time to reach full realization due to the need for field tests and adoption, models linking R&D to productivity account for lags (Alston et al., 2023). In the 2022 Fuglie et al. study, a lag structure was established: 50 years for public R&D from developed countries (peaking after 26 years—peaking refers to the assumption that the effect of R&D spending builds up over time when technology is fully disseminated and then diminishes due to the technology becoming obsolete); 35 years for R&D from developing countries, the private sector, and the CGIAR (peaking at year 10). The longer lag structure for developed countries is justified by their probable position on the technology frontier, emphasizing their focus on sustaining innovation. In contrast, other R&D expenditures place a greater emphasis on adaptative R&D to address and close the yield gap. The way that the lag structure entered the model is through the creation of an R&D stock variable from annual R&D expenditures. The current value of R&D stock is a weighted sum of past expenditures, accounting for the cumulative effects of previous investments and acknowledging the long-term nature of R&D impacts on productivity.

The weights specify the duration it takes for R&D activities to produce and diffuse useable technologies, as well as the duration those technologies remain viable once adopted. R&D elasticities were employed to quantify the percentage change in TFP, given a 1-percent change in R&D capital stock.

Once projected future R&D was estimated, these values are then linked to agricultural TFP growth via elasticities (table 2). These elasticities translate the change in R&D into TFP, and the elasticities vary by source and by region. Fuglie et al. (2022) noted that these elasticities, derived from a literature review of more than 40 studies, generally tend to be lower for developing countries compared with developed countries. A critical assumption behind the TFP growth projections is that the R&D elasticities will hold in the future. Future projections are contingent on the assumption that R&D will be as productive over the next few decades as it was over the past few decades. Note that table 2 also includes an elasticity for international spill-ins, representing the spillover of technologies from one region to another. Fuglie et al. (2022) assumed that these spill-ins occur in developed countries and in Latin America and the Caribbean (LAC).[9]

[9] Fuglie (2018) presented results from 44 studies that all (except for one) estimate spill-ins occur only in developed countries. Hence, the assumption in the 2022 piece.

Table 1
Scenario (annual) growth rates in research and development (R&D) expenditure

Scenario	Description	Public R&D									
		Least Developed Countries (LDC)									
		SSA	CWANA	LAC	China	SE Asia	S Asia	E & C Euro	Other Devel-oped	CGIAR	Private
S1	No R&D growth	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
S2	Balanced R&D growth	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	4.07%
S3	High LDC R&D growth	6.00%	6.00%	6.00%	6.00%	6.00%	6.00%	0.00%	0.00%	0.00%	4.07%
S4	High Developed R&D growth	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	5.85%	5.85%	4.07%

S1 = Scenario 1; S2 = Scenario 2; S3 = Scenario 3; S4 = Scenario 4. SSA = Sub-Saharan Africa; CWANA = Central and West Asia and North Africa; LAC = Latin America and the Caribbean; SE Asia = Southeast Asia; S Asia = South Asia; E & C Euro = Eastern and Central Europe; Other Developed = Other developed countries; CGIAR = Consultative Group on International Agricultural Research (formerly); LDC = Least Developed Countries; Developed = Developed Countries.

Note: Least developed countries (LDC) are defined by the United Nations. E & C Euro refers to the former Soviet Union and Central European countries; Other Developed is comprised of Australia, Canada, Japan, New Zealand, the United States, and Western Europe. CGIAR was formerly the Consultative Group on International Agricultural Research and now uses CGIAR as its official name. All percentages in the table refer to the rate of R&D expenditure per year.

Source: USDA, Economic Research Service using information from Fuglie et al. (2022).

Table 2
Research and Development (R&D) to total factor productivity (TFP) elasticities

Region	Elasticities of R&D Capital					
	Total (all R&D)	National public R&D	Developed interna-tional spill-in	LDC international spill-in	Private R&D	CGIAR R&D
World	0.43	0.18	0.10		0.10	0.04
Other Developed	0.67	0.27	0.21		0.20	
E & C Euro	0.07	0.07				
Developing Countries	0.38	0.18	0.07		0.07	0.07
Asia	0.30	0.21			0.01	0.08
LAC	0.77	0.23	0.36		0.13	0.05
CWANA	0.19	0.15				0.04
SSA	0.17	0.13				0.04

LDC = Least developed countries; CGIAR = Consultative Group on International Agricultural Research (formerly); E & C Euro = Eastern and Central Europe; LAC = Latin America and the Caribbean; CWANA = Central and West Asia and North Africa; SSA = Sub-Saharan Africa; Other developed = Other developed countries.

Note: International spill-in refers to spillovers of technologies. CGIAR was formerly the Consultative Group on International Agricultural Research and now uses CGIAR as its official name. Other developed is comprised of Australia, Canada, Japan, New Zealand, the United States, and Western Europe; E & C Euro refers to the former Soviet Union and Central European countries. Developing countries are those not in Other developed nor E & C Euro.

Source: USDA, Economic Research Service using data from Fuglie (2018).

