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Demand for Alternative Feed Grains for Broiler Production in an Era of Global Price Uncertainty: The Case of Sorghum

Michael E. Johnson, Angelica Williams, Constanza Valdes, Kayode Ajewole, and Jayson Beckman

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Abstract

Global demand for chicken meat has grown more than fivefold since the 1960s, from 6.2 to 33.9 pounds per person today. The expansion of broiler production to meet this growing demand has also increased the need for feed. However, the demand for feed is complex, as these feedstuffs are also used for human consumption and biofuels, and broiler farmers tend to be risk averse for input prices. This study looks at how the increased demand for broiler feed may have affected the demand for feed alternatives among some of the world's major broiler producing countries when faced with uncertain global feed prices and rising feed costs. The study examines these countries' willingness to substitute sorghum for corn and what this substitution means for future sorghum exports from the United States. Results indicate a high substitution effect of sorghum for corn may have occurred over this period when price risk is considered. Whenever the price of sorghum fell sufficiently below that of corn and if corn prices were more volatile, risk-averse broiler producers shifted to sorghum. Countries that strongly showed this behavior are China, the United States, Egypt, and, to some degree, Mexico.

Keywords: broiler production, feed demand, optimal feed formulation, risk aversion, sorghum

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

Demand for Alternative Feed Grains for Broiler Production in an Era of Global Price Uncertainty: The Case of Sorghum

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What Is the Issue?

The demand for chicken meat is expected to grow considerably due to urbanization, income, and population growth, especially in developing and emerging economies. This increase in demand means that there will likely be a corresponding increase in feed demand. For major exporting countries of feedstuffs (grains and oilseeds), such as the United States, this presents an opportunity to increase their share of global exports. However, the Coronavirus (COVID-19) pandemic era and the Russia-Ukraine war brought new uncertainty in feedstuff prices—especially among grains that have multiple uses, including food, biofuels, and feed. Corn and wheat prices have been especially affected and are among the commonly used grains in broiler feed formulations. Understanding the price responsiveness of demand can help assess whether other grain substitutes (such as sorghum) offer a real potential for growing their share in broiler feed formulations, especially under conditions of rising feed costs and price uncertainty. This study estimates the responsiveness of risk-averse broiler producers to feed price volatility.

What Did the Study Find?

The study found a high rate of substitution between sorghum and corn, especially among risk-averse feed producers between September 2017 and June 2023, for which data on monthly prices were available for all the countries sampled. The ease of substitutability of corn for sorghum in feed formulas is easier now because of new lines of tannin-free sorghum cultivars that improved sorghum's digestibility and, therefore, its substitutability with corn in livestock feed. The results of this study show that—whenever the price of sorghum fell below that of corn and in the presence of greater price risk for corn in global markets, as occurred following the Russia-Ukraine war, risk-averse producers would shift to sorghum. Countries that strongly showed this behavior are China, the United States, Egypt, and, to some degree, Mexico.

A similar pattern of substitution is seen in sorghum for soymeal, but this pattern primarily occurred for starter -and grower-feed. Finisher feeds tended to favor more corn and soymeal proportions in this study's feed formulation results, as the focus is mostly on energy and protein at this final stage of broiler growth.

Overall, the study finds that sorghum offered a viable potential for increased use in broiler feed formulations. This could be important during times when global grain and oilseed markets are volatile, especially for some of the most common grains in feedstuffs—corn and wheat.

The United States has the potential to grow its markets for sorghum feed, especially in countries where demand for corn has rapidly grown in competition with other uses but also during times when global markets are uncertain.

How Was the Study Conducted?

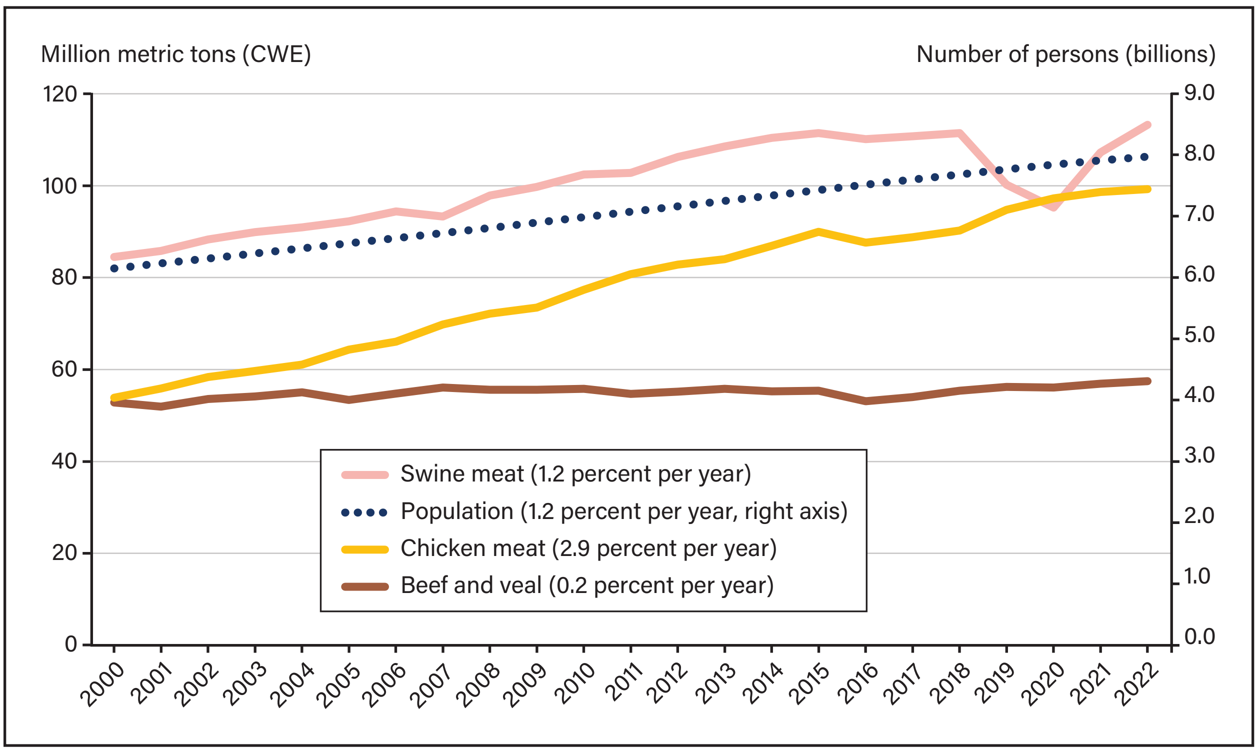
The study generated pseudo-feed demand data for broiler production among 12 of the world's major producing countries. These data are based on optimal feed compositions from a least-cost feed ration linear programming model, with price-risk considerations that relied on a range of actual observed monthly prices for feed ingredients from September 2017 through June 2023, for which data were available. Two leading broiler-producing countries were selected from each of six major regions of the world: North America, South America, Africa, Europe, Southeast Asia and East Asia, and the Pacific. Pseudo-demand data were generated due to the lack of sufficient actual demand information for broiler feed among the countries selected for this study. The resulting pseudo data on feed compositions and associated costs were then used to estimate demand elasticities for the various feedstuffs, focusing on grains (corn, sorghum, wheat, and rice), dried distillers grain solubles or DDGS (a grains byproduct), and oilseeds meal (e.g., soymeal), as well as other feed additives such as fish meal. The methodology draws on an earlier paper by Beckman et al. (2011). For actual prices and other data on grains, oilseeds, and broiler production and trade, the study relied on various domestic and international sources, including USDA, International Grains Council, United Nation's statistics on trade or U.N. Comtrade, and the U.N. Food and Agricultural Organization. Country-specific sources were used from the select countries.

Demand for Alternative Feed Grains for Broiler Production in an Era of Global Price Uncertainty: The Case of Sorghum

Introduction

Global demand for chicken meat has grown substantially over the past two decades as urban population and incomes increased.[1] World domestic consumption of chicken meat has grown at a faster pace than beef and pork, increasing at almost 3 percent per year since 2000 (figure 1). This number compares to a world population growth rate of 1.2 percent per year and a growth rate of 0.2 percent for beef consumption during the same period. Per capita chicken consumption grew more than fivefold, from 2.8 kilograms in the 1960s to 15.4 kilograms per person (or 6.2 to 33.9 pounds per person) in the current decade.[2]

Figure 1
World domestic consumption of beef, swine, and chicken meat, 2000–22



CWE = carcass weight equivalent.

Source: USDA, Economic Research Service using USDA, Foreign Agricultural Service (2023h) and United Nations Food and Agriculture Organization data (FAOSTAT).

[1] From here on, chicken meat is used to refer to what is consumed, while broiler is used to refer to production.

[2] Authors' calculations are based on USDA, FAS (2023h) data.

The growth rate in broiler production is noteworthy among some of the world's current largest producers in emerging and developing economies—including Argentina, Egypt, India, Indonesia, Poland, Russia, and Turkey—where production has grown more than 8 percent per year (on average) since 2000 (table 1). The growth rate of chicken production in Brazil, China, and Mexico has been more modest, growing at 4.5, 2.3, and 3.5 percent per year between 2000 and 2022, respectively. Broiler production in the United States (traditionally the largest global broiler producer) also grew modestly during the same period. Trade increased as demand has grown, although trade still only accounts for about 11 to 12 percent of total production according to the United Nation's Food and Agricultural Organization's database or FAOSTAT.[3] A reason for the small amount of trade is the numerous nontariff measures (NTMs) on chicken meat trade (Farris et al., 2024).

Table 1
Per capita production of chicken meat among the world's top producers, 2000–22

	Production (million metric tons)		**Average annual growth** (percent)	**Per capita production** (kilograms/person)		**Average annual growth** (percent)
	2000–2004	**2020–2022**	**2000–2022**	**2000–2004**	**2020–2022**	**2000–2022**
United States	14.7	20.5	1.8	50.9	61.1	0.9
China	9.7	14.5	2.3	7.6	10.2	1.6
Brazil	7.3	14.3	4.3	40.5	66.8	2.9
Russia	1.0	4.7	16.6	6.9	32.3	16.6
India	1.4	4.1	8.9	1.3	2.9	6.0
Mexico	2.2	3.8	3.5	21.5	30.3	1.9
Indonesia*	1.0	3.7	12.1	4.6	13.7	8.9
Thailand	1.8	3.3	3.5	28.6	45.5	2.7
Argentina	0.8	2.3	8.1	21.6	50.5	6.1
Turkey	0.7	2.3	9.8	10.9	26.8	6.7
Iran*	1.0	2.2	5.7	14.5	25.2	3.3
Poland*	0.7	2.1	10.1	17.3	56.0	10.2
Egypt	0.6	2.1	12.0	7.7	19.3	6.8
United Kingdom	1.3	1.8	1.9	21.3	27.0	1.2
Japan	1.3	1.8	1.4	10.5	14.1	1.5
South Africa	1.0	1.6	2.6	20.9	26.4	1.2
World	58.6	101.0	3.3	9.3	12.8	1.7

Note: * Data for Poland, Iran, and Indonesia were absent in the USDA, Foreign Agricultural Service Production, Supply and Distribution (PSD) database, so values from the United Nations Food and Agriculture Organization database were used. The same applies to India, where data for the most recent period were missing, and to the United Kingdom, where data were missing in an earlier period. The green highlighted countries have the highest per capita production of chicken meat in the most recent period (reflecting their role as major chicken exporters).

Source: USDA, Economic Research Service using USDA, Foreign Agricultural Service (2023h) information.

The expansion of broiler production, consumption, and trade in 2000–21 also meant increased demand for feed over the same period for chicken production. Box 1 highlights the importance of feed in chicken production and the most common feedstuffs used. As the demand for feed has increased, the global market for feedstuffs has not escaped the recent spike in grain and oilseed prices following the Russia-Ukraine war and general inflationary pressures. Prices also became more volatile in general, given a more

[3] Authors' calculations are based on FAOSTAT data.

Importance of Feed and Its Composition in Chicken Production

Feed constitutes more than 70 percent of the cost of raising broiler chickens, the rest being operation costs such as labor, energy, water, veterinary services, and maintenance costs (Alhotan, 2021). Cereal grains make up between 70 to 80 percent of feed mixes depending on the growth stage in broiler chickens. The grains in feed serve as the primary source of energy, while oilseeds and other additives make up the rest of the feed mix (20 to 30 percent) and provide a source of protein and other important nutrients (Bavaresco et al., 2020). Corn is the most common grain in broiler feedstuffs. Other grain substitutes include sorghum, wheat, rice, barley, (and to some degree) cassava meal and millet. Among protein-based feedstuffs, soybean meal is the most common with alternative substitutes, such as groundnut, rapeseed, and palm oil cakes, among others. Fishmeal and other additives enhance other nutrient and health requirements. The by-product dried distillers grain solubles (DDGS) are also used to partially replace corn and soybean meal (Hoffman & Baker, 2011).

complex global marketplace, as feed not only competes with human consumption but also with global biofuel markets. This result occurred over a longer period of growing demand for livestock products from rising incomes in developing countries (Delgado et al., 2001) together with increased demand for biofuels and reductions in direct subsidies for crop production in more developed countries (Hinrichs & Steinfeld, 2007).

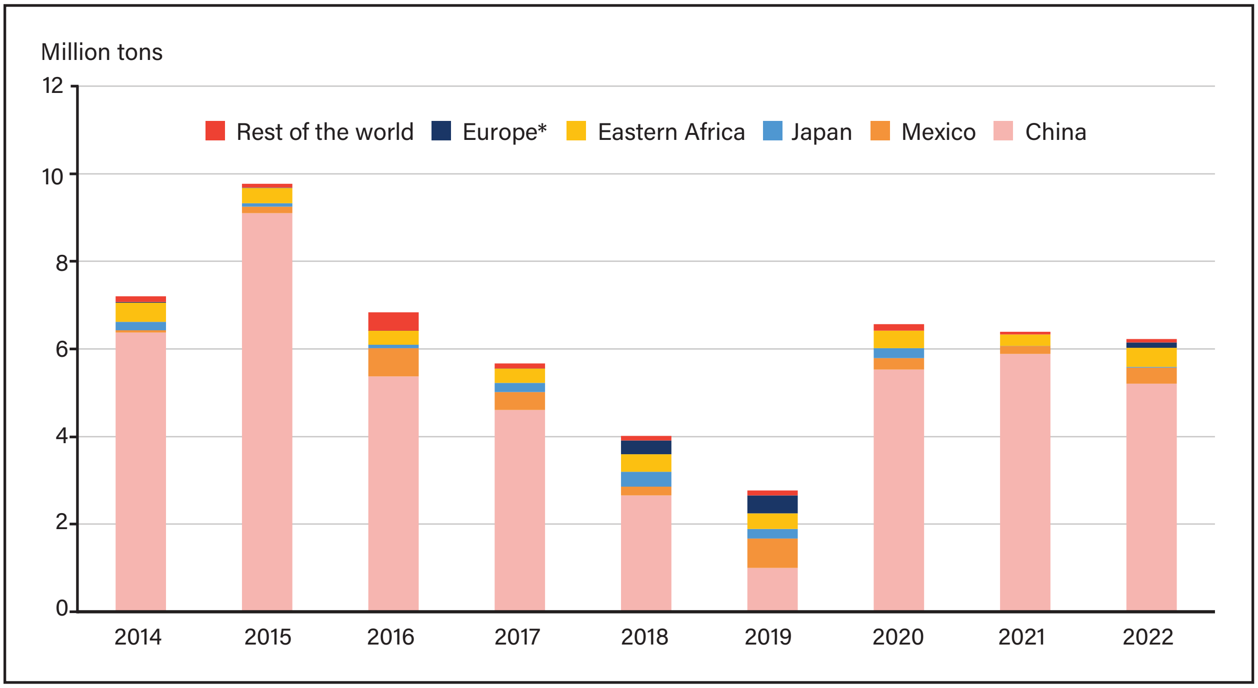
The increased episodes of higher price volatility in global markets make grain prices less predictable and incentivize risk-averse buyers to consider alternatives that offer less variable prices. Since feed makes up the bulk of broiler production costs, producers will seek a combination of feedstuffs with low cost and price risk to ensure their competitiveness to meet demand. The price risks associated with the growing interconnectedness among countries through trade in feed grains and oilseeds can be a challenge for producers. In any era of increased volatility in commodity prices, producer choices (and hence overall demand) for feed can be greatly affected, especially if broiler producers are risk averse. They may substitute between different grains or types of oilseeds, depending on price movements and the degree of variability among them.

Among the feed grains traded globally, sorghum offers a unique alternative to grains (such as corn and wheat) that are also traded heavily for food. Unlike those grains (corn and wheat), sorghum is mostly traded for livestock feed, in addition to other industrial purposes. The United States is a leading supplier of sorghum in global markets—followed by Argentina, and increasingly, Australia. Sorghum offers an alternative to other feed grains that compete with human consumption demand when prices for the latter rise above sorghum or when their predictability becomes less certain. In the past, the rise in prices had to be substantial, as sorghum was often considered more inferior due to having a lower digestibility attribute among harder and bitter traditional varieties due to the presence of high levels of tannins (Ronda et al., 2019). The introduction of new lines of tannin-free sorghum cultivars, as well as improvements in processing, made sorghum comparable with corn-based diets (Dowling et al., 2002; Ronda et al., 2019). Mostly tannin-free sorghum varieties are now grown in the United States and Australia to serve the livestock feed industries (McCuistion et al., 2019).

The level of U.S. sorghum exports fluctuated over the last decade, peaking at almost 10 million tons in 2015. For most of the period between 2014 and 2022, China has been the dominant destination for U.S. sorghum exports, followed by Mexico (figure 2). However, some European Union (EU) countries (e.g., Spain) were among the top destinations for U.S. sorghum. As broiler production grows in these countries, the demand for sorghum and other feedstuffs should also grow.

Figure 2

U.S. exports of sorghum, 2014–22



* = The bulk of imports in Europe are reported by Spain, followed by smaller volumes for France and Italy.

Source: USDA, Economic Research Service using Trade Data Monitor data (2023).

This study sought to explain how broiler-feed producers (among some of the major producing countries in the world) may have responded to rising feed costs by obtaining alternative feed ingredients during the last few years when global grain and oilseed markets experienced high price volatility. More specifically, the study examined how willing these countries may have been to substitute sorghum for corn and what this substitution means for future U.S. sorghum exports under similar circumstances. The authors anticipated that risk-averse producers were less hesitant in substituting sorghum for corn whenever the variability in corn prices exceeded those of sorghum and average prices of sorghum were equal to or lower than that of corn. This action is accomplished by estimating elasticities of demand and substitution for feed grains and oilseeds in the broiler production sector among a selective group of 12 countries using pseudo data generated by a least-cost feed-ration model that incorporates price risk.

Overview of Global Broiler Production and Feed Sector

The demand for broiler feed is expected to continue to increase rapidly due to a growing global urbanized population and increases in per-capita incomes. Chicken meat is often the most affordable source of animal protein as chickens mature quickly, can be raised in smaller spaces, and can convert feed to meat more efficiently than other livestock meat (Miller et al., 2022). Traditionally, chicken meat has mostly been produced for domestic consumption, with only about 10 percent traded in global markets. Among the largest exporters, however, this share is greater—up to 43 percent for Poland, for example (table 2). Large importers (such as China, Japan, Mexico, and South Africa) import somewhere between 10 and 20 percent of their own domestic consumption. While China and India produce some of the largest volumes due to their population size, per capita production remains very low relative to other major importers (such as Mexico, Japan, and South Africa)—10.2 kilograms/person in China and 2.9 kilograms/person in India, versus 30.3 kilograms/person in Mexico, 14.1 kilograms/person in Japan, and 26.4 kilograms/person in South Africa) (table 1).

Broiler production in India has grown, nevertheless, increasing by 195.9 percent over the last 22 years (table 2). China was slower to respond to growing domestic demand and thus increasingly relies on imports, which grew by about 50 percent over the same period.

Increased demand for chicken meat among emerging economies has important implications for future feed demand. While some countries (such as India) have been able to meet demand with increased domestic production, there is ample room for future demand growth.[4] Already, China relies on imports of feedstuffs for broiler and other livestock sectors (Shaolin et al., 2020). Other emerging economies (such as in Africa) are expected to increase production in response to growing demand as incomes and urbanization rise. For example, Egypt and South Africa saw large increases in production in the past two decades, almost fourfold in Egypt and more than twofold in South Africa (table 2). A challenge in the rest of Africa and the developing world, where sorghum is largely grown for human consumption, is the poorly developed nature of the sector—both for food and fodder. Its viability as a feed substitute for corn, therefore, remains limited. This is partly because sorghum in these parts of the world is mostly grown in marginal areas with poorly developed value chains, resulting in a general lack of access to improved seed varieties, advanced processing technologies, extension, and markets (Rao, 2019).

Table 2
Broiler production among the top country producers globally, 2022

Rank	Country (*selected)	World region	Production (million metric tons)	Exports (million metric tons)	Exports as percent of production	Imports (million metric tons)	Imports as percent of domestic consumption	Net-flows
1	United States	North America	20.55	3.35	16.3	0.07	0.4	Exporter
2	China	East Asia	14.53	0.46	3.2	0.81	5.4	Importer
3	Brazil	South America	14.28	4.18	29.3	0.01	0.0	Exporter
4	Russia		4.69	0.23	4.8	0.21	4.4	
5	India	South-east Asia	4.07	0.00	0.0	0.00	0.0	Domestic
6	Mexico	North America	3.83	0.01	0.2	0.89	18.9	Importer
7	Indonesia		3.74	0.00	0.0	0.00	0.0	
8	Thailand	South-east Asia	3.26	0.96	29.4	0.00	0.1	Exporter
9	Argentina	South America	2.28	0.19	8.4	0.01	0.4	Exporter
10	Turkey	Europe	2.27	0.51	22.5	0.00	0.0	Exporter
11	Iran		2.21	0.00	0.2	0.06	2.7	
12	Poland	Europe	2.15	0.94	43.6	0.03	2.1	Exporter
13	Egypt	Africa	2.09	0.00	0.0	0.05	2.4	Domestic
14	United Kingdom		1.81	0.36	19.6	0.77	34.7	
15	Japan	East Asia	1.76	0.01	0.3	1.06	37.6	Importer
16	South Africa	Africa	1.56	0.05	3.5	0.38	19.9	Importer

Note: Production and trade quantity values are 3-year averages, 2020 to 2022. Green represents exporters, orange are primarily importers, and blue mostly produce for domestic consumption. White rows are countries that were not selected for the study, either as insignificant importer or exporter.

