An Examination of Recent Fertilizer Price Changes

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Executive summary

As measured by the consumer price index, inflation grew 8% from April 2021 to April 2022, an annual rate unseen since the 1980s. Price increases are tied to a number of factors including supply chain disruptions, disease outbreaks, global conflicts, sudden demand shifts, and fiscal and monetary stimuli. There have also been concerns over market concentration and market power causing price increases. Agriculture has not been immune to inflationary pressures and, in fact, has faced more significant price increases than the general economy. The price increases have boosted farm revenues, with crop prices leading the charge, but have also added to farm costs, with feed, seed, labor, and land expenses growing.

One cost input that has attracted particular attention is fertilizer. While crop prices have roughly doubled over the past couple of years, fertilizer prices are two to four times higher than they were in September 2020. Energy drives the supply of fertilizer production and food drives the demand for fertilizer use, and the two biggest components of inflation right now are energy and food.

At the request of the Iowa Attorney General's office, the staff at CARD has compiled this study to examine and discuss the myriad issues impacting fertilizer markets and influencing fertilizer prices. Following are some of our findings:

- If we state as a null hypothesis "Increased production costs and commensurate supply chain issues were the main causes of increased fertilizer prices in 2021/22," we do not have enough evidence to refute that hypothesis.
- We find statistical evidence for structural changes along the fertilizer marketing chain with the pandemic coinciding with one of those structural changes.
- Statistical analyses of these structural changes point to underlying energy costs, and to a lesser extent farm demand, having more influence on fertilizer prices, although both are important.
- The argument that fertilizer firms may be taking advantage of inflation to raise prices raises more questions than answers at this point. Nevertheless, they are good questions for which we need more data.
- Juxtaposing the fertilizer industry with other food and agricultural industries and other firms shows that in some cases (e.g., net income, stock prices and risk), the fertilizer industry looks little different than other industries, while in other cases (e.g., profit growth before and after COVID-19), the fertilizer industry has performed better than many (but not all) food and agricultural industries.
- A lack of good data on the factors that impacted the marketing chain and costs for fertilizer during the COVID-19 pandemic hampers using statistical methods to discern market power.
- Iowa farmers do have alternative sources of fertilizer (manure); however, market development is not to the point that they can realize imminent relief for high fertilizer prices.

The first section of this report provides a brief discussion of the US and global fertilizer markets and explores some of the factors that have influenced fertilizer production and pricing. The second section presents a more formal analysis examining the historical relationships among fertilizer, natural gas, and corn prices and looks for structural breaks in price trends. Section 3 considers longer run and other factors and provides a brief, comparative examination of net income and stock values for fertilizer companies in comparison to other companies and to Iowa farmers and discusses concerns over market power. Section 4 outlines the usage and challenges with manure as a commercial fertilizer alternative. Section 5 provides concluding remarks.

Section 1. Recent events impacting the US and global fertilizer markets

The structure of the fertilizer market has changed over the years. The number of companies in the US anhydrous ammonia industry declined from 58 firms in 1976 to 27 firms in 2000 and the total number of plants reduced from 113 to 39 during the same period. The number of active ammonia plants was at a low of 22 in 2008 (Bekkerman, Brester, and Ripplinger 2020). The four-firm concentration ratio (measuring the share of value of the largest four firms in the US industry) for nitrogenous fertilizer manufacturing increased from 54% to 63% between 1997 to 2017 and for phosphatic fertilizer manufacturing the four-firm concentration ratio increased from 71% to 82% over the same period (Crespi and MacDonald 2022). In March 2010, CF Industries and Terra, who were previously the second- and first-largest US firms by production capacity, successfully merged. As a result of the merger, CF Industries has become the largest nitrogen producer in North America. Specifically, the capacity of CF Industries was higher than the capacity of the next three largest US firms combined (Humber 2014). Then, two of Canada's fertilizer firms, Potash Corp. and Agrium, officially agreed to combine in January 2018. The newly combined company, Nutrien, is the largest producer of potash, as well as the second-largest producer of nitrogen fertilizer in the world (Jamasmie 2017). In the North American marketplace, Nutrien controls nearly two-thirds of the potash capacity, 30% of phosphate production, and 29% of nitrogen capacity. As of 2018, the four biggest ammonia producers (CF Industries, Nutrien, DynoNobel, and Koch Industries) in the United States accounted for 75.3% of domestic production (Bekkerman, Brester, and Ripplinger 2020). The United States Department of Agriculture (USDA) announced plans to help develop greater supply and fertilizer choices in the United States and to investigate competition concerns, which will clearly take time (USDA 2022). It is important to understand the dynamics of these global markets and, especially, how fertilizer relates to energy markets.

As we shall discuss, two main variables drive fertilizer prices: energy supply and food demand. Figure 1 shows year-over-year inflation with food and energy prices subtracted. As can be seen in figure 1, the current year-over-year inflation rate not including food and energy is about 2%. The year-over-year change in unadjusted inflation (consumer price index/CPI) is currently about 8%, which means that figure 1 shows that 2 to 3 percentage points of current inflation are due to food and energy prices.

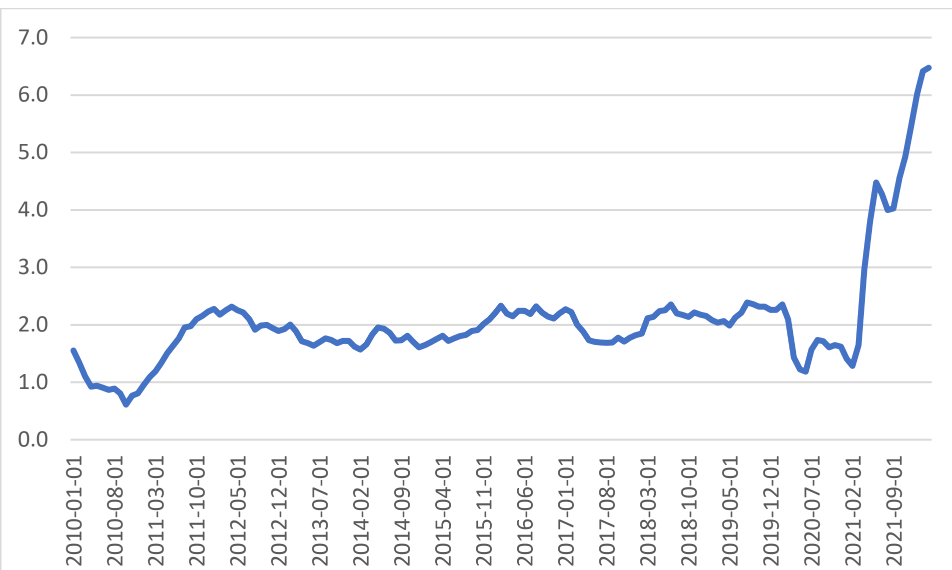

Figure 1. Year-over-year percent change in consumer price index without food or energy prices.
Source: FRED Economic Data, Saint Louis Federal Reserve https://fred.stlouisfed.org/series/CPIAUCSL#0https://fred.stlouisfed.org/series/CPIAUCSL#0. Last accessed June 2, 2022.

Worldwide crop production has increased significantly over the past several decades. Global demand for crops comes from both population growth and income growth. A key component to the crop production expansion has been the ability of the world to promote fertilizer production. Figures 2–4 outline the US and global patterns for fertilizer production since 1994. Figure 2 shows ammonia production, figure 3 shows phosphate rock production, and figure 4 shows potash production. The orange line in each figure highlights the percentage of global production within the United States, utilizing the right axis of the graph. Although ammonia, the key product for nitrogen fertilizer, can be created under a variety of processes, as far as the production of fertilizer goes, the most widely used process combines hydrogen from natural gas with nitrogen from the air. Hence, natural gas is such a critical input for modern fertilizer production that understanding the price of fertilizer necessitates understanding the price of natural gas. Unsurprisingly, most of the world's ammonia production is centered in areas with substantial natural gas deposits. Although fertilizer production is the most important use of ammonia, it is also a key component in many manufacturing processes from pharmaceuticals to plastic and textiles.

As a fertilizer, farmers can use ammonia directly but it can also be utilized to create other types of nitrogen fertilizers, such as urea or ammonium nitrate. Although global ammonia production has increased roughly 50% since 1994, US production tailed off throughout the 1990s and 2000s. The greater availability globally, combined with higher production costs domestically, led to the decline in US production. Within the last few years, the United States added some new production capacity bringing production back up to mid-1990s levels. Currently, US ammonia production is just under 10% of the global total.

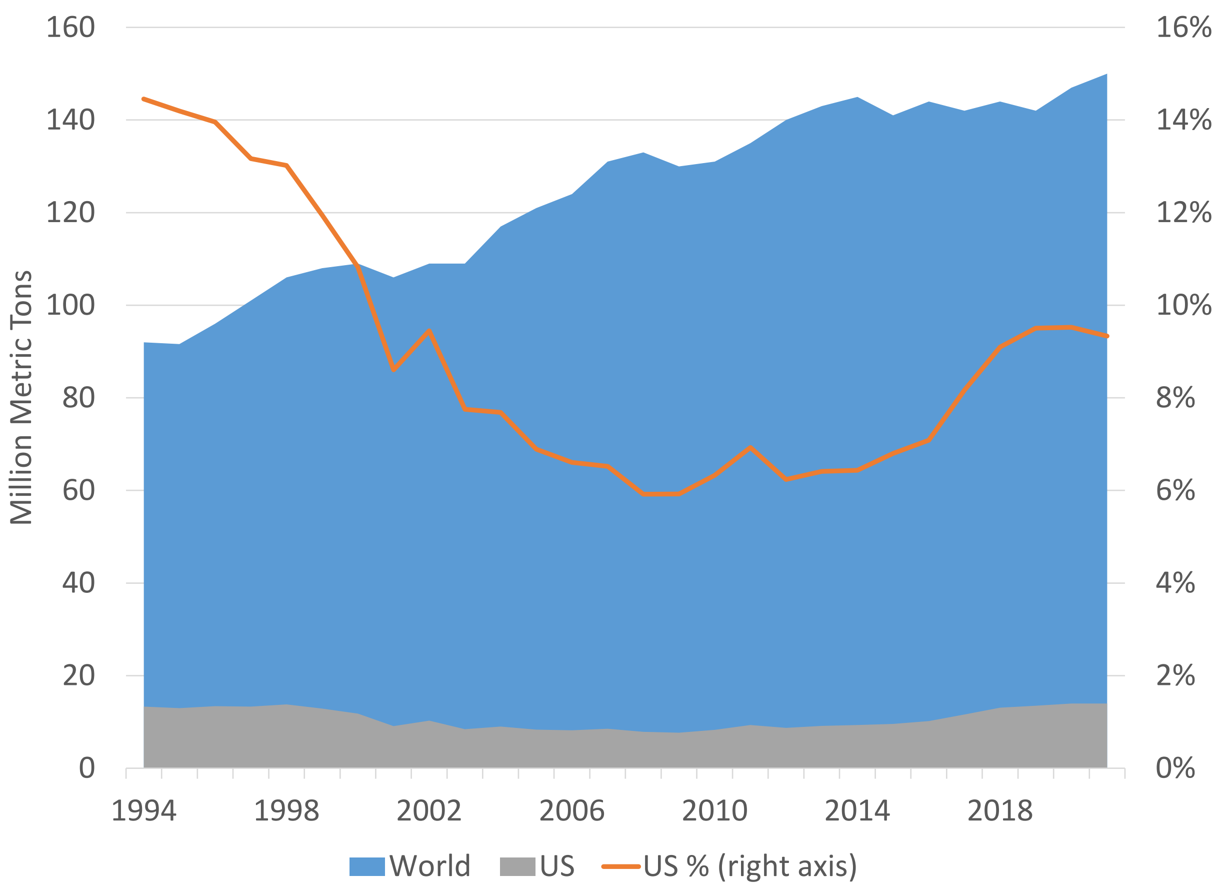

Figure 2. Ammonia production.
Source: USGS mineral commodity summaries.

Phosphate rock is mined from large deposits found throughout the globe, including the United States, China, northern Africa, and the Middle East. Beyond fertilizer, phosphate is used in animal feed supplements, agricultural chemicals (such as glyphosate, i.e., "Roundup"), and, like ammonia, has other industrial uses.

Global production doubled between 1994 and 2015, with mining expansions in many countries. Recent data show a modest reduction in phosphate mining, with much of the adjustment coming from China. Like ammonia, while global phosphate production rose, US production fell. In 1994, the United States produced approximately 30% of the world's phosphate. Currently, the United States produces 10% of the world's phosphate. Much like ammonia, the combination of larger global supplies and higher domestic production costs resulted in the decline of US phosphate production.

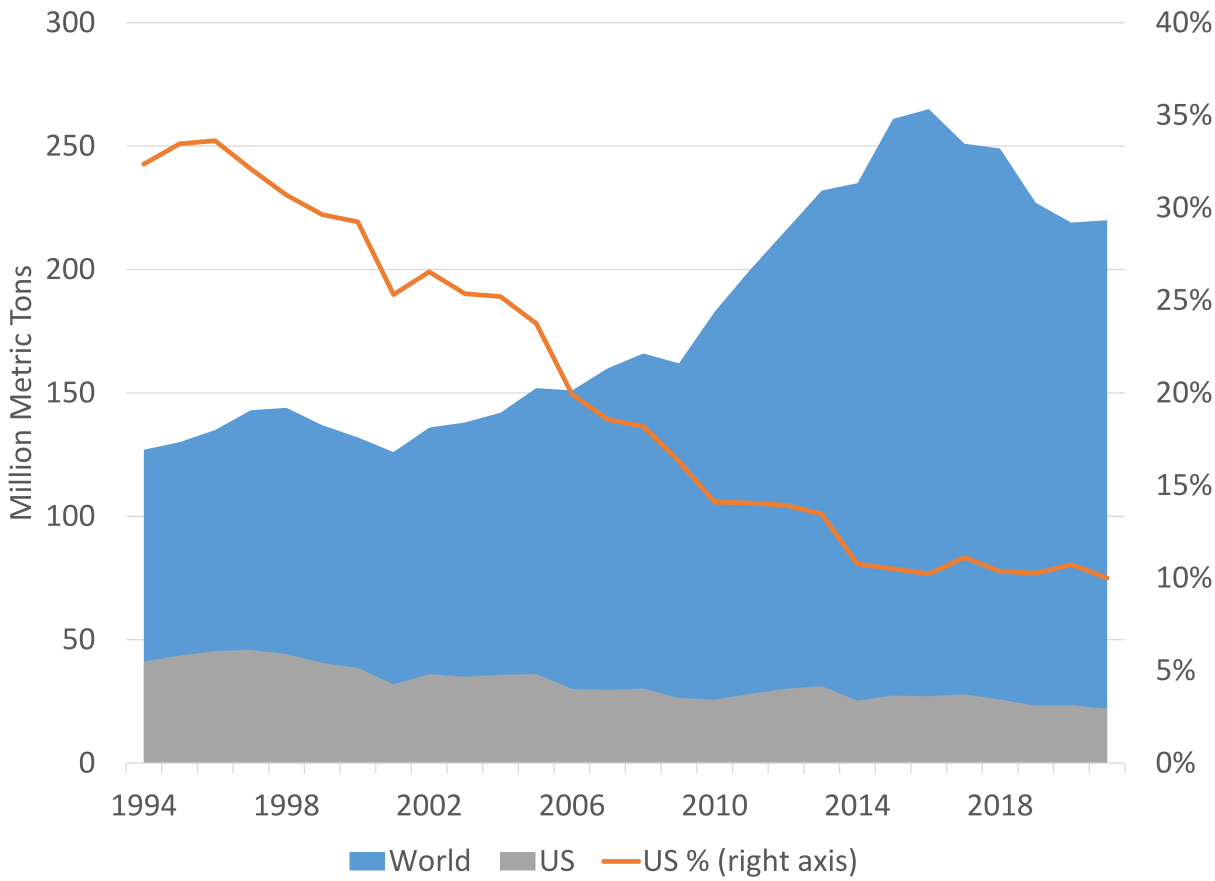

Figure 3. Phosphate rock production.
Source: USGS mineral commodity summaries.

Like phosphate rock, potash is mined from the earth. Potash provides potassium to growing plants. While there are potash deposits across the globe, the largest ones are in Canada, Belarus, Russia, the United States, and Laos, with most deposits roughly one mile underground. Not surprisingly with such deep sources, mining operations are costly. As figure 4 shows, global potash production has trended higher over time. The sharp drop in 2009 coincided with the Great Recession, as several potash facilities temporarily shut down under the burden of low prices and high stockpiles. Similar to the other fertilizer products, US production of potash has declined over the years, with current production only being 1% of the world's total.

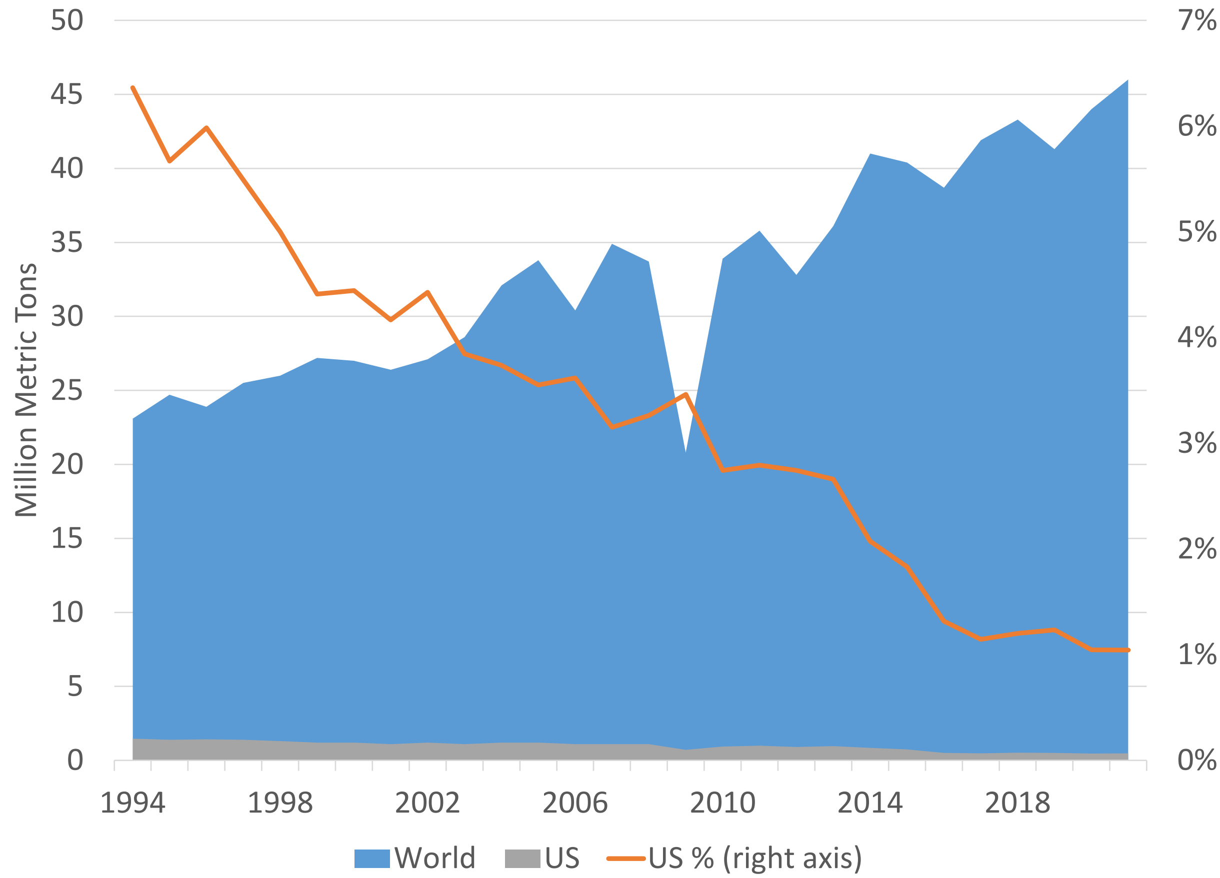

Figure 4. Potash production.
Source: USGS mineral commodity summaries.