Results for the change in TFP by 2050 are presented in table 3, organized by regions, while detailed country-specific results can be obtained from the authors. There are a couple of things to note. First, even in the absence of any additional R&D expenditures between 2016 and 2050 (evidenced by the second row in table 4 having the same values as the base year), there would still be an increase in TFP because of the lags in productivity growth realization from past investments. S2 assumed a balanced R&D growth of 3 percent for all sources, except for 4.07 percent for private R&D (table 2). This scenario generated a 55-percent increase in World TFP for 2050 relative to 2016. Over the 34-year period between the two time frames, S2 exhibited an annual growth rate of 1.6 percent. Table 4 indicates that the balanced approach would lead to a cumulative spending of $2.276 trillion of R&D in 2015 purchasing power parity (PPP) dollars. S3 assumed that least developed countries spend more; table 4 indicates spending in 2040 would be slightly more than double that of S2. Consequently, S3 achieved a higher TFP rate of 160 compared with 153. S4 considered that developed countries spend more, while S3 assumed that these countries spend less than the balanced approach, enabling them to increase their TFP to 199, a notable improvement compared with 158 in the balanced scenario.

Table 3

Total factor productivity (TFP) change to 2050 for each scenario

	Scenario	World	DC	LDC	Asia	LAC	CWANA	SSA
		(Index, 2016 = 100)						
S1	No R&D growth	120	112	124	129	121	112	107
S2	Balanced R&D growth	155	158	153	153	191	123	117
S3	High LDC R&D growth	150	126	160	166	174	130	123
S4	High Developed R&D growth	176	199	167	160	241	126	119

S1 = Scenario 1; S2 = Scenario 2; S3 = Scenario 3; S4 = Scenario 4. Developed = Developed Countries; LDC = Least Developed Countries; R&D = research and development; LAC = Latin America and the Caribbean; CWANA = Central and West Asia and North Africa; SSA = Sub-Saharan Africa.

Note: 2016 is the base year and has a value of 100.

Source: USDA, Economic Research Service using the model from Fuglie et al. (2022).

Table 4

The change in research and development (R&D) necessary to generate total factor productivity (TFP) changes in 2040

	Scenario	World	Developed	LDC	Private	CGIAR	Cumulative world spend
		U.S. dollars (billions) (2015 PPP dollars)					
	2016 (base year)	66.7	19.2	28.0	18.6	0.9	NA
S1	No R&D growth	66.7	19.2	28.0	18.6	0.9	1,402
S2	Balanced R&D growth	148.3	39.5	57.6	49.3	1.9	2,276
S3	High LDC R&D growth	187.7	19.2	118.3	49.3	0.9	2,588
S4	High Developed R&D growth	187.7	77.1	57.6	49.3	3.7	2,604

S1 = Scenario 1; S2 = Scenario 2; S3 = Scenario 3; S4 = Scenario 4. Developed = Developed Countries; LDC = Least Developed Countries; PPP = purchasing power parity; NA = not applicable.

Note: R&D spending stops in 2040 in this model, as TFP growth carries on to 2050 due to the lag structure of investment and TFP. CGIAR was formerly the Consultative Group on International Agricultural Research and now uses CGIAR as its official name.

Source: USDA, Economic Research Service using the model from Fuglie et al. (2022).

How Do the Yield and TFP Estimates Translate to Market Impacts?

The changes in yields and total factor productivity (TFP) discussed in the report will ultimately impact productivity and the production of these crops and their downstream uses. To investigate this issue, the authors used the population projections averaged across SSPs (IIASA, 2024), along with data on domestic consumption of these grains to estimate future demand for corn, rice, soybeans, and wheat (consumption data are from USDA, FAS, 2023). For rice and wheat directly consumed by the population (or, in the case of wheat, as a food product), changes in consumption were based on the projected change in population for 2050. However, as corn and soybeans are used for multiple purposes in addition to human consumption, especially as feed, distinct assumptions were made regarding their consumption patterns.[10] Global corn usage for feed was approximately 50 percent (USDA, 2015), while global soybean usage for feed was around 75 percent (Ritchie & Roser, 2021). Consequently, for those two crops, the nonfeed percentage from population to change consumption (50 percent for corn and 25 percent for soybeans) was applied. The change in gross domestic product (GDP) (also from IIASA, 2024), along with an income elasticity[11] of 0.2 for meat (Muhammad et al., 2017), was then used to determine the percentage change in meat demand. This percentage change was then applied to the remaining amount of corn and soybeans to calculate the amount necessary for feed in the future.

