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Evaluating the Impacts of Projected Yield Changes on India's Wheat and Rice Markets

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Abstract

This report evaluates how yield changes induced by volatile weather trends can impact India's production, prices, and trade of wheat and rice. Results from a computable general equilibrium model show that under two volatile weather trend scenarios (one that is considered business as usual and another that projects more volatile weather), India is expected to see an increase in average yields for both rice and wheat in the next two to three decades. While increasing per hectare yield leads to higher total rice production in this report's model, an increase in household income and population (as projected by USDA, Economic Research Service) will lead to higher per capita demand for rice in India. According to model results, this demand is expected to lead to an estimated reduction in exports of both rice and wheat to the global market. Furthermore, results indicate that countries importing from India would shift their demand to other major rice and wheat exporters.

Keywords: India, volatile weather, rice, wheat, market prices

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A report summary from the Economic Research Service *April 2025*

Evaluating the Impacts of Projected Yield Changes on India's Wheat and Rice Markets

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What Is the Issue?

India recently became the most populated country in the world, and the United Nations predicts the country's population will continue to grow and reach 1.65 billion people by 2040. In addition, USDA macroeconomic projections show that incomes in India are expected to grow by 67 percent in the next decade. These two factors, population growth and rising incomes, will increase food demand. However, India has a limited amount of arable land to produce food to meet this increased demand, especially for major staples such as rice and wheat. While India is an important exporter of wheat and rice, volatile weather trends could impact yields, affecting production and, thus, trade of these major food crops. Anticipation of potential production shortages in rice and wheat due to changing long-term weather patterns has led to restrictive policies on exports of these two major crops to suppress domestic prices and mitigate food insecurity. Under both low and high carbon concentration scenarios, estimates indicate there will be yield increases for rice and wheat in India. This report addresses whether this positive impact on yield will be sufficient to continue to meet domestic food demand and maintain India's exports.

What Did the Study Find?

Yield changes induced by altered long-term weather trends indicate a potential increase of average yields in India for both rice and wheat in the next two to three decades. The increase in yields is partly due to an expected increase in the higher carbon concentration across rice- and wheat-growing regions of India. The yield increase for both crops occurs under two scenarios: one that is considered business as usual and another that projects higher carbon concentration. This report's major findings include:

- Using a computable general equilibrium model, we found that, by 2040, projected higher yields under the higher carbon concentration scenario (known as SSP585) are expected to lead to an increase in rice production but a decrease in wheat production. Thus, more land is expected to be allocated to rice production than wheat production.

- Despite average yield improvements for rice and wheat under the SSP585 scenario, the projected increase in production of rice is not expected to meet the increase in demand for rice and wheat in India, leading to increases in domestic prices by 2040. Prices are estimated to increase by 232 percent for rice and 201 percent for wheat by 2040.
- Greater demand for rice and wheat in India is expected to lead to a decrease in exports and an increase in international wheat and rice prices.
- Countries in South Asia and Southeast Asia are expected to have the largest increase in imports of rice and wheat while concurrently having the largest decrease in imports from India. Thus, these regions are expected to turn to other major rice and wheat suppliers to meet their grain demands.

How Was the Study Conducted?

The study uses projected yield changes across Agro-Ecological Zones (a way of classifying land by moisture and temperature conditions) of India from the Agricultural Model Intercomparison and Improvement Project's (AgMIP) Global Gridded Crop Model Intercomparison to evaluate the impact of more volatile weather trends on India's rice and wheat markets. To analyze the possible impact of potential future changes in weather trends on domestic and international rice and wheat markets, yield changes for 2040 that account for altered weather trends were used in a computable general equilibrium model. In addition, we accounted for projected changes to gross domestic product and population for India and all the countries and regions in this report's models.

Evaluating the Impacts of Projected Yield Changes on India's Wheat and Rice Markets

Introduction

Changes in long-term weather trends has long-term impacts on agricultural productivity through changes in atmospheric temperature, groundwater, carbon concentration, and precipitation. Long-term weather variability is responsible for about a third of the annual shifts in agricultural yields across the globe (Porfirio et al., 2018; Howden et al., 2007). The effects of volatile weather trends vary across different regions of the world due to several factors. For instance, regional topography, such as mountain ranges, will influence the amount of warming in a location, and middle regions of continents are expected to get warmer than the coastal areas from the same temperature changes (Jägermeyr et al., 2021; UCAR Center for Science Education, 2024). Beckman et al. (2024) show that corn yields in the United States will be negatively impacted by changing weather trends while Vaiknoras et al. (2024) highlight that the Sahel region in Africa will be negatively impacted in terms of livestock biomass. The shift in crop yields due to more volatile weather trends could affect India's crop production and its supply and exports of major crops such as rice and wheat. In addition to the effect on the domestic market of major food crops, more volatile weather trends can have far-reaching effects on global food markets. For instance, the Government of India recently anticipated production shortages due to El Niño and banned exports of several varieties of rice while price surges affected the global rice market. The Government of India has argued that the export ban protects the domestic market from price surges and secures India's vulnerable population against food insecurity. However, such export bans can have a ripple effect on the global market, increasing international prices and worsening food insecurity globally. Huang et al. (2011) showed that more volatile weather trends could impact global productivity, which could lead to similar export restrictions in other exporting countries and further exacerbate global price increases and food insecurity.

The impacts of extreme weather events could affect India's trading partners as well as the global supply and prices of commodities such as wheat and rice, of which India is a major producer and exporter. Huang et al. (2011) emphasized the importance of increasing agricultural productivity in both developed and developing countries to ensure global food security, as changes in long-term weather trends affects regional weather patterns and alters the availability of arable land and water. The Huang et al. (2011) study, coinciding with the results of similar studies (see box, "Background on Changing Weather Trends"), found that tropical and semitropical latitudes will be the most heavily impacted by more volatile weather trends and that agricultural production in these areas will suffer the greatest losses. However, the study also showed that the effects will likely differ across commodities, and international trade could help balance any regional surplus or deficit for particular agricultural commodities. As shifting weather patterns alter the productivity of several factors of agricultural production, the comparative advantages of certain countries and regions will change with their climate and weather, consequently, each country will specialize in the production of commodities that it can produce most efficiently and trade these for other products.

This report analyzes the effect of past changes in longer term weather trends on Indian rice and wheat production, domestic prices, and trade by using historical data on weather, production, and trade of major grains such as wheat, rice, and soybeans in India. It also uses projected yield changes in a computable general equilibrium (CGE) framework to estimate the potential impact of more volatile weather trends on rice and wheat markets in India and across the globe. The model relied on crop yield projections (from the

Agricultural Model Intercomparison and Improvement Project's (AgMIP) Global Gridded Crop Model Intercomparison (GGCMI)) that are based on assumptions of long-term changes in weather variables, and projected changes to population and per capita income in India and major trading partner countries. The study focuses on India because it is a major producer, consumer, and exporter of agricultural products. India has had significant changes in its weather patterns over the last five decades. Some of these recent changes in weather patterns have led to policies aimed at combatting surges in the price of staples, such as rice and wheat, in domestic markets in India and consequently prevent a surge in food insecurity. As of 2022, India had the largest number of food insecure people on the globe (Zereyesus et al., 2022). Although the literature has studied the effect of more volatile weather trends on agricultural production in India, this study went a step further to consider the impact on agricultural trade. Additionally, we made a unique contribution to the literature because this study incorporates projected yield changes in India's Agro-Ecological Zones (AEZs) (Avetisyan et al., 2010) and presents changing long-term weather pattern impacts on both domestic markets and international trade of rice and wheat. The AEZs-level, projected yield changes enabled the authors to account for the potential impacts of variations in long-term weather trends on the production of both rice and wheat across India. The global effects of more volatile weather trends are well documented and not necessarily consistent across all regions of the world. The effects not only differ across regions, but studies also record differing effects of more volatile weather trends across crops. For example, Jägermeyr et al. (2021) showed that, while maize experienced the largest adverse effect from more volatile weather trends, wheat responded well to stronger carbon concentration and wheat yield increases, on average, in high-latitude regions. Halder et al. (2020) and Krishnan et al. (2007) also showed that an increase in carbon concentration had a net positive impact on rice. Therefore, this report briefly discusses temperature and precipitation trends (see boxes, "Global Temperature Trend" and "Global Precipitation Trend") and discusses the changing weather patterns of India in more detail later.

Background on Changing Weather Trends

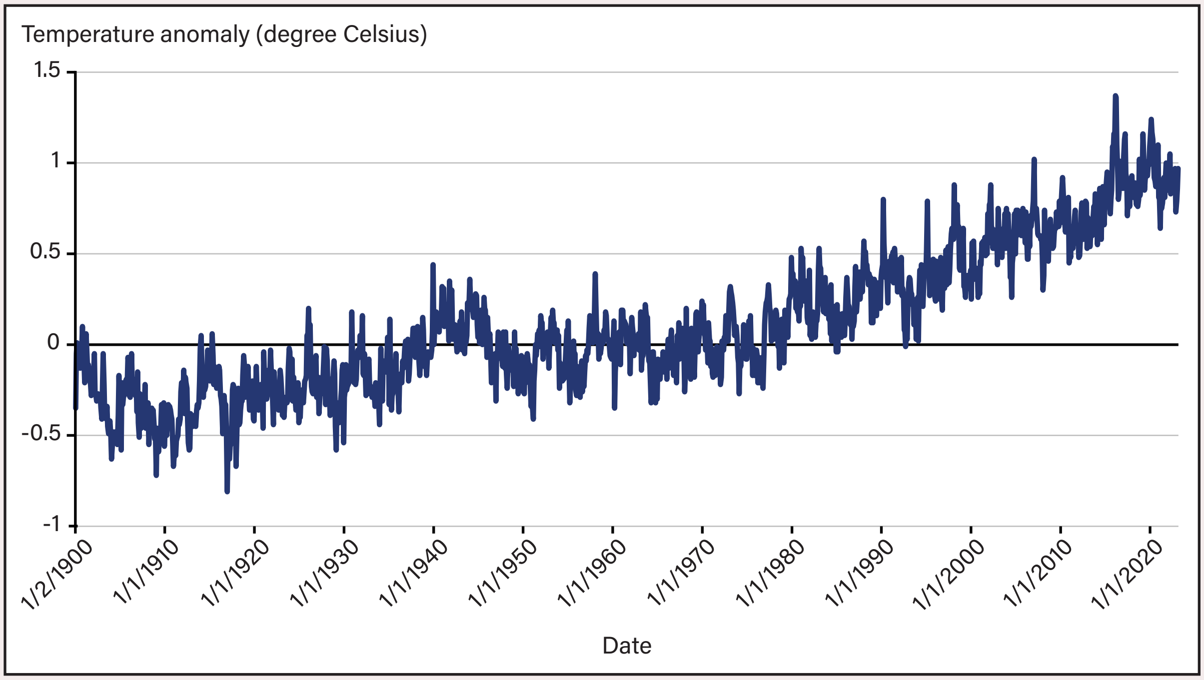
Several studies estimate the impacts of more volatile weather trends across the globe. Reilly and Hohmann (1993) found that changes in weather trends will result in relative winners and losers, as the projected changes in trends will have varying effects on agricultural productivity across regions of the world. Huang et al. (2011) showed that mid- and high-latitude countries will have a relative advantage in producing products, such as cereals and livestock, compared with low-latitude countries because of the changes in productivity caused by shifting weather patterns. Therefore, mid- and high-latitude countries would increase exports of these commodities to low-latitude countries to offset the losses caused by changes in long-term weather patterns.

More recently, Schenker (2013) analyzed the spillover effects of more volatile weather trends through international trade and found, like previous studies, that changes in long-term trends affects terms of trade and relative competitiveness. Schenker concluded that developed countries, which have a comparative advantage in the production of capital-intensive goods, are better shielded from the negative effects of more volatile weather patterns but that the net effect could potentially shift the terms of trade in favor of developing countries. This shift will result in developing countries disbursing some of their losses from more volatile weather trends to developed countries. Dellink et al. (2017) found that the relative impacts at a regional level from more volatile weather patterns, compared with its trading partners and competitors, matter more than the absolute impacts. Therefore, a country must account for not only the changes in its own agricultural productivity but also for the changes in the agricultural productivity of its trading partners and international competitors.