In general, figures 2–4 show similar stories: overall growth in fertilizer production globally coupled with shrinking US production. With the continued growth of US crop production, demand for fertilizers in the United States has been strong throughout the time period. Thus, the opposite pointing trends imply that the US fertilizer market became more globally oriented since the mid-1990s. Figure 5 displays the percentages of the base fertilizer products imported by the United States. The import curves are roughly an inverted mirror image of the US production percentages. Imports dominate the potash market, whereas they contribute a much smaller percentage of the phosphate and ammonia markets. However, even in those markets, imports are an important fixture, as currently 10% of the phosphate and 14% of the ammonia come from the rest of the world. For phosphate and potash, US consumption has relied on consistently growing imports. For ammonia, the trend of higher imports existed through the 1990s and early 2000s, but has reversed over the past decade (compare US production in figure 2 to US imports in figure 5). With the most recent expansions for US ammonia plants, the import percentage fell below early 1990s levels.

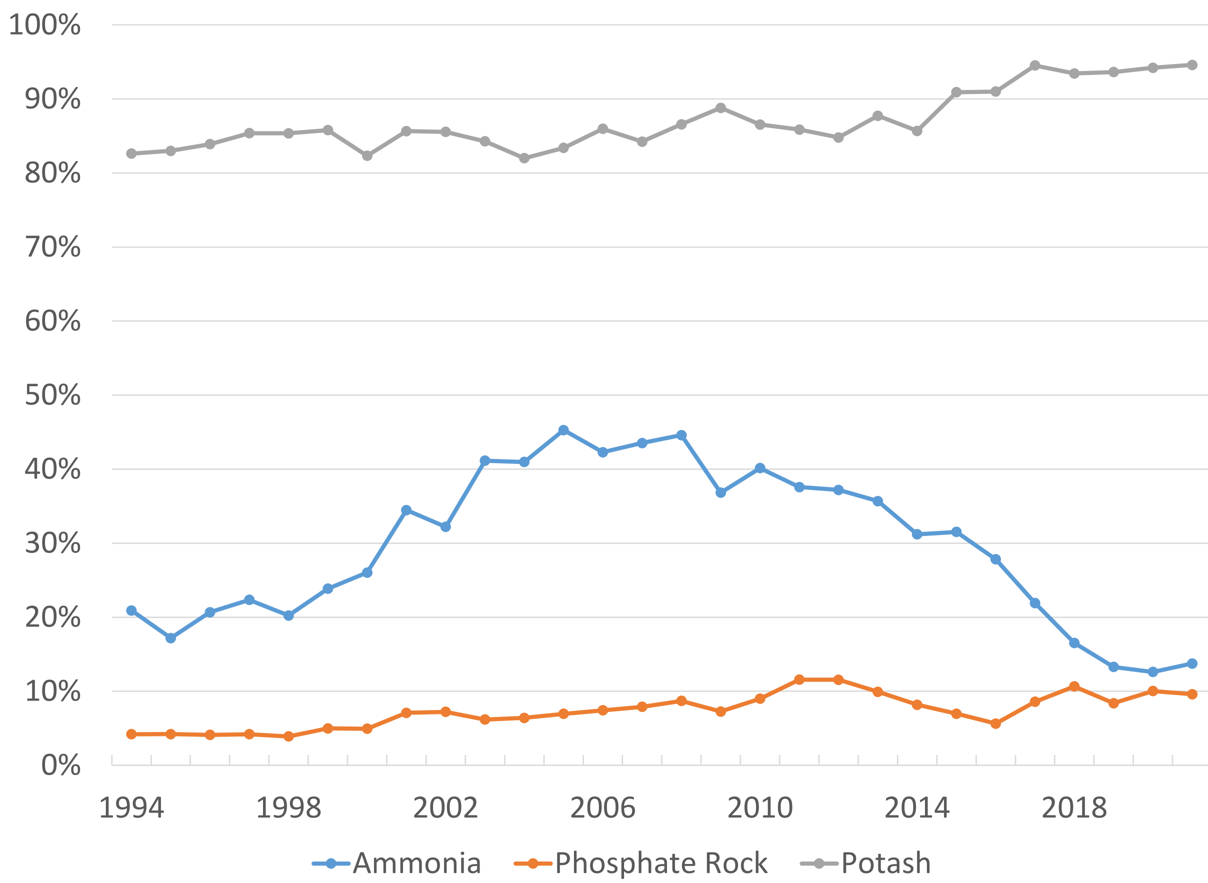

Figure 5. US reliance on fertilizer imports.
Source: USGS mineral commodity summaries.

Table 1 outlines the most recent US annual fertilizer data and highlights the United States' significant trade partners. As the data show, for ammonia and potash, residual stocks at the end of the year are minimal to nonexistent. Only with phosphate are there significant stock levels. Over the past several years, the overwhelming majority of fertilizer imports have originated from our neighbors in the western hemisphere. However, we have also pulled fertilizer supplies from countries in north Africa, Russia, and Belarus. Given the current economic sanctions on Russia and Belarus, those sources are now off-limits to not only the US market, but to European markets as well, meaning that the world is competing for nutrient sources from a significantly altered map.

Table 1. US Fertilizer Data

	Ammonia		Phosphate Rock		Potash
2021 Estimates			1,000 metric tons		
US Production	14,000		22,000		480
Imports	2,200		2,400		7,000
Exports	260				100
Apparent Consumption	16,000		25,000		7,400
Stocks	360		10,000		
US Import Sources (2017–2020)					
Trinidad and Tobago	63%	Peru	87%	Canada	75%
Canada	34%	Morocco	13%	Russia	10%
Venezuela	2%			Belarus	8%
ROW	1%			ROW	7%

Source: USGS (2022).

A few key players drive the global fertilizer supply situation. China is a major player, both in terms of production and usage. China is the largest producer of ammonia and phosphate and is the fourth-largest potash producer. Russia is the second-largest producer of ammonia and potash and the fourth-largest producer of phosphate. The United States is third for both ammonia and phosphate, and Canada is the largest producer of potash. While the United States has mainly sourced fertilizer products relatively close to home, much of the world depends on imported fertilizers. Based on the UN Comtrade Database (2022), Brazil is the biggest importer of fertilizers, pulling in nearly $10 billion of fertilizer in 2019. India is the second-largest importer and the United States is third, with both importing over $7 billion of fertilizer. China and France round out the top five importers. Russia has been the top exporter, shipping roughly $8.4 billion in 2019. China, Canada, the United States, and Belarus complete the top five exporters list. In 2019, the United States was a net importer, bringing in nearly $3 billion more than was exported.

Table 2. 2021 World Fertilizer Production

Ammonia		Phosphate Rock		Potash	
		1,000 metric tons			
China	39,000	China	85,000	Canada	14,000
Russia	16,000	Morocco	38,000	Russia	9,000
US	14,000	US	22,000	Belarus	8,000
India	12,000	Russia	14,000	China	6,000
Indonesia	5,900	Jordan	9,200	Israel	2,300
ROW	63,100	ROW	51,800	ROW	6,700

Source: USGS (2022).

Recent events

A variety of events since the start of 2020 have impacted the fertilizer industry, like many sectors of the economy. As COVID-19 first circulated around the globe, the United States designated the fertilizer industry as a critical industry, allowing US plants to maintain full operations. However, COVID-19 did reduce worker availability and limited the industry's use of contractors for plant maintenance, leading to delays in plant maintenance and slower production (AFBF 2021). The maintenance issue also factored into the problems created by natural disasters. Specifically, the deep freeze in the Southern Plains in February 2021 and Hurricane Ida from August 26–September 5, 2021. Both disasters not only directly impacted fertilizer production, but disrupted natural gas production, the major feedstock for nitrogen fertilizers. During the deep freeze, many natural gas wells froze and electrical production, especially from wind turbines, ceased, limiting the availability of natural gas while also putting demands on more of it, thus spiking the natural gas price from $2.71 per 1,000 cubic feet in June 2020 to $9.33 in February 2021 (USEIA 2022). Following the freeze, natural gas prices remained above $4 per 1,000 cubic feet throughout 2021. Hurricane Ida then added to the squeeze on natural gas production in the fall of 2021, disrupting off-shore natural gas facilities by forcing evacuations and damaging production platforms (USEIA 2021). Two months after Hurricane Ida, the US Energy Information Administration stated that the fertilizer market was still feeling the hurricane's impact from both a production and market perspective. Because of the aforementioned reasons described in the discussion on fertilizer production, the higher natural gas prices have directly translated into higher fertilizer production costs. Figure 6 shows the relative (nearby) futures pricing changes for four markets: US corn, US natural gas, UK natural gas, and urea. In general, for all commodities, prices rose slowly in 2020, before shifting to much higher levels in 2021 and 2022.

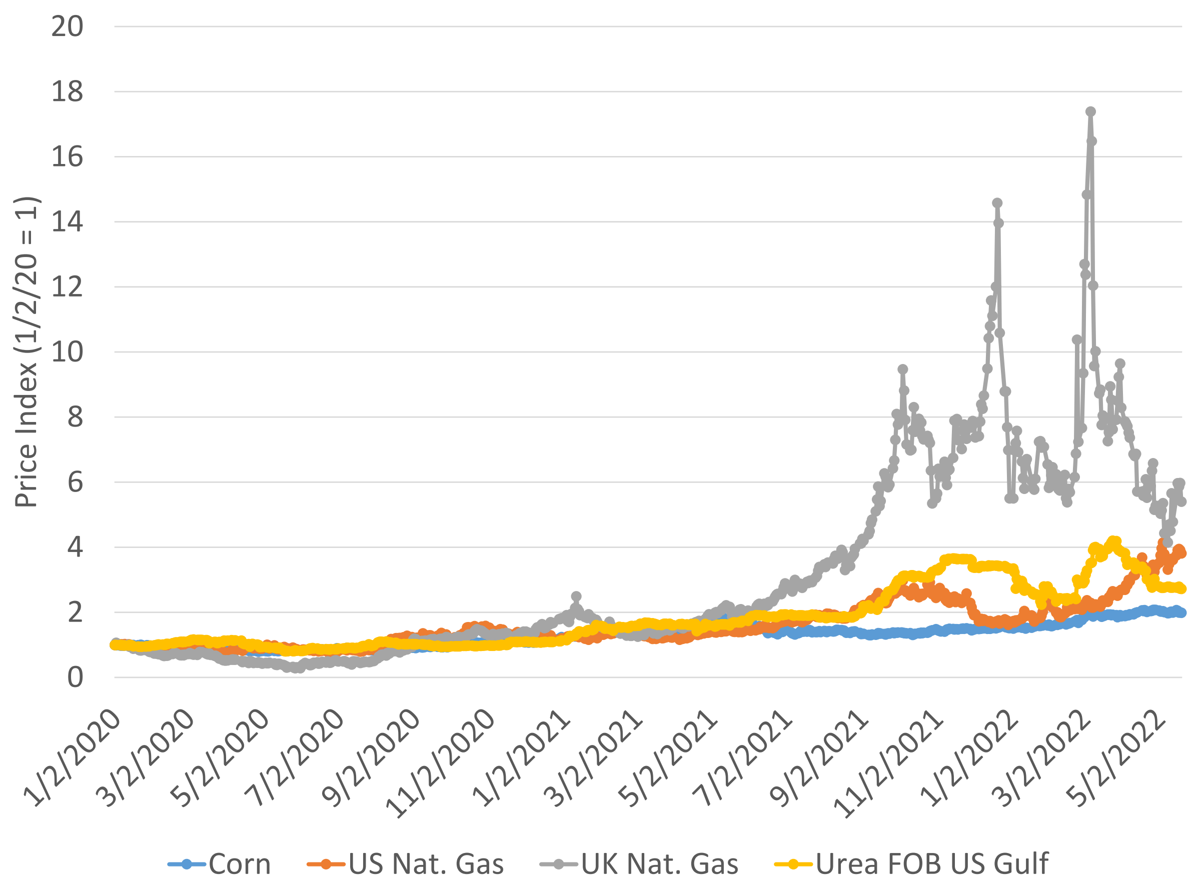

Figure 6. Price indices for corn, natural gas, and urea.

Energy is a worldwide market and natural gas issues were not limited to the United States. Towards the end of 2021, world natural gas prices, especially in the European Union and China, increased rapidly due to low inventories, high demand, and supply disruptions. EU natural gas futures substantially increased from about €19.82 per megawatt-hour (~$4.75 per 1,000 cubic feet) at the beginning of 2021 to a peak of €180.27 per megawatt-hour (~$46.75 per 1,000 cubic feet) on December 21, 2021. As a result of high natural gas prices, some fertilizer plants in Europe temporarily halted or reduced their production from September to November 2021. Tight global supplies led to higher world fertilizer prices. To compound an already tight supply situation, beginning the summer of 2021, China banned exports of urea and phosphate until June 2022. In December 2021, Russia instituted a six-month quota on various fertilizers. Since the fall of 2021, Belarus has faced a variety of economic sanctions. These last three items are important as China, Russia, and Belarus are global leaders in fertilizer exports. While the United States has not traditionally sourced fertilizer from those markets, the lack of Chinese, Russian, and Belarussian supplies on the global market has forced countries that do rely on those supplies (mainly in Europe and South America) to search for alternative sources, including the countries from which the United States purchases. At the same time, US and global demand for fertilizer was strong as crop prices rose throughout the year. Although it is difficult to discern in figure 6, given the larger changes from the other commodities shown, corn prices ended 2021 50% higher than they were at the beginning of 2020.

The strong demand signals and higher production costs for fertilizer continued into 2022. Russia invading Ukraine in late February 2020 added another confounding factor. The United States, Canada, Japan, Australia, New Zealand, Taiwan, and much of Europe responded by putting significant economic sanctions on Russia. Natural gas prices in Europe once again spiked as the conflict created uncertainty about gas supplies and trade. Fertilizer plants in France, Hungary, and Italy reduced, and in a few cases completely halted, production due to the high gas prices. To aid Europe, which relied heavily on Russian energy, the United States responded by exporting natural gas, reaching record levels. Figure 7 zooms in on the last year of figure 6 and focuses on the most recent price shifts for corn, natural gas, and urea. Given the incredible volatility in UK natural gas, with prices reaching 18 times what they were at the beginning of 2020, its scale is given on the right-hand axis. While corn prices have doubled over the past two years, the increases in energy and fertilizer swamp those price moves. Starting in September 2021, we can see the impact of Hurricane Ida in both the US and UK natural gas prices. Urea prices followed along with the natural gas prices. US natural gas prices finally moderated in December, but UK prices spiked once again, this time as Russia built up troops along the Ukrainian border. The persistence of higher natural gas costs supported higher urea prices through the winter. The start of Ukraine war sent another price spike through the energy and fertilizer markets. Recently, urea and UK natural gas prices have eased, while US natural gas prices have continued to increase.

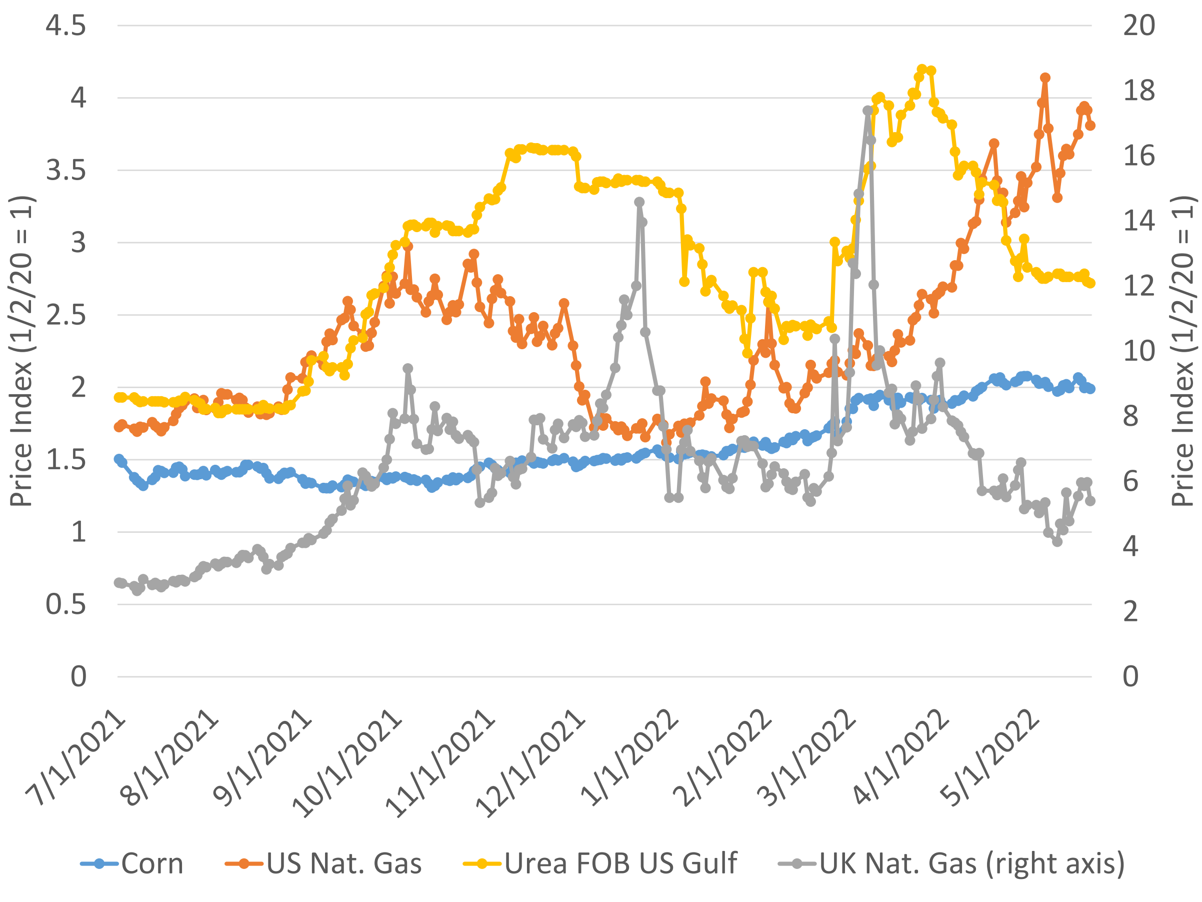

Figure 7. More recent shifts in price indices for corn, natural gas, and urea.

Section 2. Have changes significantly altered prices? A technical exploration of the statistical relationships among fertilizer, natural gas, and corn prices over time.

This section summarizes a trend analysis of the price relationships discussed in the previous section. The appendix contains the details of the technical analysis.

Several economic studies examine the relationships among fertilizer, natural gas, and corn prices. Huang (2007) indicates that the prices of nitrogen fertilizers closely correlate with natural gas prices during 2000–2005. In contrast, more recent studies show that demand pressure, rather than natural gas prices, drive the movement of fertilizer prices (Beckman and Riche 2015; Etinenne, Trujilo-Barrera, and Wiggins 2016; Li 2016; Bushnell and Humber 2017; Bekkerman, Gumbley, and Brester 2021). Economists, especially those studying trends, are always interested in the existence of structural breaks in the data. Structural breaks are unexpected changes to "normal" trends in the data that reveal themselves only through the benefit of hindsight. The search techniques are complicated—it is not uncommon for researchers, especially in finance where so much money rides on the power of a model, to argue over the existence or lack thereof of a structural break. A simple example is a change in the average price of a good from one time period to another that requires treating the new price as significantly different from the previous price. Often it is not immediately clear what led to the break, hence finding a break becomes fodder for future research. Prior literature examines the search for and presence of structural changes in the US fertilizer market. Beckman and Riche (2015) find a structural change occurring in June 2008, potentially because of an increase in corn demand. Looking over much the same period, Bushnell and Humber (2017) discover a break occurring in January 2010, the year that CF Industries and Terra Industries merged. That two different studies find two different breaks indicates that there may exist more than one structural change in this market.