The estimated changes in consumption of the four crops were compared to potential production in 2050, using the combined effects of yield and TFP changes on production (the two factors were added across each TFP scenario presented in an earlier section). Both the GGCMI and TFP estimates assumed that input use was not changing (including land), and that same assumption was made for this report. In addition, no price effects or substitution was also assumed. While a more sophisticated approach could involve the utilization of a computable general equilibrium (CGE) model (e.g., the one employed in Beckman et al., 2020), it is important to acknowledge the multifaceted nature of such models. This includes factors such as the absence of surplus or deficit in the model as markets clear. Therefore, a simpler, tractable estimate was used here. Another necessary assumption was that the change in TFP was directly applicable to the change in TFP for the crops considered by the GGCMI. This assumption was made because TFP numbers for specific crops are unavailable in the Fuglie et al. (2022) estimates, which included output for crops, livestock, and aquaculture, as well as total inputs for these sectors. Although historically, some commodities and regions within an agricultural sector have exhibited faster or slower TFP and yield growth, this simplifying assumption was made for the purpose of this analysis.

The calculations for various R&D investment scenarios are presented in table 5. First, data from IIASA (2024) indicate a 29.2-percent increase in global population and a 144.0-percent increase in global GDP. This GDP change is estimated to lead to a 28.8-percent increase in meat demand, aligning with existing literature estimating a comparable surge. For example, Alexandratos and Bruinsma (2012) projected a 48.6-percent change for 2013–50. In terms of specific crop consumption, a 29-percent increase for corn, 29.2-percent for rice and wheat (aligning with the population growth), and 28.9-percent for soybeans were estimated for this report. The projected consumption amounts stayed the same across each of the scenarios (S1–S4) since population and GDP do not change.

[10] Corn and soybeans are both also used for biofuels, but global biofuel demand is likely to not increase by as much as meat demand, as biofuels are largely produced in Brazil and the United States. (Beckman et al., 2018).

[11] The income elasticity measures the responsiveness of the quantity demanded for a good to a change in consumer income. The income elasticities for crops have traditionally been thought of as nonresponsive to changes in incomes (i.e., when consumers get more income, they switch to dairy and meat products). But recent evidence (Colen et al., 2018; Zhou et al., 2020, for China) has concluded that these elasticities could be positive.

Table 5
Estimated global future consumption and production of corn, rice, soybeans, and wheat

			2050			
		2016	S1	S2	S3	S4
Population (billion)		7.50	9.69	9.69	9.69	9.69
GDP (trillion, 2017 PPP dollars)		150.85	368.10	368.10	368.10	368.10
Consumption (billion metric tons)	Corn	1.06	1.37	1.37	1.37	1.37
	Rice	0.48	0.62	0.62	0.62	0.62
	Soybeans	0.33	0.43	0.43	0.43	0.43
	Wheat	0.73	0.95	0.95	0.95	0.95
TFP (index, 2016 base)	Agriculture	100	120	155	150	176
Yields (metric ton/ha)	Corn	5.78	4.92	4.92	4.92	4.92
	Rice	4.57	4.82	4.82	4.82	4.82
	Soybeans	2.75	2.81	2.81	2.81	2.81
	Wheat	3.42	3.77	3.77	3.77	3.77
Production (billion metric ton)	Corn	1.13	1.19	1.58	1.53	1.82
	Rice	0.49	0.62	0.79	0.76	0.89
	Soybeans	0.35	0.43	0.55	0.53	0.62
	Wheat	0.76	0.99	1.25	1.21	1.41
Production-consumption		0.12	-0.15	0.80	0.67	1.38

S1 = Scenario 1; S2 = Scenario 2; S3 = Scenario 3; S4 = Scenario 4. GDP = gross domestic product; PPP = purchasing power parity; TFP = total factor productivity; ha = hectare.

Source: USDA, Economic Research Service calculations based on population and GDP data from IIASA (2024), yield estimates from Global Gridded Crop Model Intercomparison (GGCMI) models, TFP estimates from Fuglie et al. (2022), and consumption/production numbers from USDA, Foreign Agricultural Service (2023).

The lower half of the first set of columns in table 5 presents the production estimates, combining yield estimates with TFP growth. Although the GGCMI yields for 2016 were estimated from the GGCMI models, they were close to actual 2016 yields. Since land was held as fixed in this study, the change in production for 2050 was exactly the change in yields/TFP. The production-consumption change was calculated by subtracting the estimated 2050 consumption from the 2050 estimated production, summing across the four crops to arrive at the estimate in the last row. For S1, there was a production shortfall as TFP growth is insufficient to overcome climate-induced yield changes, resulting in an inability to meet consumption. Although corn was the only crop with a decrease in GGCMI-estimated yields, the overall change in TFP by 2050 was positive but modest at 5.2 percent (that is, the change in TFP was 20 percent, but global corn yields decreased by 14.8 percent). According to this study's calculations, a 5.2-percent growth in production was not enough to keep pace with the growing consumption of corn. Rice and soybeans have no change in their production-consumption balance. On the contrary, there was an increase in the production-consumption surplus for wheat.