Global Temperature Trend

New global temperature records have been set frequently in recent years. For instance, elevated temperature records were set consecutively in 2014, 2015, and 2016 (Rahmstorf et al., 2017). The 2020 global average temperature tied with that of 2016 for the hottest years on record, with average annual anomalies at 1.01 °C and 1.02 °C for the years 2016 and 2020, respectively (National Aeronautics and Space Administration (NASA), 2023). Figure box 1 shows the differences of average monthly recorded temperatures from the long-term average temperature (monthly temperature anomalies) between 1900 and 2023. Observation of the long-term trend in temperature shows that the global temperature has been increasing at 0.04 percent each decade since 1901 (Environmental Protection Agency (EPA), 2023). Observed global temperatures in the last three decades were warmer than average, with several monthly temperatures above a 1 °C difference from the average temperature in the last 10 years. (NASA, 2023).

Box figure 1
Monthly temperature anomaly, 1900–2023



Note: Temperature anomaly is the difference between a measured temperature and a reference temperature. The reference temperature is the long-term average 1951–80 (°C).

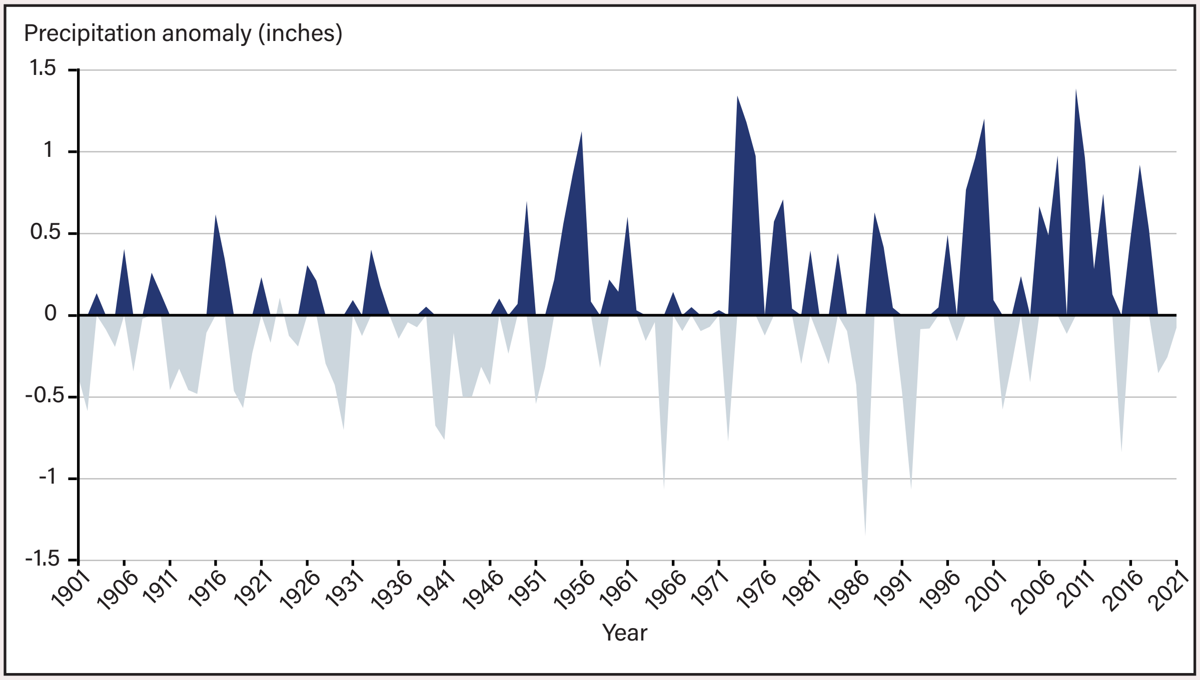
Source: USDA, Economic Research Service calculations using temperature anomaly data from the National Aeronautics and Space Administration's Goddard Institute of Space Studies (2023).

Global Precipitation Trend

Precipitation is a crucial factor for human well-being and food production across the globe. It comes in different forms, including rainfall and snowfall. The availability of water is necessary for crop and animal production, and precipitation plays a significant role in determining the amount of surface and underground water available. Extreme weather events, such as droughts, have resulted in variations in the impact of changing weather patterns across the globe. Short-term observations of precipitation across smaller areas tend to show more variation than longer-term observations across larger areas. For instance, Adler et al. (2017) showed that there is a pattern of distinct positive and negative precipitation trends across the planet, depending on location. Box figure 2 shows that precipitation anomalies have grown over time and how floods and droughts have become more severe since 1901.

Box figure 2

Annual global precipitation deviation from average, 1901–2021

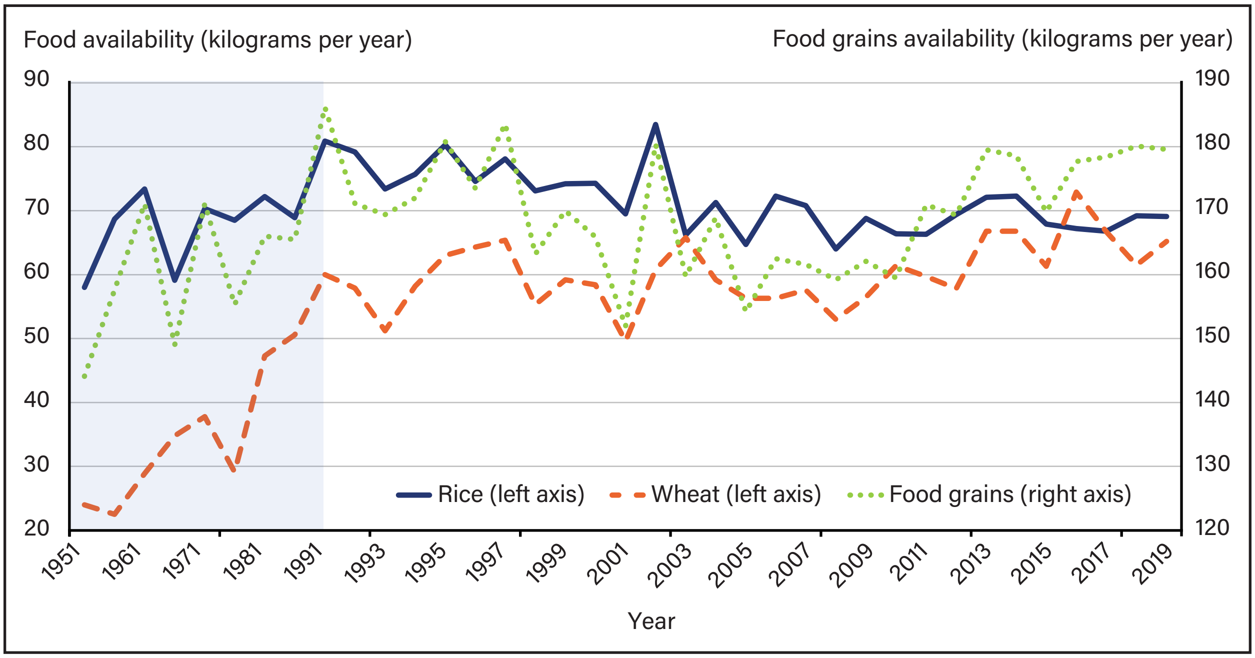


Source: USDA, Economic Research Service calculations using data from Blunden and Boyer (2022), *Bulletin of the American Meteorological Society*, *103*(8), and the National Oceanic and Atmospheric Administration.

Factors Influencing Rice and Wheat Production in India

Figure 1 shows that per capita availability of major food grains in India has plateaued in recent years after increasing steadily between the 1950s and early 1990s.

Figure 1
India's net per capita availability of food grains, 1951–2019

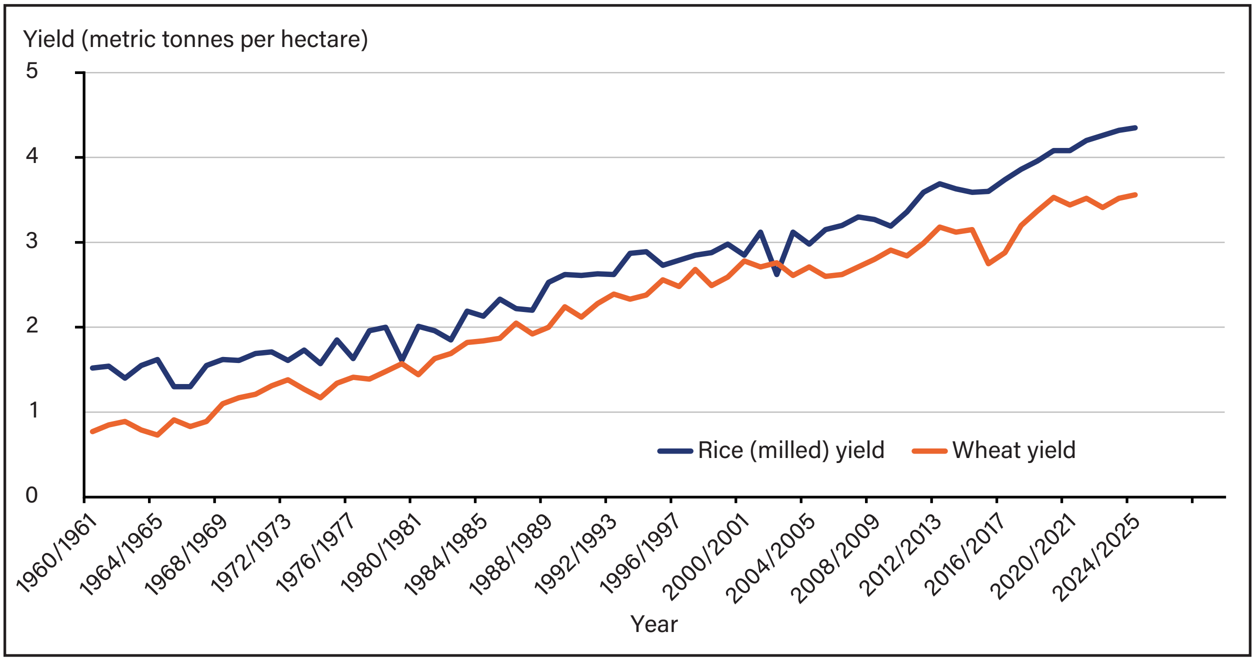


Note: Prior to 1991, data was only available every 5 years.

Source: USDA, Economic Research Service using data from the Government of India (2022a).

Over the last few decades, the average annual yield of rice and wheat in India has maintained an upward trend (figure 2). Rice is cultivated in India's humid tropical weather; therefore, there is potential for a yield increase under a suitable crop management practice that adapts to varying weather conditions (Halder et al., 2020). In the early 1950s, rice yield was, on average, higher than that of wheat. Since the mid-1960s, however, India's average wheat yield has steadily remained higher than that of rice (figure 2). Irrigation is a major contributor to high wheat yield in India, with over 85 percent of India's wheat produced under irrigation (Zaveri & Lobell, 2019; Jha et al., 2007). In all, average yields of rice and wheat grew from below 1 ton per hectare in 1950 to over 2.5 tons and 3.5 tons per hectare in 2018 for rice and wheat, respectively. In addition to having a higher average yield than rice, wheat's share of India's total food grain production area has increased by 14 percentage points between 1950 and 2020, while rice production's share of total food grain production in India has remained around 35 percent in recent years (figure 3). Because of differences in heat and water requirements for optimum growth of several crops, the impact of changing weather trends is expected to differ across crops and across geographical areas in India. For example, Kumar and Khanna (2023) analyzed the effects of volatile long-term weather trends on rice, maize, and wheat yields in India using data from 1966 to 2015 and found that the impacts differed across commodities. Kumar and Khanna showed that increases in precipitation enhanced rice productivity but adversely affected wheat and maize productivity. Furthermore, there was no observable adaptation against rising temperatures for rice and wheat, but there was adaptation for wheat against changes in precipitation (Kumar & Khanna, 2023).