This section builds upon the general observations of section 1. We examine three research questions. First, how has the relationship among natural gas, corn, and fertilizer prices changed over time? Second, and, relatedly, have there been significant structural breaks in these trends and when? Third, in light of the first question, how much do natural gas and corn prices pass through to nitrogen fertilizer prices?

Understanding the structure of the US fertilizer industry is crucial for farmers and policymakers since fertilizer is the main input of crops to improve yields. To examine the stability of the relationships among natural gas, nitrogen, and corn prices, we apply tests for multiple structural changes introduced by Bai and Perron (1998, 2003). This section uses monthly data of anhydrous ammonia, granular urea, Henry Hub natural gas, international natural gas, and corn price series from January 1997 to February 2022.[1] As discussed in section 1, ammonia is both a fertilizer product and the primary raw material to produce other nitrogen fertilizers. Urea is the world's most popular nitrogen fertilizer. The first step to determining whether there are trending relationships among corn, fertilizer, and natural gas is to determine the existence of correlation in the time series, known as cointegration. We test for cointegration in the relationship among fertilizer, gas, and corn prices, then we estimate the pass-through rates of domestic and international natural gas and corn prices to fertilizer prices using a seemingly unrelated regression (SUR) approach, accounting for the presence of a long-run relationship.

The results show that over time fertilizer prices mainly respond to input cost changes rather than demand-side effects.

While fertilizer prices may be rising due to firm responses to demand alone, our analysis provides statistical evidence that prices are responding to cost factors. Prior to November 2009, the variation in Henry Hub natural gas prices primarily contributed to the changes in anhydrous ammonia prices. After 2009, ammonia prices more closely follow international natural gas price changes, which is consistent with the discussion in section 1 concerning the US markets' higher import reliance and relatively high global natural gas prices. Conversely, international gas prices relate more to urea prices than do domestic prices before 2000. Afterward, the fluctuation in Henry Hub gas prices has more impact on urea prices. However, the results vary across time, methods, and model specifications. While the pass-through analysis shows a positive relationship between ammonia and corn prices in some periods, the Granger causality tests on vector error correction (VEC) and

[1] Located near Lafayette, Louisiana, the Henry Hub is a pipeline interchange in the Gulf Coast and is the major natural gas trading point in North America. We use the price of natural gas at the Henry Hub as the price base for natural gas throughout the world and is the standard delivery point for NYMEX contracts, for example.

vector autoregression (VAR) suggest corn price changes have no direct impact on ammonia prices in all periods. The disparity in the outcomes could result from contemporaneous changes in corn and ammonia prices. Ammonia prices follow more closely the changes in these three price factors, while other missing factors, such as the expectation and completion of capacity expansion projects, changes in government regulation, and increasing costs of transportation and storage seem to affect urea prices.

The analysis in this section examines two types of fertilizers, anhydrous ammonia and urea, and three factors that might affect fertilizer prices: corn prices and domestic and international natural gas prices. The sample is monthly frequency during January 1997–February 2022. We find four structural changes in the relationship among ammonia, gas, and corn prices: (*a*) June 2007; (*b*) November 2009; (*c*) September 2016; and (*d*) October 2019.

Anhydrous ammonia structural breaks

a) The first structural change around June 2007 links to a combination of increasing domestic gas production and global demand for biofuel.
b) The second break around November 2009 is likely because of CF Industries' Terra acquisition and decreased domestic gas prices.
c) The third break in September 2016 likely occurred because of expansion in US production capacity of fertilizer, high corn supply, and the merger between Agrium and Potash Corp.
d) The period after the last structural break beginning around October 2019 covers the COVID-19 pandemic and price increases from Eastern European conflicts and related natural gas disruptions.[2]

Urea structural breaks

When considering urea prices, we find four different structural breaks: (*a*) February 2000; (*b*) April 2008; (*c*) January 2011; and, (*d*) June 2013. Although anhydrous ammonia and urea are substitute inputs, they are affected by different factors. Breaks (*a*) and (*b*) in 2000 and 2008 likely occurred because of the shift in natural gas prices, while weather conditions likely caused breaks (*c*) and (*d*) in 2011 and 2013, respectively.

Pass-through

We also estimate pass-through rates of natural gas and corn price changes to anhydrous ammonia and urea prices. Based on structural changes, we examine five periods in the pass-through tests.

Period	Ammonia	Urea
1	Jan. 1997 – May 2007	Jan. 1997 – Jan. 2000
2	June 2007 – Oct. 2009	Feb. 2000 – Mar. 2008
3	Nov. 2009 – Aug. 2016	Apr. 2008 – Dec. 2010
4	Sept. 2016 – Sept. 2019	Jan. 2011 – May 2013
5	Oct. 2019 – Feb. 2022	June 2013 – Feb. 2022

The statistical evidence points to the variation in Henry Hub natural gas prices as the major contributor to the shift in anhydrous ammonia prices during the pre-November 2009 period. However, ammonia prices instead depend more on international natural gas prices afterward, most likely due to high import reliance and relatively high international natural gas prices. The transmission of corn price changes on ammonia prices increased in June 2007, reflecting higher global demand for ethanol. Although the impact of corn prices gradually declined,

[2] A note on the precision of the dates in the structural analysis. Although October 2019 precedes the worldwide shutdown from the pandemic, the monthly dates should be taken as approximations. The statistical analysis looks for a "best guess" and the true break could be a few months before or after the given date.

its effect on ammonia prices regained with a counter-effect from natural gas prices at the Intercontinental Exchange based in the United Kingdom (ICE) after September 2019.

The impacts of natural gas and corn price changes on urea prices are less consistent across methods and specifications. International natural gas prices relate more to urea prices than do domestic prices before 2000. After that, urea prices rely more on Henry Hub natural gas prices. In spite of inconsistent results, corn price changes began playing a critical role in the shift in urea prices in 2011.

The positive pass-through of corn prices to ammonia prices in periods 2, 3, and 5 and urea prices in period 4 might possibly be due to market power in the US fertilizer industry as fertilizer prices follow its marginal product. However, the results vary across time, methods, and model specifications. While the pass-through estimation considers the contemporaneous change until three-month lagged effects, VEC and VAR regressions include only one-month lagged of the dependent variables. The Granger causality tests on the VEC and VAR models suggest corn price changes have no direct impact on ammonia prices in any period, even though we find an indirect effect.

Fertilizer prices are likely to rely more on input costs than output prices most of the time. In recent years, anhydrous ammonia prices depended on international natural gas prices, while urea prices rely more on domestic natural gas prices. Additionally, ammonia prices track more closely the changes in these three price factors, while other missing factors seem to affect urea prices.

Section 3. Potential long-run and other market factors

As supply chains improve, ports reopen, labor becomes more available, and energy prices ease, the expectation is that fertilizer prices will decline in the second half of 2022 as producers gear up production. However, this does not mean that prices will return to "normal" levels as several factors could prevent fertilizer prices from going back to their mid-2020 level. Figure 8 shows a selection of bi-weekly fertilizer prices in Iowa where, as discussed in previous sections, one can see the increase in prices for all types of fertilizers since fall of 2021.

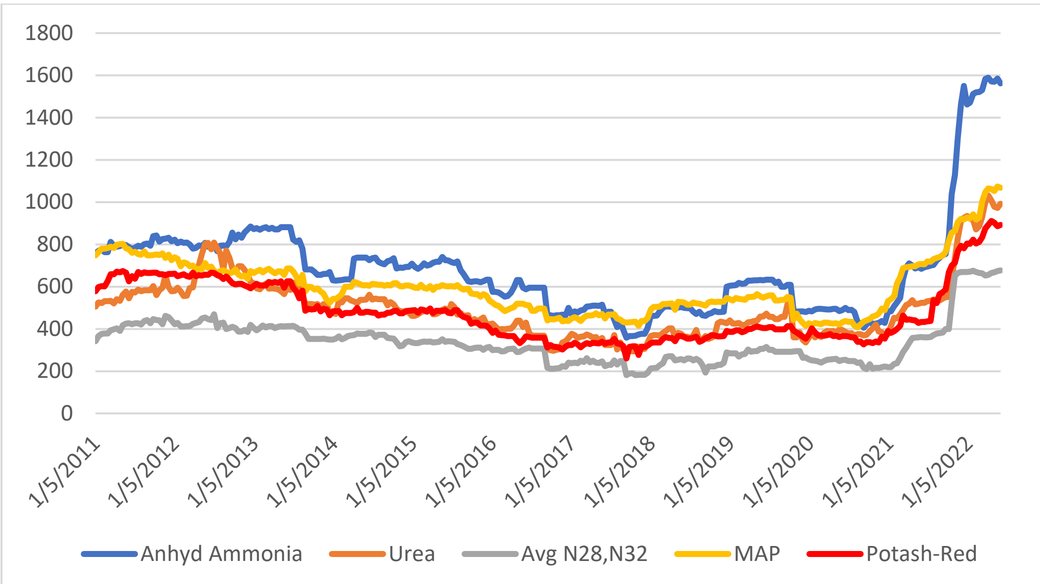

Figure 8. Selected Iowa fertilizer prices (Average dollar per ton).

Notes: In weeks of missing data, we extrapolate prices from prior three-week and post three-week average prices.
Source: USDA-AMS, https://mymarketnews.ams.usda.gov/viewReport/2863, various reports.

Factors to consider in the short and longer term include natural gas demand and supply, changes in trade policy or economic sanctions, increased acreage demand by farmers, and potential market power in the fertilizer industry.

Despite earlier declines in EU gas prices, high natural gas prices in Europe will likely persist due to the Russia-Ukraine war and climate change regulations. The EU household and industrial sectors use natural gas to generate electricity and heat. Additionally, leading up to the Russia-Ukraine war, the European Union had become highly dependent on Russian gas with 44% of EU gas imported from Russia in 2020. Within the past few months, Europe has relied more on US exports of liquefied natural gas, putting pressure on the US market. Meanwhile, many countries see natural gas as a greener source of energy than coal and oil. As climate regulations become stricter and more firms look to source energy from greener sources, demand for natural gas will likely rise, at least in the near term, causing higher global natural gas prices.

On the trade front, domestic manufacturers can and have requested tariffs on fertilizer imports to reduce what they see as unfair foreign competition. The United States lifted its previous anti-dumping duties on ammonium nitrate and urea imports from Russia in August 2016; however, in March 2021, Mosaic Co. petitioned for tariffs on phosphate imports from Russia and Morocco. Meanwhile, CF Industries has filed a complaint on UAN imports from Russia and Trinidad and Tobago. If the United States implements anti-dumping and countervailing duty on these imports, they will last for at least five years and add an extra cost of $12.78 per acre of farmland (Bergmeier 2022). The US Department of Commerce could impose UAN tariffs following the preliminary results from its report on the market price of fertilizer imports from Russia and Trinidad and Tobago.

High crop prices could also spur farmers into increasing acreages and/or farming their acreages more intensively. Smith (2022, p. 4) finds this a "plausible factor behind rising fertilizer prices." If fertilizer companies are responding to perceived increases in demand, the increased prices seen today could reflect an expectation of demand tomorrow. Crespi, Saitone, and Sexton (2012) and Sexton (2013) argue that there seems to be at times a symbiotic relationship between agribusinesses and farmers that stifles firms from fully exercising short-term market power for fear of losing longer run relations. While the USDA looks to ease the burden on farmers through credit and other policies, it could signal all input suppliers that they can either raise prices or lower them less slowly without harming farmers.

Market power: "Greedflation"?

The conventional wisdom among non-economists is that large firms in highly concentrated industries exert their power over the markets in ways that highly competitive smaller firms would not and that such market power harms buyers. It is worth spending a little time explaining what economists mean by market power. In the context of the fertilizer industry, market power would be the ability of a firm to profitably set its fertilizer price above the firm's marginal cost of creating the fertilizer product. A firm facing strong competition (a "perfectly competitive firm") sets the price for its fertilizer close to, if not at, the firm's marginal cost of fertilizer production. In other words, the perfectly competitive firm earns just what it cost to produce the last unit of the fertilizer. This does not mean the perfectly competitive firm makes no profits, rather, in economic parlance, the firm makes no "economic profits," which are profits over and above what economists refer to as "normal profits." A monopoly, a single firm in an industry, has the greatest potential for economic profit, whereas a small firm competing against many other small firms makes the least amount of economic profit in the textbook case. When economists talk of a firm with "market power" they mean the firm is able to earn economic profit.

Where conventional wisdom and economists begin to part is that while economists agree concentration is a necessary condition for market power, they have for decades now mostly abandoned the assertion that concentration is sufficient for market power. While 1960s and 1970s economists might simply look for correlations between the level of concentration in an industry and the reported profits of a firm as evidence, those practices have been mostly abandoned, and, where they are still used, require a great deal of justification. Sexton and Lavoie (2001) and Crespi and MacDonald (2022) provide lengthy literature reviews of many of these early studies as well as the evolution of the profession's focus on techniques that supplanted concentration as a proxy for market power.

The reasons for the de-linkage of explicit examinations of market power and concentration are myriad, but central to many of them are the chicken-egg issue of whether an industry is concentrated because firms in the industry keep rivals from entering and/or collude and thus increase their market power or is there high concentration because the firms that remain in the industry were the most competitive and, as a result of the competition, the firms that remain are the low-price producers with less real market power. This latter argument can be compelling in two cases, both of which exist in fertilizer markets. First, in industries with significant economies of scale where the fixed costs from capital assets are a feature of production and manufacturing, costs fall as they are spread over more output. When huge economies of scale exist, fewer firms can produce more product with lower average cost. In such industries, adding firms will raise cost and shedding firms will lower cost. Secondly, in the case of a homogeneous product, such as fertilizer where branding and product differentiation is not strong, firms compete more fiercely than in the case where customers show loyalty to one brand or another. Nitrogen is nitrogen and phosphorus is phosphorus, despite the label on the package. If firms are competing in prices with a mostly identical product, buyers will seek the low-price firm whether there are 1,000 producers or four. Because of that, firms earn their profits on market share since the firm that sells the most is the most profitable. Prices will differ little and typically reflect transportation and other logistical issues instead of production costs.

One explanation of rising prices (DePillis 2022) is "greedflation." This explanation is that firms with market power are, essentially, taking advantage of worldwide inflation as a justification to raise prices more than they need to. Recently, the Biden administration argued that meat processing companies were taking advantage of market power during the pandemic's induced supply chain problems to gain abnormal profits–thus both taking advantage of and adding to inflation (Deese, Fazili, and Ramamurti 2021). Nobel laureates Joseph Stiglitz (Stiglitz 2022) and Paul Krugman (Krugman 2022) both argue independently that the recent inflation surges can also cause large firms to exploit market power. Says Stiglitz on oil companies, "But what we are seeing today is a naked exercise of oil producers' market power. Knowing that their days are numbered, oil companies are reaping whatever returns they still can." Says Krugman, "It's not foolish to suggest that some corporations have seen widespread inflation as an opportunity to jack up prices by more than their costs have increased without experiencing the usual backlash." Yet few other economists agree. Ioanes (2022) presents a recent survey of economists finding, "67 percent — disagreed or strongly disagreed with the statement, 'A significant factor behind today's higher US inflation is dominant corporations in uncompetitive markets taking advantage of their market power to raise prices in order to increase their profit margins.' Only 7 percent of those surveyed agreed or strongly agreed with the statement." The potential for market power and greedflation in today's US and global fertilizer industry has been a topic of discussion in the business and popular press (e.g., DePillis 2022; Eller 2022; Soni 2022); however, there is no recent analysis in economics journals (the most recent studies to our knowledge are mostly pre-pandemic: Hernandez and Torero 2013; Li 2016; Bushnell and Humber 2017; Bekkerman, Brester, and Ripplinger 2020). Greedflation is a possibility, but there could be other reasons for firms raising prices. It could be that in the expectation of inflation, you want to lock in profits now believing things may get much worse later, for example. Another reason could also be to raise prices when demand is strong in part to compensate the losses when demand was weak (2017 and 2018 saw low prices for fertilizer, as figure 8 shows). Bunge, Mosaic, and Nutrien have seen record profits in 2020–21 but all had losses in 2018–19.

Figure 9 shows the percentage change each month from one year ago (these are the same prices in figure 8). Inflation, measured by CPI (seasonally adjusted), also shows the same year-over-year change but with its axis on the right in order to better compare these changes. If greedflation is occurring, why are the changes diverging now, and why in earlier years did the companies not take advantage of higher inflation when the year-over-year CPI was positive but the fertilizer price changes were actually negative? The price changes are positively correlated (CPI and the fertilizer price changes have correlations around 0.8), but why not take advantage of even small changes in inflation at other times if greedflation is a symptom of market power?

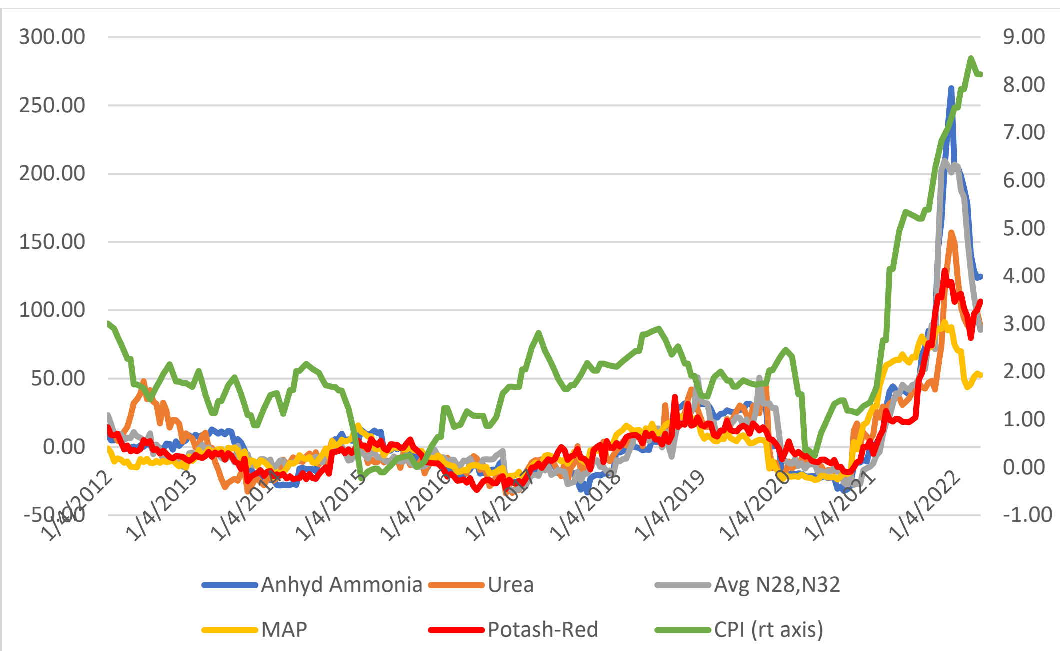

Figure 9. Year-over-year percent change in Iowa fertilizer prices compared with year-over-year percent change in inflation.

Another curiosity of fertilizer markets that goes against greedflation is that, since we began this report at the start of the year, some fertilizer prices recently fell (Wiesemeyer 2022), which the year-over-year changes in figure 9 show. It is always a curious thing if firms are exerting market power and increasing prices then suddenly reverse course. Since fertilizer market concentration has not changed, why would firms choose to stop exerting their market power? We could ask the same question a different way by looking at historical market structure. From 1997 to 2017 (the latest year for which we have data), the four-firm concentration ratio for nitrogen fertilizer manufacturing increased from 54% to 63%, and for phosphatic fertilizer manufacturing it increased from 71% to 82% (Crespi and MacDonald 2022). Both increases are around 10 percentage points, which is large but not greatly larger than their size two decades earlier. The merger to create Nutrien occurred in 2018, so why wait until 2021–22 to exert market power? If the story is simply one of concentration and "greedflation" where firms in a concentrated industry exert their market power, there are a number of observations that seem curious.