For the scenarios with increased R&D expenditures in the future—which leads to greater TFP growth—surpluses were observed, both in total and for each of the four crops. However, much of the surplus was attributed to rice and wheat. It is important to note that the numbers in the tables hinge on a couple of assumptions. First, the consumption calculation, especially concerning feed for livestock, could put tremendous pressure on corn and soybeans due to the substantial estimated increase in GDP. Given that these projections extend beyond 25 years, various factors, such as changes in diet, price impacts, and substitution effects, could influence future demand. In addition, the use of alternative feed sources, such as distiller's dried grains with solubles (DDGS), might impact the projected feed demand (Beckman et al., 2011). The changes in production hinge on TFP, if it grows as estimated by Fuglie (2018) for the given level of increased R&D investment, then surpluses for corn, rice, soybeans, and wheat are anticipated. The increase in TFP outweighs any decrease in yields, although declining yields do affect the overall increase in TFP required and the investment in R&D.

Production Changes for the United States

Table 7 presents results specifically for the United States, a major producer and exporter of the four crops. In 2016, the United States had a production-consumption surplus of 0.166 billion metric tons,[12] surpassing the global surplus of 0.12 billion metric tons. Despite projected decreases in U.S. corn, rice, and soybean yields by 2050, the authors examined whether this affected the United States' ability to contribute to global food security. Under the scenario with no additional R&D investment (S1), results indicated that the United States would maintain a production-consumption surplus (0.105 billion metric tons), albeit with a deficit in corn of 0.01 billion metric tons. Rice had no change in its surplus (of 0.003 billion metric tons), while soybeans had a slight increase (from 0.061 billion metric tons to 0.069 billion metric tons.) These changes were attributed to the smaller yield decreases for rice and soybeans compared with the TFP gain. Similar to the global result, greater TFP growth in scenarios S2, S3, and S4 led to greater production-consumption surpluses for the United States. The most substantial surplus occurred in S4, where the 133.41-percent increase in TFP resulted in a production-consumption surplus of 0.767 billion metric tons.

Table 6
Estimated U.S. future consumption and production of corn, rice, soybeans, and wheat

			2050			
		2016	S1	S2	S3	S4
Population (Billion)		0.32	0.37	0.37	0.37	0.37
GDP (trillion, 2017 PPP dollars)		18.54	33.54	33.54	33.54	33.54
Consumption (billion metric tons)	Corn	0.314	0.362	0.362	0.362	0.362
	Rice	0.004	0.005	0.005	0.005	0.005
	Soybeans	0.056	0.064	0.064	0.064	0.064
	Wheat	0.032	0.037	0.037	0.037	0.037
TFP (index, 2016 base)	Agriculture	100	117.48	179.58	136.85	233.41
Yields (MT/ha)	Corn	10.960	9.338	4.925	4.925	4.925
	Rice	8.110	8.548	4.817	4.817	4.817
	Soybeans	3.490	3.563	2.808	2.808	2.808
	Wheat	3.540	3.901	3.769	3.769	3.769
Production (billion metric tons)	Corn	0.385	0.352	0.591	0.426	0.798
	Rice	0.007	0.008	0.013	0.009	0.016
	Soybeans	0.117	0.133	0.206	0.156	0.269
	Wheat	0.063	0.080	0.119	0.092	0.153
Production-consumption		0.166	0.105	0.460	0.215	0.767

S1 = Scenario 1; S2 = Scenario 2; S3 = Scenario 3; S4 = Scenario 4. GDP = gross domestic product; PPP = purchasing power parity; TFP = total factor productivity; ha = hectare.
Source: USDA, Economic Research Service calculations based on population and GDP data from IIASA (2024), yield estimates from Global Gridded Crop Model Intercomparison (GGCMI) models, TFP estimates from Fuglie et al. (2022), and consumption/production numbers from USDA, Foreign Agricultural Service (2023).

[12] The authors go to three decimal places for the U.S. results, given that rice consumption was less than 0.01 billion metric tons in 2016.

Conclusion

Climate scientists predict a future characterized by rising temperatures, increased aridity, and more extreme weather events like droughts or floods. Projections indicate that these changes will intensify over time. Throughout history, agricultural production has generally been resilient, providing the world with the necessary food to feed the population (although famine and hunger are persistent in some areas and periodic in others, often due to climatic disturbances such as drought and flooding). Most population projections show increases, with some estimates suggesting an increase from 8 billion people in 2022 to 11 billion in the future. Such an increase would demand much more food, necessitating increased agricultural production. A significant reason that agricultural production has managed to meet the population's food needs is through increasing agricultural productivity, such as from increasing yields. However, yields are highly dependent on the climate. Excessively high temperatures could lead to harmful growing degree days, and reduced precipitation could result in less groundwater available for irrigation.

Many crop models estimate that crop yields could decrease in the future due to the potential for increased climate stress. To consider how crop yields might impact the future, yield projections for corn, rice, soybeans, and wheat for 2050 from the Global Gridded Crop Model Intercomparison (GGCMI) project were used to examine how these yields could affect production. Additionally, scenarios considering total factor productivity (TFP) growth consistently showed an overall increase in TFP (TFP plus yield changes), contributing to enhanced food production. However, the findings highlight that a surge in global food demand for these four crops may lead to a production-consumption deficit if TFP growth is insufficient. For the United States, one of the largest producers and exporters of these products, climate change could impact the country's ability to trade, assuming TFP growth is insufficient.