Source*:* USDA, Economic Research Service using USDA, Foreign Agricultural Service data (2023h).

[4] There have been exceptions. In 2021, for example, the Indian Government permitted the importation of up to 1.2 million metric tons of genetically modified soybean meal due to meet the demand of the domestic feed industry (USDA, FAS, 2022d).

In South America, Brazil and Argentina have a comparative advantage in broiler production, with ample feed availability, given their large natural resources in agriculture. Argentina also has a favorable climate for growing wheat, which is one of its major export commodities. Commercial broiler producers in both countries rely on large vertically integrated commercial enterprises that tie producers with independent farmers via integrated production contacts, as is the case in the United States (USDA, Foreign Agricultural Service (FAS), 2022).[5] The type of integration may vary in large scale operations. Some countries have fully integrated systems that involve most parts of the production process, from breeding, hatchery, feed mill, assembly of live birds, and broiler slaughtering to distribution. How the integrated system evolved also varies by country. For some countries, the integrated system was initially dominated by the feed industry, while in others, it was either the breeding company or the hatcheries that were responsible (Narrod et al., 2007). The move towards large-scale integrated broiler industries in general helped ensure lower transaction costs and production efficiencies, especially as different feed mixes are required at various growth stages of a broiler. Because transaction costs for obtaining the right formulation can be costly, formal delivery contracts and well-coordinated supply chains helped reduce such costs (Upton, 2007).

This study focused on 12 of the top broiler-producing countries in the world, selecting two from each of six of the world's major regions: North America, South America, Africa, Europe, Southeast Asia and East Asia, and the Pacific (table 2). Among those countries that produce mostly for domestic consumption, we retained India due to the sheer size of the sector; the country may eventually have to rely on feed imports if demand for chicken meat expands exponentially with income growth, as occurred in China. China's broiler sector has already begun to rely heavily on feed imports, as pork and chicken meat demand have expanded with income growth. The final selection of countries includes the United States and Mexico in North America, Argentina and Brazil in South America, Poland and Turkey in Europe, India and Thailand in Southeast Asia, China and Japan in East Asia, and Egypt and South Africa in Africa.

Among the selected 12 countries, demand for specific feed grains for broiler production is likely to vary by country and region, depending on availability and price in domestic markets over the study period. While corn and soymeal are favorites for broiler feed in all countries, commercial producers may often substitute with alternatives, as their relative prices change by a certain amount. As pointed out earlier, the ease of substitutability of corn for sorghum in feed formulas is more possible today because of the introduction of tannin-free sorghum cultivars, and therefore, its substitutability with corn in livestock feed. Risk-averse producers are likely to select feed grains that exhibit fewer uncertainties regarding price. Moreover, many small-scale producers who dominate in developing countries (such as India) may prefer to rely on locally available grains.

Sourcing lower priced feedstuffs among commercial producers, either from domestic or international sources, is critical to maintaining lower costs of production and competitiveness of broiler production. Several countries imported a large share of their total consumption of the major feed grains and soybean meal (table 3). For these countries, trade is important for maintaining adequate access to feedstuffs for broiler production. To better understand each region's underlying conditions for broiler production and accessing feedstuffs in more detail, this study briefly reviews each region and select country's feed grain sector based on the authors' data analysis, USDA, Foreign Agricultural Service Global Agriculture Information Network reports, and other literature sources. Appendix 4 provides a summary of each country's feed sector in more detail and organized by region.

[5] Vertically integrated enterprises typically rely on a large-branded broiler producer supplying day-old chicks, feed formulation, extension, and veterinarian services. Farmers rearing the broilers provide the land, labor, other inputs (e.g., water and electricity), and housing infrastructure. Such integrated systems take advantage of scale economies to be more profitable. Despite their presence, a small number of backyard operations exist with the larger enterprise operations in countries such as Brazil, for example (Valdes et al., 2015). Backyard operations are small-scale producers that manage their own operations, usually for their own consumption or a local market.

Table 3
Imports as a percent of domestic consumption of feed grains and soymeal among the world's top broiler producers, 2022

Country	Wheat	Rice	Barley	Corn	Sorghum	Soymeal
Argentina	0.1	0.4	0.0	0.1	0.1	50.9
Brazil	54.4	13.1	61.3	3.7	0.5	2.7
China	6.5	3.8	72.6	7.5	78.5	57.0
Egypt	54.9	15.0	17.6	57.4	0.1	56.6
India	0.0	0.0	2.8	0.0	0.0	8.7
Japan	89.0	8.4	81.1	99.8	99.2	64.0
Mexico	71.7	76.1	30.0	39.9	7.2	54.3
Poland	7.5	117.5	6.6	7.5	106.2	95.7
South Africa	46.7	115.4	0.0	0.0	0.7	0.4
Thailand	96.0	0.4	100.0	21.3	0.0	64.1
Turkey	46.6	38.2	38.7	36.2	-	83.7
United States	8.8	25.2	9.4	0.2	0.0	1.2

Source*:* USDA, Economic Research Service using USDA, Foreign Agricultural Service data (2023h).

Estimating Broiler-Feed Demand With Price Risk

The demand for feedstuffs for broiler meat production is typically derived from the necessity to ensure an adequate nutritious diet of energy and protein requirements needed for the birds to grow healthy at the least cost. Corn and soymeal are the most common feedstuffs, given their advantages as energy and protein sources, as well as being safe from unwanted antinutritional factors (such as high fiber content or nonstarch polysaccharide, which may reduce growth performance at high levels) (Alhotan, 2021). However, increasing corn prices could lead to broiler producers opting for grain substitutes (such as wheat, sorghum, barley, and rice) as energy sources. Soymeal may also be replaced with other oilseeds, such as groundnut meal, and other nutrient additives rich in protein, such as fishmeal (box 1). Additionally, the recent spike and volatility in grain prices (following supply chain disruptions during the COVID-19 pandemic and presently from the effects of the Russia-Ukraine war) are also affecting broiler production by raising price risks and overall costs. This development has important implications for the price responsiveness of feed grain demand among risk averse broiler producers worldwide.

This report addressed this issue of the price responsiveness of feed grain demand among risk averse broiler producers by estimating the price elasticities of demand for four major grains and their byproducts (corn, wheat, rice, and dried distillers grain with solubles (DDGS)) using results of optimal feed formulations from a least-cost feed-ration model and actual monthly price data between September 2017 to June 2023. The inclusion of DDGS builds on earlier findings that show DDGS's potential use in an era of increasing demand for biofuels (Beckman et al., 2011).[6] Several data limitations prevent estimating these elasticities econometrically with actual feed demand data. First, disaggregated data on feedstuff demand (destined primarily for the broiler industry worldwide) are not readily available in many countries. A second limitation is the nonuse of some of these feedstuffs in several countries due to limited domestic production—making it difficult for any forward-looking analysis where the potential use of alternatives to corn (such as wheat, rice, sorghum, and DDGS) is assessed.

[6] DDGS is a byproduct from ethanol production when grains such as corn are used.

Generating Pseudo-Demand Data for Broiler Feed

Given the data limitations, the authors adopted an approach that has been used before in assessing potential demand for feed using pseudo data generated by a least-cost feed-ration linear programming (LP) model. The application of linear programming is a classical tool employed for assessing the least-cost combination of feedstuffs in formulating livestock feed (Alhotan, 2021). The programming uses a mathematical approach of determining a combination of feedstuffs that meet certain nutrient requirements at the lowest cost (Dowling et al., 2002). The authors modified the classic model to incorporate price risk using a mean-variance framework that incorporates the standard deviation of prices and a risk premium parameter in the least-cost feed-ration model, as described in Hazell and Norton (1986).

The mean-variance analysis of decision making under price risk is theoretically consistent under the expected utility theory of Von Neuman and Morgenstern but only under the special cases where the underlying income distribution is assumed to be normal and the utility function is quadratic (Coffey, 2001; Hazell & Norton, 1986). Unfortunately, a quadratic utility function has been criticized as the function results in increasing absolute risk aversion and a maximum value beyond which the marginal utility of income declines (Hazell & Norton, 1986). In the real world, one would expect income risk to be asymmetric, having varying weights for upward versus downward risk. Despite these limitations, however, empirical studies have been able to demonstrate the closeness (or second order approximation) of the quadratic-utility function compared with other more desirable functions (Hazell & Norton, 1986; Levy & Markowitz, 1979). The mean-variance analysis also seems to perform reasonably well when compared with models that attempt to apply different weights for downward risk (see, for example, Grootveld & Hallerbach (1999)). Given the difficulty of eliciting actual risk preferences among feed producers and determining a more appropriate utility function, the authors believed the mean-variance framework is relevant (as a second-order approximation) for their empirical application, as the framework is consistent with the economic theory of decision making under price risk. The authors' empirical application for determining optimal feed formulations covers the entire period for which they had monthly price data. They then used these generated results from the linear programming risk model (as their pseudo data), in combination with the historical prices, to estimate a feed demand system and derive both own- and cross-price elasticities of demand from the coefficient estimates.[7]

One of the earliest applications of using pseudo data generated by the least-cost feed-ration model to estimate demand for feed grains is the work by McKinzie et al. (1986), and, more recently, Beckman et al. (2011). McKinzie and his co-authors estimated a complete set of direct- and cross-price elasticities of demand for livestock feedstuffs in the Netherlands. Their approach required repeated solutions over varying prices to determine changes in demand quantities. In the first stage of determining optimal feed demand quantities, the authors stressed the importance of capturing a sufficient distribution of relative prices to ensure that the linear programming-basis changes in optimal solutions occur. This finding is because numerous basis changes are needed to reduce a possible bias in the econometric demand estimations because the error terms in the estimation will be a direct result of the chosen relative price distribution. Elasticities are then calculated from the econometric estimations of the price responsiveness of feed demand.

The more recent work by Beckman et al. (2011) uses a similar approach. Rather than arbitrarily generating various relative price combinations, they generate a larger artificial sample using a normal distribution that is derived from the mean and covariance of actual observed relative prices over time. In contrast, the current authors used actual price data, given a sufficient length in the period used and variations in relative prices

[7] It should be noted at the outset that a caveat of the linear programming model is that the model is static in nature and may not capture some of the dynamics involved in switching between different grains. For example, there may be adjustment costs associated with the type of grain handling and processing required when switching between grains or those associated with product branding. For the latter, for example, large-scale producers may not wish to change the feed composition so quickly if there is a risk it will affect certain characteristics of their chicken meat which consumers have come to expect. In this case, the transition between feed compositions may occur more slowly to allow for appropriate adjustments to take place.

that can allow for sufficient basis changes in the linear programming model results. The existence of large variations in the observed prices over time also allowed the authors to incorporate price risk in the model using 3-month moving averages and variances. Pseudo-data approximations have been applied in various other forms when faced with limited data, especially for forward-looking-type analyses. For example, in agriculture, Hertel and McKinzie (1986) and Preckel and Hertel (1986) used pseudo data derived from an agricultural model to estimate supply and demand response functions to new proposed policies. An important drawback, and therefore a caveat, is that the resulting elasticity estimates tend to be biased upwards. Peeters and Surry (1997) found the pseudo-data approaches result in larger elasticity estimates than those produced by actual time-series data. However, this approach is less a concern for this report, as the insights into the relative differences between countries in their optimal feed formulations, their responsiveness to price changes in seeking substitutes, and whether the resulting own- or cross-price elasticities of demand are more elastic or inelastic are just as valuable in determining the potential of grain substitutes (such as sorghum) for growing their share in broiler feed formulations.

Incorporating Price Risk

Incorporating price risk in assessing broiler-feed demand has usually been concerned with uncertainty about the availability of nutrients in feedstuffs. Typically, the standard least-cost feed-ration model assumes that all parameters and variables in the model are known with certainty. But, such an assumption falls apart quickly when information about the availability of nutrients in the constraints or on the future movement of prices is not known with certainty. Uncertainty about the availability of nutrients is especially common with DDGS grain byproducts, as their quality can vary widely, depending on the primary feed grain and production techniques used by each individual plant. An early study incorporating probabilistic or stochastic constraints to a feed formulation model on the availability of nutrients is Van de Panne and Popp (1963). Since then, others have extended it further, including Pierre and Harvey (1986), Beckman et al. (2011), and Peña et al. (2017).

Uncertainty in selecting the least-cost feed formulation can also be caused by concerns of income risk due to the variability of relative prices over time. To the authors knowledge, only a few studies have incorporated such income risk considerations for feed-cost minimization with price uncertainty. Yet this information is important in an industry that typically faces very small profit margins (BFAP, 2019; FAO, 2007). An exception is a study by Coffey (2001), who introduced price risk within the mean-variance (E-V) framework in the objective function of a least-cost feed-ration model. Under this framework, a risk-averse decision maker can choose an optimal mix of ingredients in a feed ration that makes tradeoffs between price risk and net income. For example, Coffey (2001) was able to show that a risk-averse producer may be willing to accept higher expenses to minimize variability and, therefore, income.

The authors adopted a similar approach in this work, recognizing the limitations of the E-V framework, as noted earlier. To compute means, variances, and co-variances of feed ingredient prices over our selected period while still maintaining a historical time trend, the authors chose to use 3-month moving values. This process has several advantages. First, the process allowed sufficient degrees of freedom from the sample size to estimate price elasticities of demand. Second, it also more reasonably assumes that most risk-averse producers are likely to form their expectations of future price movements based on the most recently observed price behavior. When incorporating risk, the authors assumed the highest sensitivity to price risk by adopting a maximal level of risk aversion in their model (appendix A, section 2). To the best of the author's knowledge, this may be the first time such an approach has been used in evaluating past feed-demand behavior under income risk using the 3-moving average and variance of actual historical prices as they do here. Beckman et al. (2011), for example, generated a random sample of prices based on the distribution of actual prices to ensure a sufficient sample of linear programming results for estimating demand elasticities. A detailed mathematical presentation of our modified least-cost linear programming model under price risk is provided in the appendix.

Data Description and Sources

For this report's data needs, the least-cost linear programming model requires accurate information on relative feedstuff prices, the specific nutrient content of feedstuffs, and the nutrient requirements during the starter, grower, and finisher growth periods of a broiler chicken. For price data, a systematic approach to selecting which data source to use was adopted:

- First, the USDA's baseline database on monthly export prices at the international level and producer prices at the country level was used.
- Further gaps were filled using other recent USDA sources, such as Outlook reports and the USDA, ERS Feed Grains database.
- Where there were still some gaps, the authors relied on the International Grain Council's (IGC) price database, as well as the Organization for Economic Co-operation and Development's (OECD) and Food and Agriculture market databases on monthly and annual producer prices for each sample country.

Producer prices were converted to market prices by assuming a 15-percent added marketing margin consistently across each country.[8] Monthly prices are converted to U.S. dollar values if the prices were reported in local currency units using monthly average exchange rates. The prices were deflated to real dollar values using the U.S. gross domestic product deflator at 2015 constant values. Because the authors assumed all countries were able to import feed grains and oilseeds (depending on their competitiveness with domestic markets during the period of our study), they allowed countries to use imported feedstuffs so long as their domestic prices were higher than the import parity price. The import parity price is the sum of the world price plus freight (from the United Nation's data on maritime freight costs by major region), plus any import tariffs (from the United Nations Conference on Trade and Development (UNCTAD) Trade Analysis Information System (TRAINS) data on tariffs), plus port charges (5 percent).[9] The final set of international prices for feed grains and soybean meal over the selected period naturally varied by country, whether by reported domestic market prices or the authors' calculated import parity prices, whichever was lower (figure 3).

For the nutrient content of feedstuffs, the authors relied on information for each feedstuff from the National Research Council (1994). The minimum and maximum required nutrients at each growing stage of a broiler chicken were adapted from various sources, including the National Research Council (1994) and USDA, NRCS (2020). Summaries of the nutrient content of feedstuffs and requirements for each growth period, respectively, are in the appendix (tables A.1, A.2).

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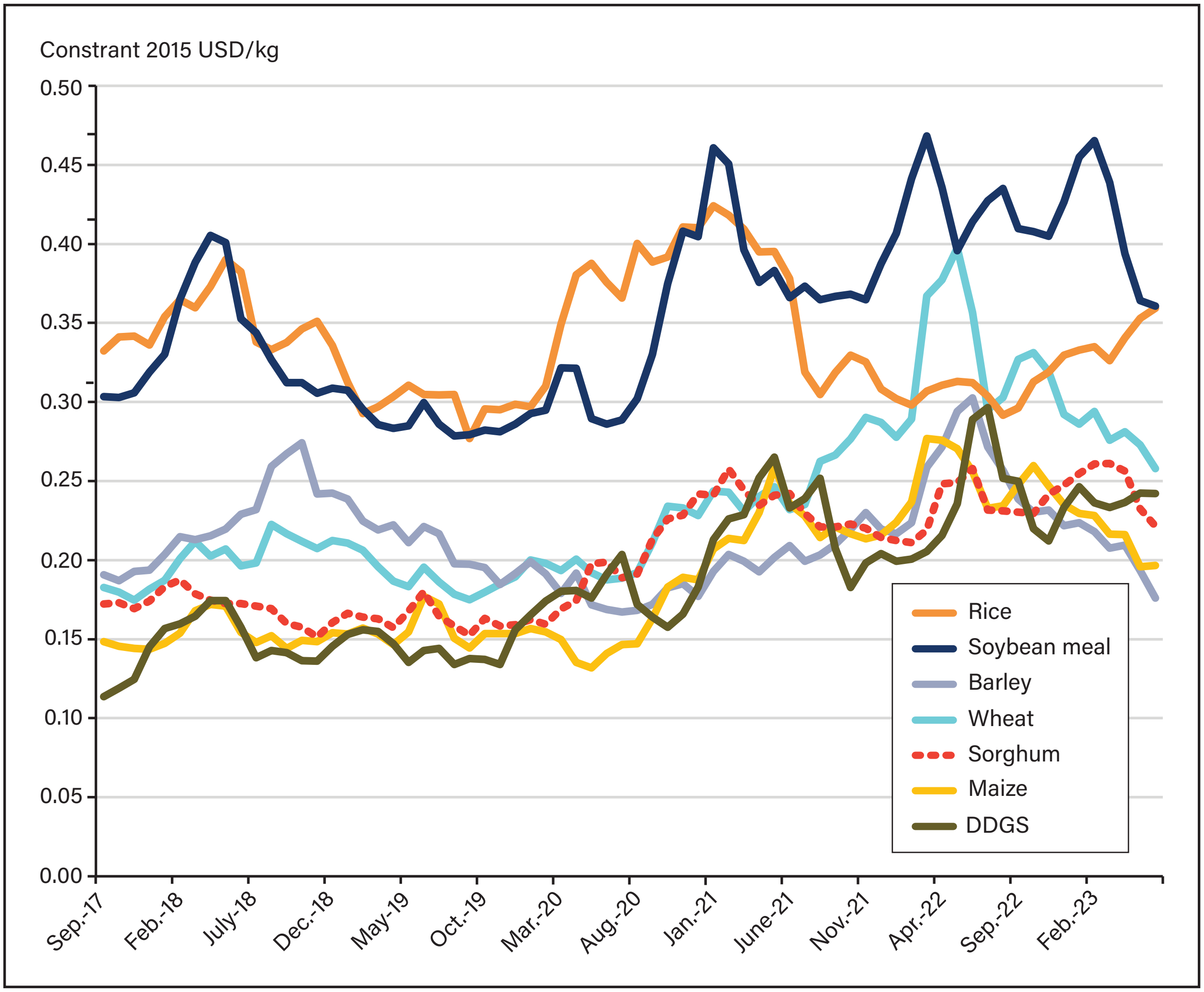
[8] In the absence of such information everywhere, the authors used the average price margins for yellow corn between market prices in Kansas City, MO, and the Gulf Ports freight on board export price between 1990 and 2022, using data from USDA Outlook reports and applied prices consistently. This process will obviously vary by commodity, country, and over time, but the authors did not have such information available.

[9] While some countries impose high tariffs on imports for food consumption, this process is less common when it is destined for feed use. The authors chose to use simple averages of actual applied tariffs, not the declared most favored nation rates in the United Nations TRAINS database.

Figure 3
Real international prices of feedstuffs, September 2017–June 2023



USD/kg = U.S. dollar per kilogram. DDGS = Distiller's dried grains with solubles.

Source: USDA, Economic Research Service graphic illustration using price data from the International Grains Council.

Estimating Own- and Cross-Price Elasticities of Feed Demand

The linear programming model was run for each broiler growth period to incorporate differences in energy and nutrient requirements and availability in starter, grower, and finisher diets and over the historical prices of the various feed ingredients. Total feed-mix demand was calculated as a weighted average across the three growing periods (weighted by number of weeks—3 out of 8 weeks for starter and grower feed and 2 out of 8 for finisher feed). Results are reported for both scenarios of with and without risk aversion using 3-month moving averages and co-variances in this report's full data set of 68 observations between November 2017 and June 2023.[10]

With results of marginal shares of optimal feed compositions available, together with the corresponding relative historic price combinations driving the results, the authors were able to estimate the price elasticity of

[10] September 2017 was the earliest period in which sufficient sources of monthly prices were available across all feedstuffs in our study. The first 2 months are dropped in accordance with a 3-month moving average series.

demand for these feedstuffs.[11] Following others who have estimated livestock feed demand (e.g., McKinzie et al. (1986) and Beckman et al. (2011)), this process was accomplished using a translog cost function and its corresponding derived system of feed-cost share equations, as specified in the appendix. Estimations were achieved using the seemingly unrelated regression (SUR) econometric model. Resulting coefficient estimates were then used to calculate both own- and cross-price elasticities of feed demand or PEDs (see the appendix for more details). To measure the relative degree of substitution between feedstuffs, the authors also calculated Morishima elasticities of substitution (MES). Most economists have viewed these elasticities as more theoretically appropriate for measuring factor substitutions (Blackorby & Russell (1989); Nguyen & Streitwieser (1998)).

Results

Optimal Feed Mix Formulations

Results from the linear programming least-cost feed-model show the optimal feed formulations based on their nutrient content and mean prices at the starter, grower, and finisher stages of growth. Results are aggregated as weighted totals across the different diet formulations for each stage of growth (as explained earlier), while more detailed results by growth stage are also presented in the appendix. Partially driving the model results are the relative historical price combinations and their correlates (table 4). A second driver is the restrictions on nutrient requirements for growth and their availability among each of the feedstuffs (appendix tables A.1, A.2).