If prices increase more than costs increase, it is worth considering whether firms are exploiting market power. If Brazil has lower yields and US farmers see the price of soybeans go up with no change to their US farm costs, is that market power or supply and demand? It is possible that firms are exerting market power during this inflationary period, but with all of the impacts to fertilizer markets, it may be difficult to discern.

As discussed in Sexton and Lavoie (2001), models for testing market power directly from the data that circumvent the concentration-profit ("chicken-egg") issue exist. The challenge in testing for market power using these models is that, there are so many confounding and arguably abnormal factors recently influencing fertilizer pricing—including a plethora of supply chain disruptions from weather to fires to the pandemic to trade policy—all of which would impact the results from and the conclusions made from these market power models if researchers did not adequately account for them.

An estimating issue with many of the commonly used techniques, referred to as New Empirical Industrial Organization (NEIO) models, is that researchers must statistically estimate a firm's marginal cost based on the underlying data in order for the models to determine market power. The goal is to compare the fertilizer price with the estimate of the fertilizer manufacturer's marginal cost, since such costs are unreported. These models let the data reveal the marginal cost through sophisticated statistical techniques. Such parameterizations of the marginal cost are akin to averages over the data sample and, hence, measured with error. During the last few years, because of many of the issues hitting the food, fertilizer, and natural gas markets all at the same time, controlling for these myriad impacts would prove difficult and, it is not clear what the models might be revealing about marginal cost. As shown in section 2, we have discerned a number of structural breaks in the price and cost data. Structural breaks are an indication that "something" has fundamentally changed in the market. The concern we have is that NEIO models are quite likely to impose some sort of normality on the last few years as if marginal cost in these years were in some sense equivalent to marginal cost in previous years. Recall one issue in particular: the US government deemed fertilizer manufacturing an essential industry (Krebs 2020). This means that during the pandemic the industry continued producing as best it could while navigating labor issues, shortages, and transportation issues from other industries, some of which the US government did not deem essential. We would be skeptical of an analysis that relies upon a statistical parameterization of marginal cost using data before, during, and after the pandemic that did not take account important cost factors of the "during" phase, many of which economists are still trying to unravel. This does not mean researchers cannot perform such an NEIO analysis (indeed we are sure that they will), but researchers must be especially careful in the estimations and conclusions drawn from such models. An obvious need would be more data, unfortunately because data collection is slow, it may take years to answer whether firms exerted unusual market power during 2021/22 or whether the changes were mostly due to costs along the supply chain.

Can profitability tell us anything?

We know that after shale gas development in the United States, low natural gas prices led to an expansion in domestic fertilizer production. Even though new firms could enter the market, existing firms also expanded their production capacity, resulting in increased market concentration but also increased supplies (Bekkerman, Brester, and Ripplinger 2020). There have also been a couple of high-profile mergers within the industry, and, by 2019, the four largest firms in the United States accounted for 72% of ammonia production capacity (USGS 2021). Of the six publicly traded companies examined in this section, each financial report differs. Nutrien, because of its focus on nitrogen and potash products, breaks its reports into specific sectors and may be illustrative. Nutrien's gross manufactured margin rose by 290% on its nitrogen products between 2020 and 2021 after falling by 34% from 2019 to 2020. For potash, Nutrien's gross manufactured margin rose by 186% from 2020 to 2021 after falling by 36% from 2019 to 2020 (Nutrien 2020, 2021).

Economists are always cautious ascribing too much by simply looking at firm profitability because reported accounting profits and reported margins are not identical to the economic profits economists seek when measuring market power. Profitability can arise in concentrated industries for a variety of reasons. Margins will increase more with market power than without, but increasing margins or other increasing profitability by itself does not (necessarily) mean market power. Margins change under perfect competition as well (Wohlgenant 2001). Nonetheless, because the popular press commonly discusses profits, stock prices, and returns, tables 3, 4, and 5 present financial details for discussion.

Table 3 compares the six publicly traded fertilizer companies (top of table) with other publicly traded food and agribusiness firms. Clearly, fertilizer companies did very well in 2020 and 2021 compared to most other firms. However, they also had mostly poorer profitability in 2018 and 2019. Only three non-fertilizer companies had negative profits in either 2018 or 2019, whereas half of fertilizer companies had negative profits in those years. If you sum the net income of every firm in table 3 for all four years (approximately $291 billion from 2018 to 2021), each of the fertilizer companies averaged about 1% of the total net income, placing them near or at the bottom of the food and agricultural group (the top five were Walmart with 17% of total net income of the firms in table 3, Pepsi with 12%, JBS SA and Coca-Cola each had 11%, and McDonald's had 8%).

Although they were near the bottom in terms of net income, if you look at the growth rates, the story is different. Table 4 presents the average growth rates moving from 2018–19 to 2020–21 for each industry in table 3. The average agricultural/food industry doubled its profitability as measured by either net income or earnings per share of common stock. The fertilizer industry was third in terms of rate of growth, only slightly behind "Industrial Distribution/Ag Equipment" and "Farm Products/Food Distribution/Conglomerate."

There are two common measures of farm income: (*a*) gross farm income, which measures the total value of crop and livestock output plus government farm program payments; and, (*b*) net farm income, which reflects income after subtracting farm expenses in the current year. Over the past decade, US and Iowa farm income have seen dramatic swings: US net farm income peaked at 2013 thanks to historically low interest rates, ethanol demand, and strong agricultural exports; however, a near-50% drop in farm income over the next three years and a slow recovery since 2016 followed. Since 2019, net farm income has seen significant increase due to several unique factors. First, commodity prices are substantially higher in 2021 and 2022—the 2021 season-average corn and soybean prices are 60% and 32% higher than year ago levels, respectively, and are at the highest levels since 2013 (Zhang 2021). Second, US farmers received record-level ad hoc federal government payments from 2018 to 2022, especially from the Market Facilitation Programs and the coronavirus aid programs. The record-level $46 billion in government payments is the primary reason for 2021 US net farm income reaching its highest level since 2013. Third, despite weather challenges, the crop yields in major production regions such as Iowa remain robust and stronger than expected.

USDA's Economic Research Service forecasted in February 2022 that US net farm income will decrease by $5.4 billion or 4.5% from 2021 to $113.7 billion in 2022, which is the second-highest level since 2013 (USDA 2022). This decline is due to increases in nearly all categories of production expenses, especially feed, labor, interest, and fertilizer expenses, as well as smaller direct government payments. The ongoing Ukraine war and the continuing supply chain issues led to further increases in commodity prices as well as production costs, but the majority of producers have opportunities to lock a profit margin.

Table 4 also presents average net income returns for Iowa farms through 2021. By comparison, Iowa farmers saw a 77% return in net cash farm income. Net accrual farm income has risen even faster as the value of farm inventories jumped as well. The accrued net farm income of commercial Iowa farms averaged $341,834 in 2021. Such an income level is 170% higher in real terms than in 2020 and 66% higher than the previous peak income observed in 2012. The 2021 average cash net farm income in Iowa was estimated at $153,383, 14% higher than in 2020 and the third-highest level on record after 2012 and 2013.

Multi-year trends suggest that overall farm liquidity has improved substantially in 2021, offsetting most of the persistent erosion of liquidity observed since 2014. However, increasing input costs, cash rental rates, and the uncertainty stemming from weather variability, the war in Ukraine, and supply chain disruptions, are major risk factors in 2022 and the foreseeable future.

Table 3. Agricultural Industry Net Income from Continuing Operations ($1000s; Publicly Traded Co's), 2018/19 and 2020/21

Symbol	Company	Industry	2021	2020	2019	2018	18/19 to 20/21
BG	Bunge Limited	Fertilizer	2,078,000	1,145,000	(1,280,000)	257,000	415%
CF	CF Industries Holdings, Inc.	Fertilizer	917,000	317,000	493,000	290,000	58%
FMC	FMC Corporation	Fertilizer/Inputs	804,700	579,800	540,700	645,500	17%
MOS	The Mosaic Company	Fertilizer	1,630,600	666,100	(1,067,400)	470,000	484%
NTR	Nutrien	Fertilizer	3,153,000	459,000	992,000	(31,000)	276%
YAR.OL	Yara Intl	Fertilizer	449,000	691,000	599,000	159,000	50%
CTVA	Corteva, Inc.	Agricultural Inputs	1,812,000	736,000	(288,000)	(4,991,000)	148%
ZTS	Zoetis Inc.	Drug Manufacturers/Animal Health	2,037,000	1,638,000	150,000	1,428,000	133%
AGCO	AGCO Corporation	Farm & Heavy Construction Machinery	897,000	427,100	125,200	285,500	222%
CAT	Caterpillar Inc.	Farm & Heavy Construction Machinery	6,489,000	2,998,000	6,093,000	6,147,000	-22%
CNHI	CNH Industrial N.V.	Farm & Heavy Construction Machinery	1,723,000	(493,000)	1,422,000	1,068,000	-51%
DE	Deere & Company	Farm & Heavy Construction Machinery	5,963,000	2,751,000	3,253,000	2,368,400	55%
LNN	Lindsay Corporation	Farm & Heavy Construction Machinery	42,572	38,629	2,172	20,277	262%
ADM	Archer-Daniels-Midland Company	Farm Products	2,709,000	1,772,000	1,379,000	1,810,000	41%
TSN	Tyson Foods, Inc.	Farm Products	3,047,000	2,140,000	2,022,000	3,024,000	3%
SEB	Seaboard Corporation	Farm Products/Food Distribution/Conglomerate	570,000	283,000	283,000	(17,000)	221%

Symbol	Company	Industry	2021	2020	2019	2018	18/19 to 20/21
ANDE	The Andersons, Inc.	Food Distribution	99,662	7,710	18,307	41,484	80%
SYY	Sysco Corporation	Food Distribution	524,209	215,475	1,674,271	1,430,766	-76%
CAG	Conagra Brands, Inc.	Food Manufacturing	1,298,800	840,100	680,200	794,100	45%
ACI	Albertsons Companies, Inc.	Grocery Stores	1,619,600.00	850,200.00	466,400.00	131,100.00	313%
KR	Kroger Co.	Grocery Stores	1,655,000	2,585,000	1,659,000	3,110,000	-11%
WMT	Walmart, Inc.	Grocery Stores	13,673,000	13,510,000	14,881,000	6,670,000	26%
TITN	Titan Machinery Inc.	Industrial Distribution/Ag Equipment	66,047	19,356	13,953	12,182	227%
HRL	Hormel Foods Corp.	Packaged Foods	908,839	908,082	978,806	1,012,140	-9%
KR	Kellogg Company	Packaged Foods	1,655,000	2,585,000	1,659,000	3,110,000	-11%
GIS	General Mills, Inc.	Packaged Foods	2,339,800	2,181,200	1,752,700	2,131,000	16%
JBSAY	JBS S.A.	Packaged Foods	20,486,561	4,598,311	6,068,368	25,199	312%
KHC	Kraft Heinz Co.	Packaged Foods	1,012,000	356,000	1,935,000	(10,192,000)	117%
PEP	PepsiCo, Inc.	Packaged Foods/Beverages—Non-Alcoholic	7,618,000	7,120,000	7,314,000	12,515,000	-26%
KO	Coca-Cola Co.	Packaged Foods/Beverages—Non-Alcoholic	9,771,000	7,747,000	8,920,000	6,685,000	12%
YUM	Yum! Brands, Inc.	Restaurants	1,575,000	904,000	1,294,000	1,542,000	-13%
DRI	Darden Restaurants	Restaurants	632,400	(49,200)	718,600	603,800	-56%
MCD	McDonald's Corp.	Restaurants	7545200	4730500	6025400	5924300	3%

Notes: Years reflect annual financial statements for the given calendar year. Net income is from continuing operations. We calculate percentage change from 2018/19 to 2020/21 following convention of using the absolute value of the 2018/19 net income average to account for cases of negative net income. Values differ from a similar table by Wongpiyabovorn, Hart, and Crespi (2022) for this reason.
Source: Yahoo! Finance (www.yahoofinance.com) including industry definitions other than the category of "fertilizer."

Table 4. Percentage Change 2018/19 to 2020/21 by Industry

Industry	Net Income	EPS
Fertilizer	217%	222%
Other Inputs	148%	149%
Drug Manufacturers/Animal Health	133%	136%
Farm & Heavy Construction Machinery	93%	95%
Farm Products	153%	154%
Farm Products/Food Distribution/Conglomerate	221%	222%
Food Distribution	2%	-9%
Food Manufacturing	45%	29%
Grocery Stores	109%	115%
Industrial Distribution/Ag Equipment	227%	222%
Packaged Foods	85%	97%
Packaged Foods/Non-Alcoholic Beverages	-7%	-7%
Restaurants	-22%	-21%
ALL INDUSTRIES	**98%**	**100%**
Average Iowa Farm	**77%**	**na**

Notes: “na” not applicable. See notes from table 3. EPS is earnings per share calculated as net income from continuing operations divided by common shares outstanding. We base Iowa farm net income on Iowa Farm Business Association data summarized by ISU Extension utilizing net cash farm income for 2018 and 2021 (https://www.extension.iastate.edu/agdm/wholefarm/pdf/c1-10.pdf).

Table 5. End-of-Year Average Stock Price Changes, 2018/19 to 2020/21

Fertilizer Industry	Stock Price Chg	Beta (6/3/22)
Bunge Limited (BG)	54%	0.49
CF Industries Holdings, Inc. (CF)	28%	1.02
FMC Corporation (FMC)	42%	0.81
The Mosaic Company (MOS)	25%	1.57
Nutrien (NTR)	42%	0.81
Yara Intl (YAR.OL)	34%	0.39
Other Large Cap Firms		
WalMart (WMT)	34%	0.50
Amazon (AMZN)	68%	1.23
Market Index		
S&P 500 Index	40%	na
Average Iowa Farm	Land Price Chg	
	34%	na

Notes: “na”=not applicable. See notes from table 3. Stock prices, Beta, and the S&P 500 Index come from Yahoo! Finance and are the end-of-year reported values adjusted for splits and dividends unless otherwise noted. We estimate Iowa land price changes from the 2018 and 2021 statewide values in the ISU Land Value Survey (https://www.extension.iastate.edu/agdm/wholefarm/pdf/c2-70.pdf).

Table 5 provides stock prices, risk (measured by Beta), and other returns across a variety of sectors. As measured by comparing the averages for the end of year 2018 and 2019 to the same measures for the pandemic years of 2020 and 2021, returns vary greatly. For a comparative discussion of risk and reward, we also add two firms (Amazon and Walmart) that, unlike fertilizer producers, have a large number of products for sale; however, like fertilizer producers, they were hit with supply chain issues during the pandemic. Also, for comparison, we include the S&P 500 index, which tracks a portfolio of 500 large cap stocks led by technology giants.

The fertilizer industry average net income return (table 4) was actually higher than that of Walmart and Amazon; however, investors rewarded Amazon and Walmart in terms of average stock price returns (table 5) at the end of the year (from a high of 51% for Bunge to a low of 25% for Mosaic and 31% on average for the fertilizer group vs. 51% on average for Amazon and Walmart). At the end of 2021, the fertilizer group's average stock return (31%) was also lower than the return of the S&P 500 (40%).

Net income (table 4) and stock prices (table 5) are not the same thing as measures of economic profit that account for market power; however, they provide insight into how investors look at the companies. Stock prices, especially, reflect what investors think the potential for earnings are, and stock price returns for these companies before and during the pandemic should reflect investors' broader market perceptions of each firm's risk and return. The takeaway from examining stock price returns is that the fertilizer industry is similar to the broader market from an investment return perspective.

What about risk? As measured by each firm's five-year Beta in table 5, all fertilizer firms except Mosaic are less than or as risky as a large portfolio (theoretical Beta of 1). With an average Beta of 0.84, fertilizer companies are arguably less risky than Amazon (Beta of 1.23) but riskier than Walmart (Beta of 0.5) and the stock price returns seem to be rewarding the risk, as expected. If investors thought the fertilizer industry could exert market power for a considerable period of time beyond the present, we might expect to see high stock returns commensurate with the high net income returns and low risk. Financial intuition is often illusory, but there is little in table 5 suggesting that investors, at least, are rewarding firms' long-run stock prospects differently for one industry or another.

Although stock prices are not available for Iowa farmers, if we examine land prices, table 5 shows that there was a 34% average increase in Iowa farmland price from 2018/19 to 2020/21 (compared with a 31% increase in the stock price of the fertilizer industry). Put simply, land value is the net present value of all discounted future income flows. With certain assumptions imposed, one could think of land value being net income divided by an interest (discount) rate.

To understand the changes in land value over time and across space, it is useful to examine how net income and interest rates will change over the next few years. Improving commodity prices, rising farm income, and lower interest rates tend to exert upward pressures on land values.[3]

For both farm income and land value gains, most of the increase in value has come over the past 18–24 months. Untangling any relations from underlying market conditions affecting all firms is difficult; however, a recent study by Outlaw et al. (2021) finds that corn farmers' incomes and fertilizer prices do seem to move together.

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[3] In a recent *Agricultural Finance Review* article, Basha, Zhang, and Hart (2021) develop an autoregressive distributed lag model that allows them to quantify the short-term and long-term impacts of farm income and interest rate changes on farmland values. Consistent with the previous literature, their main results reveal a positive and significant relationship between land values and contemporaneous gross farm income (e.g., Featherstone, Taylor, and Gibson 2017). In particular, their results show that farmland values in the three I-states (Iowa, Illinois, and Indiana) grew 1.55% with a 10% increase in contemporaneous gross farm income. In addition, the lagged farm income also contributed to an increase but to a lesser extent and is not statistically significant. In other words, their model shows that farmland market capitalization occurs quickly in response to changes in farm income induced by either government payments or commodity price fluctuations. Another heuristic analysis using the past 100 years of Iowa farmland values shows that changes in gross farm income, as opposed to changes in investor demand or interest rates, has been the primary cause for the changes in farmland values. For example, for every 10% change in gross farm income, on average, the Iowa farmland market will move in the same direction the following year by about 4%–5%.

More analysis of market power issues is needed. Simply examining profitability returns or stock prices with farm income is difficult because issues such as trade, weather, and COVID-19 are impacting farms as well as their input suppliers. We do not know enough, but we do know that the last two years have greatly impacted all markets. While profitability in the fertilizer market is certainly high, it is also high in other markets as well; and, while profitability growth rates are high, taken over a longer view, they do not seem to be unusual for all food and agricultural firms. Thus, it is difficult to discern whether firms are taking advantage of inflation at this point.

Section 4. Searching for alternative sources of nutrients

With the dramatic rise in prices for commercial fertilizer products, many farmers have sought alternative sources for the crop nutrients their crops require. Farmers have long utilized manure, which is produced as a joint product with the live-weight of animals and animal products (Roka and Hoag 1996; Ritz 2016), as fertilizer for crops and as a soil amendment (MacDonald et al. 2009). Utilizing manure for fertilizer is an efficient and potentially revenue-generating use of what otherwise would be a waste product. Additionally, given that a variety of livestock species and many operations produce manure, it serves as a source of fertilizer that is largely resilient to international shocks that have plagued the commercial fertilizer market.

Iowa ranks first in total corn production in the United States and consequently has a large need for fertilizer (USDA-NASS 2022). Iowa also produces a lot of manure. Table 6 shows Iowa animal operations and inventory for major livestock species in the state. Iowa leads the nation in egg production, has the second-most hog operations in the United States and the largest hog inventory by a wide margin, and has the most cattle feedlots and the fourth-largest cattle-on-feed inventory in the United States. Even though it is often overshadowed by the swine, egg layer, and cattle feeding sectors, other animal production has long played an important role in Iowa's diverse agriculture industry. For example, Iowa ranks in the top ten nationally for beef cow operations and inventory, milk cow operations, operations producing wool from sheep, milk goat inventory, and turkey inventory.