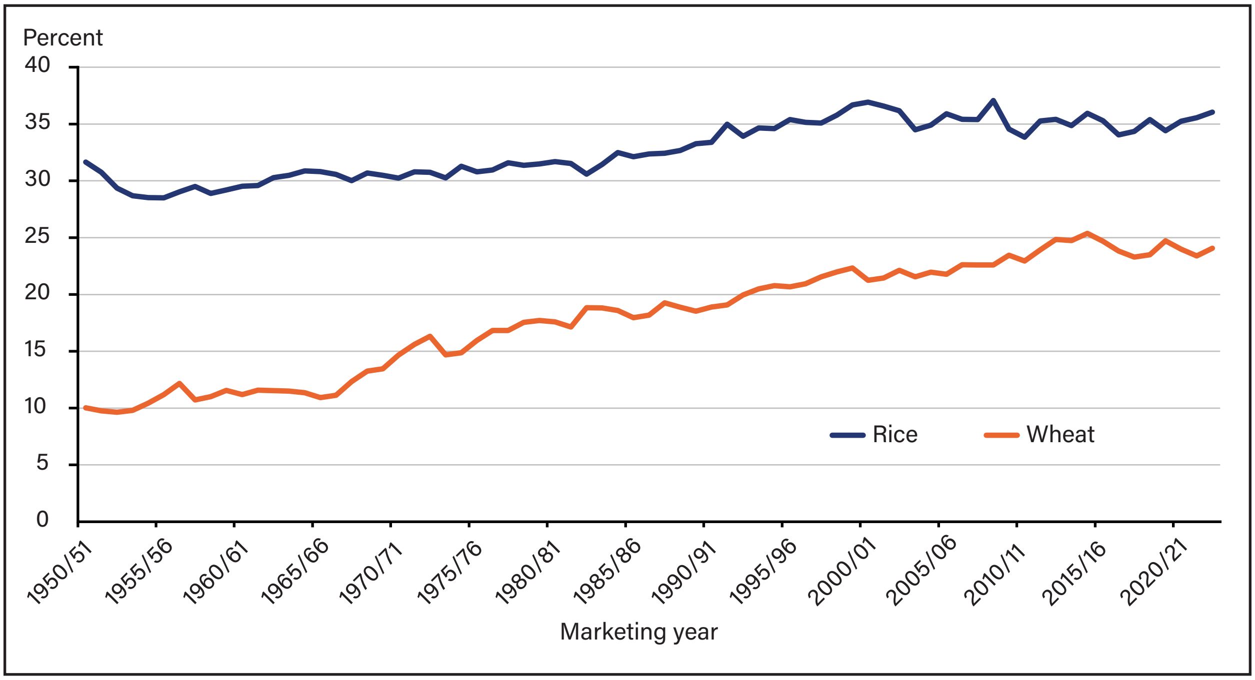
Figure 2
India's wheat and rice yields, 1960/61 to 2024/25



Note: The rice yield represents milled rice yield.

Source: USDA, Economic Research Service using data from USDA, Foreign Agricultural Service, Production, Supply, and Distribution online database.

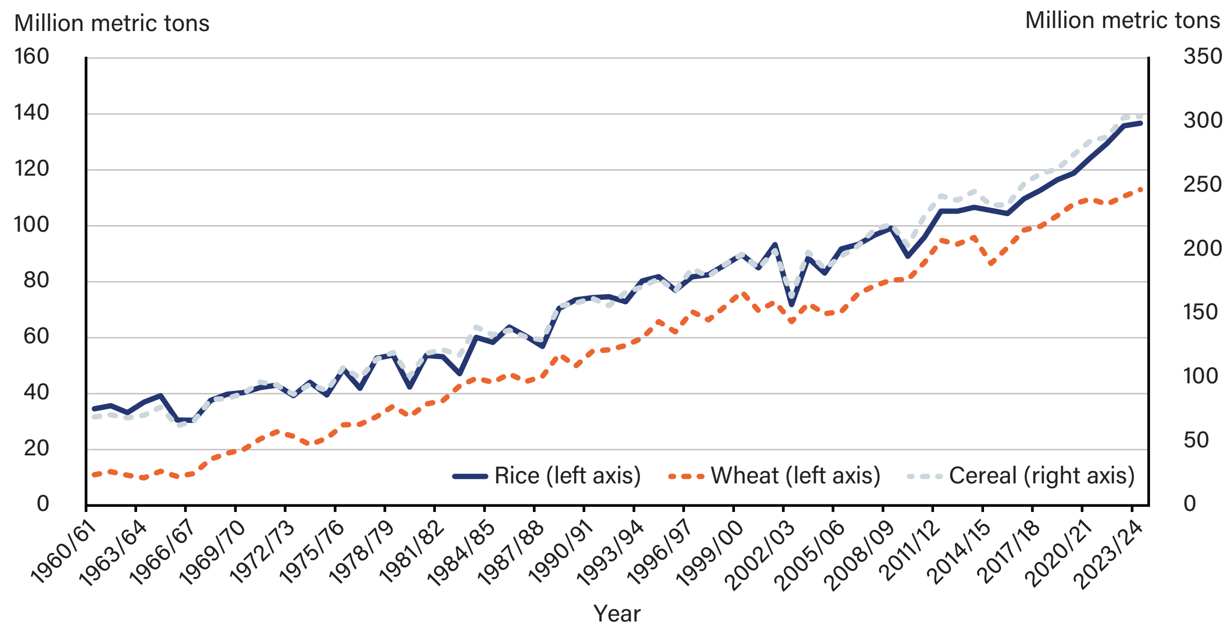
Figure 3
Proportion of India's rice and wheat to total food grain production, by area, 1950/51 to 2022/23



Source: USDA, Economic Research Service using data from the Reserve Bank of India.

Continuous annual yield increases, in combination with increases in India's production area for rice and wheat, have led to significant growth in the production of these major grains over the years. Figure 4 shows that India's production of rice and wheat more than doubled from 1961 to 2019, following a similar path as that of overall cereal[1] production. The upward shift in production in the 1970s is attributed to the adoption of high-yielding varieties, in addition to other supportive output and input policies (Jha et al., 2007).

Figure 4
India's production of major grains, 1960/61 to 2023/24



Note: The Reserve Bank of India includes other coarse grains like corn, barley, millet, and sorghum in their measure of cereals.

Source: USDA, Economic Research Service using data from the Reserve Bank of India.

Overview of Rice and Wheat Consumption in India and the Rest of the World

Global per capita consumption of wheat has increased in recent years. Overall, economic growth and changes in dietary preferences have influenced demand for staples, such as rice and wheat, across the globe. In addition to common factors, such as gross domestic product (GDP) per capita, prices, and previous demand affecting grain consumption, countries such as India have seen a relatively stable per capita consumption of rice. As per capita income has grown, however, there has been an increase in demand for other high-value foods, such as chicken, dairy products, meat, fruits, and vegetables (World-Grain, 2024).

While economic growth in India has been increasingly diversifying demand for food in India, a continuous increase in per capita demand for major grains is expected because about 18 percent of India's population is still classified as food insecure (Zereyesus et al., 2023). Box figure 3 shows that India's consumption of rice and wheat has grown rapidly in recent years. Per capita consumption of rice in India has stayed above the world average since 2010, and per capita wheat consumption is also on an upward trend. The Government of India introduced a policy to distribute an extra 5 kilograms of rice and wheat to vulnerable consumers during the Coronavirus (COVID-19) pandemic.

continued on next page ►

[1] The Reserve Bank of India includes other coarse grains like corn, barley, millet, and sorghum in their measure of cereals.

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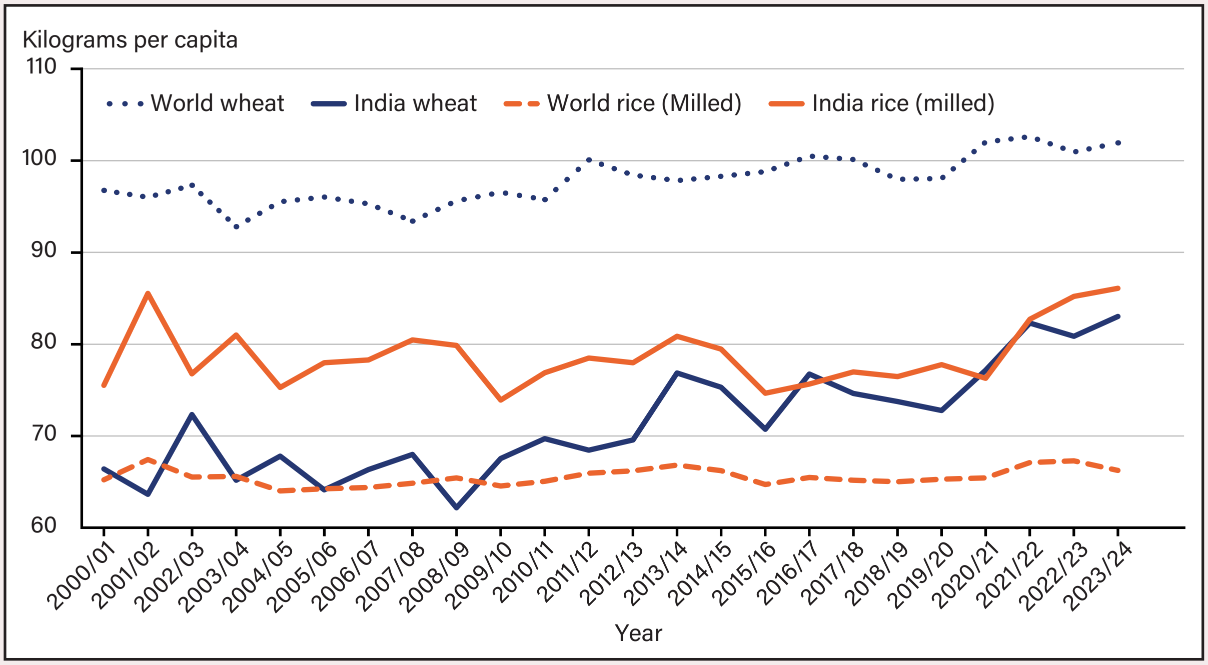
Box figure 3

Per capita consumption of wheat and rice in India and the world average, 2000/01 to 2023/24



Source: USDA, Economic Research Service using data from USDA, Foreign Agricultural Service, Production, Supply, and Distribution online database.

Domestic Support Toward Rice and Wheat in India

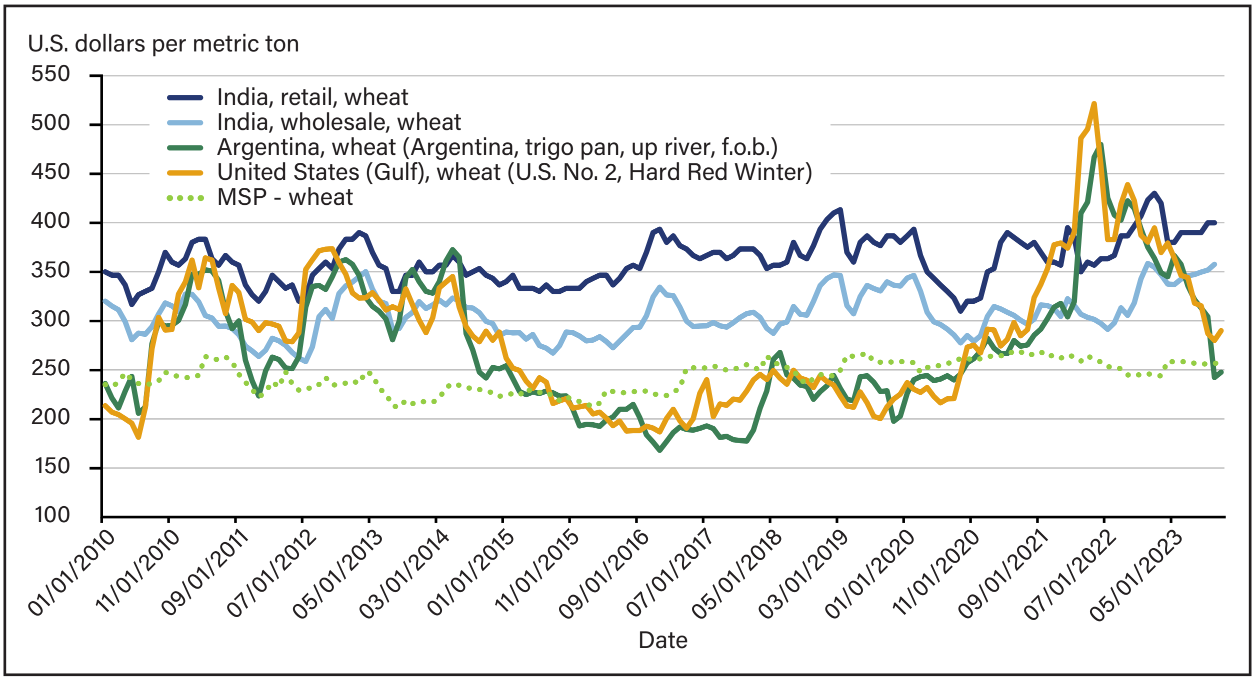
To capture the impact of volatile long-term weather trends on wheat and rice yields over the years in India, it is important to account for major subsidies to agriculture, which influence crop production practices in the country. The Government of India has long played a key role in the improvement of agricultural production in the country through domestic support and trade policy. Several policies aimed at increasing the domestic production of major crops and stabilizing prices for domestic consumers were implemented to help tackle food insecurity in the country (see box, "Overview of Rice and Wheat Consumption in India and the Rest of the World"). For instance, minimum support prices (MSPs) were implemented for both wheat and rice to shield domestic producers from volatile international prices and maintain profitability when growing these crops. Over the last two decades, India's MSPs were successful in insulating domestic wheat and rice prices from international prices and preserving a stable level of production.