The yield estimates from GGCMI indicate that corn, rice, and soybean yields could be impacted earlier than previously estimated. However, TFP could still outpace any yield decrease, underscoring the crucial role of agricultural investment in sustaining global food production. A significant unknown factor in both yield and TFP estimates is the influence of future technology. The yield estimates only consider how climate change could affect future crop yields, while the TFP estimates assume that R&D growth leads to a constant rate of TFP growth. However, these estimates could be subject to alteration based on technological advancements in the future.

With the help of additional data, future research is expected to analyze the further market impacts of climate change. An online tool hosted by MyGeoHub (Jägermeyr et al., 2023) has been developed to deliver these data, providing flexible ways to aggregate information. The tool facilitates access to the extensive collection of climate impacts on crop yields documented in this report. Future USDA, ERS work will consider how different aspects of climate change (e.g., affecting livestock production) further impacts agricultural markets.

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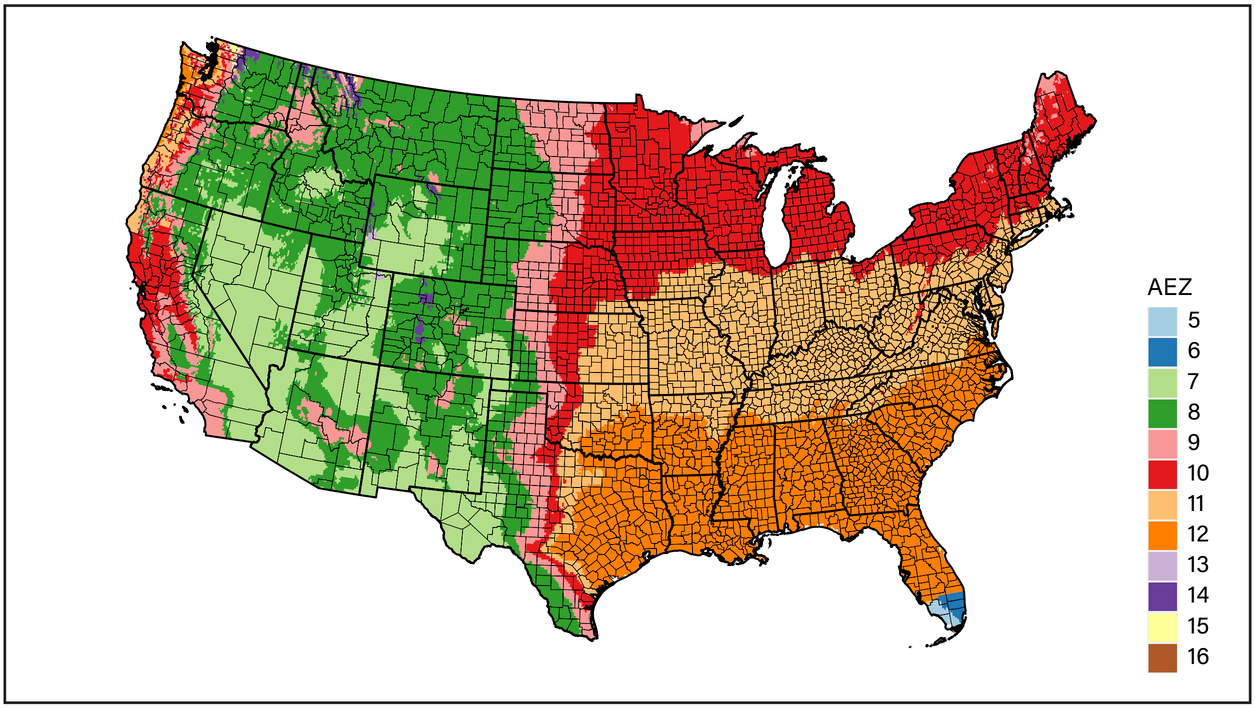
Appendix A: U.S. Corn Yield Changes, 1983–2052

The United States is the world's largest producer of corn, contributing 31.48 percent to the global corn output in 2021. This production share was achieved despite the United States accounting for only 16.69 percent of the total global corn land. The key factor driving this substantial production relative to land area is the yields achieved by the United States. To gain insights into the reasons behind the observed decrease in U.S. corn yields under projected climate conditions, the changes across Agro-Ecological Zones (AEZs) were examined for this report. Figure A.1 shows where AEZs are located in the United States. Most land for corn cultivation is located in AEZ 10 (44.9 percent) and AEZ 11 (37.6 percent).[13]

Figure A.1
Map of U.S. Agro-Ecological Zones (AEZs)



Note: Alaska, Hawaii, and U.S. territories are not shown due to space constraints.