Table 6. Iowa Major Livestock Operations and Inventory in 2017

Commodity	Operations[1] in 2017 (Rank)	Inventory[2] in 2017 (Rank)
Cattle		
Beef cows	19,171 (9)	938,818 (10)
Milk cows	1,592 (10)	223,579 (12)
Cattle on feed	4,942 (1)	1,644,497 (4)
Hogs	5,660 (2)	22,730,540 (1)
Sheep, including lambs	2,801 (11)	167,208 (11)
Wool[3]	1,198 (7)	665,714 (12)
Goats	8,826 (26)	225,760 (16)
Milk goats	2,787 (19)	106,529 (4)
Angora goats	410 (24)	4,884 (21)
Meat and other goats	6,542 (28)	114,347 (20)
Poultry		
Layers	4,425 (22)	56,554,774 (1)
Broilers	884 (19)	3,447,238 (25)
Turkeys	462 (21)	4,793,219 (8)

Source: 2017 Census of Agriculture.
[1]Operations with Inventory.
[2]December 1 Inventory.
[3]Operations with Production and Production measured in pounds.

Iowa's major production and use of manure provides opportunities for complementarities between row-crop and livestock production. A 2014 survey reveals that 98% of Iowa cattle feedlot operations apply the manure they produce to cropland they own or manage (Schulz 2014); and, nationally, 76% of hog farms in 2009 applied manure on their own farm (Key et al. 2011). There does not appear to be robust trade for manure in Iowa, which is not surprising given the survey findings. Most Iowa cattle feedlots indicate they do not sell their manure (Schulz 2014); and, nationally, only 5% of hog farms sell manure (Key et al. 2011). Earlier studies reveal that only 5% of US dairy farms and 16% of US hog farms remove manure from their operations, and any manure markets that do exist tend to be highly localized (MacDonald et al. 2009). However, in an economic environment where demand outpaces commercial nutrient supplies, and sustainability practices are front-of-mind, is a larger market for manure economically viable? And, if not, what are the roadblocks to viability?

The livestock producer's problem

Economic theory tells us that livestock producers, like all economic agents, make decisions to maximize profits while reducing costs. In the current context, we are considering decisions related to raising livestock and selling manure. We can organize our thinking regarding the decisions of a single livestock producer in the following manner:

$$\Pi(q) = pq - c(q) + fmq - dmq \tag{1}$$

where Π represents profits earned by a livestock producer from raising livestock; q represents the quantity of livestock produced; and, p is the prevailing livestock price.

Cost function $c(q)$ represents how much it costs to produce quantity q of livestock. Since it costs more to raise additional livestock at the margin (i.e., at capacity), this cost function is a so-called "U-shaped" cost function that embodies fixed costs with increasing marginal costs. This model also considers manure. Each of the q head of livestock produces m amount of manure in total, and f is the fertilizer value of the manure from a single head of livestock. Finally, it costs d to apply the manure from each head of livestock. Heuristically, this d can be thought of as the 5%–9% of total financial expenditure for cattle production that the plurality (46%) of cattle feedlots in Iowa spend on collection, storage, handling, and application of manure (Schulz 2014).

The value of f relative to d determines whether livestock manure has a positive or negative value as a co-product. Conceptually, application cost d always applies, but the value of f varies depending on prices for commercial fertilizer, whether a livestock operation has crops, and if there is a market available for manure. For livestock operations that do not have (enough) land for their manure, (excess) manure can have either a positive or negative value. If the manure can be sold for price $f > d$, then manure has a positive value overall. If $f < d$, or even worse, if there is no market for livestock manure and $f = 0$, then application costs result in manure having a negative value. In the case of operations with livestock and crops, f typically has a positive value since it serves as a revenue generator for the livestock side of the operation (or a cost-of-production reducer for crop production).

We calculate the optimal quantity of livestock the livestock producer should raise by first taking the derivative respective to variable q as:

$$\frac{\partial \Pi(q)}{\partial q} = p - c'(q) + (f - d)m \tag{2}$$

Because individual livestock producers are small relative to the total market, they cannot independently impact livestock (or fertilizer) market prices, so they will optimize by producing q^* quantity of cattle, such that their marginal cost of livestock production equals the net livestock price. This net livestock price is the price of the livestock adjusted for the fertilizer value and application cost of manure:

$$p + (f - d)m = c'(q^*) \tag{3}$$

The left-hand side of equation (3) depicts the marginal revenue of producing one more head of livestock, while the right-hand side represents the marginal cost of that additional head. As one would expect, all else equal, the optimal quantity of livestock q^* increases as livestock price p increases. Most germane to the subject of a manure market is that, as manure value f increases relative to application cost d, it becomes optimal for a livestock producer to raise more livestock. This highlights the importance of taking manure value into consideration when calculating livestock production returns and placement decisions (Roka and Hoag 1996).

An example in this case is often useful. Consider a cattle feedlot that placed $q^* = 100$ steers weighing 750 pounds in August 2021. According to the Iowa State University Extension and Outreach Estimated Livestock Returns for finishing yearling steers, total costs for producing 1,300 pound finished steers marketed in January 2022 were $1,805/head (ISUEO 2022). In equation (3), this is represented by $c'(q^*)$. In January 2022, these steers could be sold for $1,796/head, which is reflected by p. Without taking revenues from manure into consideration, this leads to a loss of almost $9/head, and a total loss of $900 (-$9/head x 100 head) on the five-month investment.

Though no publicly quoted manure market exists, it is possible to roughly approximate the value of manure as fertilizer by adding up the commercial value of the nutrients it replaces (Roka and Hoag 1996). The Estimated Livestock Returns series calculates a $16/head manure credit for cattle placed in August 2021 and closed out in January 2022. The mathematical expression $(f - d)m$ in equation (3) represents this credit. When we include it in the returns calculation, per-head profits increase to just over $7/head, or $700 on the total investment.

Figure 10 shows the calculated manure credit for feedlots marketing yearling steers and wean-to-finish hog operations from January 2015 through April 2022 (ISUEO 2022). Manure from wean-to-finish swine operations, estimated to be worth $2.64/head as fertilizer in January 2021, is now worth $9.35/head. This example highlights the critical role a manure market in the state of Iowa could play, especially when commercial fertilizer prices are high. Without a market, it is difficult to discover the true value of manure as fertilizer. Effective price discovery for manure would benefit livestock producers who may have manure to sell, and crop farmers who may want to use manure as fertilizer.

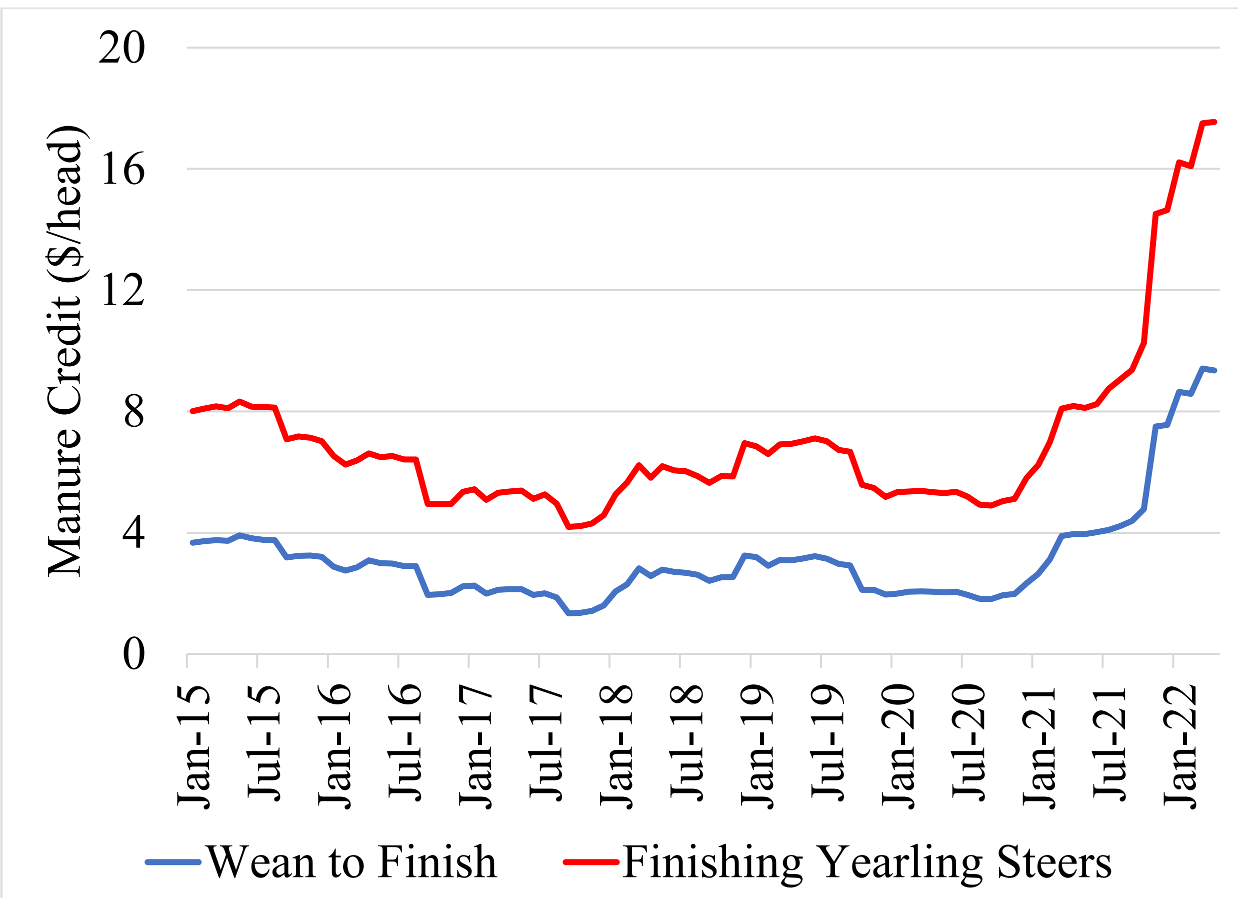

Figure 10. Estimated manure credit ($/hd) for wean-to-finish swine operations and cattle feedlots finishing yearling steers, January 2015 to April 2022.
Source: ISUEO (2022)

How much fertilizer does Iowa livestock produce?

Any market requires both buyers and sellers. It is not possible to know, with absolute precision, the supply of manure in Iowa, but it is possible to estimate *potential* supply and *potential* demand. According to estimates utilizing data from the 2012 Census of Agriculture, manure could supply about 30% of Iowa's nitrogen and phosphorus fertilizer needs (Anderson 2014). These estimates account for livestock populations, manure nutrient availability, and crop nutrient-assimilative capacity.

Farms that have both livestock and crops already utilize much of the potential manure supply. In fact, estimates using corn and soybean acreage in 2012 indicate that approximately 17% of Iowa's farmable acres received manure (Anderson 2014). In 2006, only 5% of total planted acreage received manure in the United States (MacDonald et al. 2009). However, it is possible that some of the farms are over-applying manure for the sake of disposal, and thus it could be spread on far more cropland acres (MacDonald et al. 2009). Even so, many farms might not be looking to sell any of their manure—99% of Iowa cattle feedlots indicate they have enough land to utilize the manure produced by their operations (Schulz 2014).

Shocks and trends in the livestock industry can further reduce the amount of manure that might be available. Specifically, as of June 3, the 2022 outbreak of the highly pathogenic avian influenza (HPAI) virus has affected more than 13 million birds in commercial and backyard flocks in Iowa (USDA-APHIS 2022). This reduced flock size decreases the amount of poultry manure produced in the state. The beef cattle industry is three years into the downturn of the current cattle inventory cycle and the spike in costs has been a leading factor in swine industry contraction. When livestock inventories decline so too does the manure co-product.

Opportunities and challenges

The combination of livestock and crop production in Iowa provides a unique agricultural system that leads to economic advantages from complementary production, but using livestock manure as a substitute for commercial fertilizer presents several opportunities and challenges. Table 7 highlights some of these opportunities—the highest ranked reason is because it adds to soil organic matter, and the second-highest ranked reason is that cattle feedlot manure is a good source of phosphorous.

Table 7. Major Reasons Some Crop Producers May Be Willing to Use Feedlot Manure

	Number Reporting	Mean
Adds to soil organic matter	190	4.4
Good source of phosphorus	188	4.3
Good source of other nutrients	191	4.2
Increases yields above yields with commercial fertilizer alone	191	4.2
Reduces cost of fertilizer program	191	4.2
Corrects low yielding parts of fields	192	4.2
Good source of nitrogen	192	4.0
Manure use supports feeding operations that use our corn or corn co-products	191	3.8
Less leaching loss of nitrogen with manure	191	3.6
Reduces soil erosion	189	3.6
Improves water infiltration	188	3.5
Makes the land easier to till	188	3.4
Prefer organic nutrient sources	186	3.3

Notes: Adapted from Table D11 in Schulz (2014). Respondents were asked "Do you agree or disagree that the following factors are major reasons for some crop producers to be willing to use feedlot manure?" where 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree.

Table 8 reports Iowa cattle feedlot operator ratings for why crop farmers are reluctant to use manure. The fertilizer value of manure depends on nutrient concentration, and nutrient concentration varies according to animal species, animal genetics, production management and facility type, and the details of manure collection, bedding, storage, handling, and agitation for land application (Sawyer and Mallarino 2016). Similar factors influence the total amount of manure produced by livestock (Iowa DNR 2021). Roughly 77% of fed cattle in Iowa are finished in an open lot, while only 4% are finished in a building with a slatted floor or deep pit (Schulz 2014). Open feedlots tend to have relatively low costs for manure handling, but they also have relatively low nutrient capture and value (Euken et al. 2015). By comparison, more than 90% of swine sites, and 99% of all pigs, are housed in facilities with no outside access (USDA 2015). This means that manure from hog operations will be more consistent in plant-available nutrient content than manure from cattle feedlots. As table 8 shows, unpredictable nutrient availability is a leading reason why Iowa cattle feedlot operators think crop farmers are reluctant to use manure for fertilizer. Manure nutrient analyses is recommended (Sawyer and Mallarino 2016), but table 9 shows that only 56% of Iowa feedlot operators that transfer manure off their farms offer manure analysis.

Table 8. Reasons Some Crop Producers are Reluctant to Use Feedlot Manure

	Number Reporting	Mean
Manure application causes compaction	187	3.7
Manure use is subject to too many regulations; too much book-keeping	185	3.4
Nutrient application is too uneven	184	3.3
Nutrient availability is too unpredictable	185	3.3
Manure use causes complaints of odor	186	3.2
Manure use requires too much time	185	3.2
Manure often contains unwanted material	188	3.1
Ground cover disturbed with incorporation or injection of manure	186	3.0
Manure use requires too much management	185	3.0
Manure use delays planting crops	187	2.9
Manure use causes complaints of flies	185	2.9
The cost of manure use is too high	185	2.8
Manure use causes complaints of road traffic	186	2.8
Manure use increases the risk of contaminating surface or ground water	185	2.7
Manure use causes complaints of noise	186	2.5

Notes: Adapted from Table D12 in Schulz (2014). Respondents were asked "Do you agree or disagree that the following factors are major reasons for some crop producers to be reluctant to use feedlot manure?" where 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree.

Even when exact nutrient values of manure are determined, it is important to keep in mind that not all nutrients are available for plant use right way, if ever. On the other hand, commercial fertilizers (e.g., anhydrous ammonia) contain nutrients that are ready for immediate use by crops (Sawyer and Mallarino 2016). Phosphorous and potassium contained in animal manure are estimated to be 100% available for plants (eventually), but only 30%–50% of nitrogen from beef and dairy cattle manure (solid or liquid) is available in the first year after application (Sawyer and Mallarino 2016). An additional 10% of the nitrogen is available in the second year, and 5% in the third, but not all nitrogen becomes available even as time progresses. Further reducing the effectiveness of cattle manure as a source of nitrogen is volatilization, which leads to a 15%–30% loss of nitrogen for solid manure applied using broadcast methods with no incorporation (Sawyer and Mallarino 2016). Immediate incorporation reduces this nitrogen loss to 5% or less, but only 20% of Iowa feedlots use this practice (Schulz 2014). Furthermore, as shown in table 9, no feedlot operators that transfer manure off their farms include incorporation of the manure within 24 hours.

Table 9. Agronomic Services Feedlot Operators Include with Off-Farm Transfer of Manure

	Number Reporting	**Percent Reporting**
None	10	37.0%
Soil testing	8	29.6%
Manure analysis	15	55.6%
Crop consultant services	1	3.7%
Record keeping	6	22.2%
Injection of manure	4	14.8%
Measurement of application rate	8	29.6%
Application rate adjustment for individual fields or crops	6	22.2%
Incorporation of manure within 24 hours	0	0.0%
Tillage to address compaction from manure application	1	3.7%
Other	0	0.0%
Total respondents reporting	**27**	

Notes: Statistics may reflect multiple answers. Adapted from Table D13d in Schulz (2014). Sample reflects subset of producers that typically transfer manure off their farms.

Table 10. Most Common Financial Arrangement(s) for Off-Farm Manure Transfer

	Number Reporting	**Percent Reporting**
I give away manure at no charge or payment	6	22.2%
I pay users of manure to accept manure	0	0.0%
I charge per unit volume, weight, or load	13	48.1%
I charge per unit distance manure is hauled	5	18.5%
I charge per unit of nutrients provided	4	14.8%
I charge for specific services provided	6	22.2%
Other*	6	22.2%
Total respondents reporting	**27**	

Notes: Statistics may reflect multiple answers. Adapted from Table D13c in Schulz (2014). Sample reflects subset of producers that typically transfer manure off their farms.
*Other: Trade for cornstalks (5), No answer provided (1).

Table 11. Whether Producers Partner with Other Businesses or Individuals to Transfer Manure off Farm

	Number Reporting	**Percent Reporting**
No partners	12	42.9%
Crop farmers	14	50.0%
Crop consultants	1	3.6%
Fertilizer dealers	1	3.6%
Brokers for organic products	3	10.7%
Other	0	0.0%
Total respondents reporting	**28**	

Notes: Statistics may reflect multiple answers. Adapted from Table D13b in Schulz (2014). Sample reflects subset of producers that typically transfer manure off their farms.

A number of issues related to transportation and application of manure also hinder development of a manure market. In 2006, for example, over half of US harvested crops were on farms with no livestock production, and manure can be expensive to transport even short distances (MacDonald et al. 2009). Further complicating the matter is that, as shown in table 10, 48% of Iowa cattle feedlots that sell manure charge for their manure by unit volume, weight, or load, which does not account for transportation costs. Figure 11 depicts the density of cattle and calves, hogs and pigs, and corn production in Iowa according to the 2017 Census of Agriculture and highlights the importance of manure transportation costs. Cattle production is concentrated in the northwest and northeast corners of the state. Hogs and pigs are mostly located in the northern half of the state with a large production region in the southeastern corner. By comparison, corn production is much more prevalent and uniformly distributed across the state. Even with elevated commercial fertilizer prices, not all corn acreage is located close enough to livestock operations for manure to be an economically viable fertilizer source when considering transportation costs.