India also enforces import duties and export restrictions on wheat and rice, which restricts trade of these products and benefits either producers or consumers, depending on the policy. For instance, import duties are targeted toward keeping the domestic price stable and boosting local production, as producers are protected from international competition. Conversely, export restrictions lead to a relative abundance of wheat or rice domestically, which reduces the price and mitigates food insecurity threats from high global prices. Each of these policies benefits one group (producers or consumers) at the expense of the other. Thus, these import duties and export restrictions are unfixed and are dependent on market conditions and the current needs of India's producers and consumers. For instance, in 2008, India imposed an 8,000 Indian rupees ($160) per metric ton export duty on basmati rice to protect local consumers from rising international rice prices but removed this duty in 2009 when international rice prices stabilized (Hudson, 2022). To the same effect, in

2022 and 2023, India banned exports of various varieties of rice and imposed a 20-percent tax on exports of parboiled nonbasmati rice in the wake of global inflation, causing international rice prices to rise (Singh & Beillard, 2023). India also imposed restrictions on wheat and rice imports, such as its basic custom duty on imports of wheat, which increased from 10 to 20 percent in November 2017 and increased again to 30 percent in March 2018 (Hudson, 2022). Figures 5 and 6 show that India's policies have contributed to creating a buffer between India's domestic and international wheat and rice prices.

Figure 5 shows that U.S. and Argentinian prices were far more volatile than India's domestic prices from 2010 to 2022. The figure also shows that when international wheat prices fell below India's MSP price in 2010 and again from 2015 to 2020, the country's domestic retail and wholesale prices remained relatively high. This indicates there was a low transmission of international wheat prices into India's domestic market and that India's producers were shielded from international price shocks. The global rice market differs from wheat in that it is relatively thin. In other words, of the rice and wheat produced globally, a lower percentage of rice is exported than that of wheat. This often leads to soaring prices in the international rice market, which the Government of India counters with export restrictions, such as the export duty in 2008. These policies keep India's domestic prices low and shield consumers from high international prices (figure 6).

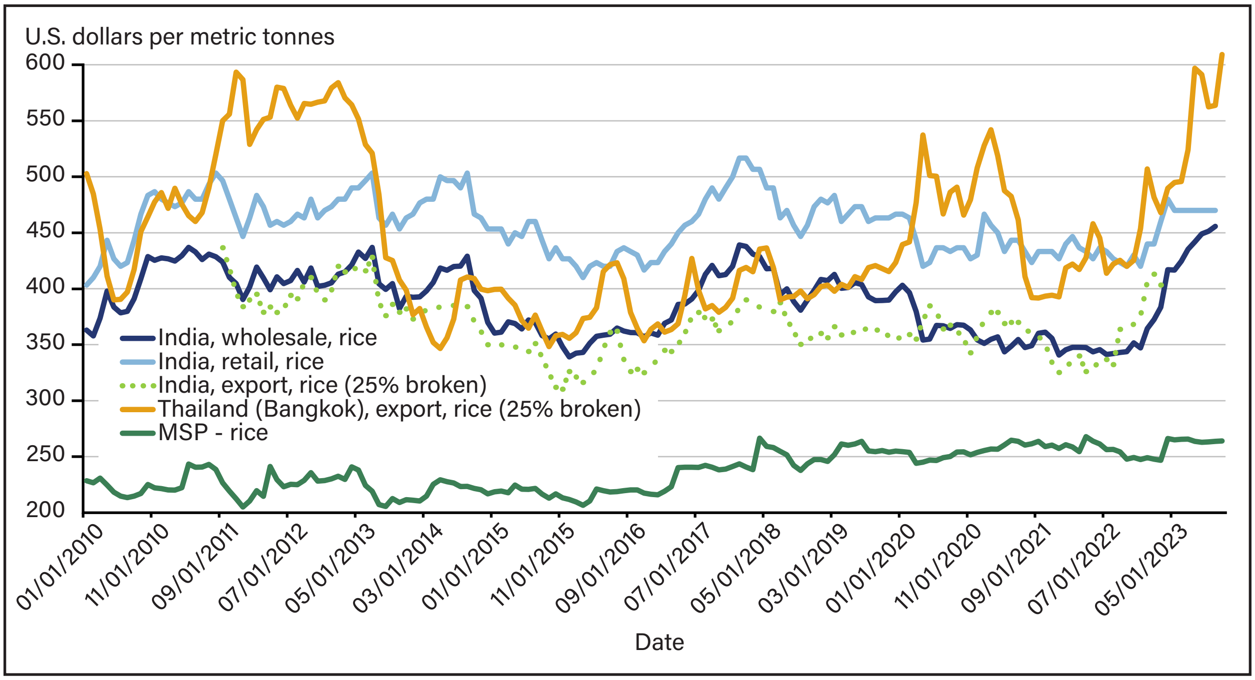
Figure 5
India's domestic and export wheat prices, 2010–23



MSP = minimum support price; FOB = free on board.

Source: USDA, Economic Research Service (ERS) calculations using USDA, ERS Agricultural Exchange Rate data, domestic, and international prices from the Food and Agriculture Organization of the United Nations (FAO), and MSPs from the Reserve Bank of India.

Figure 6
India's domestic and export rice prices, 2010–23



MSP = minimum support price.

Source: USDA, Economic Research Service (ERS) calculations using USDA, ERS Agricultural Exchange Rate data, domestic, and international prices from the Food and Agriculture Organization of the United Nations (FAO), and MSPs from the Reserve Bank of India.

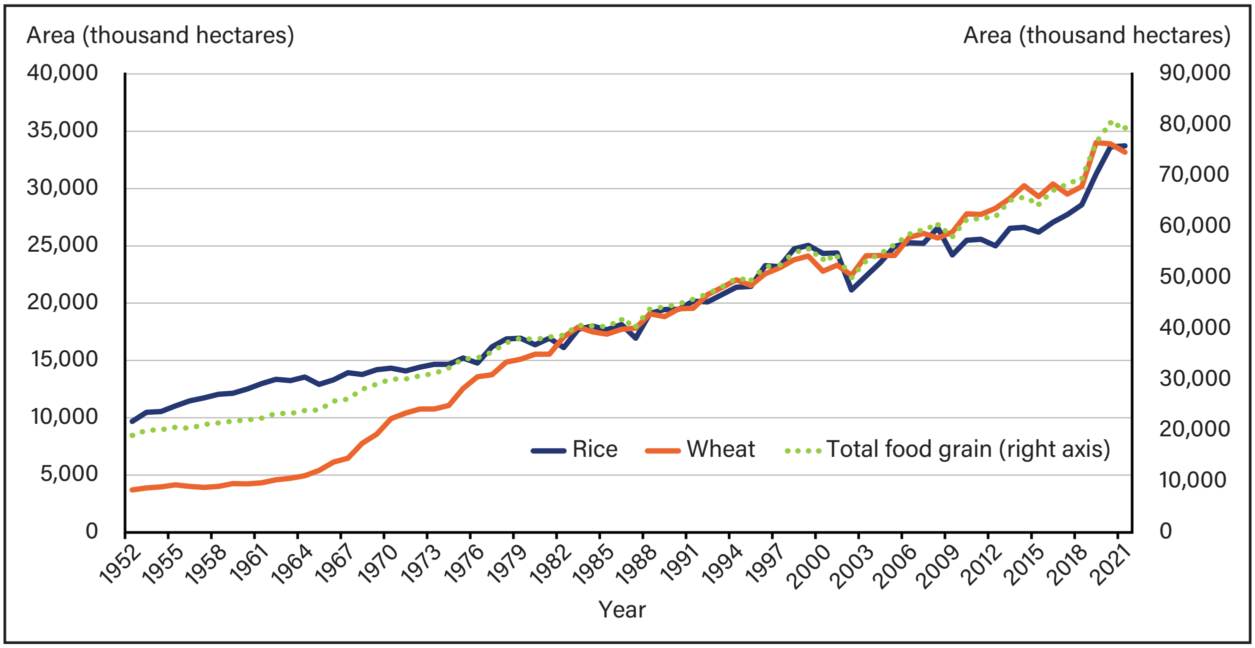
India's domestic support policies promote steady production of wheat and rice and reduce India's reliance on imports to meet domestic consumption. These policies also, however, artificially raise India's domestic wheat and rice prices, which harms consumers and prevents India's producers from shifting production to other commodities that may be more efficiently produced. As a result, these domestic policies create market inefficiencies that have clear economic consequences but may also have unforeseen impacts on the environment.[2] For instance, suppose that the reason India's wheat and rice producers need MSPs to maintain competitiveness with foreign suppliers is that the production of these crops requires more inputs (i.e., fertilizers, diesel or electricity for pumping water from wells for irrigated crops, pesticides, and herbicides) in India than in foreign countries. If this is true, then these MSPs would directly cause excessive use of these inputs, which could exacerbate India's shifting weather patterns. India's MSPs may also encourage farmers to produce commodities that may be more efficiently produced in other countries, which diverts resources away from the production of commodities that India produces more efficiently and results in the misuse of valuable arable land.

In addition to price controls and international trade policies on major crops in India, the Government of India has policies in place that subsidize agricultural inputs such as irrigation water, power, and fertilizers (Jha et al., 2007). Since the early 1960s, increases in irrigated land area occurred across cropping areas of India. The expansion of India's agricultural sector is reflected in rice and wheat, the country's two major food staples. Growing demand for food due to population growth led to an expansion of agricultural land with irrigation facilities, making India the second-largest irrigated country in the world (Gupta et al., 2022). Figure 7 shows that the irrigated land area used for rice and wheat production has risen steadily over time, following the general upward trend in irrigated land for total food grain production in India. The figure also

[2] We did not consider future changes to subsidies in our model because it was difficult to determine at which price point India's subsidies to agriculture could increase (decrease).

shows that the total hectares devoted to wheat production were less than half those of rice production in 1952, but also that hectares of wheat production have increased significantly over time and have been greater than those of rice production since 2008.