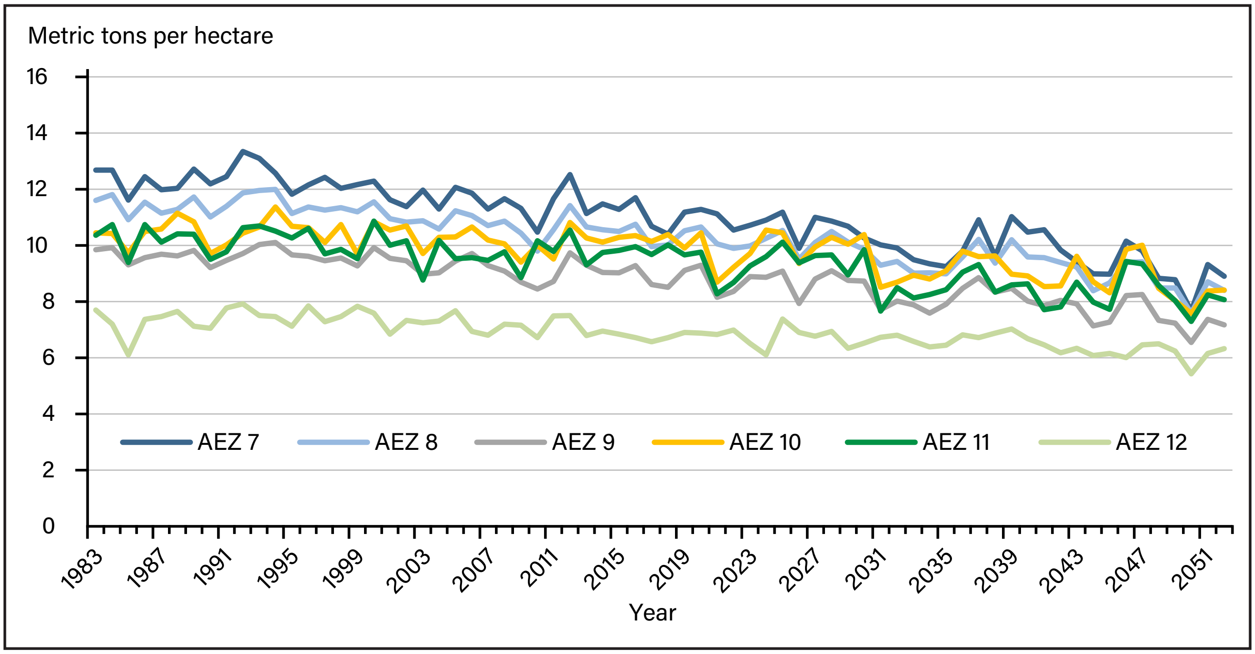
Source: USDA, Economic Research Service using data from Aguiar et al. (2022).

Please note that there was an overall decline in corn yields across all AEZs in the United States during 1983–2050 (figure A.2). Although AEZ 12 experienced a relatively smaller decrease (-15.6 percent), it is essential to recognize that this AEZ represented only 3.4 percent of the total corn cultivation land in the United States in 2014 (the base year for the data). AEZ 10, depicted by the yellow line, indicates a significant decline in yields, with a percentage change of 21.0 percent for 2050 relative to the baseline. The largest declines in U.S. corn yields were observed in AEZs 7–9. While AEZ 7 has a small amount (2.0 percent) (Beckman et al., 2023) of total U.S. corn land, AEZs 8 and 9 accounted for 20.0 percent and 13.8 percent of U.S. corn land, respectively. AEZs 7, 8, and 9 are all located in regions that are drier than the other AEZs. Although all U.S. corn cultivation occurs in temperate climates, the variation in moisture levels contributes to the diversity in AEZs across the country.

[13] Calculations on land in cultivation are based on data from Aguiar et al. (2022). Note that in their data, corn is grouped with other coarse grains; but in the 2023/24 marketing year, corn had a 90-percent share of area harvested (USDA, FAS, 2023). Similarly, soybeans are grouped with oilseeds in their data; but soybeans had a 92.7-percent share of total oilseed production in 2023/24 (USDA, FAS, 2023).