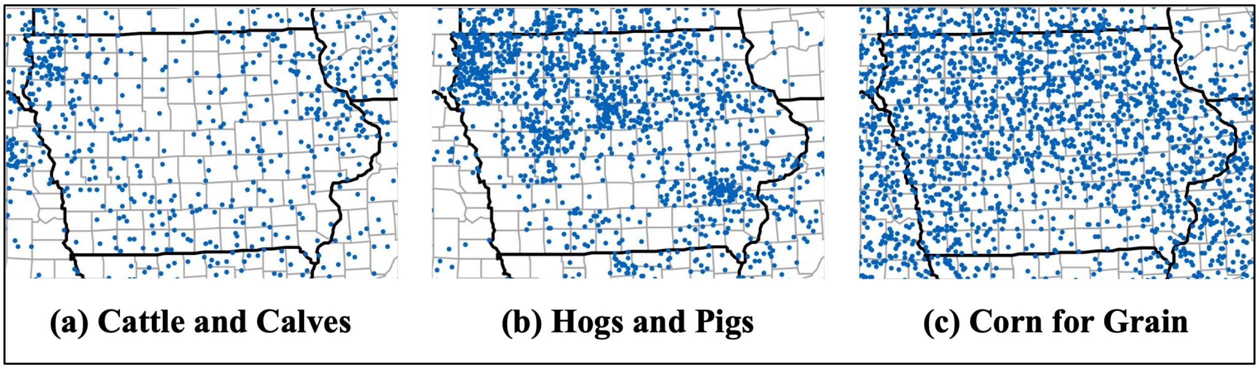

Figure 11. Density of Iowa cattle and calves inventory (1 dot = 10,000 cattle and calves), hogs and pigs inventory (1 dot = 20,000 hogs and pigs), and corn for grain harvested acres (1 dot = 10,000 acres), 2017.
Source: 2017 Census Ag Atlas Maps.

In regard to application issues, table 8 shows that compaction from manure application is perceived by Iowa cattle feedlots as the highest-ranked reason for crop producers being reluctant to use feedlot manure for fertilizer, with fewer than 9% of respondents disagreeing or strongly disagreeing with this statement (Schulz 2014). At the same time, only 4% of Iowa cattle feedlots that transferred manure off their operations in 2014 provided tillage to address compaction from manure application (table 9). The second-highest ranked reason for crop producers likely being reluctant to use feedlot manure for fertilizer is that manure use is subject to too many regulations. Manure application also requires specialized equipment and equipment operators, which subjects manure sellers to machinery and labor markets and associated challenges. All told, manure is an important but imperfect substitute for commercial fertilizer.

Moving forward

Considering these challenges, Iowa's livestock producers and crop farmers may have to adjust practices for a state-wide manure market to develop. As shown in table 11, nearly 43% of cattle feedlot survey respondents who transferred manure off their farm did not partner with anyone to do so, though partnerships between livestock producers and crop farmers, crop consultants, fertilizer dealers, and organic product brokers are possible. Livestock producers could also consider adopting agronomic services such as those listed in table 9, which would make their manure more marketable and alleviate crop farmer concerns about using manure as fertilizer. Finally, there may be an opportunity for a so-called "market maker" to enter the scene and facilitate manure transfers.

Section 5. Conclusion

The US economy is going through a substantial inflationary period. The inflationary pressures relate to supply chain disruptions, disease outbreaks, global conflicts, trade disputes, sudden demand shifts, and possibly market power. Inflation is impacting agriculture, boosting both farm revenues and costs.

One cost category has attracted particular attention for its increased pricing: fertilizer. While crop prices have roughly doubled over the past couple of years, fertilizer prices are two to four times higher than they were 18 months ago. At the request of the Iowa Attorney General's office, the staff at CARD conducted this study to examine the myriad issues impacting fertilizer markets and influencing fertilizer prices.

US and global crop production and the need for commercial fertilizer increased significantly over the past several decades. While the United States is both a major crop and fertilizer producer, US agriculture requires significant imports of fertilizer. A few key nations impact the global fertilizer markets: the United States, China, and Brazil on the consumption side and the United States, China, Russia, and Canada on the production side. Since the start of 2020, multiple issues have affected the fertilizer industry: COVID-19, supply chain issues, natural disasters, and global conflicts. Those issues provide a menu of reasons for limited supplies and higher prices.

The historical analysis finds four potential structural breakpoints for ammonia and urea pricing, but with different times for the breakpoints for each product. The breakpoints align with a variety of fertilizer supply and demand issues, such as the boosts to crop demand via biofuels, expansions of fertilizer production capacity, and company mergers. We estimate pass-through rates of natural gas and corn price changes to anhydrous ammonia and urea prices within these structural break periods. The results show the varying relationships among fertilizer, domestic natural gas, international natural gas, and corn prices. Analyses imply fertilizer prices are likely to rely more on input costs than output prices most of the time. In recent years, anhydrous ammonia prices have depended on international natural gas prices, while urea prices relied more on domestic natural gas prices.

The fertilizer industry is concentrated, though not as concentrated as other agricultural industries such as beef processing. It also has large economies of scale and the product is homogeneous. For these and other reasons, a simple correlation between recent profits and concentration is suspect. The industry suffered losses in previous years, for example, although its concentration was mostly unchanged. Because of the structural breaks and issues discussed in this report, we are cautious of analysis using traditional economic methods to discern market power. Those methods rely upon statistical parameterizations of underlying and unreported production cost components, which most certainly would have changed during the pandemic. The fertilizer industry average net income return over the past few years is high but comparable to other large industries, especially when taken over a longer run as fertilizer companies had low (sometimes negative) profits prior to 2020. The fertilizer industry's average stock price return is also comparable to that of other firms in other large industries and comparable with a large portfolio of other firms and seems to be commensurate with its relative risk. A similar comparison to Iowa farm incomes and land value returns shows that the fertilizer returns actually lag those slightly. We also find that while livestock manure can provide many of the nutrients needed from commercial fertilizers, it is still an imperfect substitute.

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Appendix

Technical analysis of structural changes in section 2

US natural gas and corn prices are likely to experience structural changes resulting from the shale gas revolution and increasing demand for ethanol, respectively, both of which impact domestic fertilizer prices. To test for stationarity of individual price series, we use the GLS-based unit root test with multiple structural breaks under both null and alternative hypotheses proposed in Carrion-i-Silvestre, Kim, and Perron (2009). Since the number of breaks in each price series is unknown, we identify the number of breaks by applying the sequential testing procedure in Kejriwal and Perron (2010). We next investigate whether the relationship among fertilizer, natural gas, and corn prices has been stable over time. Based on the stationarity test results, all price series are integrated of order 1. We then apply the tests for multiple structural breaks in linear models of Bai and Perron (1998, 2003). The tests endogenously determine the number of structural changes and estimate the breakpoints. An advantage of these methods is that they allow for serial correlation and heterogeneity in the errors when no lagged dependent variable presents as a regressor. We express the linear regression with m structural break ($m + 1$ regimes) as:

$$y_t = \boldsymbol{x}_t' \boldsymbol{\beta} + \boldsymbol{z}_t' \boldsymbol{\delta}_j + u_t \tag{1}$$

where $t = T_{j-1} + 1, \ldots, T_j$; $j = 1, \ldots, m + 1$; $T_0 = 0$, $T_{m+1} = T$, and T is the sample size; The breakpoints $(T_1, \ldots, T_m)$ are unknown.

$$S_T(T_1, .., T_m) = \sum_{i=1}^{m+1} \sum_{t=T_{i-1}+1}^{T_i} \left[y_t - \boldsymbol{z}_t' \boldsymbol{\delta}_j\right]^2 . \tag{2}$$

Denote $S_T(T_1, \ldots, T_m)$ as the sum of squares residual with the estimated parameters. We then obtain the estimates of break points by a global minimization of the sum of squared residuals:

$$(\hat{T}_1, \ldots, \hat{T}_m) = arg \min_{T_1, \ldots, T_m} S_T(T_1, \ldots, T_m)$$

We employ two classes of tests for multiple unknown structural breaks introduced by Bai and Perron (1998). The first test is the double maximum test of no structural break $(m = 0)$ versus an unknown number of structural breaks given an upper bound $(0 < m \leq M)$. The test statistics are based on $\sup F$-statistics. There are two versions of test statistics: unweighted $(UDMax\, F_T)$ test statistics with equal weights across $\sup F$-statistics; and, weighted $(WDMax\, F_T)$ test statistics with individual weights based on critical values. Another test is the sequential test of the null hypothesis of l breaks against the alternative of $l + 1$ breaks. The test focuses on the difference in the sum of squared residuals between two models. Nevertheless, the Bai and Perron tests are highly sensitive to the kind of tests, the assumption on the number of breaks, and trimming parameters (Muthuramu and Uma Maheswari 2019).

Error correction model

After identifying the number of breaks and break dates in the cointegrated regression, we explore the relationship among fertilizer, natural gas, and corn prices using time series analysis. Theoretically, a shock in the natural gas market would affect the supply of fertilizers because natural gas is the main feedstock for producing nitrogen fertilizers. Likewise, an exogenous shock in the corn market would impact fertilizer usage as corn is the major nitrogen-intensive crop. We employ a vector error correction model (VECM), which can differentiate between short- and long-run relationships. Although the previous literature finds fertilizer markets have a subtle effect on natural gas and corn prices (Beckman and Riche 2015; Bekkerman, Gumbley, and Brester 2021), the weak exogeneity test by Johansen (1988) suggests that fertilizer prices are not the sole endogenous variable in the model. Hence, we apply the VECM as the main method in this study.

Before estimating the VECM, we utilize the Johansen (1988, 1991) cointegration test to verify the presence of a cointegrating relationship. With the presence of structural breaks, we split the sample into subsamples based on the results from the structural break tests. We choose one lag length for all periods based on the Schwarz-Bayesian Information Criterion (SBIC). Then, we estimate the VECM specification with the system of four equations written as:

$$\Delta\log(Y_{i,t}) = b_{F,i}\Delta\log(F_{t-1}) + b_{HH,i}\Delta\log(P^{HH}_{t-1}) + b_{ICE,i}\Delta\log(P^{ICE}_{t-1}) + b_{Corn,i}\Delta\log(P^{Corn}_{t-1}) + \alpha ECT_{i,t-1} + \phi_i^{'}W_t + e_{i,t} \quad (3)$$

$$ECT_{i,t} = \log(F_t) - \varphi_{HH,i}\log(P^{HH}_t) - \varphi_{ICE,i}\log(P^{ICE}_t) - \varphi_{Corn,i}\log(P^{Corn}_t) \quad (4)$$

where $i \in \{F, HH, ICE, Corn\}$; $Y_{i,t}$ denotes a vector of dependent variables, consisting of F_t, P^{HH}_t, P^{ICE}_t, and P^{Corn}_t; F_t is either anhydrous ammonia (P^{AA}_t) or urea prices (P^{Urea}_t); P^{HH}_t, P^{ICE}_t, and P^{Corn}_t are the prices of Henry Hub (HH) natural gas, UK Intercontinental Exchange natural gas (ICE), and corn prices, respectively; W_t is a set of quarterly dummy variables controlling for seasonality; the parameter $b_{2,i}$- $b_{4,i}$ represents the short-run input and output price transmission elasticity; α is the speed of adjustment from the short-run deviation to the long-run equilibrium; ECT_t denotes error correction term at time *t* defined in equation (4); φ_1- φ_3 are the long-run price transmission elasticity; and, e_t is an *iid* error term. In equation (3), the first four terms on the right-hand side are vector autoregression (VAR) terms. Intercepts may be included in VAR and ECT. To achieve the best fit, we select the model specification for each period based on SBIC.

If we do not detect cointegration in a period, a VAR is more suitable than the VECM because an error correction term is not necessary when there is no long-run relationship to which the levels of the variables tend to return. As a result, we adopt the VAR method to examine the short-run relationship among the variables for the periods with no cointegration. The model specification for the VAR is the same as equation (3) without ECT term.

Pass-through estimation

We estimate the pass-through rates of the explanatory variables (natural gas and corn prices) to nitrogen fertilizer prices by employing the unrestricted distributed lag model. We incorporate the presence of multiple structural breaks by adding dummy variables representing different regimes (the first regime is the base group). In addition, we include interaction terms between the long-run relationship and time dummy if we find cointegration in a period. For simplicity, we can write the system of regressions on nitrogen prices with two regimes and one cointegration only in the second period as:

$$\Delta\log(\boldsymbol{F}_t) = \alpha + d_2 + \sum_{l=0}^{L}\boldsymbol{\delta}^1_{z,l}\Delta\log(\boldsymbol{Z}_{t-l}) + \sum_{l=0}^{L}\boldsymbol{\delta}^2_{z,l}\Delta\log(\boldsymbol{Z}_{t-l})\,d_2 + \alpha ECT_{t-1}d_2 + \phi_1'\boldsymbol{W}_t + \phi_2'\boldsymbol{W}_t d_2 + \boldsymbol{\varepsilon}_t \quad (6)$$

where F_t denotes a vector of anhydrous ammonia and urea prices, $[P^{AA}_t, P^{Urea}_t]'$, at time t; X_t represents a set of explanatory variables; W_t is quarterly dummy variables controlling for seasonality; ε_t represents error terms, $[\varepsilon^{AA}_t, \varepsilon^{Urea}_t]'$; and, d_2 is the dummy variable for the second regime. The summation of the distributed lag coefficients, $\beta^1_{PT} = \sum_{l=0}^{L}\beta^1_l$, is the cumulative pass-through to nitrogen prices in the first regime. We compute the pass-through rates of other regimes by $\beta^j_{PT} = \sum_{l=0}^{L}\beta^1_l + \sum_{l=0}^{L}\beta^j_l$, where $j = 2$. If a pass-through is complete after L periods, then $\beta_{PT} = 1$. The lag length L is three in this study.

We estimate equation (3) using seemingly unrelated regression (SUR), which allows correlation of error terms across equations. Explanatory variables include: (*a*) US natural gas futures prices; (*b*) ICE futures prices; and, (*c*) corn futures prices. Bushnell and Humber (2017) suggest the ICE price to capture the impact of international natural gas prices as countries in Eastern European and Middle East regions are some of the top exporters of anhydrous ammonia.

We include US and international natural gas prices to capture the shift in the supply side of nitrogen fertilizer production, while corn futures represent the change in demand for nitrogen fertilizers. However, these explanatory variables cannot fully explain the variation in nitrogen fertilizer prices. There are other factors that might affect fertilizer prices, for example, potential market power, changes in government regulation, and fertilizer's transportation and storage costs. In addition, the omission of the costs of transportation and storage could also result in a biased estimation. Particularly, transportation and storage costs positively relate to corn prices.

Data

Data used in this study are of monthly frequency during the period of January 1997–February 2022 (302 observations), which covers several changes in the US fertilizer industry discussed earlier. We obtain HH natural gas spot prices, which represent US natural gas prices, from the US Energy Information Administration. We use wholesale prices of anhydrous ammonia and granular urea sold within the US Corn Belt, which we obtain from Green Markets/Bloomberg, to represent nitrogen fertilizer end user price. We obtain the prices of No. 2 yellow corn nearby futures traded on the Chicago Board of Trade from Bloomberg. Additionally, we use ICE natural gas futures prices obtained from Bloomberg as international natural gas prices.

Table A1 reports the summary statistics for the dataset. Over the period, anhydrous ammonia prices are higher and more volatile on average over the entire sample than urea prices. Intuitively, ammonia contains a higher amount of nitrogen than urea and hence would carry a higher price. Meanwhile, the ICE natural gas prices averaged $6.42/MMBtu, which is greater than the mean of HH prices at $4.17/MMBtu. Table A2 shows the correlation structure across the variables for the entire sample. The correlations between international natural gas and fertilizer prices are substantially higher than those of domestic gas and nitrogen prices. In addition, corn prices highly correlate with fertilizer prices.

Table A1. Summary Statistics for the Entire Sample

Variables	Mean	Std. Dev.	Min	Max
Full sample (302 Obs):				
Ammonia	454.92	228.14	140	1,450
Urea	314.75	147.12	105	880
HH	4.17	2.14	1.63	13.42
ICE	6.42	4.58	1.19	33.84
Corn	370.05	154.90	180.25	806.50

Note: Table A1 shows the summary statistics of anhydrous ammonia, urea, HH, ICE, and corn prices. The unit of measure for nitrogen is $/short ton, for natural gas is $/MMBtu, and for corn is ¢/Bu. HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas.

Table A2. Correlation Coefficients for the Entire Sample

	Ammonia	Urea	HH	ICE	Corn
Jan 1997 – Feb 2022 (302 Obs):					
Ammonia	1				
Urea	0.93	1			
HH	0.25	0.30	1		

	Ammonia	Urea	HH	ICE	Corn
ICE	0.82	0.78	0.34	1	
Corn	0.80	0.79	-0.02	0.59	1

Note: Table A2 shows the correlation coefficients among anhydrous ammonia, urea, HH, ICE, and corn prices. HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas.

Empirical results for structural breaks

In checking for stationarity, if there are structural breaks in the price series, the conventional unit root test may not provide an accurate outcome. Hence, we identify the number of structural breaks in individual price series with the test proposed by Kejriwal and Perron (2010). We find at least one structural change in all price series over the sample period, allowing the use of a GLS-based unit root test allowing for multiple unknown structural breaks and both level and slope shifts developed by Carrion-i-Silvestre, Kim, and Perron. (2009). Although some test statistics for ICE gas prices show rejection of the null hypothesis of a unit root at the 5% significance level, all GLS-based test statistics cannot reject the null hypothesis of a unit root at the 1% significance level for all other series. Thus, we conclude that these individual series are integrated.

We find three structural breaks in the first differenced urea price and one structural break in the ICE gas price series. We do not detect a break in the other price series. Without a structural break, we can apply the Augmented Dickey-Fuller (ADF) unit root test to the first-differenced ammonia, HH gas, and corn prices. We use Carrion-i-Silvestre, Kim, and Perron's (2009) method for testing stationarity in first-differenced urea and ICE prices. The stationarity test results show a strong rejection of the null hypothesis of a unit root in the first differences of all price series. Thus, we conclude that all price series are integrated of order one or I(1), and their first differences are stationary.

We use the method outlined in Bai and Perron (1998, 2003) to test for the existence of structural breaks in the relationship among natural gas, corn, and fertilizer prices. The least-squares regressions are in the form of $\Delta\log(F_t) = \alpha + \sum_{l=0}^{3} \beta_{x,l} \Delta \log(X_{t-l}) + \phi' W_t + \varepsilon_t$, where F_t denote fertilizer prices (anhydrous ammonia or urea), X_t represents HH natural gas, ICE natural gas, and corn prices, and W_t is a set of quarterly dummy variables. The functional form is consistent with the pass-through estimation, without the presence of a long-run relationship. We only test the parameters $\beta_{x,l}$ for parameter stability. We apply the tests with 10% trimming, and the maximum number of breaks is five.

Table A3 shows the results of the Bai and Perron (1998, 2003) tests for multiple structural changes in the relationship among ammonia, natural gas, and corn prices. The stability tests with ammonia prices find four to five breaks in the relationship, with the most common number being four structural breaks. Despite the inconsistency between the break dates, we focus on the results from double maximum tests allowing for heterogeneous error distribution across regimes because these break points are consistent with the results from sequential tests.

The detected structural break in the relationship among anhydrous ammonia, natural gas, and corn prices are June 2007, November 2009, September 2016, and October 2019. The first detected break occurred in June 2007, in part, because of shale gas development and the biofuel boom. The merger agreement between CF Industries and Terra Industries in March 2010 is likely to be the main reason for the structural change in November 2009. After the third break occurred in March 2016, many production capacity expansion projects were completed, which increased domestic nitrogen production. Lastly, we find another break in October 2019, covering the period of the COVID-19 pandemic.

Table A3. Number of Breaks and Estimated Break Dates for Ammonia

Ammonia	# of Breaks Determined	Estimated Break Dates
Regressors: Henry Hub natural gas, ICE natural gas, and corn prices		
Heterogeneous error distributions		
Double Maximum test		

Ammonia	# of Breaks Determined	Estimated Break Dates
$UDMax\ F_T$	4	2007M06, 2009M11, 2016M09, 2019M10
$WDMax\ F_T$	4	2007M06, 2009M11, 2016M09, 2019M10
Sequential test		
Sequential F	5	2007M06, 2009M11, 2013M07, 2016M09, 2019M10
Homogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	4	2007M06, 2009M11, 2017M05, 2019M10
$WDMax\ F_T$	4	2007M06, 2009M11, 2017M05, 2019M10
Sequential test		
Sequential F	5	2007M06, 2009M11, 2013M07, 2016M09, 2019M10

Note: We use Bai and Perron's (1998, 2003) stability tests with a trimming percentage of 10%.