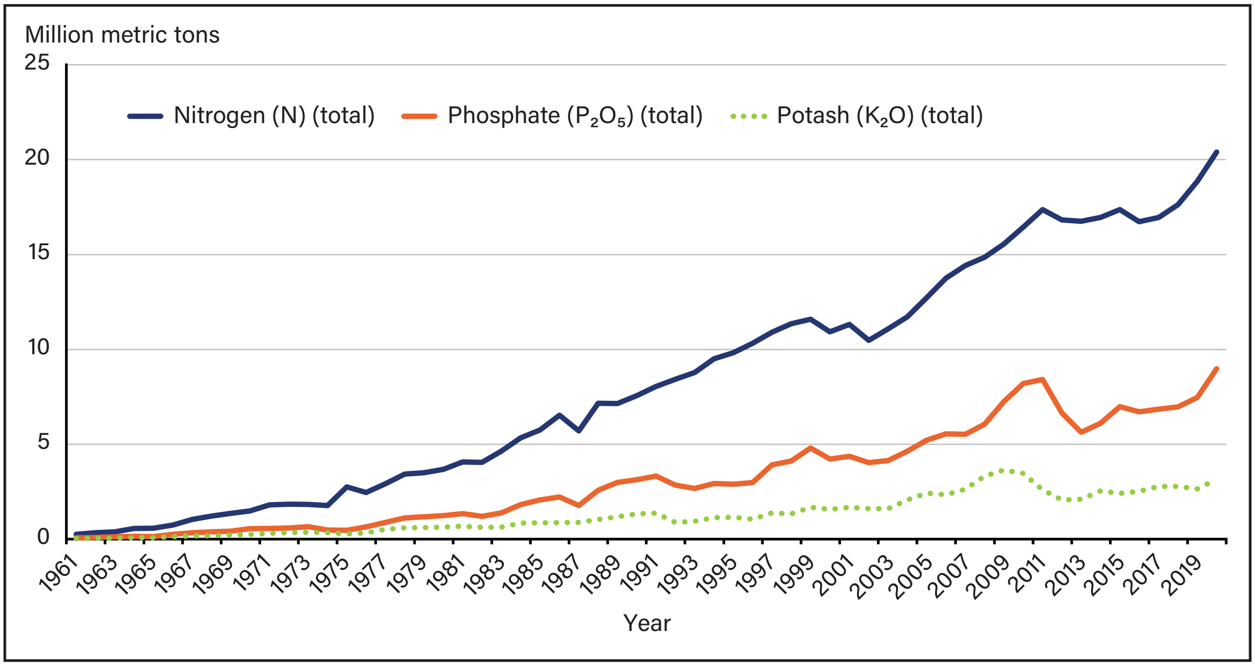
Figure 7
India's irrigated cropland by commodity, 1952–2021



Source: USDA, Economic Research Service using data from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

Besides irrigation systems, the last several decades have seen major changes to other agricultural production inputs in India as well. The use of major inputs such as fertilizers have significantly increased since the 1970s, especially the application of nitrogen-based fertilizers. Figure 8 shows the trend in consumption of nitrogen, phosphate, and potash fertilizers in India from 1961 to 2019. The application of nitrogen fertilizers alone has increased from less than 250,000 metric tons in 1961 to 20.4 million metric tons in 2020. Government subsidies aimed at increasing production by reducing the cost of these fertilizers have likely contributed to this sizable increase in fertilizer usage.

Figure 8
India's fertilizer uses by nutrient (million metric tons), 1961–2020



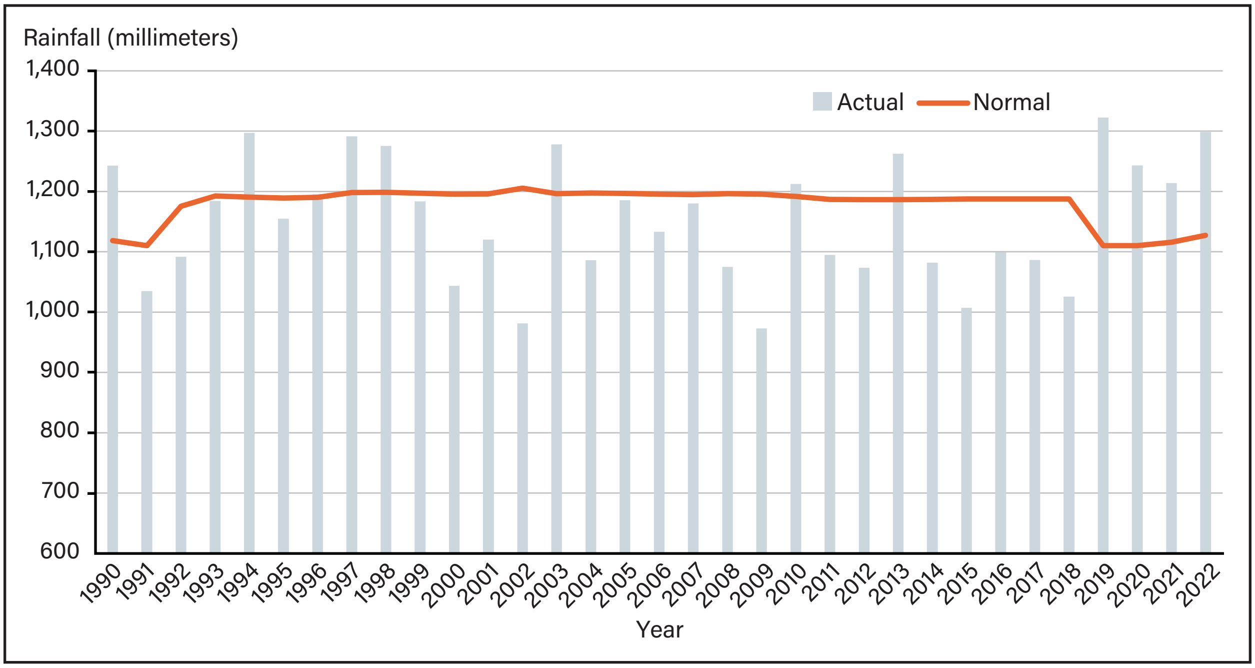
Source: USDA, Economic Research Service using data from the Reserve Bank of India.

Although India's fertilizer subsidies were first put in place with the goal of achieving food security for the country's growing population, the intentions of these subsidies have evolved since the introduction of the Retention Price Scheme (RPS) in 1977 (Gulati & Banarjee, 2015). Fertilizer subsidies from 1977 to 1991 that were directly targeted at achieving food security were revised as part of national economic reform between 1991 and 2003. A new pricing scheme was introduced in 2003 to focus more on agricultural productivity (Shamrao, 2011). The current fertilizer policy, introduced in 2022, is tagged "One Nation, One Man, One Fertilizer," with the aim of uniform fertilizer production and branding across India. The Government of India has considerable influence on fertilizer production because, on average, government subsidies cover up to 90 percent of the cost of production to manufacturers (Government of India, 2022b). While fertilizer contributes to yield growth, an excessive use of fertilizer comes with environmental consequences such as soil degradation, altering soil pH, and water pollution through runoff. Nitrogen fertilizer contributes to an increase in carbon concentration because not all the nitrogen in the fertilizer is taken up by crops (Celikkol Erbas et al., 2017; Menegat et al., 2022; Martre et al., 2024).

The Impact of Volatile Weather Trends on India's Precipitation and Temperature

The impact of volatile weather trends can be observed from changes in major weather variables over time. In recent years, several extreme weather events in India have occurred that have impacted agricultural production. For instance, Rawat et al. (2022) reported that about 68 percent of India is prone to drought at various levels. Figure 9 shows that India has experienced a reduction in annual rainfall relative to the normal level (a 30-year average) in multiple years in the last two decades. In fact, since 2000, only 3 years have received enough rainfall to be considered "above normal."

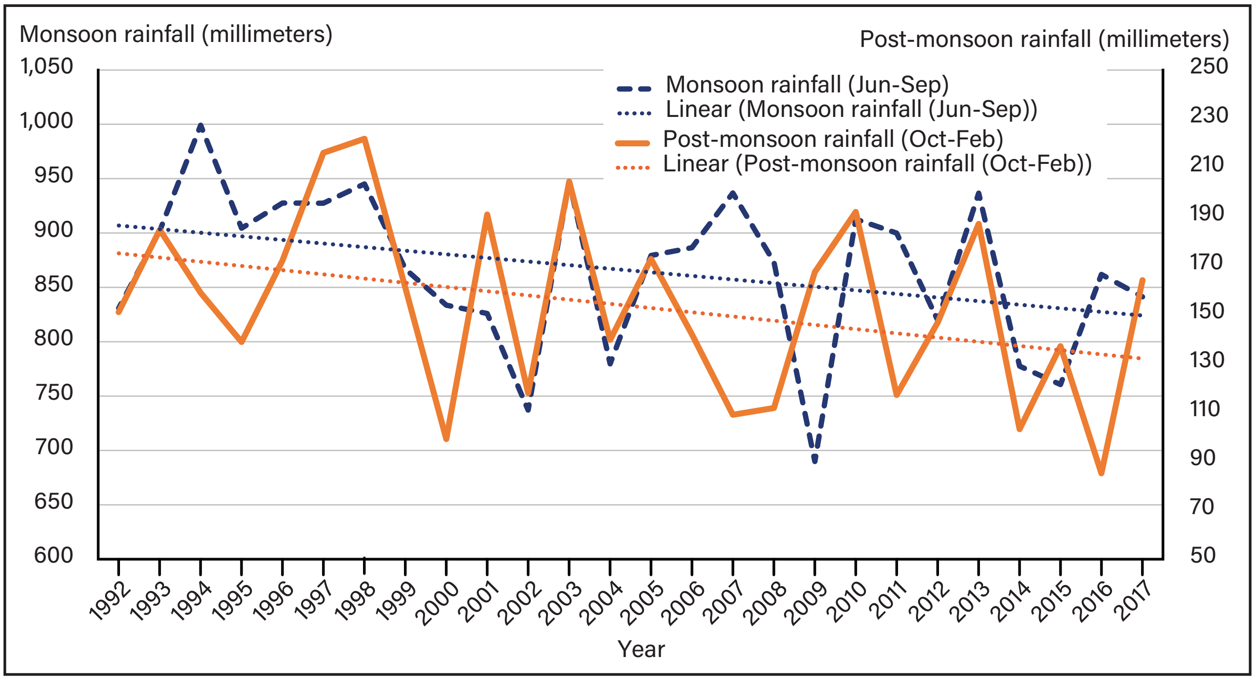
Figure 9
India's actual and normal annual rainfall, 1992–2022



Source: USDA, Economic Research Service using data from the World Bank Group (2023).

The kharif rice growing season aligns with the monsoon season from June to September, whereas the wheat growing season (October to February) aligns with the post-monsoon season in India. Figure 10 illustrates that the amount of rainfall in India during both growing seasons followed a downward trend from 1992 to 2017. Since the early 1990s, the lowest amount of rainfall during any rice growing season occurred in 2009, when monsoon rainfall in India was slightly below 700 millimeters. The lowest recorded rainfall during India's wheat growing period was in 2016, during which post-monsoon rainfall was less than 90 millimeters.