Figure A.2

Changes in U.S. corn yields across Agro-Ecological Zones (AEZs), 1983–2052

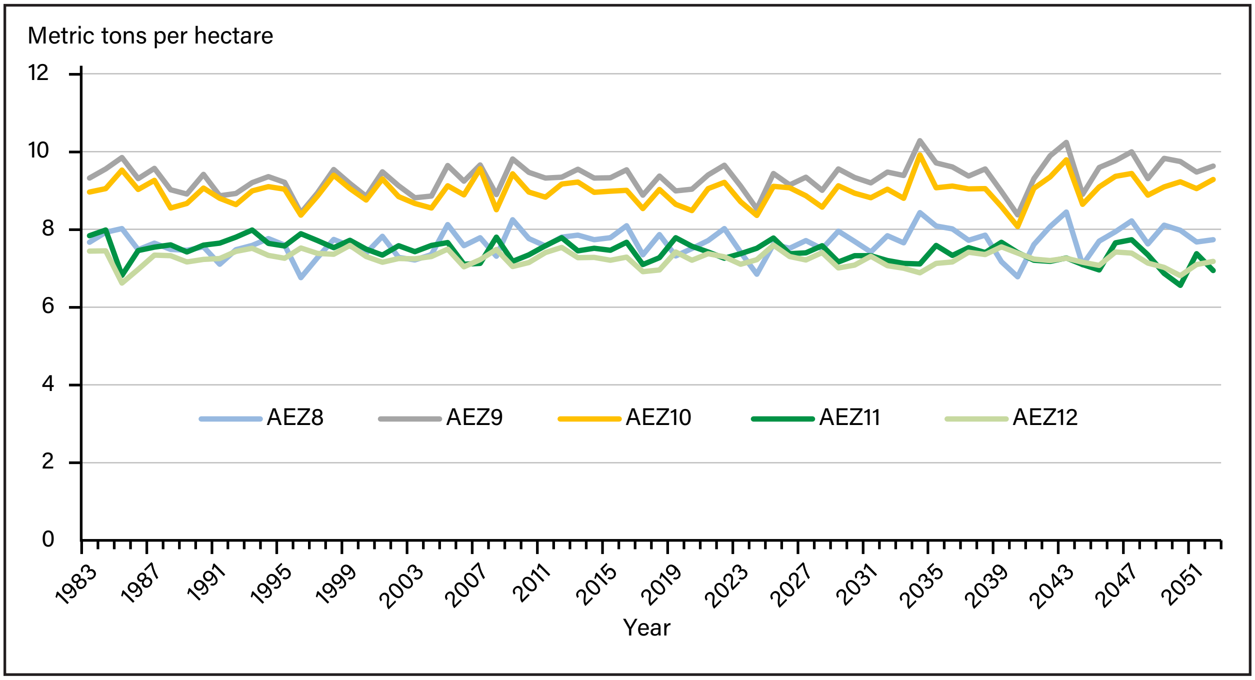


Source: USDA, Economic Research Service using data from Jägermeyr et al. (2023).

Appendix B: U.S. Rice Yield Changes, 1983–2052

The United States is not one of the world's largest producers of rice, but it has historically been among the largest exporters (in the top five). U.S. rice yields are shown in figure B.1. U.S. yields have historically been higher than the global average. And even though U.S. yields decreased to 2050 (by -3.38 percent), they were still higher than the global average. In terms of changes by AEZ in the United States, AEZs 8 to 10 all had increases—but AEZ 11 and AEZ 12 had decreases. Given that the majority of U.S. rice is grown in these two AEZs (83.2 percent of the total), there was an overall decrease in U.S. rice yields.

Figure B.1
Changes in U.S. rice yields across Agro-Ecological Zones (AEZs), 1983–2052

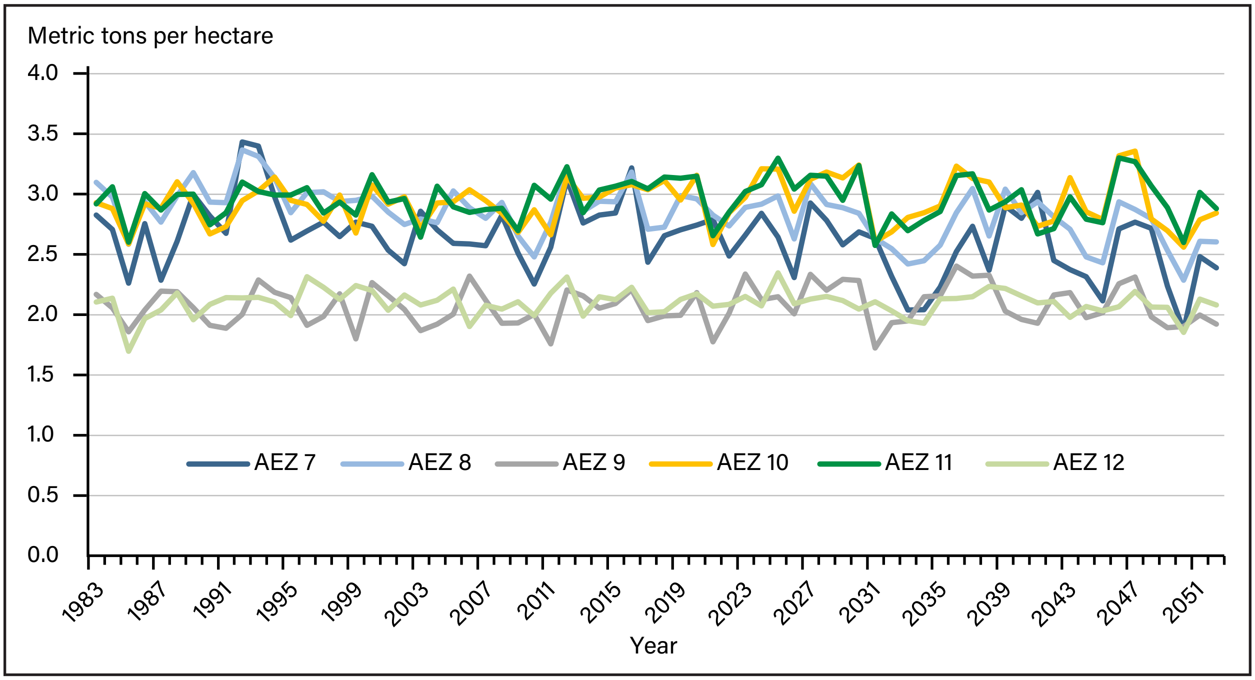


Source: USDA, Economic Research Service using data from Jägermeyr et al. (2023).