The structural break tests on urea prices in Table A4 show different outcomes with none or 4–5 structural changes. Together with the results of the tests with a 15% trimming parameter, four structural breaks are the most common outcome. Thus, we conclude that there are four structural changes in the relationship among urea, natural gas, and corn prices: (*a*) February 2000; (*b*) April 2008; (*c*) January 2011; and, (*d*) June 2013. The disparity in detected break points indicates that shocks during the sample period hit anhydrous ammonia and urea markets differently.

Table A4. Number of Breaks and Estimated Break Dates for Urea

Urea	# of Breaks Determined	Estimated Break Dates
Regressors: Henry Hub natural gas, ICE natural gas, and corn prices		
Heterogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	4	2000M02, 2008M04, 2011M01, 2013M06
$WDMax\ F_T$	4	2000M02, 2008M04, 2011M01, 2013M06
Sequential test		
Sequential F	0	-
Homogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	5	2000M07, 2004M10, 2008M04, 2011M01, 2013M06
$WDMax\ F_T$	5	2000M07, 2004M10, 2008M04, 2011M01, 2013M06
Sequential test		
Sequential F	0	-

Note: We use Bai and Perron's (1998, 2003) stability tests with a trimming percentage of 10%.

Prior to 2000, fertilizer producers operated at nearly full capacity. However, natural gas prices increased in the second half of the year due to the tight natural gas supply, leading to a halt in nitrogen fertilizer production in some areas. Low utilization rate and plant closure continued for years due to volatile natural gas prices, low fertilizer demand, and high inventory. The decline in fertilizer production and plant closure may be the reason for the structural change detected in February 2000. After a peak in HH natural gas prices in June 2008, domestic fertilizer production regained its pace, supported by high natural gas production and increased demand for biofuel. As a result, we find a structural break in April 2008.

The possible cause of the break point in January 2011 is the 2011 food crisis. In mid-2010, food prices began to increase again after a decline from the 2008 food crisis. A drought in various countries, including the southern United States, Mexico, Europe, Ukraine, and western Russia, contributed to high food prices worldwide in 2011–2012. In the United States, the severe drought continued until 2013 in most parts of the country. After March 2013, drought conditions gradually improved across the United States. As a result, fertilizer prices declined in the second half of the year, coinciding with a structural change in June 2013.

Empirical results for error correction model

Based on Bai and Perron's (1998, 2003) structural break tests, we split the database for ammonia into five subsamples, with the breakpoints June 2007, October 2009, August 2016, and September 2019. In addition, the unit root tests find that all price series are I(1), so data are suitable for the VECM. We can examine the short- and long-run impact of natural gas and corn markets on fertilizer prices using the VECM. Based on the model selection by SBIC, we include intercepts in ECT in equation (4) in the third and fifth periods (November 2009–August 2016 and October 2019–February 2022), and no constant is in either ECT or VAR terms for the rest of the periods.

Table A5 shows that the long-run relationship among fertilizer, gas, and corn prices exists in period 1 (January 1997–May 2007), period 4 (September 2016–September 2019), and period 5 (October 2019–February 2022). The number of detected cointegration is mostly consistent with the results of the weak exogeneity test on the speed of adjustment parameters in table A6. In the first and fourth periods, two variables are endogenous, even though we only find one endogenous variable in the last regime. In the first two regimes, anhydrous ammonia prices are endogenous at the 1% significance level, while HH gas prices are endogenous in the last three periods. Additionally, ICE natural gas prices are endogenous in periods 1 and 4.

Table A5. Johansen Cointegration Tests

	Trace Statistics		Max Statistics		# of Coint.
	$r = 0$	$r \leq 1$	$r = 0$	$r \leq 1$	
Period 1: Jan 97 – May 07	52.6***	24.7**	27.9**	15.3	1
Period 2: Jun 07 – Oct 09	34.4	11.6	22.9	6.9	0
Period 3: Nov 09 – Aug 16	39.9	20.3	19.6	13.4	0
Period 4: Sep 16 – Sep 19	54.8**	26.7	28.1*	10.6	1
Period 5: Oct 19 – Feb 22	53.6***	20.0	33.6***	17.2*	1

Notes: *, **, and *** denote a rejection of the null hypothesis at the 0.1, 0.05, and 0.01 significance levels, respectively. All models include quarterly dummy variables as exogenous variables and two lags. For periods 1, 2, and 4, we do not include an intercept in either ECT or VAR, while the models have an intercept in ECT in the rest of the periods. We choose model specifications for each period by SBIC.

Anhydrous ammonia prices have negative and significant adjustment parameters until October 2009. The adjustment speed of ammonia prices peaks at 48% during the second period. Meanwhile, domestic natural gas price is endogenously driven by ammonia and international gas and corn prices, with a speed of adjustment of 29%–30% during November 2009–September 2019. The adjustment speed has dropped to 9% since October 2019. In the fourth period, the international natural gas (ICE) price adjusts towards its long-run equilibrium at a half-speed of domestic natural gas (HH) prices. However, the ICE price is endogenous to the system in the first period with a positive adjustment parameter, indicating that the system is unstable and corn prices would be gradually diverting from the long-run equilibrium.

Table A6. Estimates of the Speed of Adjustment (α)

	Ammonia	HH	ICE	Corn
Period 1: Jan 97 – May 07	-0.08***	-0.11	0.30***	0.03
	(0.03)	(0.08)	(0.07)	(0.04)
Period 2: Jun 07 – Oct 09	-0.48***	0.16	0.48	0.30
	(0.14)	(0.21)	(0.39)	(0.25)
Period 3: Nov 09 – Aug 16	-0.10	-0.29***	0.12	0.01
	(0.06)	(0.11)	(0.10)	(0.09)
Period 4: Sep 16 – Sep 19	-0.06	-0.30***	-0.14*	0.03
	(0.04)	(0.08)	(0.07)	(0.04)
Period 5: Oct 19 – Feb 22	0.01	-0.09***	-0.004	0.01
	(0.01)	(0.02)	(0.03)	(0.01)

Notes: *, **, and *** denote a rejection of the null hypothesis at the 0.1, 0.05, and 0.01 significance levels, respectively. All models include quarterly dummy variables as exogenous variables and two lags. For period 3, we include an intercept in ECT, while the models include no intercept in either ECT or VAR in the rest of the periods. We choose model specifications for each period by SBIC.

Table A7 shows the long-run relationship among anhydrous ammonia, natural gas, and corn prices. HH natural gas price changes positively and significantly affect ammonia prices. Meanwhile, the increase in demand for corn due to the biofuel boom led to a rise in ammonia prices during June 2006–February 2014. In the last two periods, natural gas prices correlate with ammonia prices, after we detect no long-run relationship in the third period. International gas prices positively impact fertilizer prices, whereas the effect of domestic gas prices is negative. Intuitively, international prices also affect domestic gas prices because of the increase in international trade of US natural gas. Thus, the shift in domestic natural gas prices partially cancels out the effect of global gas price changes.

Table A7. Long-term Relationship among Ammonia, HH, ICE, and Corn Prices

Cointegrating Eq.	Ammonia	HH	ICE	Corn
Period 1: Jan 97 – May 07	1	-0.07	-0.59***	-0.84***
		(0.13)	(0.12)	(0.02)
Period 2: Jun 07 – Oct 09	1	-0.41***	-0.15**	-0.89***
		(0.08)	(0.07)	(0.02)
Period 3: Nov 09 – Aug 16	1	0.28***	-0.65***	-0.09
		(0.10)	(0.14)	(0.13)
Period 4: Sep 16 – Sep 19	1	2.20***	-0.67***	0.14
		(0.52)	(0.25)	(0.92)
Period 5: Oct 19 – Feb 22	1	15.6***	-6.07***	-1.57***
		(2.50)	(0.92)	(0.21)

Notes: *, **, and *** denote a rejection of the null hypothesis at the 0.1, 0.05, and 0.01 significance levels, respectively. All models include quarterly dummy variables as exogenous variables and two lags. We do not include an intercept for periods 1, 2, and 4 in either ECT or VAR, while the models include an intercept in ECT in the rest of the periods. We choose model specifications for each period by SBIC.

For urea, Bai and Perron's (1998, 2003) stability tests detect four structural changes: February 2000; April 2008; January 2011; and, June 2013. We perform Johansen cointegration tests and the VECM on the relationship among urea, natural gas, and corn prices. Table A8 shows that we detect one cointegration at the 5% significance level for all periods.

Table A8. Johansen Cointegration Tests of Urea, Natural Gas, and Corn Prices

	Trace Statistics		Max Statistics		# of Coint.
	$r = 0$	$r \leq 1$	$r = 0$	$r \leq 1$	
Period 1: Jan 97 – Jan 00	52.7***	20.5	32.2***	15.3	1
Period 2: Feb 00 – Mar 08	55.6**	28.8	26.8*	18.5	1
Period 3: Apr 08 – Dec 10	41.2**	10.9	30.3***	9.29	1
Period 4: Jan 11 – May 13	68.9***	39.1**	29.8**	19.3	1
Period 5: Jun 13 – Feb 22	42.9**	15.1	27.8**	14.6	1

Notes: *, **, and *** denote a rejection of the null hypothesis at the 0.1, 0.05, and 0.01 significance levels, respectively. All models include quarterly dummy variables as exogenous variables and two lags. For periods 2 and 4, we include an intercept in ECT, while the models include no intercept in either ECT or VAR in the rest of the periods. We choose model specifications for each period by SBIC.

Similar to ammonia, urea and domestic natural gas prices are the main endogenous variables in the system in the long term (see table A9). Urea prices are endogenous with negative signs in periods 2–4, while HH natural gas prices are endogenous and negative in the first and last periods. Although the speed of adjustment parameters of ICE natural gas prices are significantly negative in the first regime, international natural gas prices divert from their long-run equilibrium during the second and fourth periods. Likewise, corn prices' adjustment parameters are positive at the 90% confidence level in the second and final regimes.

Table A9. Estimates of the Speed of Adjustment (α) for Urea

	Urea	HH	ICE	Corn
Period 1: Jan 97 – Jan 00	-0.004	-0.015*	-0.04***	-0.005
	(0.005)	(0.009)	(0.01)	(0.004)
Period 2: Feb 00 – Mar 08	-0.10**	0.16	0.45***	0.10*
	(0.05)	(0.12)	(0.11)	(0.06)
Period 3: Apr 08 – Dec 10	-0.72***	0.04	0.19	-0.06
	(0.12)	(0.20)	(0.25)	(0.19)
Period 4: Jan 11 – May 13	-0.32**	0.16	0.43***	-0.08
	(0.15)	(0.16)	(0.12)	(0.15)
Period 5: Jun 13 – Feb 22	-0.04	-0.21***	-0.05	0.05*
	(0.03)	(0.04)	(0.05)	(0.03)

Notes: *, **, and *** denote a rejection of the null hypothesis at the 0.1, 0.05, and 0.01 significance levels, respectively. All models include quarterly dummy variables as exogenous variables and two lags. For periods 2 and 4, we include an intercept in ECT, while the models include no intercept in either ECT or VAR in the rest of the periods. We choose model specifications for each period by SBIC.

In the long run, both natural gas and corn prices positively relate to urea prices most of the time (see table A12). However, we find a strong negative correlation between urea and ICE gas prices during January 1997–January 2000. In addition, the regression detects some weak negative coefficients (e.g., ICE natural gas price in period 3, HH natural gas and corn prices in period 4, and HH natural gas price in the final period). These negative relationships with urea prices are likely because of positive correlations between natural gas and corn prices. Hence, their effects cancel each other out.

Table A10. Long-term Relationship among Urea, HH, ICE, and Corn Prices

Cointegrating Eq.	Urea	HH	ICE	Corn
Period 1: Jan 97 – Jan 00	1	-1.72	18.93***	-3.15***
		(2.91)	(2.96)	(0.64)
Period 2: Feb 00 – Mar 08	1	-0.34***	-0.37***	-0.45***
		(0.10)	(0.08)	(0.11)
Period 3: Apr 08 – Dec 10	1	-0.52***	0.22	-0.92***
		(0.17)	(0.16)	(0.02)
Period 4: Jan 11 – May 13	1	0.51***	-2.11***	1.56***
		(0.08)	(0.29)	(0.25)
Period 5: Jun 13 – Feb 22	1	1.29***	-0.86***	-0.91***
		(0.34)	(0.19)	(0.05)

Notes: *, **, and *** denote a rejection of the null hypothesis at the 0.1, 0.05, and 0.01 significance levels, respectively. All models include quarterly dummy variables as exogenous variables and two lags. For periods 2 and 4, we include an intercept in ECT, while the models include no intercept in either ECT or VAR in the rest of the periods. We choose model specifications for each period by SBIC.

Pass-through estimations with multiple structural changes

We can now estimate the pass-through rates to anhydrous ammonia prices with four structural breaks as in equation (6). We choose three lag lengths to measure the short-run pass-through, and we include the long-run relationships based on the results of the Johansen cointegration test in table A5. Table A11 shows the results of the pass-through estimation. In panel A, the regression contains no long-run relationship. Panels B and C report the pass-through estimates with the error correction terms included in the periods in which we find the long-run relationship at 5% (periods 1, 4, and 5) and 1% (periods 1 and 5) significance levels.

In the first regime (before mid-2007), HH price variation is the major contributor to the shift in anhydrous ammonia prices. At the same time, the impact of ICE changes is insignificant in all models. However, after adjusting for long-run equilibrium, the pass-through rate of HH natural gas price drops from 54.3% to 39.4%–39.9% in panel A. As measured by corn prices, the fluctuation in the demand-side has a negative transmission on ammonia prices, consistent with a low correlation between ammonia and corn prices. The outcomes suggest that ammonia price follows closer to its marginal costs rather than relative low corn prices in the period.

In the second regime, June 2007–October 2009, rising global ethanol demand likely supported the impact of corn price variation on ammonia prices with the pass-through rates of 61.5%–68.5%. The increase in US shale gas production and higher natural gas prices abetted a stronger pass-through of domestic natural gas price changes with a pass-through rate of 57.2%–67.8%. Meanwhile, the impact of international natural gas price changes remains insignificant.

The merger between CF Industries and Terra Industries in March 2010 and higher and more volatile corn prices during the third regime, November 2009–August 2016, contributed to a moderate pass-through of corn price changes to ammonia prices at 32%–32.2%. In contrast to the previous regimes, anhydrous ammonia prices are less sensitive to the changes in HH natural gas prices with insignificant pass-through rates of 7.2%–7.4%, corresponding to a lower average HH natural gas price at $3.53/MMBtu due to high domestic supply. Instead, the fluctuation in ICE natural gas prices induces a change in ammonia prices as much as the effect of corn price changes, potentially because of high international natural gas prices relative to domestic prices.

In the fourth regime, September 2016–September 2019, unlike the previous period, the ammonia prices did not depend on the shift in either its input or output prices. The estimates of pass-through of natural gas and corn price changes are insignificant and inconsistent across the model specifications. These results are partly due to relatively low natural gas and corn prices and volatility. Additionally, market structure might change during this period as there were many fertilizer plant capacity expansions, completed by late 2015–2017, which increased domestic fertilizer production. The merger between Agrium and PotashCorp was also finalized in January 2018.

The last regime, starting in October 2019, covered the wake of the COVID-19 pandemic when demand for natural gas was sluggish at the beginning due to the lockdowns and restrictions. However, global natural gas prices started to surge in the fall of 2021, driven by supply disruptions and low inventories. With no long-run equilibrium, domestic natural gas price changes show a strong impact on ammonia prices. On the other hand, the pass-through of HH natural gas price changes is insignificant at 14.4%–32% when we include a long-run relationship. Meanwhile, the transmission of the shift in corn prices is above 100%, but it is offset by the negative pass-through of ICE natural gas price changes. The total impact of ICE and corn price changes is between 55.6%–56.9% in the final period.

The overall pass-through rates (HH, ICE, and corn price changes) to ammonia prices are highly volatile over time. The total pass-through rates are relatively low before June 2007 because of the negative effect of corn prices. The total transmission to ammonia prices peaks at 131.8%–133.3% in the second regime as a consequence of increases in domestic natural gas supply and corn demand. The overall pass-through to ammonia prices declines to 71.6%–72.8% during November 2009–August 2016 and drops further in the following period. In the last period, beginning in October 2019, the total pass-through to ammonia prices is incomplete at 70%–71.3%. The incomplete pass-through reflects the effects of other factors, such as changes in capital costs, changes in government regulations, and an increase in transportation and storage costs.

Table A11. Pass-through Estimates of Natural Gas and Corn Price Changes to Ammonia Prices

	Jan 97 – May 07	**Jun 07 – Oct 09**	**Nov 09 – Aug 16**	**Sep 16 – Sep 19**	**Oct 19 – Feb 22**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Panel A. No long-run relationship (R^2 = 0.59)					
HH	0.543	0.424	0.072	0.011	0.831
	(0.411, 0.675)	(-0.090, 0.938)	(-0.138, 0.283)	(-0.424, 0.446)	(0.445, 1.217)
ICE	0.028	0.106	0.303	0.136	-0.087
	(-0.121, 0.177)	(-0.198, 0.409)	(0.019, 0.586)	(-0.198, 0.469)	(-0.334, 0.150)
Corn	-0.104	0.803	0.353	0.039	0.194
	(-0.367, 0.160)	(0.266, 1.341)	(0.092, 0.613)	(-0.929, 1.007)	(-0.347, 0.736)
Total	46.7%	133.3%	72.8%	18.6%	93.8%
Panel B. Long-run relationships in the periods 1, 4, and 5 (R^2 = 0.67)					
HH	0.399	0.572	0.074	0.319	0.144
	(0.252, 0.547)	(0.028, 1.115)	(-0.116, 0.263)	(-0.209, 0.848)	(-0.511, 0.80)
ICE	-0.034	0.069	0.322	-0.459	-0.650
	(-0.170, 0.103)	(-0.229, 0.366)	(0.068, 0.575)	(-1.145, 0.227)	(-1.144, -0.157)
Corn	-0.358	0.685	0.320	0.512	1.219
	(-0.634, -0.082)	(0.170, 1.20)	(0.087, 0.553)	(-0.770, 1.793)	(0.525, 1.913)
Total	0.7%	132.6%	71.6%	37.2%	71.3%
Panel C. Long-run relationships in periods 1 and 5 (R^2 = 0.66)					
HH	0.394	0.678	0.072	0.063	0.320
	(0.244, 0.543)	(0.149, 1.207)	(-0.120, 0.264)	(-0.358, 0.484)	(-0.327, 0.967)
ICE	-0.033	0.025	0.327	0.250	-0.604
	(-0.172, 0.106)	(-0.270, 0.320)	(0.068, 0.586)	(-0.063, 0.564)	(-1.108, -0.099)
Corn	-0.365	0.615	0.322	-0.352	1.160
	(-0.646, -0.085)	(0.10, 1.130)	(0.084, 0.561)	(-1.245, 0.542)	(0.454, 1.867)
Total	-0.4%	131.8%	72.1%	-3.9%	70.0%

Notes: The number in parentheses reports a 95% confidence interval. HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas. The specification includes three lags of explanatory variables and quarterly fixed effects. We estimate the results by the seemingly unrelated regression with the urea equation in table A12. Breusch-Pagan (1980) tests indicate correlated errors terms across equations in all estimations.

The structural break tests on urea prices find four different structural changes. Table A12 shows the estimates of pass-through rate to urea prices using the SUR method. Panel A shows the results with no long-run relationship included. Meanwhile, the models in panels B and C contain error correction terms in all periods and periods 1 and 4, respectively. Unlike the pass-through rates to ammonia prices, the results in table A12 are not consistent with each other, indicating the existence of other factors affecting the urea market.

In the first regime (January 1997–January 2000), the outcomes indicate that ICE price changes are the sole contributor to the shift in urea prices, coinciding with low international natural gas prices relative to domestic prices. Even though corn prices are highly correlated with fertilizer prices, we detect no significant pass-through, implying other factors driving both prices.