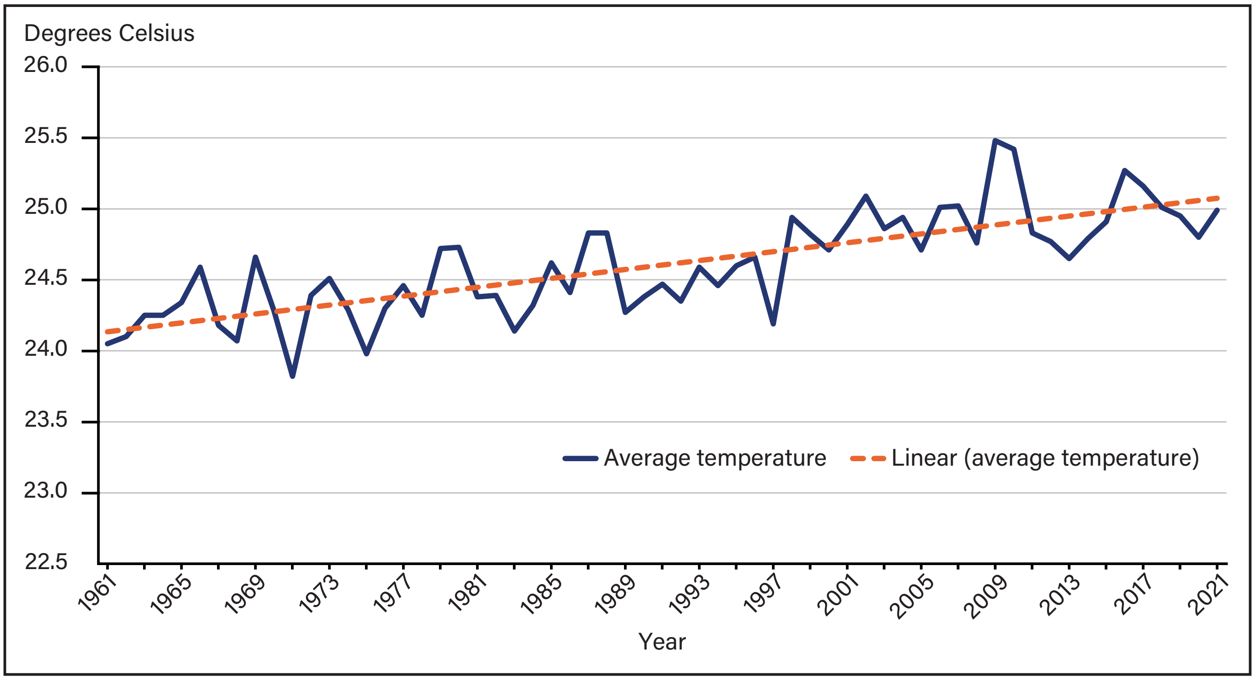
Figure 10
India's total rainfall during rice and wheat growing seasons, 1992–2017



Source: USDA, Economic Research Service calculation using data from the World Bank Group (2023).

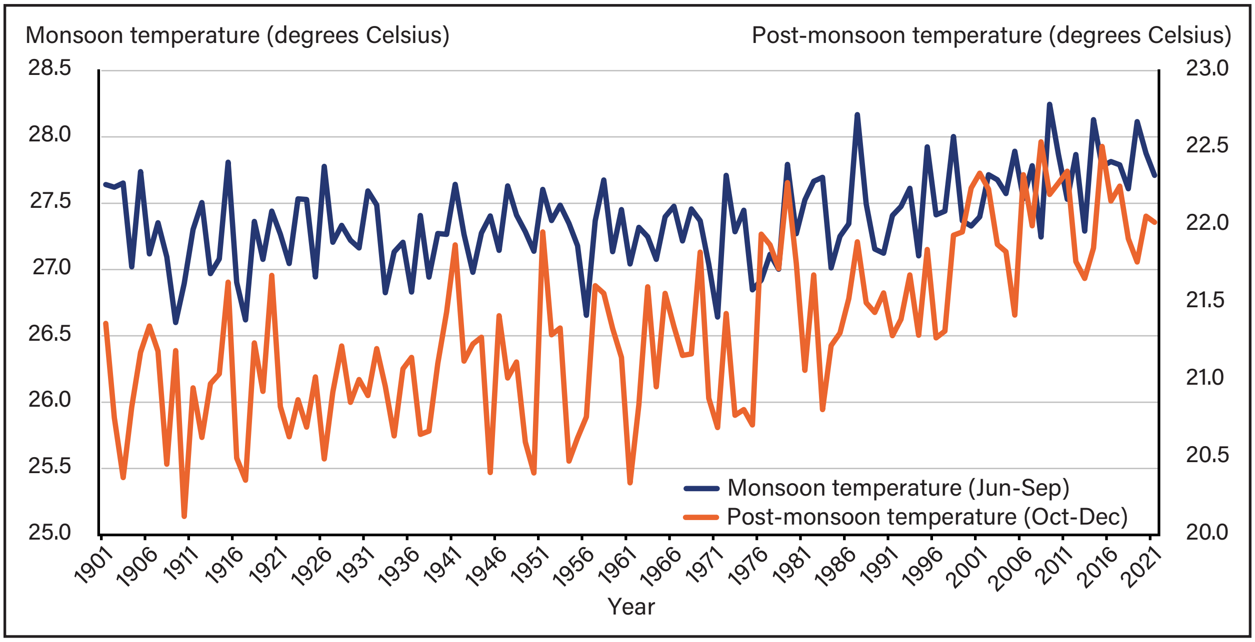
While rainfall is declining from its long-time average (normal rainfall), temperature has been increasing over the years. Figure 11 shows that India's annual average temperature increased by about 1 °C between 1960 and 2020. Figure 12 shows an increase in the average temperature during the rice growing season (known as the Kharif season, which is the monsoon period of June to September) of about 0.75 °C. Furthermore, the average temperature during the wheat growing season (known as the Rabi season, which is the post-monsoon period of October to December) increased about 1.5 °C from 1961 to 2021.

Figure 11
India's average annual temperature, 1961–2021



Source: USDA, Economic Research Service using data from the World Bank Group (2023).

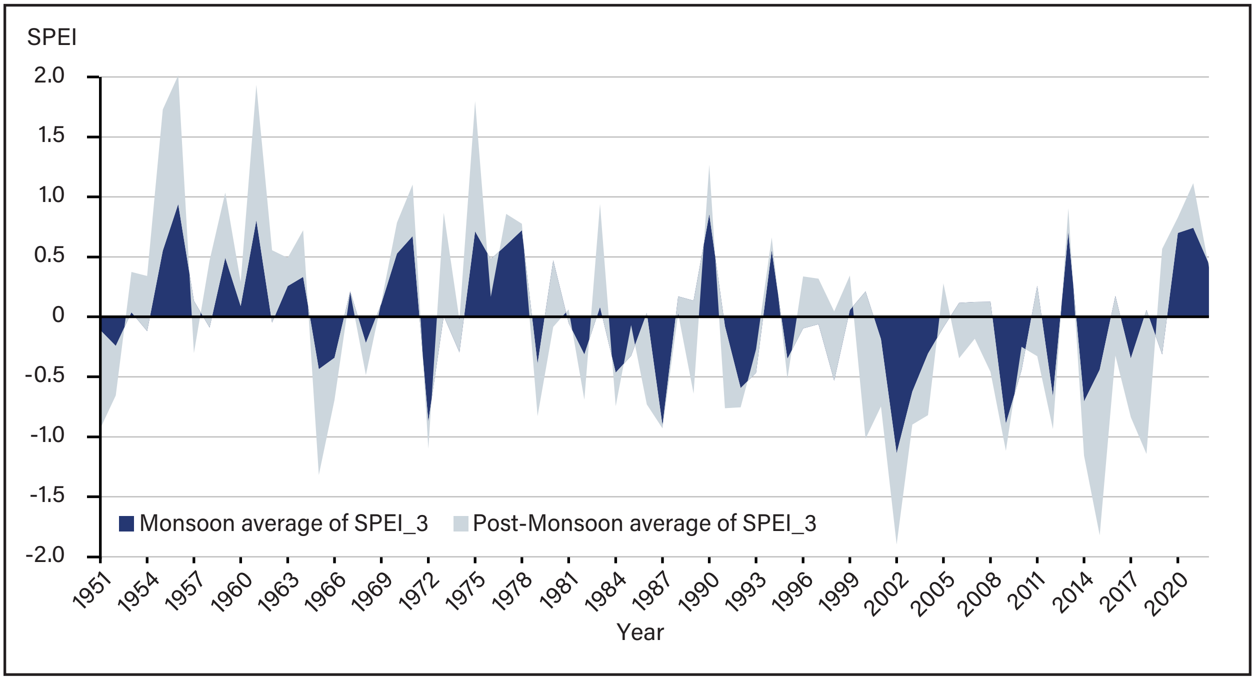
Figure 12
India's average annual temperature during the wheat and rice growing seasons, 1901–2021



Source: USDA, Economic Research Service using data from the World Bank Group (2023).

The combined effects of changes in temperature and precipitation patterns can lead to extreme events such as droughts and floods. The Standardized Precipitation-Evapotranspiration Index (SPEI) was created by Vicente-Serrano et al. (2010) to capture the combined effects of precipitation and potential evapotranspiration (temperature) in determining the severity of droughts. Figure 13 shows the time series of 3-month time scale SPEIs in India from 1951 to 2021 for the rice (monsoon) and wheat (post-monsoon) seasons. An SPEI value between 1 and -1 is categorized as normal conditions for crop production. An SPEI value of 1.5 and above equates to severely wet conditions, while any value below -1.0 is considered drought conditions. An SPEI value below -1.5 is considered severe drought (Potopová et al., 2015). Figure 13 shows that droughts in India have become more frequent in recent years.

Figure 13
Average Standardized Precipitation-Evapotranspiration Index (SPEI) for India's monsoon and post-monsoon seasons, 1951–2020



Source: USDA, Economic Research Service calculations using data from the Global SPEI database (SPEIbase) (Vicente-Serrano et al., 2010; Beguería et al., 2014).

The water supply for agricultural production in India is highly dependent on the distribution of monsoon rainfall. Over the last several years, despite the increased frequency of droughts, floods caused by heavy rainfall have damaged thousands of hectares (ha) of cropland in India. In 2016, for example, 14,157 ha of cropland were damaged by floods (ReliefWeb, 2016). Then, in 2017, about 106,000 ha of cropland in the Indian State of Assam and over 3,150 ha of cropland in the Indian State of Manipur were damaged by floods (ReliefWeb, 2018). Most recently, flooding throughout 2022 damaged 1,530,722 ha of India's cropland (ReliefWeb, 2022). Mahato (2014) projected that India's summer monsoon rainfall will increase by 20 percent by 2050, indicating that the flood damage from recent years should be expected to continue moving forward.

Precipitation and temperature, although important, are not the only factors of agricultural productivity to consider in assessing the impacts of changing long-term weather patterns. Carbon concentration, for example, also affects agricultural productivity. In fact, a recent study found that higher carbon concentrations could lead to gains in global wheat and rice yields when comparing the 1983–2013 average to the projected 2069–2099 average (Jägermeyr et al., 2021). Similar studies on the impact of volatile weather trends on India's groundnut productivity showed a positive yield response in some food production units is expected with an increase in annual rainfall and carbon fertilization (Kadiya et al., 2021). The study also found a drop in productivity for corn and soybeans when comparing the same periods. These productivity projections are on a global scale and are not necessarily indicative of regional productivity changes. In other words, though the global average yields for wheat may increase, yield changes within particular countries or regions may be positive or negative. Several other studies have evaluated the impact of volatile weather trends on agricultural productivity (e.g., Hertel & de Lima, 2020; Praveen & Sharma, 2019; Harfield et al., 2011; Nastis et al., 2012; and Habib-ur-Rahman et al., 2022).

Projected Impact of Volatile Weather Trends on India's Rice and Wheat Trade

Yield projections based on potential changes in weather patterns were used in a computable general equilibrium (CGE) model to assess the potential future impact of volatile weather trends on rice and wheat production and trade in India (Global Trade Analysis Project (GTAP), 2022). Rice and wheat yield projections until 2040 from the Agricultural Model Intercomparison and Improvement Project's (AgMIP) Data Aggregator Tool were introduced as shocks to yields across India's Agro-Ecological Zones (AEZs)[3] in GTAP. AgMIP's Global Gridded Crop Model Intercomparison (GGCMI) has yield projections for major crops, such as wheat, rice, maize, and soybeans, until 2100 (Jägermeyr et al., 2023). These projections are based on Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design (Eyring et al., 2016).

The simulation protocol for CMIP6 crop yield projections is based on two Representative Concentration Pathways (RCPs), RCP2.6 and RCP8.5 (hereafter referred to as SSP126 and SSP585, respectively) (Jägermeyr et al., 2021). Due to differences in the topographic makeup of countries and regions around the world, the results may show differences in the effects of changes in temperature and precipitation over time. For instance, CMIP6 models showed that, under SSP585, losses in crop productivity were prevalent in the low latitude tropical regions, while the highest gain in crop productivity was found at latitudes beyond 50° N and 30° S for all crops (Jägermeyr et al., 2021).[4] Table 1 shows how the land is classified by AEZs and where cropland is located in India. However, not all AEZs are suitable for rice and wheat production. For example, no rice and very small amounts of wheat are grown in AEZ 1. Furthermore, a small volume of rice is grown in AEZ 7, and very little wheat is grown in AEZ 5.