Table 4
Correlation coefficients of international monthly feedstuffs prices September 2017 to June 2023

	Wheat	Rice	Corn	Sorghum	DDGS	Soymeal	Fishmeal
Wheat	1.00	-0.21[c]	0.91[a]	0.76[a]	0.73[a]	0.77[a]	-0.23[b]
Rice	-0.21	1.00	-0.11[n]	0.25[b]	0.07[n]	0.19[n]	0.26[b]
Corn	0.91	-0.11	1.00	0.84[a]	0.81[a]	0.82[a]	-0.27[b]
Sorghum	0.76	0.25	0.84	1.00	0.85[a]	0.83[a]	-0.14[n]
DDGS	0.73	0.07	0.81	0.85	1.00	0.72[a]	-0.17[c]
Soymeal	0.77	0.19	0.82	0.83	0.72	1.00	-0.02[n]
Fishmeal	-0.23	0.26	-0.27	-0.14	-0.17	-0.02	1.00

DDGS = Distiller's dried grains with solubles. [n] = not significant at any level. [a] = significant at 1 percent. [b] = significant at 5 percent. [c] = significant at 10 percent.

Source: USDA, Economic Research Service (ERS) calculations using price data from USDA, ERS and the International Grains Council.

Among the feedstuffs, corn offers the highest energy content, followed closely by sorghum and wheat (appendix table A.1). The lower energy value for barley may have affected its failure to come into the linear programming solution for all countries and time periods. Although older varieties of sorghum have typically suffered from lower amino acid content (i.e., lysine, methionine, cysteine, and threonine)—and, therefore, a less digestible alternative to other feed grains—this constraint is not a concern for the time period analyzed as new and more digestible cultivars have since dominated global markets (Dowling et al., 2002; McCuistion et

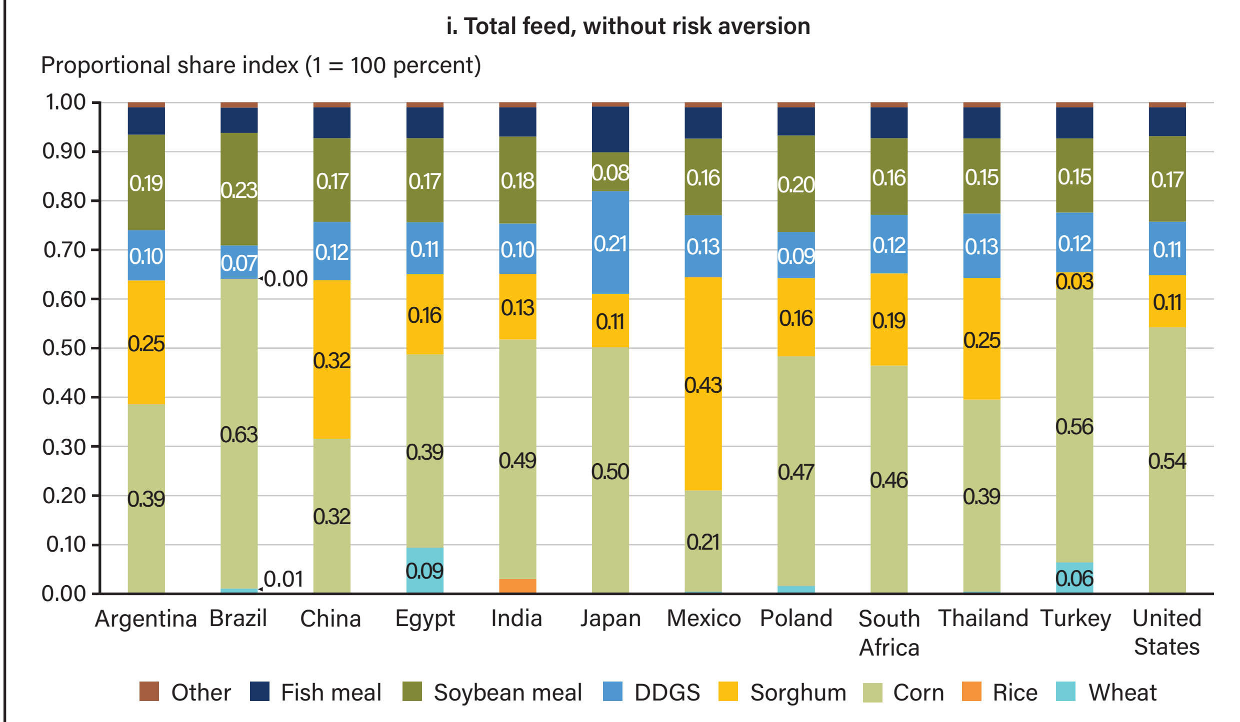
[11] We use actual prices in estimating elasticities of demand rather than the 3-month moving averages used in our linear programming risk model.

al., 2019). Conversely, the distiller's by-product, the distiller's dried grains with solubles (DDGS), has higher protein content albeit lower energy content. This finding is why DDGS tends to be used more for starter and grower feeds rather than finisher feeds, where energy is more important. Higher nutrient requirements for starter feed generally imply that nutrient rich ingredients (such as soymeal, DDGS, and fish meals) are used in greater proportions in the feed formulation when compared with finisher feed.

Recall that the linear programming risk model produces monthly optimal results of the least-cost feed ration given 3-month moving values of past observed relative price combinations and their variance and co-variances among the feed ingredients during each month in the sample.[12] Different growth stages require optimal feed compositions (appendix figure A.2).

Sorghum rarely entered the optimal solution for Brazil and Turkey, with and without risk aversion considerations (figure 4). Turkey has typically imposed high import tariffs on grains, including sorghum (up to 130 percent). Although the tariff on sorghum was removed during the COVID-19 pandemic, Turkey recently reintroduced it (USDA, FAS, 2023m). As a result, the relative price of sorghum (whether domestic or at import parity) was too high and perhaps even more volatile relative to domestic corn prices.

Figure 4
Total weighted-average mix shares of total feed averaged across time—with and without risk aversion



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[12] Detailed results for each country can be provided by the authors upon request.

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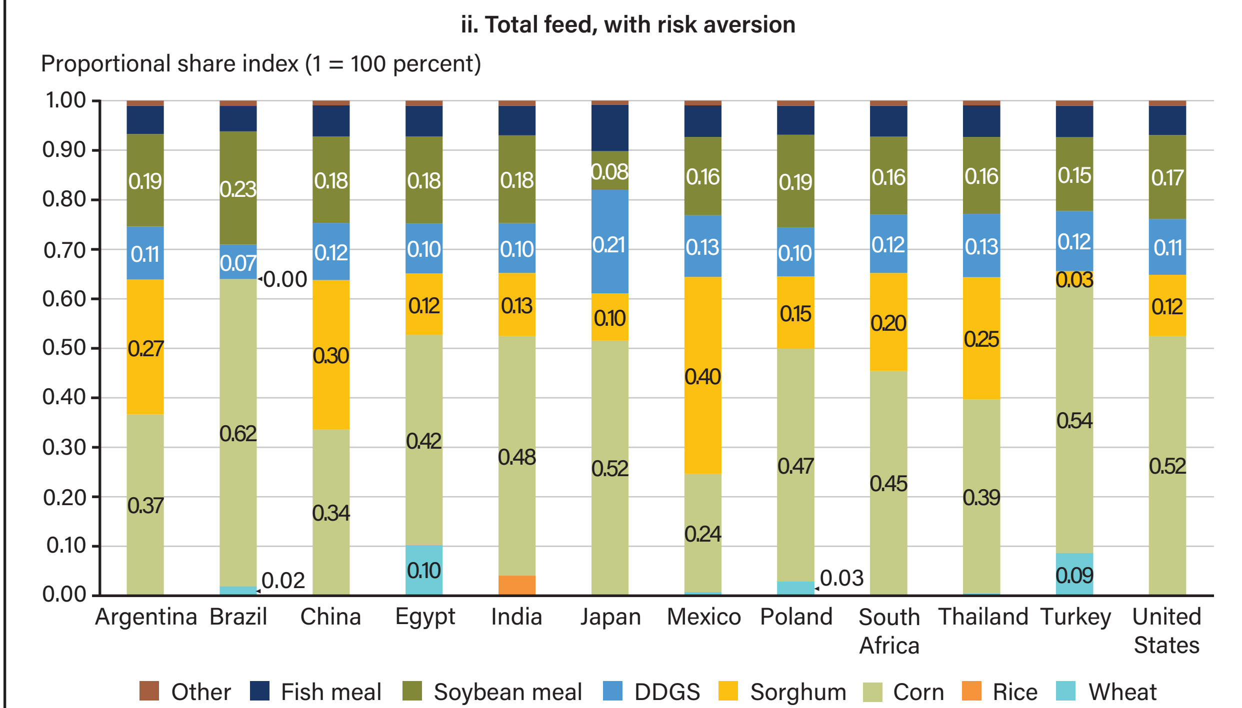


DDGS = Distiller's dried grains with solubles.

Source: USDA, Economic Research Service using General Algebraic Modeling System (GAMS) model results.

For China and Mexico, the opposite is true. Sorghum had a more favorable price relative to corn over many months—such that the feed composition is estimated by the model to have been frequently dominated by sorghum, even under price risk considerations (although their shares decreased some when risk aversion was considered in both countries).[13] While countries like China, Mexico, and Egypt reduced the share of sorghum in their feed mixes when aversion to price risk mattered, the share increased for countries such as Argentina, South Africa, and the United States and did not change much for others. This finding implies the presence of a higher variability in prices for competing grains—especially sorghum in China, Egypt, and Mexico—and corn in Argentina, South Africa, and the United States. Japan and Poland faced less price volatility in either corn or sorghum but thus opted for sorghum more often in the model results than the United States.

Among the 12 countries considered in this study, India is unique, given its lower relative prices for rice. Here, the country shifted more to rice whenever aversion to price risk mattered in the model, implying rice faced less market volatility than other grains throughout much of the period in our sample (figure 4). Turkey and Egypt are also unique in terms of wheat, which came into the solution frequently whenever the aversion to price risk was considered important among broiler farmers.

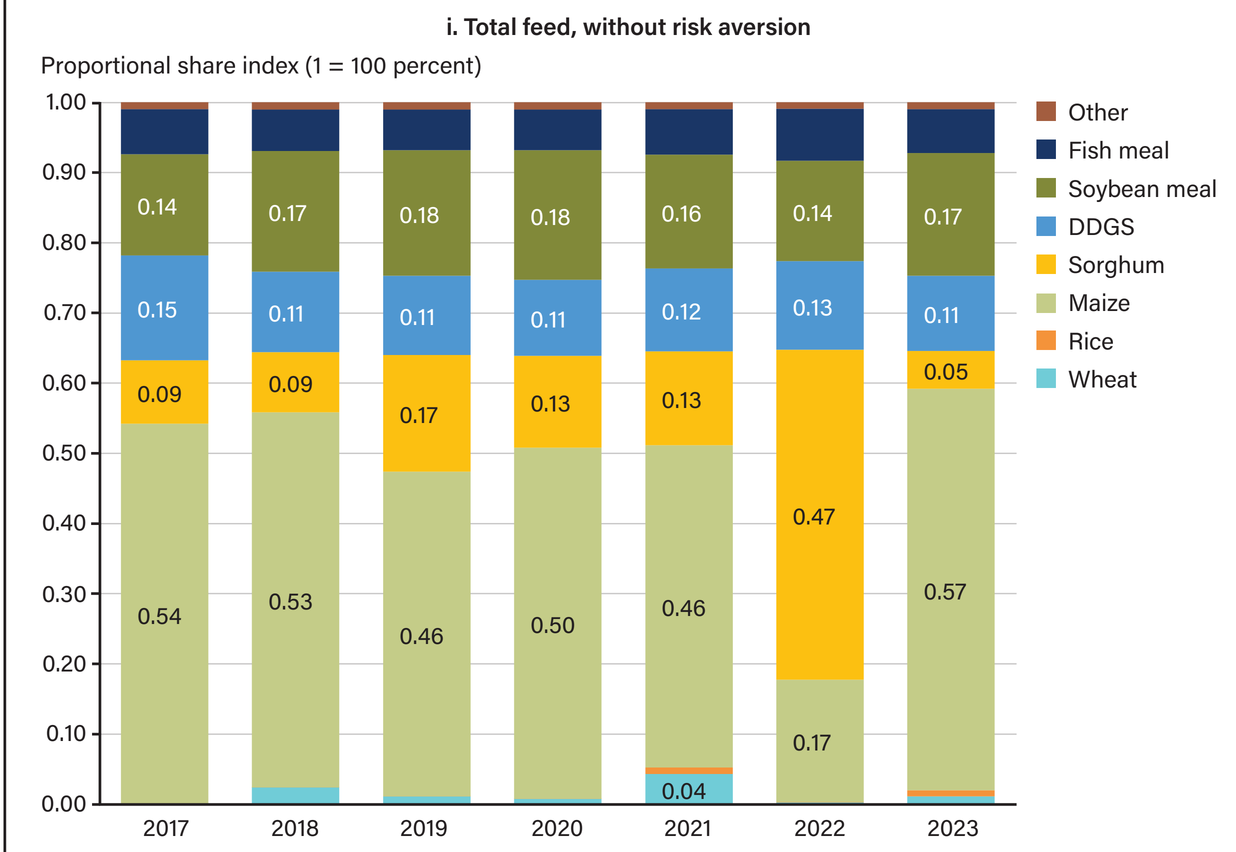
The optimal allocation of feedstuffs naturally changed over time, as relative prices changed from month to month and from year to year. If feedstuff shares in the total feed formula are averaged cross-country and annually, an aggregate picture emerges of how the total mix changed over time between November 2017 to July 2023 (the total range of data used in the model). There was a much larger substitution of sorghum for corn in the model results than any other grain or grain byproduct (DDGS) (figure 5). This result occurred

[13] For all countries, the bulk of sorghum used (when the sorghum price was more favorable) was for starter and grower feed diets, which account for 75 percent of the broiler's lifetime feeding requirements (appendix, figure A.2). This finding may be due to sorghum's slightly higher calcium content, relative to corn, a critical nutrient in the early stages of growth.

the most in 2022, where the model allocated more than a 40-percent share to sorghum in broiler-feed formulas when averaged across countries compared with 9 to 17 percent in earlier years. Although not shown in the figure, almost all the countries shifted completely to sorghum over 2 or more monthly periods in 2022 when corn prices far exceeded sorghum prices (except Brazil, Turkey, and the United States).[14] Assuming producers were mostly risk averse, the model results showed less impactful substitution effects in 2020 and 2022, when averaged across countries. The models were more impactful in other years, where the share of sorghum in the feed mix rose by 1 to 2 percentage points, with risk aversion relative to the scenario without risk aversion. These years were evidently years that some countries experienced greater volatility in monthly corn prices relative to sorghum prices (appendix figure A.1).

Figure 5

Cross-country annual averages of feed mix allocations, 2017–23



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[14] Detailed results by country can be shared by the authors upon request.

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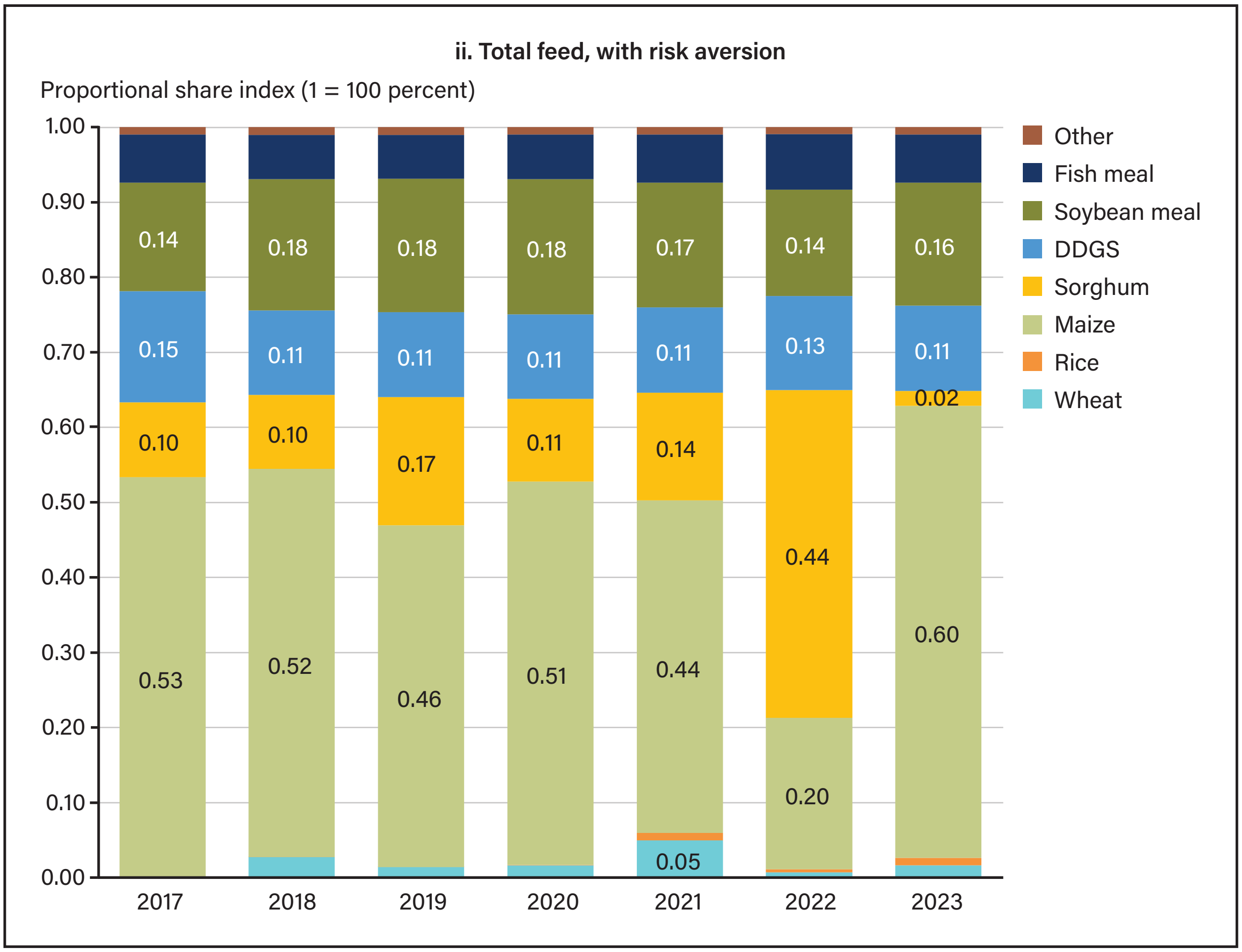
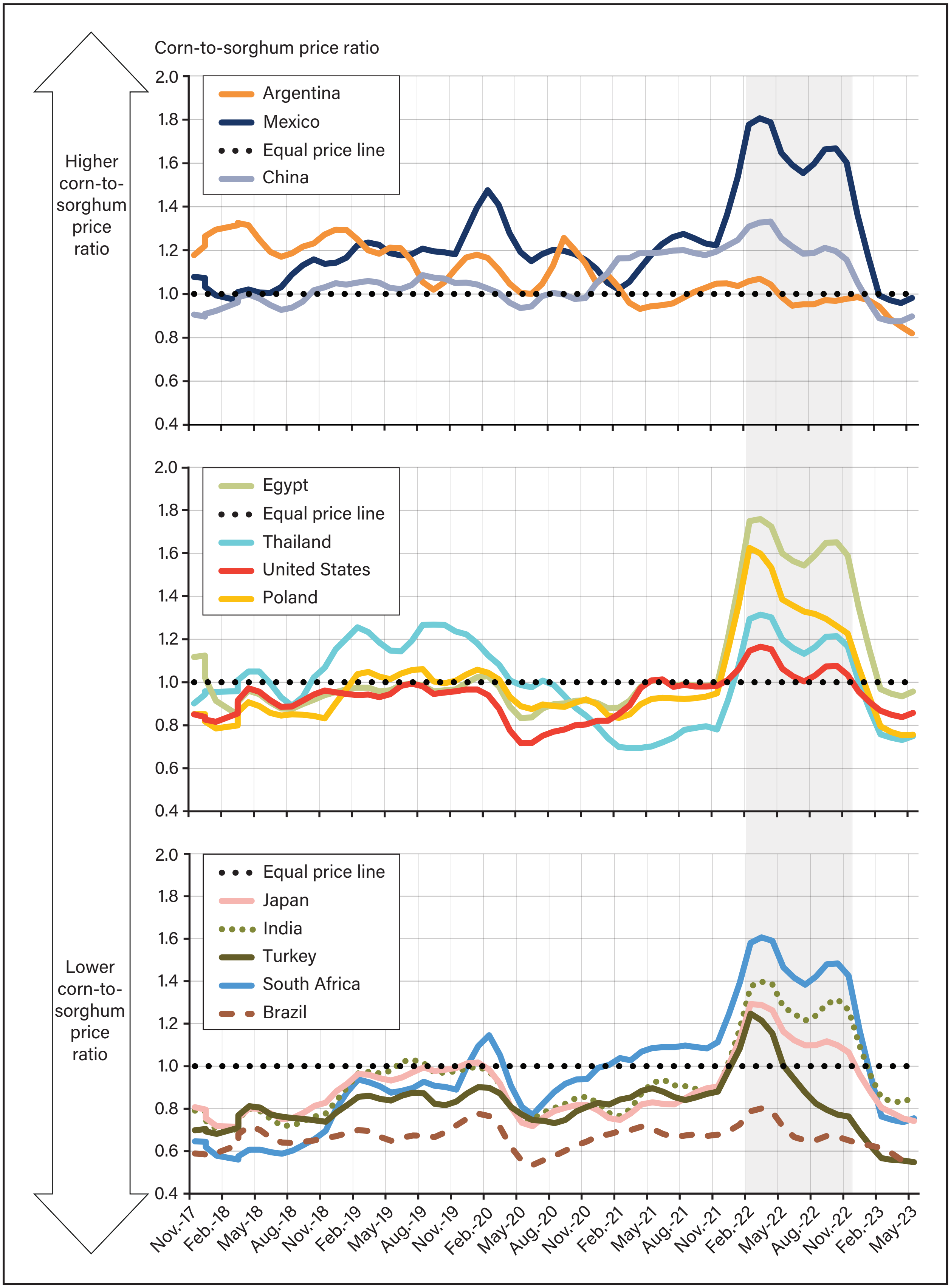


DDGS = Distiller's dried grains with solubles.