The impact of international natural gas prices on urea prices dissipates after January 2000. During February 2000–March 2008, the variation in HH natural gas prices positively transmitted to urea prices as natural gas prices rose (panels A and C). Meanwhile, the pass-through of corn price changes is negative and insignificant in the second period.

Corn price changes continue to have no effects on urea prices in the next period (April 2008–December 2010). Despite increased biofuel demand, corn prices failed to influence urea prices. In the meantime, the pass-through of domestic natural gas price changes is positive, but it is offset by the negative transmission of ICE gas price changes, and none of these pass-through estimates are significant.

In the fourth period (January 2011–May 2013), droughts led to higher commodity prices. The correlation coefficient between urea and corn prices was -0.39. Meanwhile, international natural gas prices ($8–$11 per MMBtu) were higher than domestic prices ($1.95–$4.54 per MMBtu) throughout the period. Likewise, urea and natural gas prices negatively correlate. The estimates of pass-through rates are sensitive to model specification. However, all outcomes are not statistically significant at a 95% confidence level, except HH and corn price changes in the model without any long-run equilibrium.

The final period started in June 2013 until February 2022, covering many changes affecting the industry, from improving drought conditions to COVID-19. Negative pass-through rates of HH price changes are significant when we ignore a long-run equilibrium. With the long-run relationship, the effect of HH price changes is trivial. The negative impact of corn price changes completely offset robust transmission of global natural gas price changes.

The total pass-through (HH, ICE, and corn prices) rates to urea prices are highly volatile and inconsistent across models. We find negative overall pass-through rates in periods 3 and 5, mainly due to natural gas pass-through. Furthermore, almost all pass-throughs are less than 50%. In comparison, the total pass-through to urea prices is generally lower than those of ammonia prices, suggesting that urea prices rely less on natural gas and corn prices. This is intuitive as urea contains less nitrogen content, and anhydrous ammonia is the primary fertilizer for growing corn.

Table A12. The Pass-through Rate of HH, ICE, and Corn Price Changes to Urea Prices

	Jan 97 – Jan 00	Feb 00 – Mar 08	Apr 08 – Dec 10	Jan 11 – May 13	Jun 13 – Feb 22
	(1)	(2)	(3)	(4)	(5)
Panel A. No long-run relationship (R^2 = 0.40)					
HH	0.221	0.365	0.176	0.649	-0.698
	(-0.021, 0.462)	(0.117, 0.613)	(-0.209, 0.561)	(0.118, 1.180)	(-1.179, -0.218)
ICE	0.165	0.145	-0.179	-0.278	0.951
	(-0.003, 0.333)	(-0.198, 0.489)	(-0.526, 0.177)	(-0.753, 0.198)	(-0.051, 1.953)
Corn	-0.115	-0.178	-0.071	0.882	0.082
	(-0.484, 0.253)	(-0.747, 0.390)	(-0.640, 0.497)	(0.316, 1.447)	(-0.760, 0.923)
Total	27.1%	33.2%	-7.4%	125.3%	33.5%
Panel B. Long-run relationships in all periods (R^2 = 0.49)					
HH	0.148	0.246	0.136	-0.049	-0.503
	(-0.090, 0.386)	(-0.069, 0.560)	(-0.307, 0.578)	(-1.033, 0.936)	(-1.264, 0.258)
ICE	0.20	0.338	-0.029	0.217	2.723
	(0.039, 0.360)	(-0.030, 0.705)	(-0.474, 0.416)	(-0.459, 0.892)	(1.296, 4.149)
Corn	-0.097	-0.334	0.253	0.278	-2.732
	(-0.444, 0.249)	(-0.995, 0.328)	(-0.691, 1.197)	(-0.741, 1.296)	(-4.391, -1.074)
Total	25.1%	25.0%	36.0%	44.6%	-51.2%
Panel C. Long-run relationships in periods 1 and 4 (R^2 = 0.44)					
HH	0.147	0.426	0.214	0.510	-0.582
	(-0.101, 0.395)	(0.183, 0.668)	(-0.159, 0.587)	(-0.841, 1.158)	(-1.050, -0.114)
ICE	0.204	0.248	-0.206	0.219	0.787
	(0.037, 0.372)	(-0.098, 0.593)	(-0.556, 0.144)	(-0.471, 0.910)	(-0.212, 1.785)
Corn	-0.10	-0.228	-0.045	-0.215	-0.28
	(-0.459, 0.258)	(-0.778, 0.322)	(-0.606, 0.516)	(-1.207, 0.776)	(-1.120, 0.548)
Total	25.1%	44.6%	-3.7%	51.4%	-7.5%

Notes: Numbers in parentheses report a 95% confidence interval. HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas. The specification includes three lags of explanatory variables and quarterly fixed effects. We estimate the results by the seemingly unrelated regression with the ammonia equation in table A11. Breusch-Pagan (1980) tests indicate correlated errors terms across equations in all estimations.

Granger causality test results

The results of the pass-through estimation report that the variation in domestic natural gas prices until October 2009 drove anhydrous ammonia prices. ICE and corn price changes are the major contributors up to August 2016. Since October 2019, the fluctuation in international natural gas prices has negatively affected ammonia prices, while corn price changes provide a positive impact.

Since the pass-through estimation assumes the presence of the impact of natural gas and corn price changes on fertilizer prices, we look further into the direction of the relationship among fertilizer, natural gas, and corn prices. We use the Wald causality test to determine the direction of the short-run impact.

Recall the VECM. We identify the short-run causality by the vector autoregressive terms, which are the first four terms on the right-hand side in equation (3).

$$\Delta\log(Y_{i,t}) = b_{F,i}\Delta\log\left(F_{t-1}\right) + b_{HH,i}\Delta\log(P_{t-1}^{HH}) + b_{ICE,i}\Delta\log(P_{t-1}^{ICE}) + b_{Corn,i}\Delta\log(P_{t-1}^{Corn}) + \alpha ECT_{i,t-1} + \phi_i^{'}W_t + e_{i,t} \quad (3)$$

The null hypothesis of the Wald causality test is the coefficient of lagged dependent variables is zero, indicating no Granger causality to Y_j to Y_i, where $i \neq j$. For example, when the null hypothesis is $H_0\!: b_{HH,AA} = 0$, rejecting the null hypothesis means HH price changes Granger cause ammonia price changes. This method can also apply to the vector autoregressive model since all tests are on the VAR terms.

The VECM and the VAR are the basis of the Granger causality test. Based on the 5% significance level, we detect a cointegration in periods 1, 4, and 5 for ammonia. Hence, we apply the causality tests to the VECM estimation in these periods (shown in table A13), and the tests are on the VAR model in periods 2 and 3 (shown in table A14). The numbers in tables A13 and A14 report the coefficients of explanatory variables, while the asterisks indicate the significance of the Granger causality Wald tests.

In the short run, the variation in HH and ICE prices in the first period drove anhydrous ammonia prices. Additionally, the impact of HH price changes on ammonia prices lasts through the next regime with an additional effect from corn price changes. The shift in corn prices indirectly affects ammonia prices via international and domestic natural gas prices. These results are consistent with the pass-through estimates in table A11 and the fact that domestic natural gas supply and corn demand increased during this period.

Despite the pass-through of ICE and corn price changes, we do not detect a short-run causality between November 2009 and August 2016. On the contrary, fertilizer, global natural gas, and corn price changes during the fourth period unidirectionally influence HH natural gas prices. In the meantime, the shift in anhydrous ammonia prices also affects corn prices.

In the most recent period, the shift in ICE natural gas prices is the sole factor in ammonia, HH, and corn price changes. Surging natural gas prices in Europe and Asia since the fall of 2021 have turned into a record high in global fertilizer prices due to lower operating rates in some plants. With the close connection with the global market, domestic natural gas prices also rose at a lower rate, causing higher production costs for domestically produced fertilizers.

The indirect effect of ICE price changes via corn prices may explain the counter-effects of ICE and corn price changes in the final period of the pass-through estimation since the Granger causality tests show that the variation in international natural gas prices positively influences both ammonia and corn prices. In addition, we find a positive correlation between ammonia and corn prices in the long term.

For urea, the Johansen cointegration tests detect a long-run equilibrium in all periods at the 95% confidence level. Hence, we perform the Granger causality test on the VECM estimations. Table A15 shows results. In contrast to the positive pass-through of ICE price changes to urea prices, the unidirectional causality runs from urea to ICE prices in the first regime. Meanwhile, both domestic and international natural gas prices directly affect the changes in corn prices at the 10% significance level.

In the second period (February 2000–March 2008), the shift in urea prices is forced by the changes in both natural gas prices, while ICE natural gas price variation was also driving domestic prices. Together with the pass-through estimation, HH natural gas prices are likely the main contributor to the fluctuation in urea prices, which are affected by the global natural gas market.

During January 2011–May 2013, high corn prices positively influenced urea prices, although the effect does not show in the pass-through estimates. In the last regime, we detect bidirectional causalities between urea and HH natural gas price changes, while international natural gas prices have a negative impact on corn prices.

The Granger causality tests suggest that the assumption that natural gas and corn price changes would affect fertilizer prices may not always be correct. However, the differences in model specifications between the VECM model and the pass-through estimation can be the reason for their inconsistent outcomes. Hence, we adopt the Wald test on the coefficients of the pass-through regression to examine whether they jointly affect fertilizer prices. Recall equation (6), which shows the pass-through equation (shown below). The short-run pass-through to fertilizer prices depends on the changes in HH, ICE, and corn prices and their lags. For the first period, the test for the impact of HH natural gas price changes is $H_0\colon \delta^1_{HH,0} = \delta^1_{HH,1} = \delta^1_{HH,2} = \delta^1_{HH,3} = 0$. From the second period on, the null hypothesis that HH natural gas price changes have no effect on ammonia prices is $H_0\colon \delta^1_{HH,0} + \delta^k_{HH,0} = \delta^1_{HH,1} + \delta^k_{HH,1} = \delta^1_{HH,2} + \delta^k_{HH,2} = \delta^1_{HH,3} + \delta^k_{HH,3} = 0$, where $k = \{2, 3, 4, 5\}$ is the number of periods.

$$\Delta\log(\boldsymbol{F}_t) = \alpha + d_2 + \sum_{l=0}^{3} \boldsymbol{\delta}^1_{z,l}\Delta\log(\boldsymbol{Z}_{t-l}) + \sum_{l=0}^{3} \boldsymbol{\delta}^2_{z,l}\Delta\log(\boldsymbol{Z}_{t-l})\, d_2 + \alpha ECT_{t-1} d_2 + \boldsymbol{\phi}_1'\boldsymbol{W}_t + \boldsymbol{\phi}_2'\boldsymbol{W}_t d_2 + \boldsymbol{\varepsilon}_t \qquad (6)$$

Table A16 shows that the results of the Wald test on pass-through coefficients for ammonia detect a higher number of causalities than the Granger causality tests. Most outcomes are consistent, whereas summing coefficients cancels out some impacts, and some effects are not on one-period lagged.

We confirm the fluctuation in HH natural gas prices as the major contributor to ammonia price variation throughout the first and second periods. While we find no Granger causality, the pass-through estimates are positive and significant during the second regime. The Wald tests report that the first-differenced corn prices and its lags jointly affect ammonia prices, mainly from the strong positive effect of the one-month lagged.

During November 2009–August 2016, we find no causality in either the VECM or VAR regression. However, the Wald tests on the pass-through estimation report the significant impact of HH, ICE, and corn price changes. The positive effect of HH price variation offsets the negative effects from its own coefficients. Meanwhile, the shift in ICE and corn prices mainly passes through within the same month.

In the fourth period, the results of no causality to anhydrous ammonia prices are consistent across methods. Likewise, both methods agree that ICE price variation affects ammonia prices in the last period, but they show opposite signs. The pass-thought estimation finds negative impacts of ICE price changes along with positive effects of corn price variation. Meanwhile, the VECM reports a positive causality from the shift in corn prices to ammonia prices.

For urea in table A17, the Wald tests are mostly consistent with the estimates of the pass-through rate. The major difference is domestic natural gas price changes also provide a positive impact on urea prices in the first period. However, the Granger causality tests show that urea and HH price changes negatively affect ICE prices. The Wald tests could not explain the inconsistency between model specifications of the pass-through estimations for urea prices.

The Wald tests on the pass-through estimation show inconsistent results with the Granger causality tests. Hence, we should not use the pass-through to identify the impact of a variable on a dependent variable without examining the direction. For ammonia, Granger causality tests suggest that we can use the pass-through estimates in periods 1, 2, 4, and 5. Meanwhile, urea prices are affected by natural gas and/or corn price changes in periods 2, 4, and 5.

Table A13. VEC Granger Causality Tests for Ammonia

	Jan 97 – May 07 (1)	Jun 07 – Oct 09 (2)	Nov 09 – Aug 16 (3)	Sep 16 – Sep 19 (4)	Oct 19 – Feb 22 (5)
HH → AA	0.11***	-0.07	0.05	0.09	0.02
ICE → AA	0.06*	0.003	-0.01	0.06	0.28***
Corn → AA	0.05	0.07	-0.04	-0.27	-0.18
AA → HH	0.16	0.22	0.09	0.56**	0.45
ICE → HH	0.17*	0.24**	0.02	-0.36*	-0.23*
Corn → HH	0.06	0.19	0.13	-0.71**	0.07
AA → ICE	0.08	0.58*	-0.01	0.10	0.37
HH → ICE	0.08	0.85	-0.10	0.10	0.08
Corn → ICE	0.39**	0.80**	0.04	0.21	0.74
AA → Corn	-0.07	0.30	0.18	0.32**	0.17
HH → Corn	-0.07	0.66*	0.10	-0.08	-0.18
ICE → Corn	0.02	-0.12	-0.01	0.07	0.20**

Notes: The number is the coefficient of the first-differenced of log of variables in the regression. *, **, and *** denote a rejection of the null hypothesis at the 0.1, 0.05, and 0.01 significant levels, respectively All models include quarterly dummy variables as exogenous variables and two lags. For period 3, an intercept is included in ECT, while the models include no intercept in either ECT or VAR in the rest of the periods. We choose model specifications for each period by SBIC.

Table A14. VAR Granger Causality Tests for Ammonia

	Jan 97 – May 07	**Jun 07 – Oct 09**	**Nov 09 – Aug 16**	**Sep 16 – Sep 19**	**Oct 19 – Feb 22**
	(1)	(2)	(3)	(4)	(5)
HH → AA	0.13***	0.56***	0.06	0.04	0.06
ICE → AA	0.06**	0.10	0.03	0.13	0.26***
Corn → AA	0.10	0.26	-0.04	-0.28	-0.20
AA → HH	0.10	0.18	-0.05	0.52*	-0.20
ICE → HH	0.18**	0.21*	0.12	0.04	0.03
Corn → HH	0.14	0.13	0.12	-0.72*	0.36
AA → ICE	0.24	0.45	0.05	0.08	0.34
HH → ICE	-0.001	0.22	-0.10	-0.02	0.05
Corn → ICE	0.18	0.61*	0.04	0.20	0.76
AA → Corn	-0.06	0.21	0.18	0.32**	0.25*
HH → Corn	-0.08*	0.27	0.10	-0.03	-0.10
ICE → Corn	0.02	-0.18	-0.02	-0.02	0.16**

Notes: The number is the coefficient of the first-differenced of log of variables in the regression. *, **, and *** denote a rejection of the null hypothesis at the 0.1, 0.05, and 0.01 significant levels, respectively. All models include quarterly dummy variables as exogenous variables and two lags. The models include no intercept in all periods. We choose model specifications for each period by SBIC.

Table A15. VEC Granger Causality Tests for Urea

	Jan 97 – Jan 00 (1)	Feb 00 – Mar 08 (2)	Apr 08 – Dec 10 (3)	Jan 11 – May 13 (4)	Jun 13 – Feb 22 (5)
HH → Urea	0.08	0.10**	-0.27*	-0.02	0.15***
ICE → Urea	0.09	0.07*	0.13	-0.15	0.07
Corn → Urea	0.02	0.01	-0.05	0.49**	-0.07
Urea → HH	-0.11	-0.12	0.04	-0.20	0.31**
ICE → HH	0.14	0.23**	0.08	0.48*	-0.04
Corn → HH	0.37	0.16	0.24	-0.05	0.02
Urea → ICE	-0.99***	0.08	0.33	-0.20	-0.14
HH → ICE	-0.54***	0.16	0.17	-0.12	0.07
Corn → ICE	0.09	0.32	0.53	-0.32*	0.29
Urea → Corn	-0.23	0.04	0.25	-0.29	0.06
HH → Corn	-0.23*	-0.06	0.05	0.19	-0.04
ICE → Corn	0.19*	-0.03	-0.08	-0.32	-0.23***

Notes: The number is the coefficient of the first-differenced of log of variables in the regression. *, **, and *** denote a rejection of the null hypothesis at the 0.1, 0.05, and 0.01 significant levels, respectively. In period 2 and 4, an intercept is included in ECT, while the models include no intercept in either ECT or VAR in the rest of periods. We choose model specifications for each period by SBIC.

Table A16. Wald Tests on the Pass-through Estimation for Ammonia

	Jan 97 – May 07 (1)	Jun 07 – Oct 09 (2)	Nov 09 – Aug 16 (3)	Sep 16 – Sep 19 (4)	Oct 19 – Feb 22 (5)
Panel A. No long-run relationship					
HH → AA	77.0***	43.8***	9.6**	1.3	26.5***
ICE → AA	2.1	7.1	12.0**	2.8	20.1***
Corn → AA	3.6	10.6**	15.1***	6.6	1.6
Panel B. Long-run relationships in the periods 1, 4, and 5					
HH → AA	49.9***	44.5***	11.8**	5.4	23.4***
ICE → AA	2.8	8.4*	16.0***	3.6	31.4***
Corn → AA	8.3*	11.1**	17.6***	5.2	13.0**
Panel C. Long-run relationships in periods 1 and 5					
HH → AA	48.3***	45.4***	10.8*	1.5	22.9***
ICE → AA	2.7	8.4*	15.8***	5.7	29.6***
Corn → AA	7.9*	9.4*	17.2***	10.5**	11.2**

Notes: *, **, and *** denote a rejection of the null hypothesis at the 0.1, 0.05, and 0.01 significant levels, respectively. All models include quarterly dummy variables as exogenous variables and two lags. For period 3, an intercept is included in ECT, while the models include no intercept in either ECT or VAR in the rest of the periods. We choose model specifications for each period by SBIC.

Table A17. Wald Tests on the Pass-through Estimation for Urea

	Jan 97 – Jan 00 (1)	Feb 00 – Mar 08 (2)	Apr 08 – Dec 10 (3)	Jan 11 – May 13 (4)	Jun 13 – Feb 22 (5)
Panel A. No long-run relationship					
HH → Urea	11.7**	12.0**	1.7	15.1***	11.0**
ICE → Urea	6.6	3.0	1.8	6.2	6.6
Corn → Urea	1.0	4.3	1.9	13.1**	2.2
Panel B. Long-run relationships in all periods					
HH → Urea	10.5**	3.7	0.9	7.7	5.1
ICE → Urea	9.6**	6.1	1.5	4.0	19.7***
Corn → Urea	1.4	4.0	2.0	3.3	10.7**
Panel C. Long-run relationships in periods 1 and 4					
HH → Urea	10.1**	15.8***	2.3	5.2	12.0**
ICE → Urea	9.3*	4.8	2.3	3.8	8.1*
Corn → Urea	1.3	5.6	1.8	4.8	3.2

Notes: *, **, and *** denote a rejection of the null hypothesis at the 0.1, 0.05, and 0.01 significant levels, respectively. All models include quarterly dummy variables as exogenous variables and two lags. For periods 2, 4 we include an intercept in ECT, while the models include no intercept in either ECT or VAR in periods 1, 3, and 5. We choose model specifications for each period by SBIC.