Table 1

Agro-Ecological Zone (AEZ) classifications of cropland in India

Length of growing period (days)	Moisture regime	Climate zone	GTAP class	Cropland (1,000 hectares)
0–59	Arid	Tropical	AEZ 1	160
		Temperate	AEZ 7	2,311
		Boreal	AEZ 13	0
60–119	Dry semiarid	Tropical	AEZ 2	14,586
		Temperate	AEZ 8	18,026
		Boreal	AEZ 14	0
120–179	Moist semiarid	Tropical	AEZ 3	66,269
		Temperate	AEZ 9	44,441
		Boreal	AEZ 15	0
180–239	Subhumid	Tropical	AEZ 4	33,073
		Temperate	AEZ 10	9,767
		Boreal	AEZ 16	0

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[3] AEZs classify land according to shared long-term weather patterns, precipitation, and moisture conditions (Avetisyan et al., 2010).

[4] Jägermeyr et al. (2021) more fully discussed the SSP126 and SSP585 crop projections. Conversely, in this study, we focused more on the impacts of the yield changes from the crop yield projections on domestic markets and international trades of rice and wheat in India.

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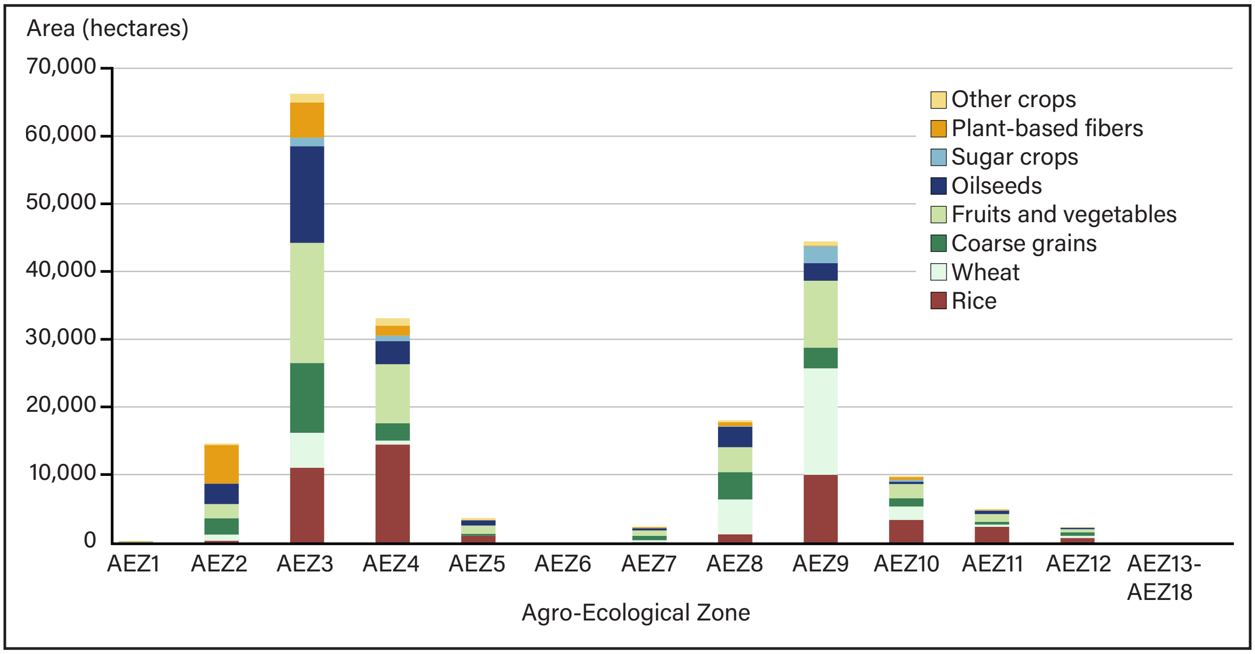
Length of growing period (days)	Moisture regime	Climate zone	GTAP class	Cropland (1,000 hectares)
240–299	Humid	Tropical	AEZ 5	3,587
		Temperate	AEZ 11	4,938
		Boreal	AEZ 17	0
>300 days	Humid; year-round growing season	Tropical	AEZ 6	0
		Temperate	AEZ 12	2,240
		Boreal	AEZ 18	0

GTAP = Global Trade Analysis Project.

Source: USDA, Economic Research Service calculations based on Aguiar et al. (2019), The GTAP Data Base: version 10, *Journal of Global Economic Analysis*, *4*(1).

Only 5 zones cultivate more than 10,000 hectares of crop in a year, which are AEZs 2, 3, 4, 8, and 9. Figure 14 shows the production area of major crops across GTAP's 18 AEZs of India. AEZ 3 is the dominant agricultural production zone in India, followed by AEZ 9 and AEZ 4.

Figure 14
Average production area across the Agro-Ecological Zones (AEZs) of India, by crop category



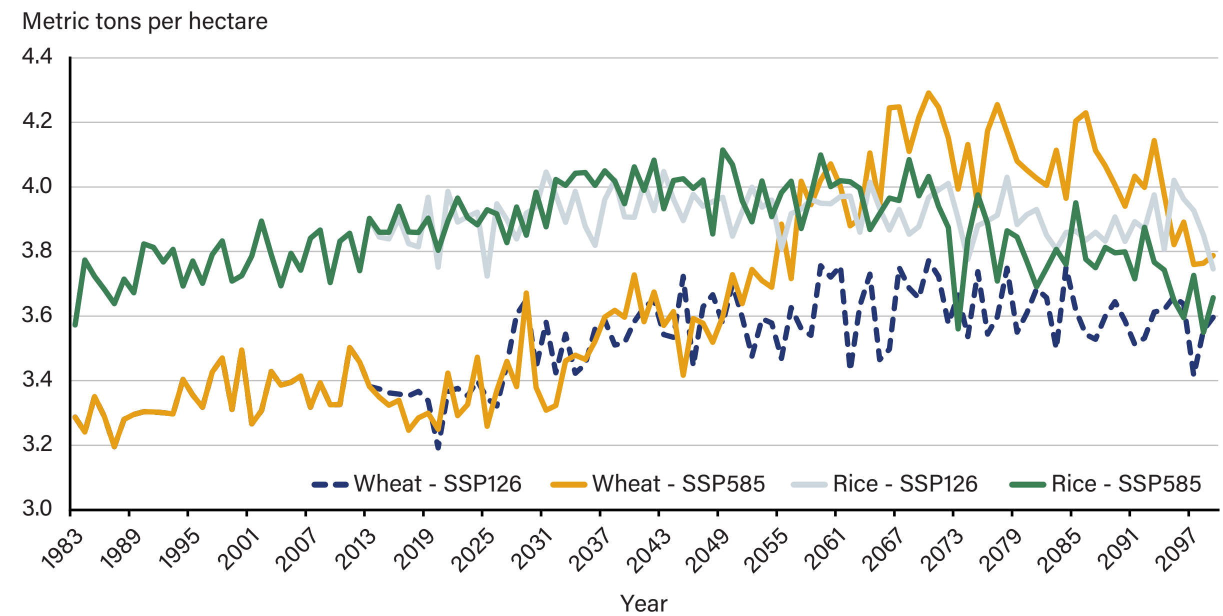
Note: AEZs 6, 13, 14, 15, 16, 17, and 18 have zero production area.

Source: USDA, Economic Research Service calculations using data from the Global Trade Analysis Project-Agro-Ecological Zone (GTAP-AEZ) Data Base (Aguiar et al., 2019).

Figure 15 shows the long-term projected changes in wheat and rice yields in India under two scenarios, SSP126 and SSP585. Average yields of rice and wheat were projected to grow under both scenarios over the next several decades (see box "Overview of Yield Projections"). Other studies have also found the potential for future increases in rice yield under different scenarios. For instance, Harder et al. (2020), using experimental data and a Crop Environment Resource Synthesis (CERES)-Rice model, projected that rice yields will increase (at a decreasing rate) between 2020 and 2050. Jägermeyr et al. (2021) also estimated that higher carbon concentrations will likely lead to gains in global wheat and rice yields. India is currently below several major rice and wheat producers in terms of yield, so there is room to increase productivity outside of the projected yield increases due to changes in long-term weather patterns. Using these yield change estimates in the Global Trade Analysis Project (GTAP) computable general equilibrium (CGE) model,[5] this report assesses the potential effects of volatile weather patterns on India's wheat and rice production and trade.

Figure 15

Projected yields for wheat and rice under two scenarios, 1983–2099



Source: USDA, Economic Research Service calculations using data from Jägermeyr et al. (2023), *AgMIP data aggregator tool*.

Overview of Yield Projections

Long term weather models help us understand how human actions will affect the environment in the future and how to mitigate or adapt to these changes. Several of these models have predicted future changes to global and/or regional weather patterns based on current trends. Although long-term weather trend models have a level of uncertainty, using projected changes to temperature and precipitation from a consensus of models allows us to predict several changes to the natural and social environment, including crop production (USDA, 2023). Understanding future changes to the environment based on different emission scenarios provides the tools to mitigate major changes to the environment, manage associated risks, and create a means to adapt to the changing environment. Furthermore, studies have shown that those areas that have contributed the least to carbon concentration are the most affected by changes in long-term weather patterns. Effects on human and natural resources include damage to terrestrial and freshwater ecosystems (IPCC, 2023). In India, land is in production in the first 12 Agro-Ecological Zones (AEZs), although AEZ 1 contains such a small portion of land that its yield changes are not considered here. Table B.1 shows the effects of changes in long-term weather pattern on rice and wheat yields by

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[5] While CGE models are preferred by many researchers to analyze global trade policy issues, these models have limitations. One major limitation of CGE models is that they are not empirical in the sense of econometric modeling. Furthermore, CGE simulations are based on assumptions of circumstances that are sensitive to change, and change is always expected in the real world (GTAP, 2022).

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Overview of Yield Projections

Long term weather models help us understand how human actions will affect the environment in the future and how these changes can be mitigated or adapted to. Several of these models have predicted future changes to global and/or regional weather patterns based on current trends. Although long-term weather trend models have a level of uncertainty, using projected changes to temperature and precipitation from a consensus of models allows us to predict several changes to the natural and social environment, including crop production (USDA, 2023). Understanding future changes to the environment based on different emission scenarios provides the tools to mitigate major changes to the environment, manage associated risks, and create a means to adapt to the changing environment. Furthermore, studies have shown that those areas that have contributed the least to carbon concentration are the most affected by changes in long-term weather patterns. Effects on human and natural resources include damage to terrestrial and freshwater ecosystems (IPCC, 2023). In India, land is in production in the first 12 Agro-Ecological Zones (AEZs), although AEZ 1 contains such a small portion of land that its yield changes are not considered here. Table B.1 shows the effects of changes in long-term weather pattern on rice and wheat yields by 2040 based on two Representative Concentration Pathways (RCPs): SSP126 and SSP585 (Jägermeyr et al., 2021). The percent changes in yields were derived from projected changes in annual average maximum and minimum daily temperatures, annual daily precipitation totals, average soil moisture levels, and other soil conditions at different global warming levels.

Table B.1
Volatile long-term weather pattern impacts on rice and wheat yields in India by 2040

	Rice yield change (percent)		Wheat yield change (percent)	
	SSP126	SSP585	SSP126	SSP585
AEZ 2	7.5	6.85	-1.14	5.23
AEZ 3	3.11	4.91	0.4	5.88
AEZ 4	2.31	8.52	1.05	10.25
AEZ 5	3.24	4.57	3.4	4.92
AEZ 6	3.89	5.29	3.87	1.47
AEZ 7	-4.24	-1.47	10.11	11.77
AEZ 8	-2.66	-1.12	9.66	14.77
AEZ 9	2.51	6.69	2.92	7.91
AEZ 10	3.15	5.43	7.03	11.91
AEZ 11	-0.39	3.41	2.41	10.97
AEZ 12	3.18	4.42	4.3	8.47
India	1.56	5.25	6.18	11.31

Note: The effects of volatile long-term weather patterns differ across Agro-Ecological Zones (AEZs). This is supported by Jägermeyr et al. (2021), the impact of long-term weather trends on global agriculture emerge earlier in a new generation of long-term weather trends and crop models, Nature Food, 2(11), who noted that geographical differences, especially differences in altitude, contribute to differences in impacts from changing weather patterns. SSP126 and SSP585 are two Representative Concentration Pathways (RCPs) in the simulation protocol for CMIP6 crop yield projections, which are otherwise known as RCP2.6 and RCP8.5, respectively.