Source: USDA, Economic Research Service using General Algebraic Modeling System model results.

The drop in relative prices for sorghum over corn in 2022 made sorghum a more attractive option for most countries—even replacing corn altogether. The increase in sorghum use reflected the higher observed corn-to-sorghum price ratios, as well as the variability and uncertainty in corn prices that followed the Russia-Ukraine war. Russia and Ukraine are major producers of corn but produce little to no sorghum in comparison. Sorghum (as a substitute) failed to come into the solution in cases where domestic suppliers of corn were more competitive with imports, as in the case of Brazil (figure 6). Conversely, countries like Argentina, China, Egypt, Mexico, and Thailand faced higher corn-to-sorghum prices over most years, while the rest experienced this result only recently (between February 2022 and December 2022; shaded area in figure 6).

Figure 6
Sorted national corn-to-sorghum price ratios, 3-month moving average, September 2017–June 2023



Source: USDA, Economic Research Service (ERS) using price data from USDA, ERS and the International Grains Council.

Price Elasticities of Feed Demand and Substitution

The results from the estimates of own- and cross-price elasticities of demand (PED), including computations of Morishima elasticities of substitution (MES), under each scenario of with and without risk aversion are based on the linear programming model derived optimal feed mixes (appendix table A.3) Recall that the caveat explained earlier that these estimates are biased upwards in general as the feed demand shares used to estimate the PEDs are the pseudo data from the linear programming model. However, the interest should focus on their signs, relative differences between the alternative feedstuffs and between countries, and the extent of price responsiveness (that is, whether the PEDs show to be either more or less elastic) under the two scenarios of with and without risk aversion.

Price Elasticities of Feed Demand

All own-price elasticities of demand (or PED) values for corn or sorghum were negative, as the authors expected; that is, an increase in the own-price of either would have reduced demand for that same feedstuff (appendix table A.3). Additionally, the cross-price elasticities were positive for both grains, indicating both served as feed substitutes; that is, a rise in the price of one feedstuff would increase the demand for the other. This finding is true for most other feedstuffs, with the exception of the grain by-product DDGS, which showed negative values with most of the grains (see table A.3 in appendix). That means that DDGS mostly complemented other grains as DDGS brought nutrients in which natural grains have less. Overall, most of the PED estimates were statistically significant at the 1-percent level, and the performance of the regression results showed reasonably good fits, especially for corn and sorghum.

The PEDs can be read as the percent change in quantity demanded for a specific grain, given a 1-percent change in its own price (for own-PEDs) or that of another feedstuff ingredient (for the cross-PEDs). For example, under the scenario without risk aversion, Argentina had own-PED and cross-PED values of -3.515 and 3.366 for the change in the quantity demanded of corn due to a change in the corn and sorghum price, respectively (first column in table 5). This finding implies the quantity demand for corn (as estimated by the linear programming model) decreased by 3.5 percent in Argentina whenever its own price increased by 1 percent or that the quantity demand for corn increased by 3.4 percent whenever sorghum prices increased by 1 percent.

Table 5

Own- and cross-price elasticities for corn and sorghum, with and without risk aversion

a) Own-price PEDs						
	Without risk aversion		With risk aversion		Percent change of with risk relative to without risk aversion	
PercentΔ in Q / (1 percentΔ in P)*	Corn (corn)	Sorghum (sorghum)	Corn (corn)	Sorghum (sorghum)	Corn (corn)	Sorghum (sorghum)
Argentina	-3.515	-5.986	-3.822	-5.568	8.7	-7.0
Brazil	-0.135	-	-0.318	-	135.6	
China	-7.367	-6.892	-6.582	-7.019	-10.7	1.8
Egypt	-3.022	-7.120	-2.564	-8.360	-15.2	17.4
India	-6.537	-2.680	-2.533	-9.050	-61.3	237.7
Japan	-2.323	-10.538	-2.079	-11.064	-10.5	5.0
Mexico	-4.500	-1.767	-3.836	-1.907	-14.8	7.9
Poland	-3.053	-7.530	-3.078	-7.490	0.8	-0.5
South Africa	-2.018	-4.370	-2.005	-4.127	-0.6	-5.6
Thailand	-3.169	-4.986	-3.099	-4.832	-2.2	-3.1
Turkey	-1.836	-16.927	-1.892	-16.164	3.1	-4.5
United States	-2.370	-10.494	-2.427	-9.181	2.4	-12.5

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b) Cross-price PEDs						
	Without risk aversion		With risk aversion		Percent change of with risk relative to without risk aversion	
PercentΔ in Q / (1 percentΔ in P)	Corn (sorghum)	Sorghum (corn)	Corn (sorghum)	Sorghum (corn)	Corn (sorghum)	Sorghum (corn)
Argentina	3.366	6.277	3.633	5.886	7.9	-6.2
Brazil	-	-	-	-	-	-
China	7.200	6.862	6.436	7.004	-10.6	2.1
Egypt	2.226	6.194	1.736	7.278	-22.0	17.5
India	-0.166	-0.011	2.273	8.415	+	+
Japan	2.348	10.157	2.060	10.540	-12.3	3.8
Mexico	3.926	2.108	3.332	2.331	-15.1	10.6
Poland	2.594	8.100	2.255	7.863	-13.1	-2.9
South Africa	1.787	4.569	1.825	4.278	2.1	-6.4
Thailand	3.038	4.941	2.920	4.785	-3.9	-3.2
Turkey	0.874	13.376	0.763	12.969	-12.7	-3.0
United States	2.340	10.442	2.402	8.964	2.6	-14.2

Note: PED = price elasticities of demand. * This describes the percent change (Δ) of quantity demanded (Q) due to a 1-percent change (Δ) in price (P) or referred to as the price elasticity of quantity demanded.

Source: USDA, Economic Research Service summary of results in appendix table A.3.

The own-price elasticity of sorghum across most countries was higher relative to that of corn (with or without risk aversion).[15] That is feed producers (on average) showed to be less sensitive to a change in corn prices when the producers chose to use corn in their feed mix than when choosing to use sorghum following a change in sorghum prices over the selected period. Most notable were Argentina, Egypt, Japan, Poland, Turkey, and the United States (and to some degree South Africa and Thailand). Countries with some of the highest PED values for sorghum included Egypt, Japan, Poland, Turkey, and the United States. In most cases, the high PEDs stem from a lower frequency by which sorghum came into the linear programming model solution as a viable substitute for corn. This result occurred as observed sorghum prices exceeded corn prices much of the time, and additionally, for some countries, the presence of other competing lower priced substitutes such as wheat (Egypt, Poland, and Turkey).

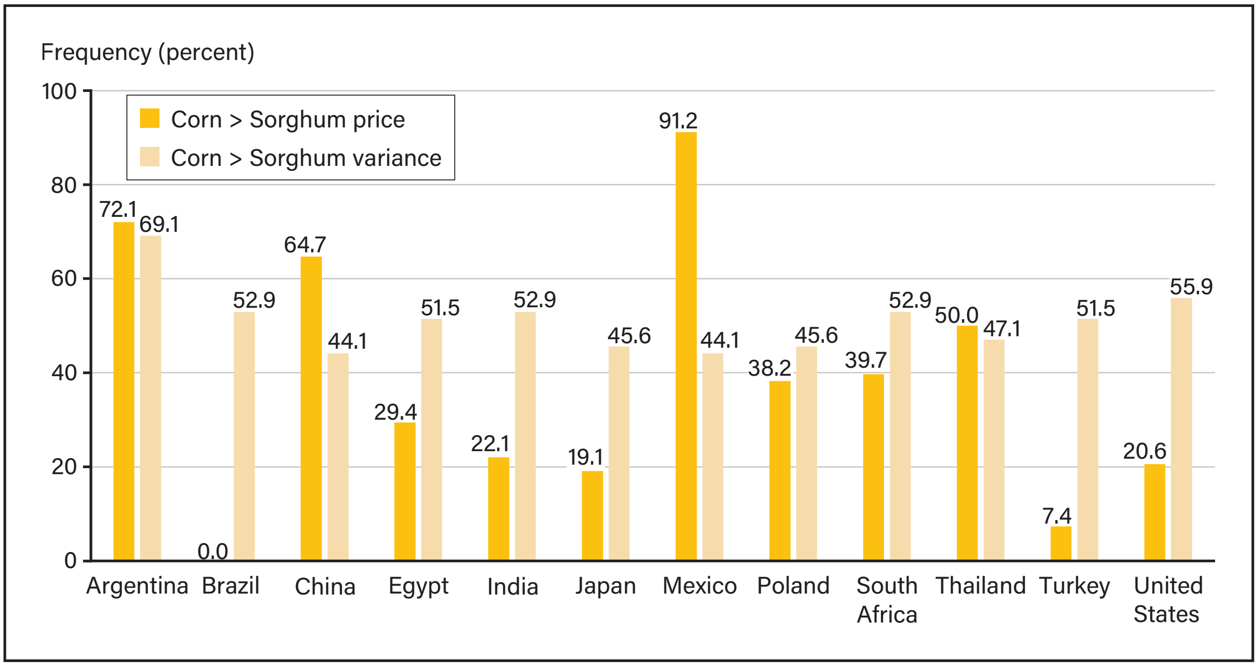
Only China, India, and Mexico showed to be less sensitive to sorghum price changes, given their own lower PED values for sorghum compared to corn. That is, they were more sensitive to changes in corn prices when choosing to use corn in their feed mix and therefore more likely to seek alternative substitutes for corn, such as rice and sorghum in India and sorghum in Mexico and China. As a result, corn was only partially used in their feed mixes during the finisher-growth stage whenever corn prices rose above sorghum prices by some small amount (appendix figure A.2). While China and Mexico faced higher corn-to-sorghum prices for much of the time, India experienced higher sorghum-to-corn prices more than 75 percent of the time (figures 6, 7). This finding indicates the presence of an alternative substitute to sorghum (in this case, rice). Rice competed with sorghum whenever corn prices spiked (as high as they did after 2021), effectively reducing the sensitivity of sorghum demand in the linear programming model to price changes compared with corn.

When the observed price of corn was higher than that of sorghum across the countries in the authors' sample, the price affected the frequency when sorghum may have been a more favorable grain substitute for corn in

[15] Excluding Brazil, where sorghum never entered the solution.

our optimum feed mix results and ultimately, the authors corresponding PED estimates (in some cases, wheat or rice would be viable substitutes) (figure 7). The frequencies when the price variance of corn (a 3-month moving variance) was higher than that of sorghum across the same sample of countries become relevant later when results under the scenario with risk aversion are presented.

Figure 7
Frequency of episodes when the 3-month moving average and variance of actual corn prices was higher than that of sorghum by country, November 2017–June 2023



Source: USDA, Economic Research Service (ERS) using price data from USDA, ERS and the International Grains Council.

Cross-price PEDs of corn and sorghum generally reflected the same pattern with their own price elasticities in terms of the absolute magnitude of their PED values (table 5).[16] For example, Argentina, like most other countries, showed a similar magnitude of the demand responsiveness of corn (whether negatively or positively) to changes in corn and sorghum prices. The same was true for the demand responsiveness of sorghum, given changes in either price. Unlike Argentina, however, the responsiveness was higher than that of corn for most countries and in both cases—whether it was due to a change in corn or sorghum prices. It was especially prominent for countries such as Turkey, Japan, Poland, and the United States. As noted earlier, these are among the countries that faced fewer episodes of corn prices rising above sorghum prices. As with the own-PEDs, and in contrast with other countries, China and Mexico appeared more sensitive in the quantity demanded of corn due to a change in sorghum prices than a change in the quantity demanded of sorghum following a change in the price of corn. For China, however, the differences were small and, therefore, almost equally sensitive in terms of both own- and cross-PED values for corn and sorghum. This is a country that frequently substituted between sorghum and corn throughout the sample period.

A key hypothesis of this study was the expectation that the increased demand for sorghum (as an important substitute for corn) would not only be affected by higher corn to sorghum prices but by the variance in their prices if it was assumed that feed producers were risk averse. If the variance of corn prices was sufficiently large and the price of sorghum was only marginally higher than corn on average, producers may still choose

[16] India again was an exception where its value was close to nil, again indicating the presence of an alternative substitute, rice, which came into the solution in the latter years.

to substitute sorghum for corn, given the high volatility and uncertainty in corn prices. The authors examined for any differences between the PED estimates when risk aversion matters (the "with risk aversion" scenario) and those when it does not (the "without risk aversion" scenario).

Taking risk aversion into account resulted in PED estimates that were either larger or smaller than the without risk aversion scenario in different countries, depending on the underlying 3-month moving variance and co-variance of domestic market prices through time (table 5). For example, among feed ingredients showing lower own- or cross-PED values after risk aversion was introduced, this change would occur if the variance in the own-price over time was lower than that of alternative substitutes. In other words, risk-averse feed producers were less responsive to price changes of alternative feedstuffs whenever there was higher price volatility among them relative to the feed ingredient already in use. The opposite was true for higher own- or cross-PED values that resulted when risk aversion was introduced.

Countries that showed lower own- or cross-PED values for corn and slightly higher values for sorghum (after risk aversion was introduced) are China, Egypt, Japan, and Mexico. The implication is that for these countries, the quantity demanded for corn (sorghum) became less (more) sensitive to its own price or that of sorghum (corn), all other prices held constant, when risk aversion was important (table 5). In other words, when price risk was introduced, risk-averse broiler-feed producers became more sensitive (or hesitant) to using sorghum (relative to corn) when corn or sorghum prices changed by a small amount. The opposite was true with the responsiveness of the quantity demanded for corn—which became less sensitive (or less hesitant) to using corn when risk aversion was important. This result naturally occurred whenever sorghum prices showed to be more volatile than corn prices for much of the time. That is, the affected countries experienced greater frequencies (more than half of the time) when the 3-month moving variance of the sorghum price was higher than that of corn (figure 7). However, despite having a higher variance, sorghum would still come into the model solution, so long as observed sorghum prices were sufficiently lower than corn prices for much of the time, as occurred in China and Mexico.[17] India shares the same results in the change of its own-PED values when risk aversion mattered but the change in its cross-PED value for sorghum differed. Instead, the change was even more pronounced after an aversion to price risk was introduced among broiler farmers, such that the quantity demanded of sorghum (following a change in corn prices) was far more responsive than in a case without risk aversion. This result is because while corn and sorghum prices were highly variable in India for much of the time, sorghum prices were rarely lower than corn prices (only about 22 percent of the time). Demand for both grains competed with rice as a viable feed substitute—one that often had a very low variance in price as it is typically subsidized.

A few countries, such as Argentina and the United States (and to some degree, South Africa), experienced both higher own- and cross-PED values for corn and lower values for sorghum when risk aversion mattered. Evidently, these countries faced a higher volatility in corn versus sorghum prices, as shown by the greater frequencies when the 3-month moving variance of corn prices was higher than that of sorghum (figure 7). For these two countries, the quantity demanded of corn due to either a change in corn or sorghum prices became more sensitive with risk aversion, while the quantity demanded of sorghum became less sensitive to both prices (table 5).

Results for countries such as Poland, Thailand, and Turkey were mixed. While these countries also had higher own-PED values for corn and lower values for sorghum when risk aversion mattered, both cross-PEDs for corn and sorghum declined. In other words, risk-averse broiler producers became more hesitant to substitute either grain when the other price changed—evidently because there was sufficient volatility in both prices or other viable alternatives for corn (other than sorghum) were less volatile for some of the time. An example is wheat in Poland and Turkey, following a spike in global corn prices.

[17] While China and Mexico had less occurrences (about 44 percent of the time) when the 3-month moving variance of corn prices was higher than that of sorghum, the countries had more occurrences of higher corn-to-sorghum price ratios for much of the time (figures 6, 7).

Morishima Elasticities of Substitution

When risk aversion is considered, the differences in own-PEDs and cross-PEDs reflect changing substitution effects, as the variability of prices between the substitutes changed over time. To measure the relative degree of substitution between feedstuffs under both conditions (with and without risk aversion), the authors calculated Morishima elasticities of substitution (MES) from the regression results as the most appropriate when dealing with multiple inputs, as described in the appendix. Like the PED value estimates, the authors' estimates of MES values are biased upwards because they used pseudo-demand data derived from the linear programming model. The authors were only interested here in their signs and relative differences between countries, feed ingredients, and the two risk aversion scenarios (table 6). The MES values in the table measure the substitution effect on the feed-demand ratios of the listed commodity in each row (y) with that of each commodity in the columns (x) following a 1-percent change in the price of the commodity in each column (x). Therefore, the values can be interpreted as the degree to which producers would substitute y for x—or the use of y in place of x without changing output—following a change in the price of x.

Limiting the discussion to the substitution effect of corn and sorghum, and later soymeal, results showed high MES values between corn and sorghum for China, Japan, the United States, Poland, and Turkey—implying a very high substitutability between the two grains in these countries (table 6). Nevertheless, for all sample countries, the values were all positive and relatively large, implying a strong substitution effect between corn and sorghum in general. When risk aversion was introduced, however, most countries showed a slight decrease in their MES values, as might be expected.

Risk-averse feed producers became less willing to replace corn with sorghum whenever the price variance of sorghum was much higher than that of corn (and vice versa when substituting corn for sorghum), unless the change in prices was sufficiently large. The exceptions were Egypt, India, and Japan—where the substitution effect increased. For these countries, the increased willingness to substitute one for the other when the aversion to price risk was important reflects their estimated higher own- and cross-PED values in the quantity demanded of sorghum following either a change in sorghum or corn prices (table 5).

Table 6
Morishima elasticities of substitution: corn and sorghum

	Feed-x											
	i. Without risk aversion						ii. With risk aversion					
	Wheat	Rice	Corn	Sorghum	DDGS	Soymeal	Wheat	Rice	Corn	Sorghum	DDGS	Soymeal
a. Corn (percent change in input demand ratio of corn to feed-x due to a 1-percent change in the price of feed x)												
Argentina	-	-	-	9.35	1.79	0.08	-	-	-	9.20	1.56	0.43
Brazil	11.00	-	-	-	1.97	1.74	10.64	-	-	-	1.33	1.50
China	-	-	-	14.09	1.26	1.79	-	-	-	13.46	1.06	1.39
Egypt	7.29	-	-	9.35	0.81	0.70	6.67	-	-	10.10	0.96	0.71
India	-	15.98	-	2.51	1.34	1.16	-	5.13	-	11.32	1.14	0.81
Japan	-	-	-	12.89	0.44	3.54	-	-	-	13.12	0.45	3.73
Mexico	-	-	-	5.69	0.53	-0.64	-	-	-	5.24	0.48	-0.48
Poland	12.63	-	-	10.13	1.74	1.50	13.44	-	-	9.75	1.58	1.25
South Africa	-	-	-	6.16	0.40	0.05	-	-	-	5.95	0.51	-0.06
Thailand	-	-	-	8.03	0.99	0.46	-	-	-	7.75	0.70	0.61
Turkey	11.98	-	-	17.80	0.58	0.03	10.12	-	-	16.93	0.43	-0.13
United States	-	-	-	12.83	1.02	1.63	-	-	-	11.58	0.76	1.24

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	Feed-x											
	i. Without risk aversion						ii. With risk aversion					
	Wheat	Rice	Corn	Sorghum	DDGS	Soymeal	Wheat	Rice	Corn	Sorghum	DDGS	Soymeal
b. Sorghum (percent change in input demand ratio of sorghum to feed-x due to a 1-percent change in the price of feed x)												
Argentina	-	-	9.79	-	0.11	3.28	-	-	9.71	-	0.31	2.92
China	-	-	14.23	-	1.43	1.79	-	-	13.59	-	1.12	1.47
Egypt	9.36	-	9.22	-	0.03	1.03	9.27	-	9.84	-	-0.16	1.29
India	-	11.90	6.53	-	1.04	1.24	-	6.43	10.95	-	0.66	1.72
Japan	-	-	12.48	-	0.96	6.18	-	-	12.62	-	1.22	5.72
Mexico	-	-	6.61	-	0.20	0.45	-	-	6.17	-	0.21	0.30
Poland	12.57	-	11.15	-	0.92	2.90	13.17	-	10.94	-	0.83	2.19
South Africa	-	-	6.59	-	0.08	0.53	-	-	6.28	-	0.26	0.37
Thailand	-	-	8.11	-	1.01	0.69	-	-	7.88	-	0.69	0.88
Turkey	15.47	-	15.21	-	1.14	-0.74	13.19	-	14.86	-	0.64	-0.43
United States	-	-	12.81	-	0.35	2.52	-	-	11.39	-	0.31	2.04

DDGS = Distiller's dried grains with solubles. MES = Morishima elasticities of substitution.

Note: Rows represent feed-demand ratios of the listed commodity y, with respect to each commodity x, in the columns. The columns represent 1 percent price changes for each commodity x listed. Therefore, each MES value can be read as the percentage change of a commodity-demand ratio (commodity y in a row/commodity x in a column) due to a 1-percent change in the price of the commodity x. As previously noted, because these values were estimated using pseudo data, the values will tend to be biased upwards compared with real world behavior.

Source: USDA, Economic Research Service calculations based on regression results (appendix A, section 3).

Partial input substitutions also occurred between grains and oilseeds. The substitution of soymeal for sorghum appears quite strong, as demand for soymeal was relatively more sensitive to sorghum price changes than to prices of other grains or byproducts, such as DDGS (table 7). The substitution was especially high for Japan, Turkey, and the United States. As in the case of corn or sorghum (table 6), most countries experienced declining MES values of soymeal for sorghum when risk aversion was considered—with the exception of Egypt, India, and Japan (and, to some degree, China). In other words, the willingness to substitute soymeal for sorghum increased in these countries if it was assumed feed producers were risk averse. All four countries were more likely to substitute soymeal for sorghum when risk aversion mattered because of the higher volatility or the variance and covariance of soymeal relative to sorghum prices (appendix figure A.1). The opposite was true for the rest of the countries that experienced falling MES values for soymeal when it was assumed producers were risk averse. Apparently, in these countries, sorghum prices were more volatile relative to soymeal.