Appendix C: U.S. Soybean Yield Changes, 1983–2052

Given that the United States is a major producer of soybeans, the authors examined how yields in U.S. Agro-Ecological Zones (AEZs) are impacted based on the Global Gridded Crop Model Intercomparison (GGCMI) projections. These yields are shown in figure C.1. First, note that in all AEZs, the United States was estimated to have a decrease in soybean yields when comparing 2050 with the baseline. AEZ 11 accounts for the majority of cultivated soybean land in the United States (45.2 percent), and that AEZ has a 19.6 percent decrease in soybean yields. Recall that for corn, the largest yield decreases by AEZ in the United States were in AEZs 7–9, where the land is drier. For soybeans, the largest decrease was in one of those AEZs (AEZ 7).

Figure C.1
Changes in U.S. soybean yields across Agro-Ecological Zones (AEZs), 1983–2052



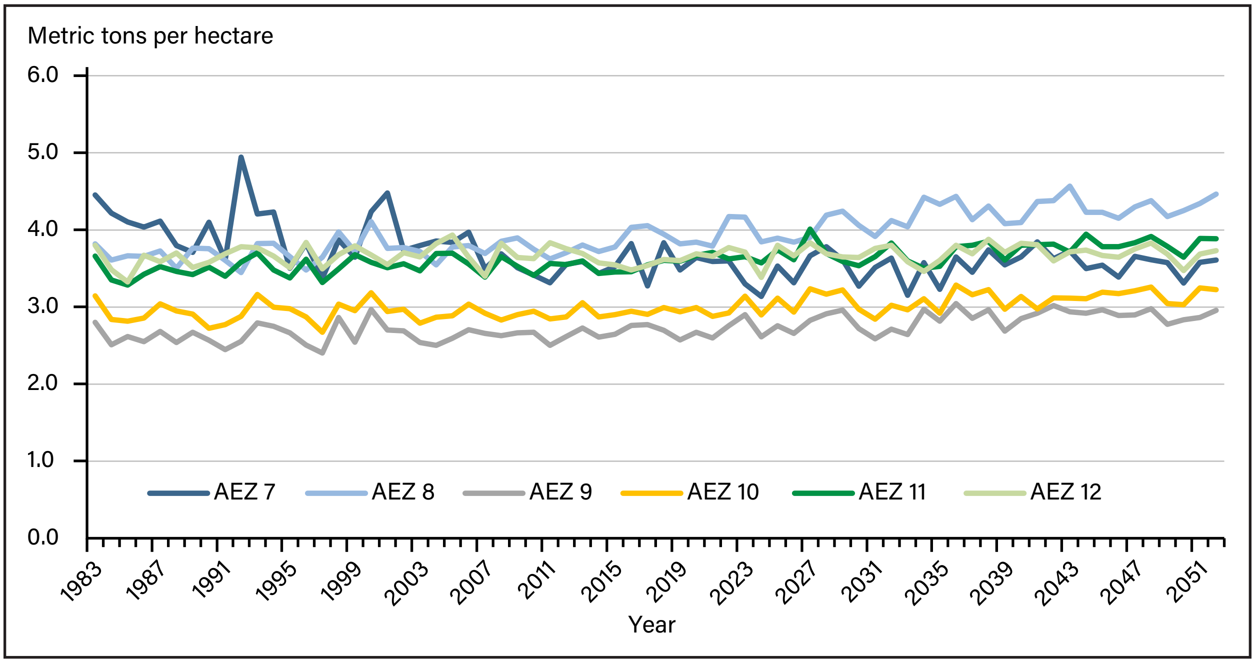
Source: USDA, Economic Research Service using data from Jägermeyr et al. (2023).

Appendix D: U.S. Wheat Yield Changes, 1983–2052

Figure D.1 shows the changes in U.S. yields by AEZ for wheat during 1983–2050. Wheat is also grown in AEZ 14 in the United States, but the amount is minimal (less than one-tenth of a percent of total U.S. wheat acreage), so it is not shown here. AEZ 8 has the highest share of land in wheat cultivation among AEZs (31.1 percent), much of this AEZ resides in what is known as the Great Plains. This AEZ was estimated to have the largest increase in yields relative to the baseline (15.7 percent) during this time span. Many U.S. AEZs were projected to experience an increase in wheat yields for 2050 compared with the baseline, with AEZ 7 being the only one to show a decrease in yields (-8.2 percent).

Figure D.1

Changes in U.S. wheat yields across Agro-Ecological Zones (AEZs), 1983–2052



Source: USDA, Economic Research Service using data from Jägermeyr et al. (2023).