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

Table B.1 shows that different emission scenarios have different effects on crop yield. In most cases, crop yield increases are experienced across the AEZs of India. Only AEZs 7 and 8 tended to show a reduction in rice yields, and AEZ 11 also showed a reduction in rice yield under the SSP126 scenario for 2040.

Projected Yield Effects on Domestic and International Markets

Using the projected yield changes in the Global Trade Analysis Project (GTAP) Model, the potential effects of the yield changes on India's wheat and rice markets were evaluated for 2040, using 2014 as the base year. Table 2 shows the effects of yield changes under the high carbon concentration scenario (SSP585) on India's rice and wheat markets in the next several decades. Both carbon concentration scenarios (SSP126 and SSP585) showed similar effects on average, but the SSP585 scenario provided the largest yield changes. By 2040, under the SSP585 scenario for each crop, production of rice is expected to increase by 11.7 percent, while wheat is expected to decrease in production by 4.0 percent.[6] Despite an increase in the average yield of wheat, increases in population and household income will increase the demand for rice. The substitution of rice over wheat production is expected to meet both domestic and international rice demand. With limited land for cultivation, yield growth is expected to be a major contributor to production increases over the next decades, but the substitution of crop area for rice will hinder increases in the production of wheat.

India's population increase will be a major factor in the demand for rice and wheat in the country. Despite increases in yields under SSP585, domestic prices of both wheat and rice are expected to more than double due to this surge in demand. Domestic rice and wheat prices are estimated to increase by 232.5 percent and 201.5 percent by the year 2040, respectively. This increase in domestic demand is expected to reduce India's exports of wheat and rice as the country diverts exports to the domestic market. Specifically, exports of rice are expected to decrease by 70.2 percent by 2040, while wheat exports should decrease by 94.3 percent. This is supported by Barua and Valenzuela (2018), who found the exports of grains and other major agricultural commodities from major producers are vulnerable to changing long-term weather patterns because it significantly alters production patterns and commodity prices.

To meet the increase in demand from population and income, India is estimated to increase imports of rice and wheat. These imports are expected to increase by 624.9 percent and 497.6 percent[7] for rice and wheat, respectively. Similarly, table 2 shows that the import price increases 111.5 percent for rice and 100.5 percent for wheat. In general, an increase is estimated for the domestic and international prices of rice and wheat.

Table 2

Effect of projected yield changes on India's rice and wheat markets by 2040 under the SSP585 scenario (percent change)

	Rice	Wheat
Production	11.72	-3.98
Domestic sales	17.67	0.40
Market price	232.52	201.45
Export	-70.19	-94.26
Import	624.85	497.62
Import price	111.46	100.49

Note: Price changes are in nominal terms.

Source: USDA, Economic Research Service using estimates from the Global Trade Analysis Project (GTAP) computable general equilibrium (CGE) model.

[6] Since land is limited, and India seems to have a comparative advantage in the global rice market, we expect more land to be dedicated to rice cultivation than wheat cultivation, thereby increasing rice production and decreasing wheat production.

[7] India imports small amounts of rice and wheat. Because the baseline rice and wheat imports are so small, the increases in imports from this report's model show a significant percentage change in the import of rice and wheat. Our model does not assume that diets would switch as income rises. If there is a switch, then demand for rice would not rise by as much, making greater surplus over production available for export.

Table 3 shows the effects of changes in the production and supply of rice and wheat in India on international prices by 2040. All major rice exporters are expected to experience an increase in their domestic price under the high-emission scenario, with India, Pakistan, Thailand, Vietnam, the United States, China, and Cambodia accounting for over 80 percent of annual global rice exports. The model indicates that domestic rice prices in Cambodia and the Philippines will increase by over 200 percent (table 3). Wheat prices doubled across all the countries in the study except for the United States which showed an increase of 95.7 percent. Price increases are a major threat to food security, especially in developing countries such as Cote d'Ivoire and Senegal, which showed increases in their domestic rice price of 152.4 percent and 188.6 percent, respectively. Wheat prices in Cote d'Ivoire and Senegal are also estimated to more than double by 2040, with increases of 142.1 percent and 204.2 percent, respectively.

Table 3

Effects of yield changes in India on international rice and wheat markets (2040) under the SSP585 scenario (percent change)

	Imports from India		Aggregate imports from world		Domestic price change	
Countries	**Rice**	**Wheat**	**Rice**	**Wheat**	**Rice**	**Wheat**
China	-85.06	-95.73	-15.80	75.28	123.75	127.67
Cambodia	24.06	-97.07	1,702.29	7.60	246.12	163.60
Thailand	-89.33	-96.47	-7.31	3.25	112.38	109.33
Vietnam	-86.54	-96.28	268.54	-0.38	194.58	126.27
Philippines	-30.67	-96.49	115.79	7.40	202.02	151.31
Pakistan	-95.83	-92.42	83.35	178.30	133.44	159.18
United States	-90.32	-98.05	-29.04	10.73	86.07	95.71
Saudi Arabia	-57.52	-98.17	9.79	3.46	91.34	120.42
Cote d'Ivoire	-66.97	-97.79	86.94	31.29	152.37	142.14
Senegal	-69.30	-97.64	62.00	29.07	188.64	204.19
Regions						
SSA	-81.88	-95.84	6.39	30.44	115.58	111.10
MENA	-86.78	-96.23	-7.14	18.31	97.20	101.46
South Asia	-13.73	-91.03	56.82	85.89	205.12	179.89
Oceania	-87.20	-96.74	-6.85	11.33	96.59	102.49
East Asia	-90.48	-96.69	-1.10	6.08	108.36	104.18
Southeast Asia	-69.72	-96.28	53.06	1.74	154.11	121.70
North America	-96.49	-97.93	-2.49	-1.66	78.10	90.60
Latin America	-97.69	-97.88	0.05	11.28	75.03	93.69
Western Europe	-93.18	-97.74	-13.36	-0.34	77.75	90.46
Rest of world	-90.29	-96.64	-14.56	15.38	93.57	102.67

SSA = Sub-Saharan Africa; MENA = Middle East and North Africa.

Note: Price changes are in nominal terms.

Source: USDA, Economic Research Service using estimates from the Global Trade Analysis Project (GTAP) computable general equilibrium (CGE) model.

Unlike domestic prices, which increased across all countries, the effects of projected yield changes on imports of rice and wheat differed across countries. This is supported by Porfirio et al. (2018), who reported that change in long-term weather patterns will affect the distribution of agricultural production, thereby affecting global markets and food supply. India's exports of rice and wheat are expected to decrease to all countries of the world. While India reduces exports, most countries in the model are estimated to increase their aggregate rice imports, except China, Thailand, and the United States. While China is the world's largest rice producer, the country is also the world's largest rice-consuming country (USDA, Economic Research Service (ERS), 2023b). China's supply gap from this reduction in imports must be met by increasing domestic production or releasing more rice to the domestic market from rice stocks. Thailand and the United States are also among the top rice exporters in the world. Both countries can fill the gap left by India's reduction in exports of rice using rice produced domestically. Most countries in this report, including the United States, are expected to increase aggregate imports of wheat by 2040. Only Vietnam will likely have a slight reduction in wheat imports by 2040, though the country showed the second-highest increase in imports of rice by 2040, with an increase of 268.5 percent.

In addition to the specific country results, the regional aggregates give a clear picture of how trade will change across the world (table 3). For instance, the South and Southeast Asian regions will likely significantly increase their rice imports by 2040 at 56.8 and 53.1 percent, respectively. Increases in income due to fast economic growth in the regions is a major factor in the demand for rice. The Western Europe, Middle East and North Africa (MENA), Oceania, East Asia, and North America regions are all estimated to reduce their imports of rice, on average (table 3). This is due to the increase in the international price of rice after India's drop in exports. Although the analyses showed significant shifts in India's rice and wheat markets due to the projected changes to long-term weather trends effect on yields, in combination with increases in income and population growth, there are other factors that may be behind this report's findings. For instance, policy interventions to mitigate the impact of changing long-term weather patterns may change the direction of markets. Technology innovation, such as the development of varieties that adapt to changing long-term weather patterns, could change the results. As income grows, there may be changes in taste, which may affect the demand for rice and wheat in India. In addition, there are possibilities of major shocks to rice and wheat markets across other major producers/exporters of rice and wheat around the globe. In addition, the projections are based on long-term weather patterns; therefore, the increasing frequency of extreme weather would likely lead to variations in the yearly yield of major crops across the ecological zones of India.

Conclusion

India has made significant strides in boosting food security over the last several decades through increasing the production of major food crops. However, with a growing population, maintaining a sustainable environment for food production will be a challenge. India is a major contributor to global carbon emissions which impacts weather patterns. As India's population grows, so does its demand for food, making changes in long-term weather trends relevant to the country's ability to guarantee its food security and ensuring a stable global supply of staple crops. For instance, India imposed trade restrictions on rice exports in 2022 and 2023 citing potential production shocks due to drought. India banned the export of nonbasmati white rice and broken rice and imposed an export tax on some other categories of rice, leading to large increases in the international market price for rice.

Agriculture is a vital sector in India because the country depends primarily on domestic food production to tackle domestic food insecurity. India is the second-largest rice producer in the world and accounts for over 40 percent of global rice exports in 2022. Although India consumes most of its wheat domestically, it is the third-largest producer of wheat in the world after China and the European Union. India's position in both the supply and consumption of these two grains makes the country particularly important to global markets. Any shock to domestic production or change in export policies on these grain commodities will influence global prices. One of the current effects of weather on trade led the Government of India to start restricting nonbasmati and parboiled rice exports in July 2023 due to anticipation of drought during the El Niño season.

Although the international trade of agricultural products contributes to global carbon emissions, it can also help alleviate the consequences of changes in global weather patterns. For example, global trade can make food available in areas where there are shortages due to extreme weather events. It also allows growers to produce commodities where they are most efficiently produced and then to trade them to countries less suited to their production. International trade reduces the inputs required to feed a global population and decreases the impact of agriculture on long-term weather trends.

This report's yield estimates indicate that India could experience increases in rice and wheat yields in the coming decades but that the effects of various emission scenarios on the level of yield increases will vary. Beyond precipitation and temperature, there are other factors of agricultural productivity to consider when assessing the impacts of changes in long-term weather trends. For example, carbon fertilization affects rice and wheat productivity. This report shows that the expected yield gains for both crops are different between the low-carbon concentration scenario (SSP126) and the high-carbon concentration scenario (SSP585). There are also other factors beyond changes in long-term weather trends that are limiting the average yield of India's major crops. Improvements in technology and agricultural policies (e.g., India's rice export trade policy) will also affect the production and average yield of the country's major crops.

The potential impact of changes in long-term weather trends is expected to differ between rice and wheat production in India; rice production is estimated to increase, while wheat production will decrease. The increase in rice production due to the projected yield increases is not expected to meet the increased domestic demand for rice in India. An inadequate supply of rice and wheat in the country's domestic markets translates into a higher domestic price of rice and wheat, which is then transmitted to the international market. India's inability to produce enough wheat and rice to meet the domestic market demand will discourage exports of these products to international markets. Markets around the world will have to shift their supply lines to other countries, such as Thailand and the United States, or change their food consumption pattern to adjust to a shortage of available rice for import from India.

This report's results are limited to the current projections on yields, economy, and population, which are prone to changes as time passes. Future policies targeted toward production, changes in irrigation, conservation, drought tolerant varieties, and changes to the structure and demand of food markets could change estimates in future production and the demand for rice and wheat in India. While the major focus of this report is on India, there are other market dynamics across other countries, including bilateral relations, that may influence the demand for India's rice and wheat. In addition, major shocks to economic variables, dietary shifts, and cultural practices can change the direction of future consumption levels of rice and wheat in India.

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