Table 7
Morishima elasticities of substitution from model results: soymeal

	Feed-x											
	i. Without risk aversion						ii. With risk aversion					
	Wheat	Rice	Corn	Sorghum	DDGS	Soymeal	Wheat	Rice	Corn	Sorghum	DDGS	Soymeal
Soymeal (percent change in input ratio of soymeal to feed-x due to a 1-percent change in the price of feed x)												
Argentina	-	-	2.39	7.20	1.86	-	-	-	2.88	6.59	1.80	-
Brazil	11.17	-	0.00	-	2.73	-	10.42	-	0.31	-	2.01	-
China	-	-	7.34	6.87	2.15	-	-	-	6.46	7.01	1.68	-
Egypt	7.88	-	2.07	6.95	1.21	-	7.12	-	1.73	8.37	1.35	-
India	-	9.70	6.51	2.33	1.50	-	-	5.12	2.13	9.30	1.50	-
Japan	-	-	0.89	11.51	1.51	-	-	-	1.04	11.73	1.47	-
Mexico	-	-	3.85	2.18	0.54	-	-	-	3.27	2.15	0.51	-
Poland	12.72	-	2.25	7.86	2.55	-	13.34	-	2.22	7.62	2.14	-
South Africa	-	-	1.81	4.51	0.42	-	-	-	1.65	4.19	0.53	-
Thailand	-	-	2.83	4.98	1.38	-	-	-	2.88	4.93	1.06	-
Turkey	11.45	-	1.37	16.81	0.81	-	9.44	-	1.36	16.10	0.61	-
United States	-	-	2.21	10.78	1.63	-	-	-	2.26	9.48	1.16	-

DDGS = Distiller's dried grains with solubles. MES = Morishima elasticities of substitution.

Note: Rows represent feed-demand ratios of the listed commodity y, with respect to each commodity x, in the columns. The columns represent 1 percent price changes for each commodity x listed. Therefore, each MES value can be read as the percentage change of a commodity-demand ratio (commodity y in a row/commodity x in a column) due to a 1-percent change in the price of the commodity x. As previously noted, because these values were estimated using pseudo data, the values will tend to be biased upwards compared with real world behavior.

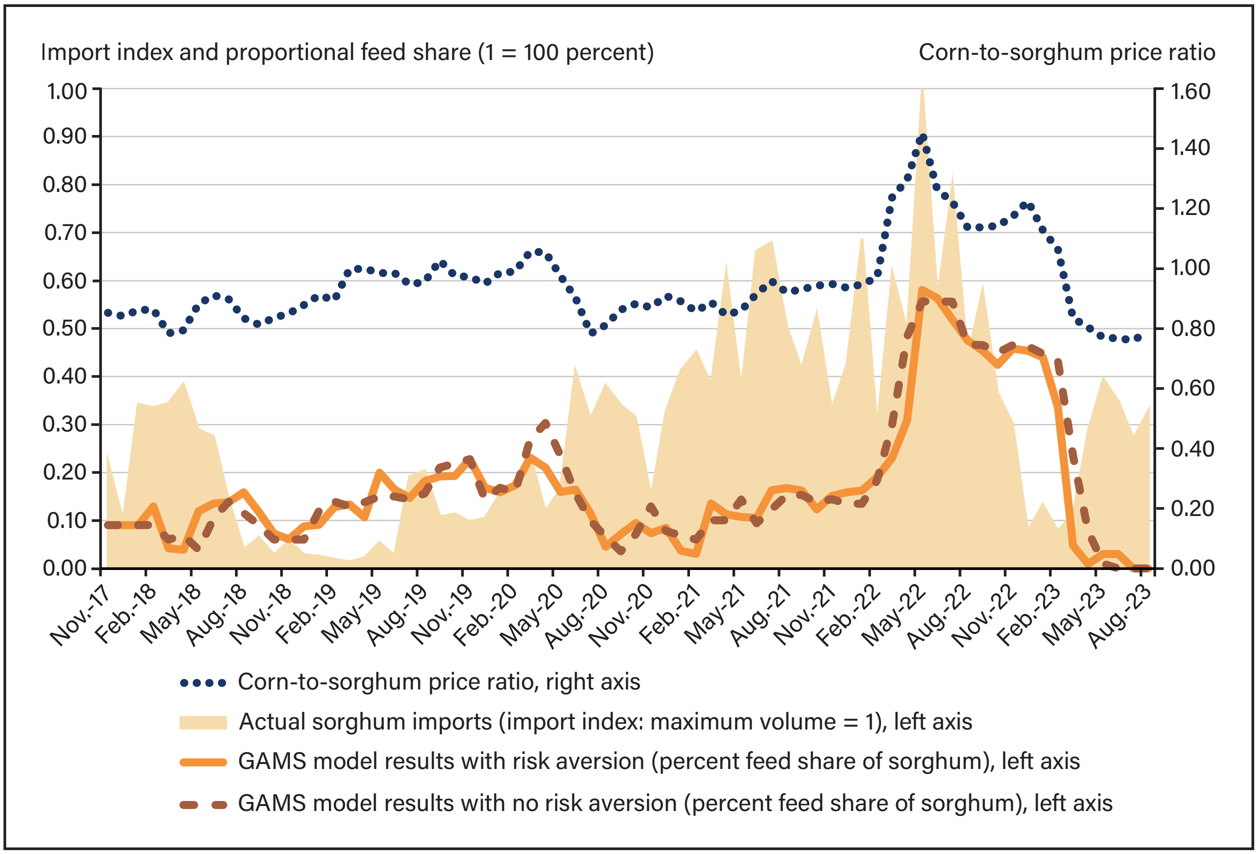
Source: USDA, Economic Research Service calculations based on regression results (appendix A, section 3).

Comparing the model results with actual import trends across all 12 countries offers 1 crude way to validate the linear programming model (figure 8). More specifically, the authors examined how well their results reflected real world behavior among feed producers in the broiler sector in each country, as the relative price of corn to sorghum varied over our sample period.[18]

[18] Ideally, comparing results with actual feed data by commodity would have been more ideal if such data existed for broiler production in each country.

Figure 8

Comparing model results of optimal shares of sorghum in broiler feed, with actual import indices of sorghum, aggregated across all 12 selected countries



GAMS = General Algebraic Modeling System.

Note: Sorghum imports were converted to an index between 0 and 1, with 1 representing the month when sorghum imports peaked. This conversion helped provide a visual comparison with optimal shares of sorghum (between 0 and 1) in the feed mix results of the linear programming feed-ration model. The 12 countries selected to include in the GAMS model are: Argentina, Brazil, China, Egypt, India, Japan, Mexico, Poland, South Africa, Thailand, Turkey, and the United States.

Source: USDA, Economic Research Service (ERS) using import data from USDA, Foreign Agricultural Service and the General Algebraic Modelling System (GAMS) model results; and price data from USDA, ERS and the International Grains Council.

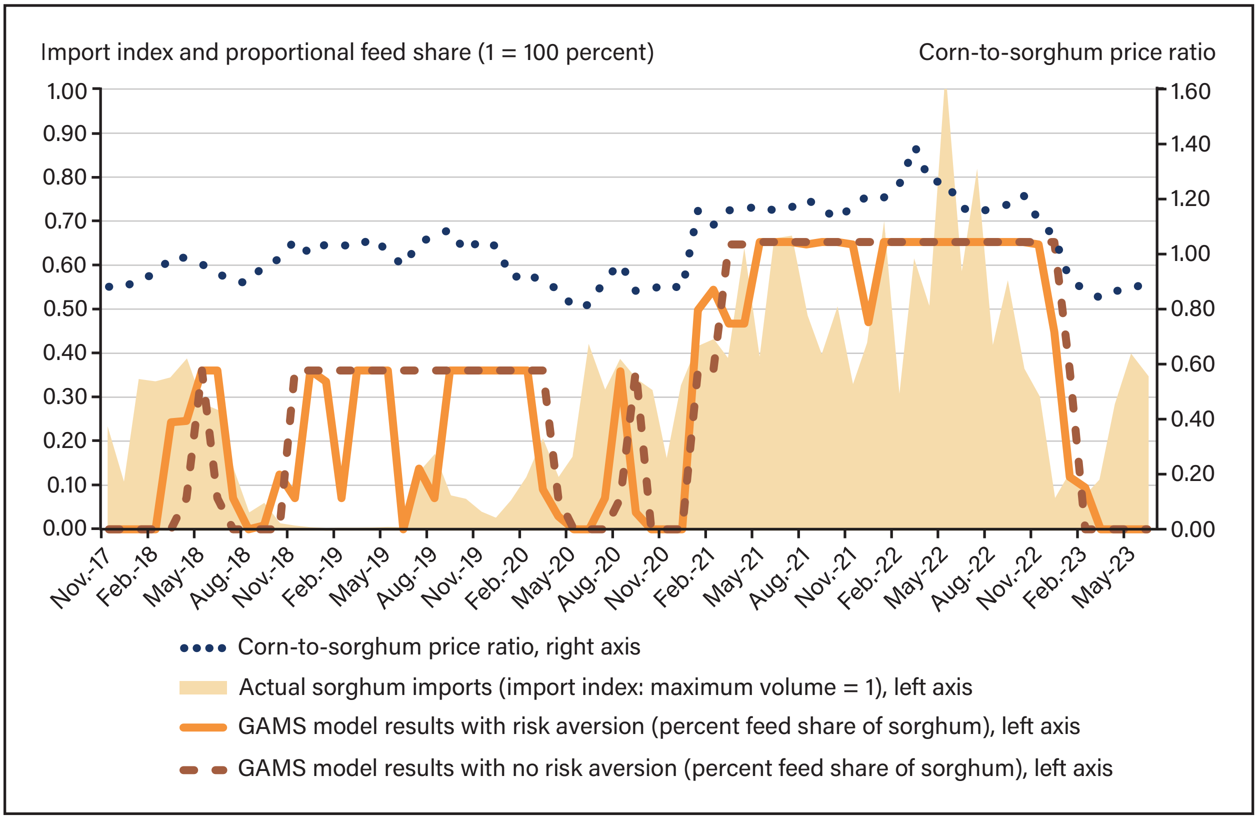
Model results of feed-mix shares are simple averages across all the countries (figure 8). Imports were calculated as a growth index of quantity volumes over time, with a maximum value taking on a value of one. This result is a very crude measure of testing the model results, as it ignores countries that may not import significant amounts of sorghum because the countries have ample domestic supply. It also does not account for restrictive trade policy measures that may prevent imports from time to time, including adjustment and information costs faced by feed producers. Moreover, imports of sorghum in each country may differ widely from our model results, as imports may have been driven by factors in other livestock sectors and industries that use sorghum, that is, besides the broiler industry. These exclusions can easily result in some discrepancies when comparing model results with the observed growth trend of actual sorghum imports over time. Nevertheless, aggregate results are reasonably close to actual trends in import growth over time for the countries in our sample.

China offers a good example in comparing the model results of feed demand for sorghum with actual imports, as China is a major importer of sorghum. While the more recent surge in sorghum imports by China since 2021 appears to reflect the model results well, there should have been higher imports in the 2018 and 2019 period (according to the model results showing a robust demand for sorghum feed) (figure

9). However, no imports were observed for much of that period, which may have been due to retaliatory trade restrictions imposed by China during the U.S.-China trade war at the time. Since then, actual Chinese imports of sorghum reflect the model results more closely. The consideration of risk aversion may help explain some of the variability observed in the recent trends of Chinese sorghum imports. The uptake in sorghum as a feedstuff increased more recently in China, as domestic corn prices surged (including their volatility), corroborating the surge in sorghum imports since 2021 (which has also since declined in 2023, as the relative price of sorghum to corn has increased).

Figure 9

Comparing model results of optimal shares of sorghum in broiler feed with actual growth index of sorghum imports by China



GAMS = General Algebraic Modeling System.

Note: Sorghum imports were converted to an index between 0 and 1, with 1 representing the month when sorghum imports peaked. This process helped provide a visual comparison with optimal shares of sorghum (between 0 and 1) in the feed-mix results of the linear programming feed-ration model.

Source: USDA, Economic Research Service (ERS) using import data from USDA, Foreign Agricultural Service, General Algebraic Modelling System (GAMS) model results, and price data from USDA, ERS and the International Grains Council.

Conclusion

Greater price volatility in global grain and oilseed markets strained the broiler feed production industry, which is highly competitive and faces thin marginal returns. Producers have the incentive to substitute inputs if prices for feedstuff rise or experience greater market volatility relative to other inputs. Increased volatility is especially important if broiler-feed producers are risk averse. A good example of this process is our estimates of the substitution effect between corn and sorghum in China. Our results showed that a 1-percent increase in the price of sorghum leads to a 13.5-percent increase in quantity demand for corn in China when risk aversion matters relative to a 14.1-percent increase when risk aversion does not matter. In other words, any change in sorghum prices is less impactful in substituting sorghum for corn if it is assumed the feed industry in China is risk averse. This result occurs because corn prices have been more volatile than sorghum prices in domestic markets. Countries that have experienced a similar pattern in the substitution between corn and sorghum are the United States, China, Egypt, and, to some degree, Mexico. A similar pattern exists in the substitution of soymeal for sorghum, but this pattern primarily occurs for starter and grower feed. Finisher feeds tend to favor more corn and soymeal proportions in the feed formulation, as the focus is mostly on energy and protein at this final growth stage.

Overall, sorghum offers a real potential for growing its share in broiler feed formulations, as was shown for Mexico and China. This process is important during times when global grain and oilseed markets are volatile, especially for one of the most favored feedstuffs—corn. Corn prices have become increasingly volatile and complex as corn's multiple uses for human consumption, feed, distilling, and biofuels have emerged over time. Sorghum shows a higher substitution effect for corn in most cases—which is promising as sorghum is mostly traded for feed purposes. The United States, therefore, has the potential to grow its export markets for sorghum feed beyond China and Mexico. This potential is especially true in countries where demand for corn has rapidly grown in competition with other uses but also during times when global markets have increasingly become more uncertain.

The substitution of sorghum for corn may not always occur as the model suggests. Other factors not captured by the model may reduce the model's ease of substitutability with other grains. For example, the perceived inferiority of sorghum's palatability and effect on broiler growth can dissuade a risk-averse broiler industry from increasing shares of sorghum in feed compositions. This result can also occur if there are uncertainties about the quality of the sorghum feed and its source. Quality can be affected by the palatability of the seed variety used and how the variety was handled and processed. There may also be practical reasons to maintain a particular feed mix, such as industry preferences associated with branding. This finding is the case in modern poultry industries dominated by large scale broiler chicken brands, where any changes in feed composition could affect certain characteristics of the chicken meat that consumers have come to expect. In this case, a slower transition between feed compositions may be required to allow for appropriate adjustments to take place.

Other factors not captured by the model are macroeconomic policies that could reduce the competitiveness of imported sorghum relative to other grains in domestic markets. This can arise from higher import tariffs or the presence of a depreciating exchange rate that make imports more expensive. They can also arise from geopolitical events that impact supply chains, such as the disruptions observed during the U.S.-China escalatory tariffs in 2019. Such geopolitical risks are real today as tensions among global trading partners due to the Russia-Ukraine war in Europe, territorial disputes in the South China Sea, and war and instability in the Middle East. These tensions can lead to what may appear as counter-intuitive results in trade flows (Gereffi et al., 2021; Pollins, 1989). All these factors are important considerations for future research.

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Appendix A

Additional Tables and Figures

Table A.1

Nutrient content of various feedstuffs, percent*

Nutrient	Wheat	Rice	Barley	Corn	Sorghum	DDGS	Soymeal	Fish meal
Energy*	3,120	2,990	2,640	3,350	3,288	2,480	2,440	2,580
Protein	11.5	8.7	11.0	8.5	8.8	27.4	48.5	64.2
Fat	2.50	0.70	1.80	3.80	2.90	9.00	1.00	5.00
Fiber	3.00	9.80	5.50	2.20	2.30	9.10	3.90	1.00
Calcium	0.05	0.08	0.03	0.02	0.04	0.17	0.27	3.73
Phosphorous	0.31	0.08	0.36	0.28	0.30	0.72	0.62	2.43
Chlorine	0.05	0.08	0.15	0.04	0.09	0.17	0.05	0.60
Sodium	0.06	0.07	1.14	0.02	0.01	0.48	0.02	0.30
Lysine	0.31	0.43	0.40	0.26	0.21	0.75	2.96	5.07
Methionine	0.15	0.22	0.18	0.18	0.16	0.60	0.67	1.95
Cystine	0.22	0.21	0.24	0.18	0.17	0.40	0.72	0.65
Threonine	0.32	0.36	0.37	0.29	0.29	0.92	1.87	2.82
Tryptophan	0.12	0.10	0.14	0.06	0.08	0.19	0.74	0.78

DDGS = Distiller's dried grains with solubles.

Note: * Relative to other nutrients, energy (ME) here is presented in Kilocalories/kilograms. Rice is broken-rice grain (brewers rice) or rice bran—as most common in Asian broiler feed. Wheat is soft white-wheat grain. Barley and corn are both as grains. Sorghum is 8–10 percent protein-variety grain. DDGS here is corn-based, Distiller's dried grains with solubles, dehydrated. Other oil-seed meal is peanut meal mechanically extracted. Fishmeal is anchovy meal and mechanically extracted.

Source: USDA, Economic Research Service using data from National Research Council (1994).

Table A.2

Minimum and maximum nutrient requirements for broiler chickens, percent*

	Starter		Grower		Finisher	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Energy*	2,900	3,500	3,000	3,800	3,100	4,000
Protein	22.0	40.0	20.0	35.0	18.0	30.0
Fat	1.00	6.00	2.00	5.00	2.00	6.00
Fiber	1.00	5.00	2.00	8.00	2.00	6.00
Calcium	1.00	1.50	0.90	1.50	0.80	1.50
Phosphorous	0.45	1.50	0.35	1.50	0.30	1.50
Sodium	0.20	0.70	0.15	0.70	0.12	2.00
Chlorine	0.20	0.70	0.15	0.70	0.12	1.50
Lysine	1.10	2.50	1.00	2.20	0.85	2.00
Methionine	0.50	1.00	0.38	1.00	0.32	1.00
Cystine	0.40	1.00	0.31	1.00	0.28	1.00
Threonine	0.80	1.50	0.74	1.50	0.68	1.50
Tryptophan	0.20	0.70	0.18	0.70	0.16	0.70

Note: * Relative to other nutrients, energy (ME) here is presented in Kilocalories/kilograms.

Source: USDA, Economic Research Service using data from USDA, Natural Resource Conservation Service and National Research Council.

Table A.3
Price elasticity of demand estimates

Percent Δ P_j	i. Without risk aversion							ii. With risk aversion						
Percent Δ Q_j^d*	Wheat	Rice	Corn	Sor-ghum	DDGS	Soymeal	Adj. R^2	Wheat	Rice	Corn	Sor-ghum	DDGS	Soymeal	Adj. R^2
1. Argentina														
Corn	-	-	**-3.515**	3.366	0.553	-1.061	0.78	-	-	**-3.822**	3.633	0.446	-0.899	0.67
Sorghum	-	-	6.277	**-5.986**	-1.126	2.140	0.66	-	-	5.886	**-5.568**	-0.804	1.589	0.50
DDGS	-	-	1.752	-1.914	**-1.234[b]**	0.625	0.40	-	-	1.281	-1.425	**-1.118[n]**	0.682	0.29
Soymeal	-	-	-1.125	1.216	0.625	**-1.143[b]**	0.52	-	-	-0.940	1.025	0.682	**-1.325[a]**	0.46
2. Brazil														
Wheat	**-10.838[a]**	-	8.712[a]	-	-5.301	12.177	0.12	**-10.291**	-	10.137	-	-1.426[n]	2.582[n]	0.15
Corn	0.162[a]	-	**-0.135**	-	0.041[n]	-0.095	0.44	0.350	-	**-0.318**	-	-0.015[a]	-0.005	0.47
DDGS	-0.750	-	0.311[n]	-	**-1.927**	0.805	0.58	-0.359[n]	-	-0.106[a]	-	**-1.340[a]**	0.667	0.51
Soymeal	0.334	-	-0.139	-	0.805	**-1.832**	0.59	0.129[n]	-	-0.007	-	0.667	**-1.500**	0.42
3. China														
Corn	-	-	**-7.367**	7.200	-0.048[n]	-0.022[n]	0.87	-	-	**-6.582**	6.436	0.026[n]	-0.090[n]	0.81
Sorghum	-	-	6.862	**-6.892**	0.126[n]	-0.020[n]	0.87	-	-	7.004	**-7.019**	0.086[n]	-0.0051	0.81
DDGS	-	-	-0.154[n]	0.427[n]	**-1.305a**	0.843	0.28	-	-	0.091[n]	0.279[n]	**-1.038[n]**	0.639	0.41
Soymeal	-	-	-0.028[n]	-0.027[n]	0.843	-1.812	0.18	-	-	-0.120[n]	-0.006[n]	0.639	**-1.476**	0.22
4. Egypt														
Wheat	**-6.834**	-	2.142	4.311	-0.761	3.385	0.54	**-6.206**	-	2.189	3.432	-0.311n	2.773	0.59
Corn	0.451	-	**-3.022**	2.226	0.224	-0.656	0.83	0.466	-	**-2.564**	1.736	0.184b	-0.541	0.75
Sorghum	2.529	-	6.194	**-7.120**	-0.557	-0.323[a]	0.82	3.067	-	7.278	**-8.360**	-0.933	0.037n	0.84
DDGS	-0.599	-	0.837	-0.747	**-0.586[a]**	0.620	0.51	-0.282[n]	-	0.781b	-0.947	**-0.778[n]**	0.574	0.38
Soymeal	1.041	-	-0.957	-0.169a	0.620	**-1.355[a]**	0.36	0.916	-	-0.839	0.014n	0.574	**-1.253[b]**	0.24

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Percent Δ P_j	i. Without risk aversion							ii. With risk aversion						
Percent Δ Q_j^d*	Wheat	Rice	Corn	Sorghum	DDGS	Soymeal	Adj. R^2	Wheat	Rice	Corn	Sorghum	DDGS	Soymeal	Adj. R^2
5. India														
Rice	-	**-9.409**	1.472[n]	8.843	-0.652[n]	0.689[n]	0.66	-	**-5.054**	0.908[n]	4.248	0.391[n]	0.522	0.67
Corn	-	6.571[n]	**-6.537**	-0.166	0.475[a]	-0.311	0.70	-	0.079[n]	**-2.533**	2.273	0.130[n]	-0.276[n]	0.71
Sorghum	-	2.489	-0.011	**-2.680**	0.170	-0.232[n]	0.74	-	1.371	8.415	**-9.050**	-0.350[a]	0.637[n]	0.76
DDGS	-	-0.744[n]	0.122[a]	0.689	**-0.868[n]**	0.630	0.56	-	0.143[n]	0.546[n]	-0.396[a]	**-1.013[n]**	0.490	0.22
Soymeal	-	0.289[n]	-0.029	-0.346[n]	0.630	**-1.468[a]**	0.33	-	0.067	-0.406[n]	0.253[n]	0.490	**-1.085[n]**	0.25
6. Japan														
Corn	-	-	**-2.323**	2.348	-0.013	-0.669	0.67	-	-	**-2.079**	2.060	-0.022	-0.464	0.55
Sorghum	-	-	10.157	**-10.538**	0.499[a]	1.967	0.71	-	-	10.540	**-11.064**	0.748	1.517[a]	0.62
DDGS	-	-	-0.029	0.255[a]	**-0.458**	1.051	0.85	-	-	-0.050	0.335	**-0.473**	0.994	0.81
Soymeal	-	-	-1.433	0.974	1.051	**-4.210**	0.85	-	-	-1.044	0.667	0.994	**-4.198**	0.78
7. Mexico														
Corn	-	-	**-4.500**	3.926	0.208[a]	-0.809	0.66	-	-	**-3.836**	3.332	0.154[n]	-0.603	0.48
Sorghum	-	-	2.108	**-1.767**	-0.131	0.276[n]	0.53	-	-	2.331	**-1.907**	-0.116	0.180[n]	0.42
DDGS	-	-	0.348[a]	-0.408	**-0.325**	0.219[a]	0.68	-	-	0.311[n]	-0.335	**-0.322**	0.188[n]	0.66
Soymeal	-	-	-0.653	0.416[n]	0.219[a]	**-0.170**	0.33	-	-	-0.571	0.244[n]	0.188[n]	**-0.121**	0.24
8. Poland														
Wheat	**-12.361**	-	7.557[a]	1.919[n]	-1.135[n]	7.691	0.33	**-12.825**	-	9.902	1.611[n]	-2.975	6.087	0.40
Corn	0.268[a]	-	**-3.053**	2.594	0.223[a]	-0.616	0.80	0.611	-	**-3.078**	2.255	0.327	-0.618	0.67
Sorghum	0.212[n]	-	8.100	**-7.530**	-0.598	0.784[b]	0.77	0.347[n]	-	7.863	**-7.490**	-0.417	0.325[n]	0.72
DDGS	-0.166[n]	-	0.921[a]	-0.790	**-1.519**	1.030	0.56	-0.722	-	1.286	-0.470	**-1.250[b]**	0.891	0.48
Soymeal	0.356	-	-0.806	0.328[b]	1.030	**-2.119**	0.40	0.519	-	-0.854	0.129[n]	0.891	**-1.864**	0.29

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Percent Δ P_j	i. Without risk aversion							ii. With risk aversion						
Percent Δ Q_j^d*	Wheat	Rice	Corn	Sorghum	DDGS	Soymeal	Adj. R^2	Wheat	Rice	Corn	Sorghum	DDGS	Soymeal	Adj. R^2
9. South Africa														
Corn	-	-	**-2.018**	1.787	0.129^{n}	-0.177	0.65	-	-	**-2.005**	1.825	0.160^{a}	-0.305	0.64
Sorghum	-	-	4.569	**-4.370**	-0.196	0.304^{n}	0.72	-	-	4.278	**-4.127**	-0.087	0.129^{n}	0.68
DDGS	-	-	0.335^{n}	-0.199	**-0.273**	0.144^{b}	0.89	-	-	0.413^{a}	-0.096	**-0.347**	0.179^{n}	0.83
Soymeal	-	-	-0.211	0.142^{n}	0.144^{b}	**-0.228**	0.76	-	-	-0.353	0.063^{n}	0.179^{n}	**-0.244**	0.41
10. Thailand														
Corn	-	-	**-3.169**	3.038	0.073^{n}	-0.236	0.77	-	-	**-3.099**	2.920	0.038^{n}	-0.158	0.74
Sorghum	-	-	4.941	**-4.986**	0.091^{n}	-0.002	0.77	-	-	4.785	**-4.832**	0.027^{n}	0.112^{n}	0.74
DDGS	-	-	0.231^{n}	0.178^{n}	**-0.920^{n}**	0.459	0.56	-	-	0.124^{n}	0.054^{n}	**-0.663^{a}**	0.394	0.57
Soymeal	-	-	-0.336	-0.002	0.459	**-0.693**^{n}	0.30	-	-	-0.223	0.096^{n}	0.394	**-0.771^{n}**	0.10
11. Turkey														
Wheat	**-11.050**	-	8.012	2.496	-0.020^{n}	2.109	0.60	**-8.990**	-	6.972	1.526^{a}	0.278^{n}	1.730	0.57
Corn	0.927	-	**-1.836**	0.874	0.036^{a}	-0.285	0.40	1.127	-	**-1.892**	0.763	-0.008	-0.331	0.50
Sorghum	4.422	-	13.376	**-16.927**	0.590^{b}	-1.058	0.32	4.195	-	12.969	**-16.164**	0.201^{n}	-0.636^{b}	0.35
DDGS	-0.009^{n}	-	0.142^{a}	0.150^{b}	**-0.547**	0.262	0.73	0.170^{n}	-	-0.030	0.045^{n}	**-0.440**	0.166^{a}	0.50
Soymeal	0.402	-	-0.470	-0.114	0.262	**-0.320**	0.84	0.453	-	-0.537	-0.061^{b}	0.166^{a}	**-0.205**	0.84
12. United States														
Corn	-	-	**-2.370**	2.340	0.108^{n}	-0.096	0.24	-	-	**-2.427**	2.402	0.102^{n}	-0.101	0.28
Sorghum	-	-	10.442	**-10.494**	-0.563	0.794^{n}	0.51	-	-	8.964	**-9.181**	-0.351^{a}	0.698^{n}	0.48
DDGS	-	-	0.528^{n}	-0.619	**-0.914**^{n}	0.720	0.53	-	-	0.469^{n}	-0.432^{a}	**-0.658^{a}**	0.501	0.45
Soymeal	-	-	-0.156	0.289^{n}	0.720	**-1.728**	0.40	-	-	-0.164	0.303^{n}	0.501	**-1.338**	0.29

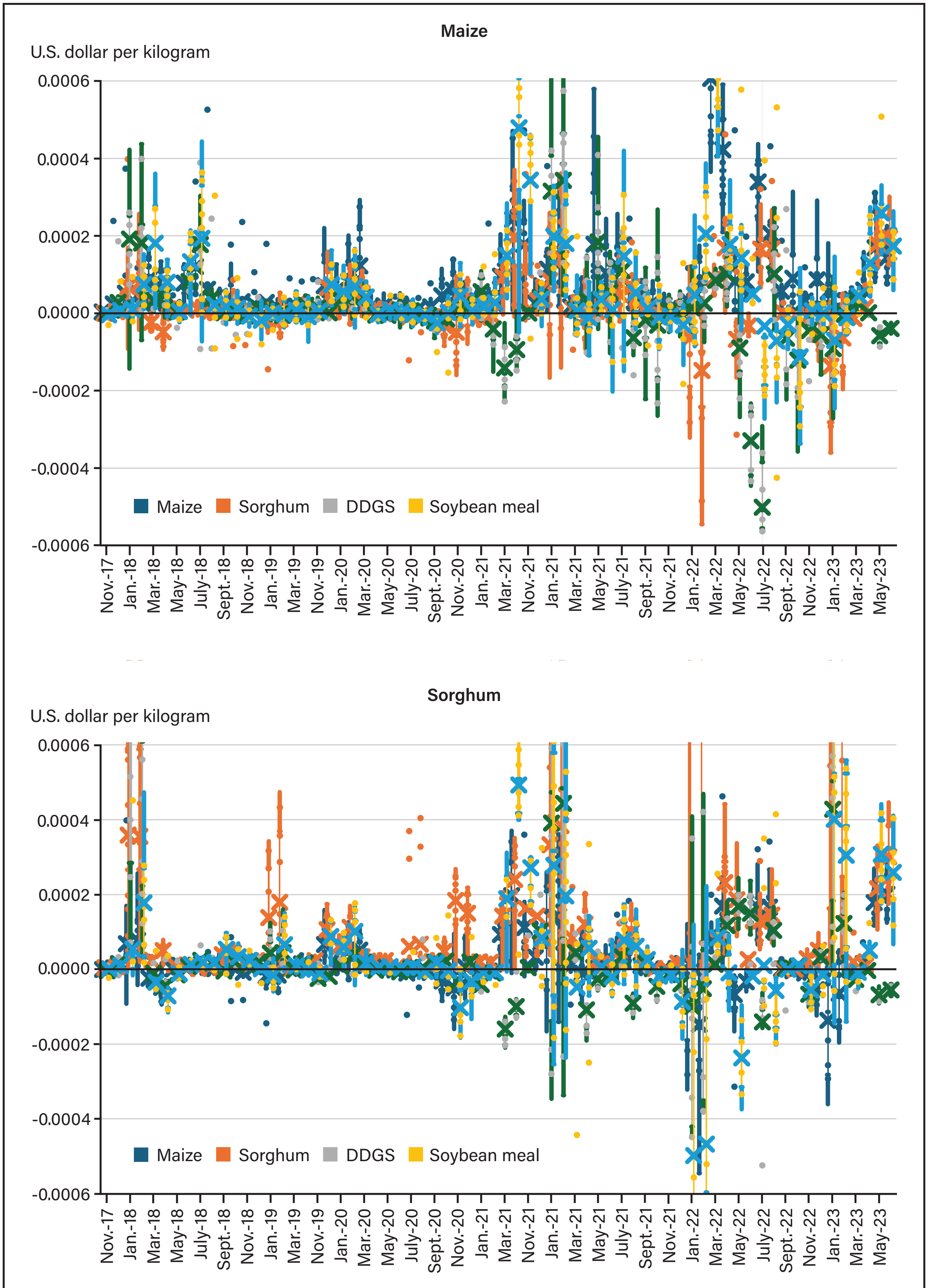
DDGS = Distiller's dried grains with solubles.

Note: Superscripts represent t-tests for statistical significance: ^{n} = not significant at any level; ^{a} = significant at 5 percent, ^{b} = significant at 10 percent, and any absence of superscripts infers a significance at the 1-percent level. Excluded feed commodities in the rows were not estimated because the commodities rarely came into the linear programming solution for the affected countries. Note that the rows represent a percent change in demand (Q_j^d) for the listed commodity j due to a 1-percent change in a commodity j price (P_j) listed in the columns. Numbers in bold are own-price demand elasticities. Because these values were estimated using pseudo data, the values will tend to be biased upwards compared with real world behavior. The interest is in their relative values when comparing across countries and commodities. * This describes the percent change (Δ) of quantity demanded (Q) due to a 1-percent change (Δ) in price (P) or referred to as the price elasticity of quantity demanded.

Source: USDA, Economic Research Service calculations based on regression results (see appendix A, section 3).

Figure A.1

T-month moving price variances and covariances among key feed ingredients across 12 countries, November 2017–June 2023



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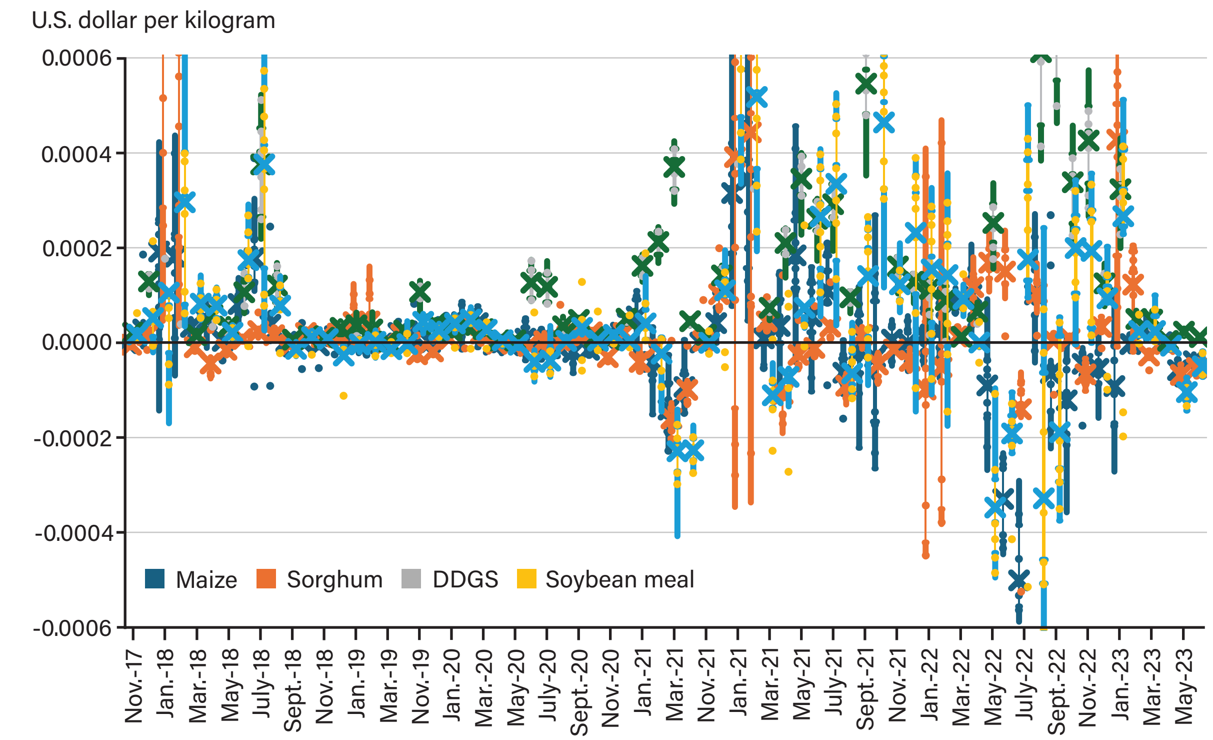
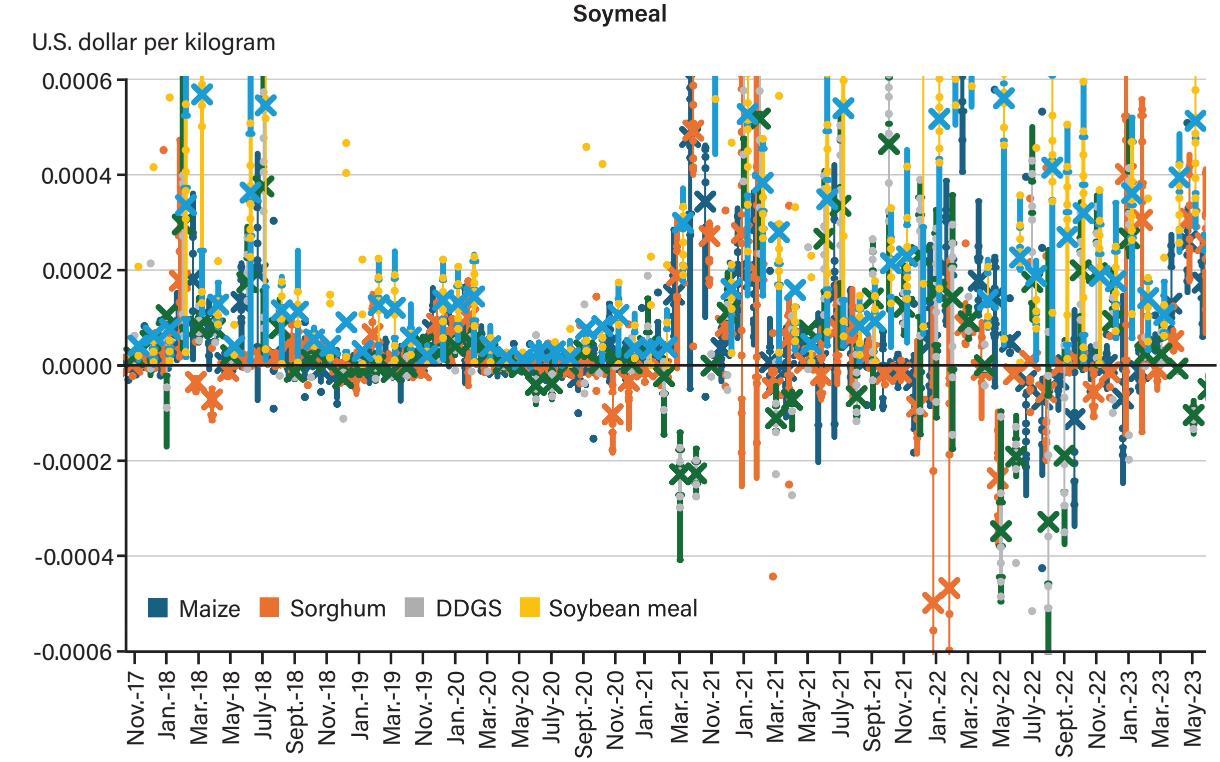


Soymeal



DDGS = Distiller's dried grains with solubles.

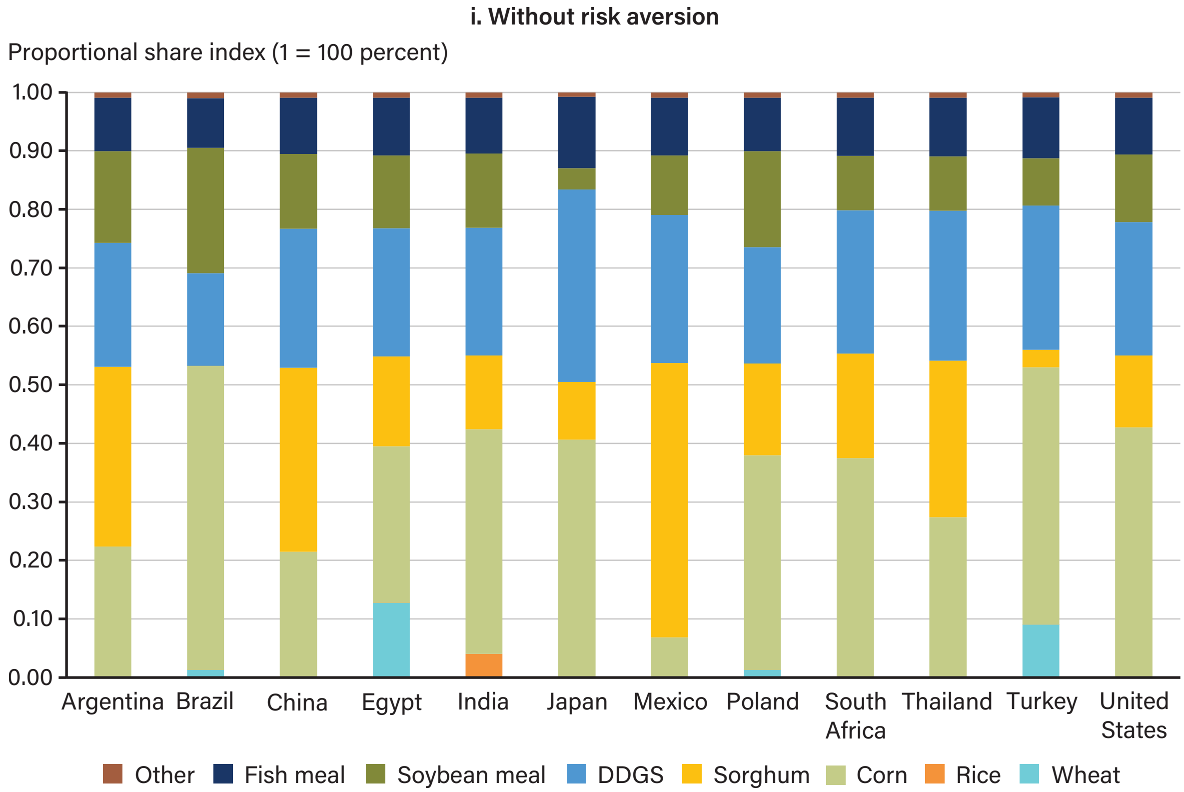
Note: Each panel represents the price covariates between a specific feed ingredient with other ingredients (in U.S. dollar/kilogram), including its own variance, which is always positive.

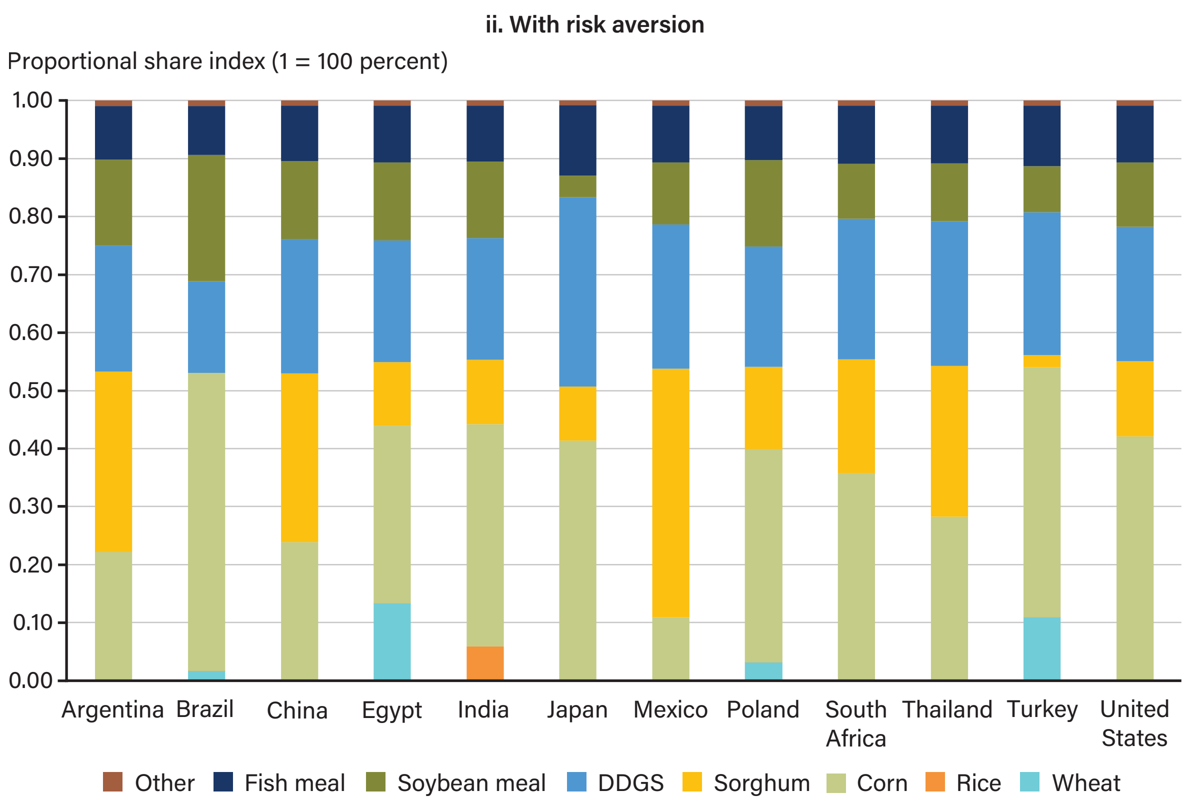
Source: USDA, Economic Research Service (ERS) using price data from USDA, ERS and the International Grains Council price data.

Figure A.2

Average optimal feed formulas at each growth stage of broiler chickens (averaged across entire sampled period) under scenarios of with and without risk aversion

a) Starter feed





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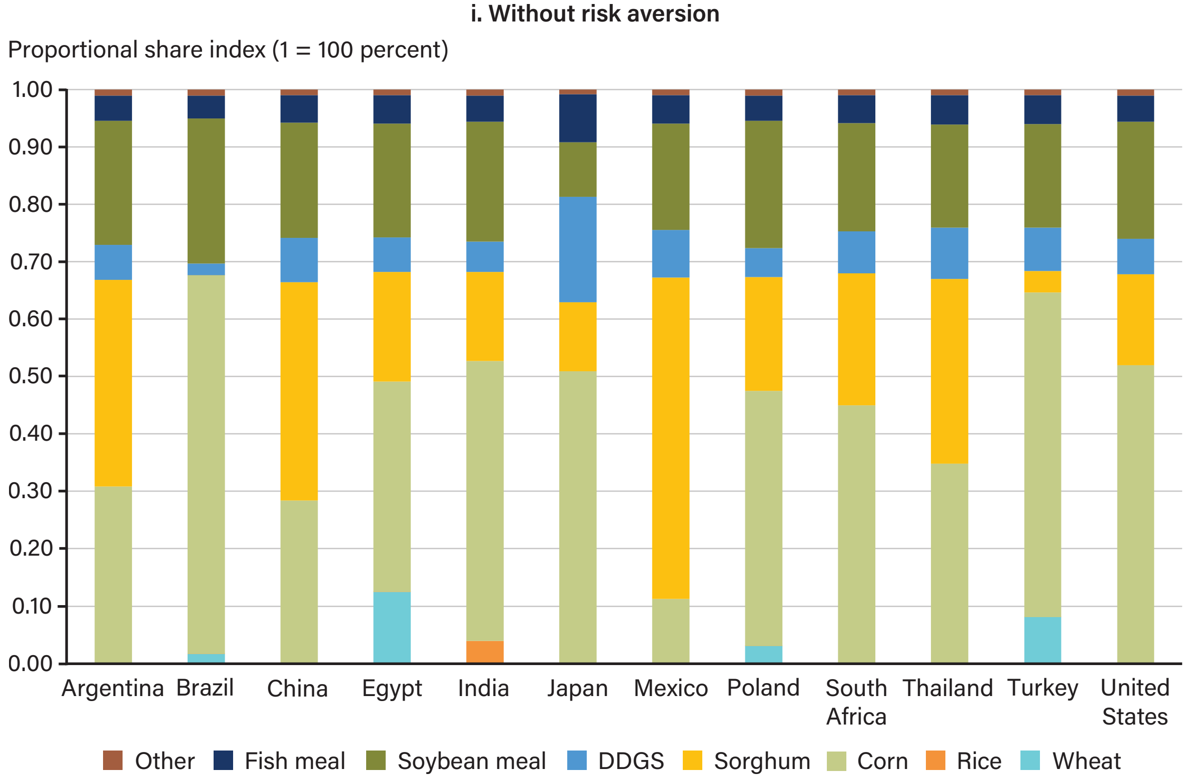
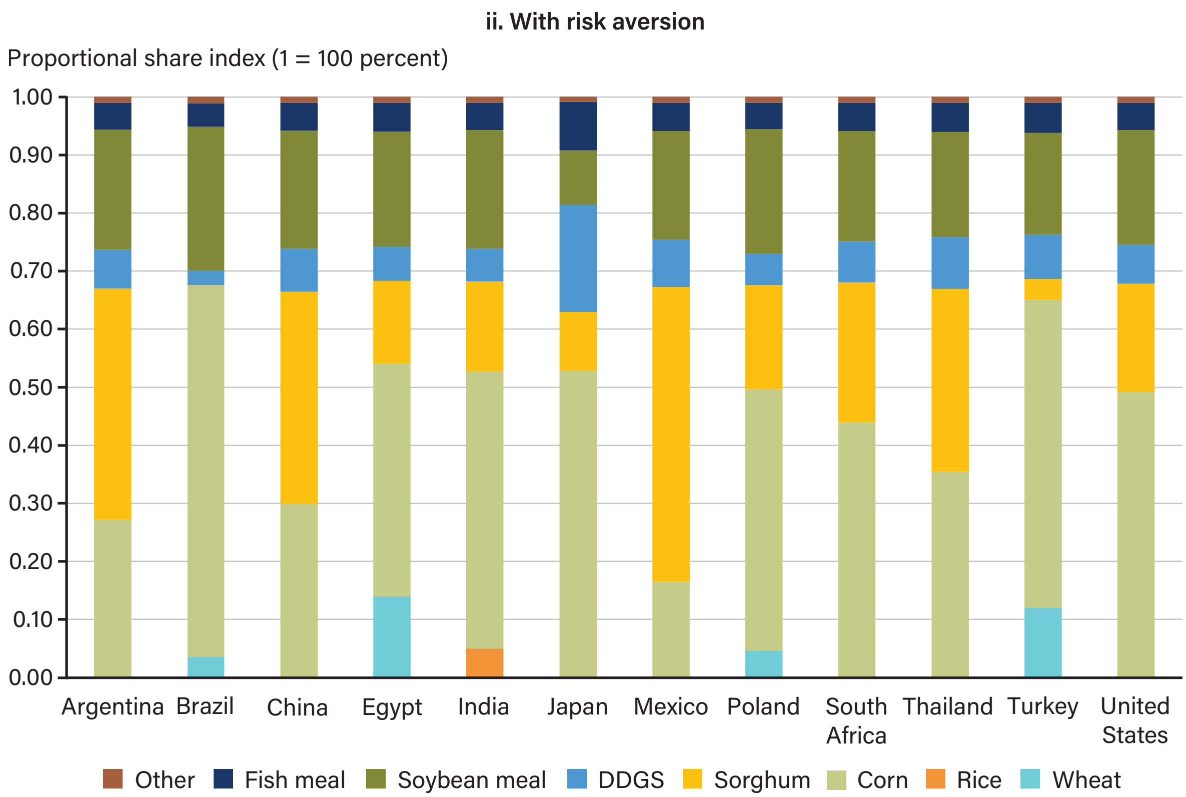
b) Grower feed





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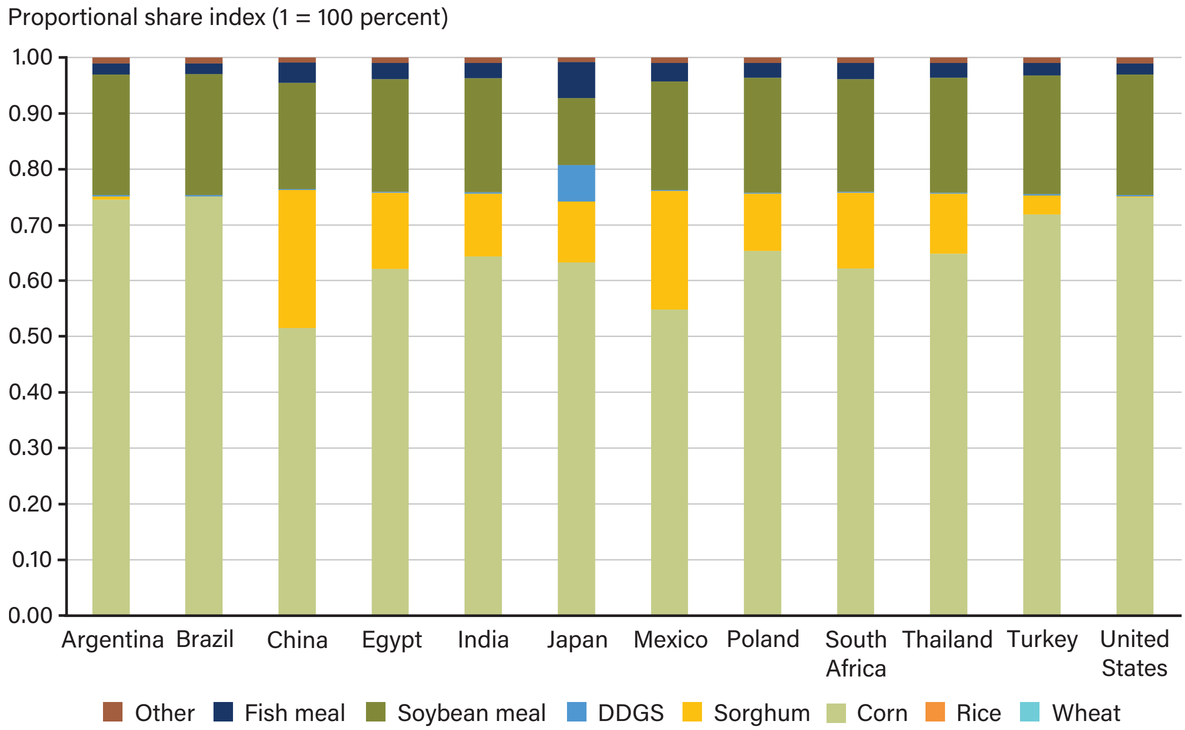
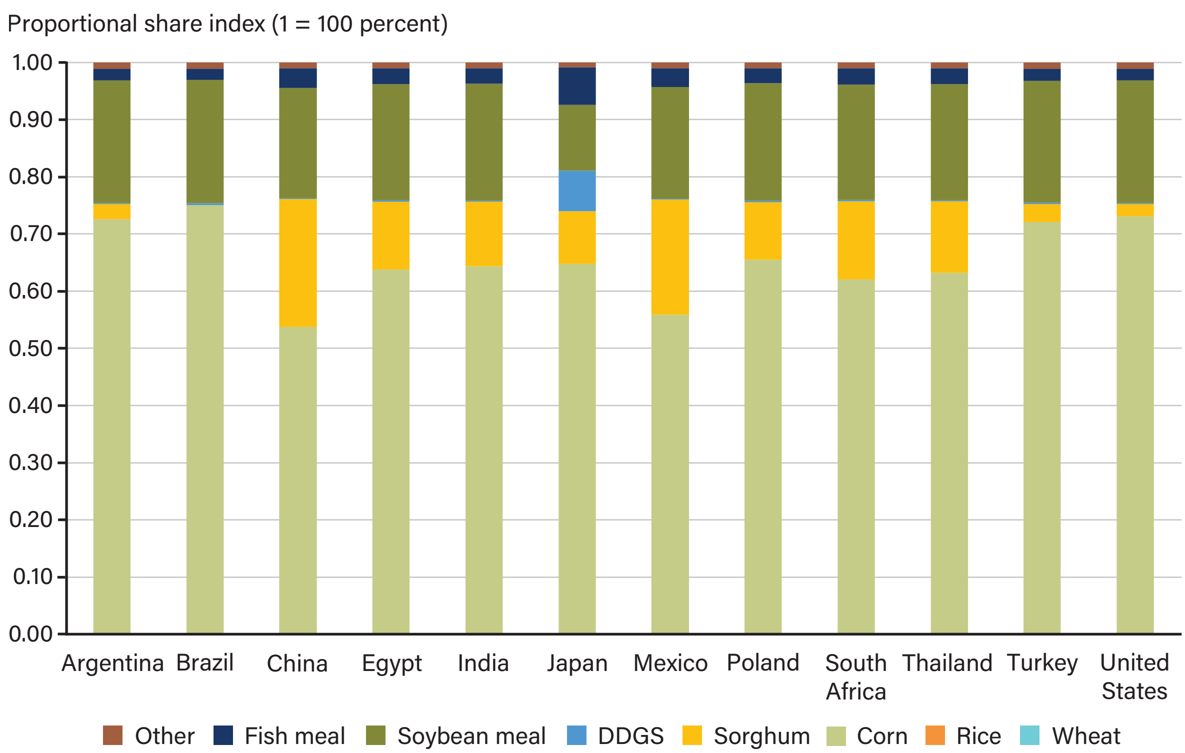
c) Finisher feed

i. Without risk aversion



ii. With risk aversion



DDGS = Distiller's dried grains with solubles.

Source: USDA, Economic Research Service using General Algebraic Modeling System (GAMS) Model results.

Appendix B

Description of Least-Cost Feed-Ration Model With Price Risk

Mathematically, the classical least cost feed ration linear programming model for each observation period *t* can be expressed as:

$$Minimize\ Z_t = \sum_{g=1}^{3}\sum_{j=1}^{J} P_{jt}X_{jgt}, \forall t = 1, \dots T \qquad (1)$$

Subject to:

$$\sum_{j=1}^{J} A_{ij}\, X_{jgt} \leq UL_{ig}, \quad \forall g = 1,2,3; \forall t = 1, \dots T \qquad (2)$$

$$\sum_{j=1}^{J} A_{ij}\, X_{jgt} \geq LL_{ig}, \quad \forall g = 1,2,3;\ \forall t = 1, \dots T \qquad (3)$$

$$\sum_{j=1}^{J} X_{jgt} = 1, \quad \forall g = 1,2,3;\ \forall t = 1, \dots T \qquad (4)$$

$$X_{jgt} \geq 0, \quad \forall g = 1,2,3;\ \forall j = 1, \dots J;\ \forall t = 1, \dots T \qquad (5)$$

Where:

P_j	=	price or unit cost of feedstuff *j* in period *t*
X_{jg}	=	composition of feedstuff *j* in the gth growth stage in period *t* of a broiler's life span: starter feed (g = 1), grower feed (g = 2), and finisher feed (g = 3).
A_{ij}	=	amount of nutrient *i* in each feedstuff *j*.
UU_i, UL_i	=	= upper (UU_i) and lower (UL_i) limits of each nutrient *i* required for each type of feed mix *k*.
N	=	total number of *i* nutrients available/required.
J	=	total number of units of *j* feedstuff.
T	=	total time *t* periods.

The objective of the model is to minimize cost in equation (1) for each period (*t*), which is the sum of the feedstuff price *j* (P_{jt}) in period *t* and their compositions (X_{jgt}) for each period *t* and growth stage *g*, subject to minimum (LL_{ig}) and maximum nutrient requirements (UL_{ig}) for each growth stage *g* in equations (2) and (3). The constraint in (2) imposes a maximum amount of a nutrient type *i* from any feedstuff *j* in feed mix type *g* to avoid problems of palatability, for example. Meanwhile, the constraint in (3) ensures sufficient nutrient requirements in the diet are being met at each stage of growth *g* (i.e. starter, grower, and finisher diets) to ensure a healthy and efficient growth rate. Equation (4) simply requires the nutrient compositions to sum to 1 (as percentages) to ensure that the total weight of feedstuffs in the feed formulation equals the total required weight. Finally, equation (5) ensures a non-negative result among all the *j* feedstuffs.

The authors extend the standard least-cost feed-ration model to incorporate price risk using a mean-variance framework. More specifically, they adapt the mean-variance approach to a mean-standard deviation version. According to Hazell and Norton (1986), although identical to the mean-variance approach (as simply the square root of variance), a useful decision rule in the mean standard deviation model introduced by Baumol (1963) is the expected gain-confidence limit (*L*). *L* is the difference between an expected return (*E*) and the product of a risk premium (ρ) and standard deviation value (σ) or $L = E - \rho\sigma$. Under this specification, a rational producer will always choose a plan that exhibits the maximum value of expected returns for a given value of the gain-confidence limit (*L*). This result implies that a producer simply needs to maximize *L* (the expected gain-confidence limit) given their risk premium ρ. For the least-cost ration model, this process is adapted to infer that a producer selects a feed ration that minimizes a cost-confidence limit or $Z = C + \rho\sigma$, where *C* is the expected (mean) least cost.

Using the mean-standard deviation approach, the authors modified the objective function in equation (1) with equation (6) below, which now includes a single risk aversion parameter (ρ) and a standard deviation matrix of relative unit costs over 3 months among all the *j* feedstuffs at each growth stage *k*. In other words, means and standard deviations are calculated from 3-month moving values across all *t* periods, such that the expected least cost for each growing period *g* ($C_{g\hat{t}}$), in the absence of any risk, is the 3-month moving average feed mix cost for a monthly period $\hat{t}$ in our sample. Given a total sample size of $T = 70$ months, this move implies a total of 68 monthly observations of 3-month moving mean and standard deviation values (or $\hat{t} = 3,..,T$).[19] The new objective function is subject to the same constraints of the standard model and repeated for each observation period $\hat{t}$ as follows.

$$Minimize\ Z_{\hat{t}} = \sum_{g=1}^{3}\left(C_{g\hat{t}} + \rho\sigma_{g\hat{t}}\right), \quad \forall\hat{t} = 3, \dots T \qquad (6)$$

Subject to:

Equations (2) to (5) above.

Where:

$$\sigma_{g\hat{t}} = \sqrt{\sum_{j=1}^{J}\sum_{k=1}^{K}\left(\frac{\left[\sum_{t-2}^{t}\left(P_{jt}X_{jgt} - \mu_{jg\hat{t}}\right)\left(P_{kt}X_{kgt} - \mu_{kg\hat{t}}\right)\right]}{3}\right)}, \quad \forall g = 1,2,3; \forall\hat{t} = 3,..,T \ \#(7)$$

$$\mu_{jg\hat{t}} = \frac{\left(\sum_{t-2}^{t} P_{jt}X_{jgt}\right)}{3}, \quad \forall g = 1,2,3; \forall j = 1,..,J;\ \forall\hat{t} = 3,..,T \ \#(8)$$

$$C_{g\hat{t}} = \sum_{j=1}^{J}\mu_{jg\hat{t}}, \quad \forall g = 1,2,3;\ \forall\hat{t} = 3,..,T \qquad (9)$$

$$0 \leq \rho \leq 1.65 \qquad (10)$$

And where:

$\mu_{jg\hat{t}}$ = the expected minimum cost of the most recent 3-month moving average, that is $\hat{t} = (t + t\text{-}1 + t\text{-}2)/3$, of optimal feedstuff *j* formulas ($x^*_{jg\hat{t}}$) for each growth stage *g* at time $\hat{t}$ across the entire period of *T* months.[20]

[19] The first 2 months in the sample drop out as they have fewer than three observations to calculate these values.

[20] The first 2 months ($t = 1,2$) are dropped, so each observation *t* represents a 3-month moving average until *t* = T.

$\sigma_{g\hat{t}}$ = the standard deviation of minimum costs from a covariance matrix of optimal feed mixes ($x^*_{jg\hat{t}}$) during each growth stage g and for the most recent 3-month moving period at time $\hat{t}$ across all T months.

ρ = a single risk-aversion parameter that can range between 0 and a maximum value of 1.65.[21] For our purposes, we only consider two extreme cases: without risk aversion (when $\rho = 0$) and with maximum risk aversion (when $\rho = 1.65$).

k = 1,..,K as an alias of feed ingredients j = 1,..,J.

Finally, using the optimal feed-mix solutions ($x^*_{jg\hat{t}}$), which represent unit shares of the feedstuff j for each growth period g and time $\hat{t}$, the authors then aggregate these to total feed formulations (or $y^*_{j\hat{t}}$) across the k growth stages as a weighted average, as shown in equation (11).

$$y^*_{j\hat{t}} = \sum_{g=1}^{3} w_g x^*_{jg\hat{t}}, \forall j = 1, \dots J, \forall \hat{t} = 1, \dots T \qquad (11)$$

The weights w_g represent for each gth growth stage (g = 1,2,3 as explained above) shares of the total life span of a broiler when feed mixes change to minimize feed costs based on minimum nutrient requirements at each stage of growth (starter, grower, and finisher diets). These weights are calculated by assuming a total life span of 8 weeks, with the first 3 weeks under the starter (g = 1) feed mix (i.e. w_1 or 0.375), another 3 weeks under the grower (g = 2) feed mix (i.e. w_2 or 0.375), and finisher (g = 3) feed mix diet (i.e. w_3 or 0.250).

Estimates are obtained from the application of the General Algebraic Modeling System (GAMS) software, using the CONOPT solver. The solver loops over all 12 countries to solve for each period (t = 70 months, September 2017 through July 2023) as 3-month moving averages and under the 2 risk aversion scenario cases (with and without risk aversion).[22]

[21] The maximum value was suggested by Hazell et al. (1986). As the authors explain, this suggestion is because, for the specific value of ρ = 1.65, the expected gain-confidence limit (Z_t) translates into measuring the 5-percent income fractile when the income is normally distributed. In the authors' case, if they use this maximum value of ρ, it translates into feed producers selecting a feed mix that minimizes their expected costs while also minimizing the probability of costs rising above this expected value (that is, $Pr\,[Z_t \geq Z^*_t] = 0.05$). The probability for such an outcome is reduced with a lower ρ.

[22] Please see footnote 11.

Appendix C

Modeling Framework for Estimating Feed Price Elasticities of Demand

With the authors' unit shares of demand for feed formulations (in total) across time at hand, including the corresponding relative prices, the next step is to use this information to estimate own- and cross-price elasticities of demand for feedstuffs. Drawing on the well-grounded literature concerning estimations of input demand, they estimate, using a translog cost function from which they can derive demand share equations for each feedstuff as a function of all feedstuff prices, as presented in Beckman et al. (2011). The translog cost function can be represented as follows:

$$\ln C = \alpha_0 + \sum_{i=1}^{n} \beta_i \ln p_{it} + \sum_{i=1}^{n} \sum_{j=1}^{m} \varphi_{ij} \ln p_{it} \ln p_{jt} \quad (12)$$

C here is total cost and α_0, β_i and ρ_{ij} are the parameter coefficients to be estimated. To ensure the cost function in equation (12) is homogenous of degree 1, two additional parameter restrictions are imposed:

$$\sum_{i=1}^{n} \beta_i = 1 \quad (13)$$

$$\sum_{i=1}^{n} \varphi_{ij} = 0 = \sum_{i=1}^{n} \varphi_{ji} \quad (14)$$

Shephard's lemma[23] states that differentiating equation (13) with respect to each input price yields the demand equations in share form, that is:

$$s_i = \beta_i + \sum_{j=1}^{m} \varphi_{ij} \ln p_{it}, \quad \forall i = 1, \dots, n \quad (15)$$

These systems of demand-share equations in equation (15) can be estimated using Seemingly Unrelated Regression (SUR)[24] while imposing the same parameter restrictions in equations (13) and (14). The estimated parameters in ρ_{ij} can then be used to calculate own and cross-price elasticities as follows:

$$e_{ii} = \varphi_{ii} + s_i - 1, \quad \forall i = j \quad (16)$$

$$e_{ij} = {}^{\varphi_{ij}}/_{s_i} + s_j, \quad \forall i \neq j \quad (17)$$

Along with these price elasticities of demand, elasticities of substitution can also be calculated. The authors calculate the Morishima Elasticity of Substitution (MES), as they deal with more than two factor inputs in the feed formulation. MES is more appropriate for measuring the ease of substitution between multiple inputs (Blackorby & Russell, 1989). MES (σ_{ij}^M) are simply calculated as follows:

$$\sigma_{ij}^M = e_{ij} - e_{ji}, \quad \forall ij \quad (18)$$

Estimates are obtained by using the STATA 17 software program.

[23] The Sheppard's lemma states that if indifference curves of the cost or expenditure function are convex, then the cost minimizing the point of a given good and price is unique.

[24] SUR in econometrics describes multiple regression equations that may appear unrelated but are correlated through their error terms.

Appendix D

Background of the World's Leading Broiler and Feed Sectors

South America—Argentina and Brazil

Brazil witnessed an impressive growth in chicken-meat production in the last 20 years, becoming the world's leading exporter of broiler meat after overtaking the United States (USDA, FAS, 2023i; Valdes et al., 2015). Brazil is the world's biggest Halal chicken meat supplier and consumer-driven packaging of chicken meat cuts and parts (USDA, FAS, 2022c). Broiler production in Brazil is a lucrative industry comparable to that of the United States. Like the United States, Brazil also has ample access to domestic suppliers of feedstuffs like corn and soybeans. The Brazilian chicken-meat industry is led by a few large firms operating under broiler integration systems that contract out to broiler chicken farmers, alongside many small and medium size producers (Valdes et al., 2015). About three-fourths of these operations are in the south and southeast regions of the country, where there is feed availability and proximity to ports for export.

In addition to broiler production, Brazil is also a major producer and supplier to international markets of grains and oilseeds. Brazil is the world's largest producer and exporter of soybeans, supplying more than 50 percent of the world's soybean trade (USDA, FAS, 2023j). The country is also the third largest corn producer and is set to become the largest exporter, accounting for 32 percent of global corn exports in 2022/23 (USDA, FAS, 2023g). This result has great advantages for broiler production in Brazil, allowing the country to remain competitive (given Brazil's ample access to feed grains and oilseeds, and hence, lower feed costs). The expansion of chicken-meat production in Brazil has naturally led to a growth in the demand for chicken feed. In 2023, Brazil's poultry population is projected to consume as much as 36.4 million metric tons of feed compounds (Agrimídia, 2023), much of which is produced domestically. The feed market in Brazil is highly concentrated, with five firms accounting for more than 47 percent of the market (CONAB, 2023).

Like Brazil, the Argentine broiler sector is dominated by large vertically integrated commercial enterprises (USDA, FAS, 2022b). Unlike Brazil, however, Argentina exports only 8.4 percent of its chicken-meat production relative to Brazil's 29.3 percent. The Argentine broiler industry is focused on supplying the domestic market. Additionally, compared to other agricultural sectors, Argentine chicken-meat exports face a 9 percent tax (USDA, FAS, 2022b). The feed industry also advanced over time, given a large livestock sector traditionally dominated by the beef industry, making Argentina among the top 10 countries globally in compound-feed production. The country enjoys ample domestic supplies, as Argentina is also a major exporter of grains and oilseeds in international markets. The principal feed grain used in broiler feed in Argentina is corn, but barley and sorghum are also used as alternatives (USDA, FAS, 2022b). Corn plays a significant role in Argentina's economy and agri-food sector, being second in importance after soybeans and its byproducts (soybean meal and soybean oil), in terms of area harvested and export revenue. In addition to corn, Argentina is also one of the world's major exporters of soybean meal, soybeans, sorghum, barley, and wheat (USDA, FAS, 2023g; USDA, FAS, 2023j). Although Argentine producers are price competitive in global grain markets, the country has a long history of macroeconomic instability and shifting policy reforms, such as changes in export taxes, export restrictions, and changes in the foreign exchange regime that affect the country's agricultural production and exports.

Among alternative feed grains, Argentina is also among the world's largest producers of sorghum and barley (USDA, FAS, 2023g). While 36 percent of Argentina's sorghum production is consumed domestically, by beef and dairy cattle operations, about 2.1 million tons were exported in 2022—making the country the third largest global sorghum exporter after the United States and Australia (Trade Data Monitor, 2023). Like the United States, China is the principal market for Argentine sorghum. Domestic use of sorghum for human consumption is rare in Argentina (USDA, FAS, 2022b).

North America—United States and Mexico

The United States remains the world's largest coarse grain producer, accounting for 25 percent of global production. The United States ranks second to Brazil as the world's largest exporter of corn (Trade Data Monitor, 2023). China is the largest destination of U.S. corn, mostly for use in feed rations, followed by Mexico and Japan (Trade Data Monitor, 2023). China is also one of the largest global producers and exporters of soybean, soybean meals, and soybean oil. While U.S. trade in grains and soybeans and their byproducts has been disrupted in recent years (2017 to 2022) by a series of trade disputes, notably with China, long-term projections indicate that U.S. coarse grain exports are expected to increase over the next decade (USDA, OCE, 2023).

Like Brazil and Argentina, the abundance of domestic feed resources, primarily corn and soybean meal, has been a crucial factor in the competitiveness of the U.S. broiler sector in global markets. Chicken meat is the major driver behind the current and long-term growth projections of global meat production, consumption, and trade for the United States—especially amid tightening global supply and strong demand, particularly in low- and middle-income countries (USDA, OCE, 2023). U.S. markets are also expected to drive demand, as the United States remains a leading consumer of chicken meat on a per capita basis at 59.7 kilograms (131.6 pounds) per person, and it has become the most consumed type of meat in the United States (USDA, OCE, 2023). However, the growing demand for chicken meat in middle-income and emerging countries will likely drive the bulk of U.S. exports in the coming decade, as chicken meat is more affordable and high in nutritional value (USDA, OCE, 2023). Among U.S. exports to middle- and low-income countries, Mexico is the largest destination, followed by China, Cuba, and Angola (Trade Data Monitor, 2023).

U.S. producers benefit from a competitive production structure that has ample access to domestic feed resources and a high price competitiveness, thanks to advancements in poultry genetics (USDA, ERS, 2023). Broiler feedstuffs in the United States are dominated by corn and soybean meal. Substitute grains include sorghum and wheat, as well as byproducts such as distiller's dried grains with solubles (DDGS). Among the grain substitutes, sorghum typically plays an important role due to its availability in domestic markets. However, its price competitiveness with corn has eroded over time, following a strong yield performance of the latter—especially with the introduction of transgenic yellow corn varieties in 1996 destined for multiple markets. Markets include distillers, feed, and ethanol (biofuels) industries, in addition to food products. As a result, supplies of corn have been relatively abundant, with corn prices usually below those of sorghum for much of the time after 1996. Nevertheless, U.S. demand for sorghum for ethanol production increased during the same period too, especially in major sorghum growing States such as Kansas and Texas, where sorghum remains cheaper than corn. This demand has helped increase the availability of sorghum-based DDGS for feed industries. Sorghum producers in the United States also continued to enjoy sufficient demand from global markets, especially China and Mexico.

In North America, Mexico is also among the world's largest chicken-meat producers (sixth in rank). Like the United States, Mexico also benefitted from access to improved poultry genetics, vertically integrated breeder facilities, and ample feed availability in domestic markets (INEGI, 2023). Mexico's broiler industry is primarily focused on the domestic market, meeting nearly 80 percent of its domestic chicken-meat consumption, the world's fifth leading consumer of chicken meat (USDA, FAS, 2023l; USDA, OCE, 2023). The industry is made up of vertically integrated large-scale companies like that of the United States, although it faces higher mortality rates due to frequent disease outbreaks. Unable to meet domestic demand, Mexico remains highly dependent on chicken-meat imports, principally from the United States but also from Brazil.

The importance of chicken-meat production in Mexico has made the country one of the largest feed producers in the world (USDA, FAS, 2022a). The preferred grains for broiler feed in Mexico include corn, sorghum, soybean meal, and DDGS in lesser quantities. In the early 2000s, the broiler industry used 70 percent sorghum and 30 percent corn for the grain composition in feed, but these rates have been changing in favor of corn (CONAFAB, 2020). Sorghum's importance in the domestic feed industry is primarily because Mexico is one of the world's major sorghum producers, after the United States and Nigeria (USDA, FAS, 2023h). As a result, the country has often enjoyed a price advantage over corn (Arnade & Davis, 2019; Ramírez González et al., 2003).[25] The feed industry in Mexico is dominated by either standalone commercial feed operators or large scale integrated commercial chicken-meat producers (Ornelas-Eusebio et al., 2020). Although Mexico produces its own significant amounts of corn and sorghum, it often must rely on imports from the United States (Zahniser et al., 2019). Mexico's heavy reliance on imports has made it the third largest U.S. corn importer, behind the European Union and China (Trade Data Monitor, 2023).

Eastern Asia—China and Japan

China and Japan are the largest broiler producers in Eastern Asia, in addition to being major importers of feed grains. The broiler industries in both countries are well developed and are major consumers of animal feed. In China, however, the development of the broiler industry has grown and modernized in more recent decades (since 2000) as urban populations and incomes rise (Gale, 2015). In response, a strong concentrated state and industry cooperation effort has helped to expand agri-businesses in the broiler sector—both in processing and cold storage. Larger lead firms (often referred to within the country as dragon heads) were encouraged to expand through government tax rebates, low- to no-interest rate loans, and public infrastructure investments (Schneider, 2016). The number of these dragon-head firms in the broiler and pork industries has expanded in number and in the scope of agri-food ownership and control. Under contractual agreements, the dragon heads help provide access to technology, information, and market opportunities among millions of broiler producers in major producing regions. The production contracts involve farmers being provided with chicken coops built according to the lead firm's specifications, receiving day-old chicks to raise to the target weight set by the firm, gaining access to veterinary products on a credit, and adhering to strict guidelines for the farmers to follow on feed inputs and disease prevention (Liu et al., 2023). A key challenge for the sector has been controlling and mitigating Avian influenza and other diseases, as these diseases greatly affected the further development of the sector (Liu et al., 2023).

The growth in chicken-meat consumption and production in China has meant an increased demand for feed resources. The commercial production of feed for chicken-meat production accelerated throughout the early 2000s, with some feed companies growing to become some of the world's largest by 2014 (Gale, 2015). This dramatic growth of the feed sector in China has also helped develop the broiler sector into a more intensive production system. Initially, foreign firms played an important role in the development of the feed industry and operated in eastern parts of the country where the broiler sector grew the most (Bingsheng & Yijun, 2007). Private domestic feed companies also emerged after 2000, and today, according to China's Feed Industry Association (CFIA) reports, overall animal feed production has witnessed record levels of output since 2020 (USDA, FAS, 2023e). In its latest CFIA report, the Chinese feed industry reported a production output for the month of July 2023 alone at 27.13 million metric tons.

The sheer size and growth of the feed sector in China is one reason the country remains one of the world's leading importers of feed grains, especially corn and sorghum. The feed industry substitutes between grains depending on price movements. For example, like the rest of the world, price levels of corn substitutes have increased significantly since 2021. More recently, favorable corn prices have led feed mills nationwide to start using 30 percent more corn in feed rations at the end of 2022, according to a CFIA report (USDA, FAS, 2023e).

In the eastern Asian region, and like China, Japan has also seen a steady growth trend in commercial broiler production. Japan's sector is characterized by a small number of large farms (about 2,150 in total, according to USDA, FAS (2023k)), which are vertically integrated with broiler brands as in the United States. While the

[25] For example, Arnade and Davis (2019) found that elasticities of feed-grain demand, with respect to a change in chicken output in Mexico, are much higher for sorghum than corn (3.541 versus 0.064, respectively). They also found that the demand for sorghum for feed was less elastic to its own price changes (-0.165) compared to corn (-0.373)—implying a higher sensitivity to changing corn prices relative to sorghum.

number of farms fell as the industry consolidated, production increased during the same period. To feed the growing industry, Japan is estimated to produce about 24 million metric tons of formula feed but with most of the feedstuffs imported (USDA, FAS, 2023b). Coarse grain imports make up 99 percent of Japan's total coarse grain consumption, with the bulk of imports being corn and barley, followed by sorghum, oats, and rye but in smaller amounts. Corn constitutes about 50 percent of Japan's compound feed production in total (Skorbiansky et al., 2018). The United States is a major supplier of corn, as Japan imposes no import tariffs on U.S. corn feed. Corn imports reached 15 million tons, 90 percent of the total coarse grain imports for 2022/23 (USDA, FAS, 2023b). Feed mills are known to typically use substitute feed grains (such as wheat, rice, and sorghum whenever corn prices rise too high), as occurred throughout 2021 through 2022. Broiler production consumed 39 percent of sorghum during this period (USDA, FAS, 2023b). Barley and wheat are more commonly used for cattle and swine feed.

Southeast Asia—India and Thailand

In most Southeast Asian countries, broiler production is mainly for the domestic market. However, given the sheer size of these markets, especially India, the region is one of the largest producers of chicken meat globally. In India, the commercial sector has also been expanding to meet the demand of growing and richer urban populations—such that production has increased almost fourfold since 2000. Despite this, the country still has some of the lowest per capita consumption rates. India has continued to protect its domestic poultry sector, denying access to chicken-meat imports from all suppliers, including the United States. India has even banned chicken-meat imports from any country that has reported incidences of avian influenza despite its own numerous outbreaks (Zhuang & Moore, 2015).

According to Mehta and Nambiar (2007), poultry remains the preferred and most consumed meat in India for social and economic reasons. The expansion in domestic production, especially among vertically integrated commercial firms, has helped push prices downward. Compared to Thailand, however, India still has a long way to go, especially for processed chicken-meat products, as domestic broilers are mostly found in wet markets. For feed, corn and soybean meal remain the preferred feedstuffs, with common substitutes such as rice bran and groundnut cake (Mehta & Nambiar, 2007). There is typically sufficient availability of domestic corn, but the country has been known to occasionally import corn. India grows a lot of wheat and rice, much of it under government price support schemes. Coarse grains such as sorghum and millet are also widely grown but mostly for human consumption, as in West Africa. Although rice and sorghum offer important alternatives to corn for feed millers, they also compete with demand for both human consumption and among distilling companies (like corn elsewhere in the world).

Compared to India, Thailand has a much more developed commercial broiler sector and is a leading exporter of chicken meat in Asia (table 1). In the European Union, for example, Thailand competes with Brazil as a major supplier of chicken meat (Van Horne, 2018). According to the same author, Thailand competes well in international markets because dark leg meat is more popular in domestic markets, and therefore, the country can export chicken-breast meat at more competitive prices. Additionally, Thai exporting firms produce some of highest quality chicken-meat products due to strict oversight by the Thai Government for maintaining food safety and environmental concerns. All exporting firms require certification from the Thai Government.

As the chicken-meat export sector has grown in Thailand, so has the feed manufacturing industry. The feed mills rely on imports for 50 to 60 percent of total feed for broiler production—especially for wheat, soybeans, and soybean meal—while accessing corn mostly from domestic sources (Skorbiansky et al., 2018). Rice is rarely used despite being the country's leading agricultural crop. At times, however, the Thai Government may auction old rice from stocks to use as animal feed. This event occurred in 2017 when auction prices for feed rice fell below the price of corn by as much as 30 percent (Skorbiansky et al., 2018). In early 2022, as feed costs increased due to rising grain prices following the Russia-Ukraine war, the Thai Government tried to encourage feed mills to blend in broken rice with feed corn to relieve the rising costs (USDA, FAS, 2023d). A large competitor for feed grains in Thailand is the growing swine production sector, as in China.

Among other feedstuffs, Thailand also uses distiller's dried grains with solubles (DDGS) in feed formulations. The United States accounted for 97 percent of all DDGS imports to Thailand in 2021 (USDA, FAS, 2023d). Barley imports mainly come from Australia under a duty-free agreement. Prices for all imported grains and DDGS have been on the rise since 2021, leading Thai feed millers to shift to locally produced corn (including duty-free imported corn) and broken rice.

Europe—Turkey and Poland

In Europe, Turkey and Poland are among some of the largest global chicken-meat producers and exporters. Chicken meat was Turkey's fifth largest agricultural export by value in 2021 (USDA, FAS, 2023f). For feed grains, Turkey is a net importer, with imports supplying 26 percent of total domestic consumption in 2022/23. Of those imports, corn constitutes the largest in terms of volume, followed by barley. Turkey is also a major importer of wheat but mostly for human consumption. This result is in sharp contrast to corn and barley, which are predominantly imported for feed and other uses. Among the feed grains, corn production increased recently (in the 2022/23 growing season), as farmers expanded the area under harvest and moved from cotton to corn as cotton prices fell, or in some cases, double-cropping wheat and corn (USDA, FAS, 2023f). The major Turkish corn-growing regions are Central Anatolia, Southeast Anatolia, Cukurova, and the Aegean regions. Broiler feed is mostly made up of corn and soymeal, although wheat may also be used as a substitute, depending on price movements.

Relative to Turkey, Poland serves as one of the largest producers and exporters of chicken meat in the European Union, exporting both to markets within the European Union and globally. However, the sector also struggles with periodic outbreaks of Highly Pathogenic Avian Influenza (HPAI), which can affect exports as countries ban chicken meat from Poland. Like in the rest of the world, Polish chicken-meat production was also severely affected during the Coronavirus (COVID-19) pandemic as demand slowed and supply chains were disrupted (USDA, FAS, 2021). Nevertheless, despite these challenges, since 2021, the country has been able to maintain its position as the EU's largest broiler producer and feed consumer. The destinations of Polish chicken-meat exports to the European Union are dominated by the Netherlands and Belgium, but they are mostly for re-exports. Among feed grains grown in Poland, wheat dominates production, followed by barley and corn. The country also exports all three grains, importing far less than Poland exports. Poland exports mostly to Saudi Arabia, South Africa, and Germany (USDA, FAS, 2021).

Africa—Egypt and South Africa

Egypt and South Africa have some of the largest broiler-production industries on the African continent. Like most other countries, corn and soybean meal are the typical choice for feed. The broiler industry in Egypt is an important and growing agricultural industry that mostly produces chicken meat for domestic consumption. Although a large portion of commercial poultry producers are small scale in nature, the larger commercial sector (composed of fully integrated operations) has been growing. Even though broiler production closely meets domestic demand, the country remains a net importer of chicken meat (see table 2 for more information).

The broiler sector in Egypt faces numerous challenges, including periodic disease outbreaks and rising feed costs. The commercial sector relies heavily on grain and other feedstuff imports for its broiler feed needs (FAO, 2022). For example, according to USDA, FAS (2023a), domestic corn production in Egypt supplies less than 35 percent of its feed demand needs. Imports are typically obtained from Brazil, Argentina, and Ukraine. Typically, feed mills in Egypt prefer a feed mix consisting of 70 percent yellow corn, 19.4 percent soybean meal, 3.4 percent wheat bran, and 1.9 percent broiler concentrates (fish or meat meals), according to a recent USDA Global Agricultural Information Network (GAIN) report (USDA, FAS, 2023a). The mix may be substituted with other grains, particularly as global corn prices spiked after the Russia-Ukraine war, a major source of grain in Egypt. Coupled with a deprivation of the country's exchange rate, domestic grain and feed prices doubled between 2020 and 2022, further exacerbating inflationary pressures on food prices (FAO, 2022).

In Africa, South Africa has one of the most advanced large scale poultry sectors in Sub-Saharan Africa, and poultry production is the largest agricultural industry in the country (Bagopi et al., 2016). Feed demand is therefore a vital part of the agricultural sector, consuming about 30 percent of total corn consumption in the country. Overall, the poultry industry is composed of large integrated producers, as well as large commercial standalone feed mills. However, since 2010, the broiler industry, in particular, has begun facing increased competition from chicken-meat imports from Brazil, the European Union, and the United States, primarily because of a stronger local currency and rising domestic feed costs (BFAP, 2019). As a result, chicken-meat imports rose significantly in 2010–15, making up to 53 percent of domestic consumption (BFAP, 2019). The industry has since reclaimed market share—partially due to some protectionist measures—with imports accounting for about 15.9 percent of domestic consumption in 2022, down from 24.1 percent in 2018 (SAPA, 2022). However, the rising frequency of electricity-load shedding occurrences (i.e., the periodic interruption of electricity supply to maintain the integrity of the electric grid during peak demand periods) threatens the industry's future competitiveness.

Among feed grains, the broiler industry typically prefers corn over sorghum for most years, depending on price movements and availability. South Africa produces both yellow and white corn, including genetically modified organism varieties (one of the first countries to do so in Sub-Saharan Africa). The country's agricultural output is mostly from large-scale commercial operations, growing sufficiently large quantities so that the feed and broiler industry rarely needs to import grains or oilseeds, aside from rice and wheat. This result is similar to that of other leading broiler producing countries (such as Argentina, Brazil, and the United States). The demand for feed accelerated between 2000 and 2010, and chicken-meat consumption grew at above 6 percent annually and has since leveled off as the overall economy slowed down after that growth spurt (Pienaar et al., 2021). According to a recent USDA Global Agricultural Information Network (GAIN) report (USDA, FAS, 2023c), corn demand for animal feed is expected to continue this flat trend due to challenges of a slow growing economy, made worse by increased disruptions in electricity supply. Rising feed costs are also reducing demand, as profit margins for chicken-meat production have eroded over time (Nkukwana, 2019; SAPA, 2022).