Evolution in the Relationship between Nitrogen Fertilizer and Natural Gas Prices in the U.S.

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Abstract

The U.S. nitrogen fertilizer industry has experienced several changes over the past two decades, such as innovation in natural gas extraction, increasing demand for corn at the global level, and mergers between fertilizer producers. In this paper, I found three structural changes in the relationship between nitrogen and natural gas prices: (i) in October 2006; (ii) in March 2010 and (iii) in October 2016. By estimating the pass-through rates to anhydrous ammonia and granular urea prices, the results show that the changes in Henry Hub natural gas price strongly influence on both ammonia and urea prices before March 2010. However, the international natural gas price instead plays a dominant role afterward, potentially because of a domestic production capacity constraint and relatively high price of international natural gas. The positive impact of corn price changes is observed between October 2006 and September due to an increase in demand for fuel ethanol.

1. Introduction

To maintain food production for the growing world population, nitrogen fertilizer is commonly applied in U.S. agriculture to support crop yields and improve product quality. Nitrogen is an essential nutrient for crops and accounted for 57 percent of total nutrient consumption in 2014. One crop that intensively uses nitrogen fertilizer is corn, which is the largest crop in the United States in 2019 (87.2 million acres planted or 36.8% of total acreage planted[1]). Corn is the main feedstock for ethanol, which is blended in transportation fuel in the United States because of its abundance and low price, and is the main feed row crop in the United States.

Natural gas is the primary input used to produce nitrogen fertilizers, typically accounting for 72%-85% of ammonia production cost (Huang, 2007). Since 2006, there has been a substantial increase in shale gas production in the U.S. due to a combination of innovations in horizontal drilling and hydraulic fracturing. The technological progress has increased domestic natural gas production, so natural gas prices eventually dropped and have remained at a historically low level since 2009.

A lower price for natural gas into nitrogen production has the potential to decrease the price of nitrogen fertilizer. However, there are two other factors that are likely to increase nitrogen prices. The first factor is global corn production expansion to meet the demand for ethanol driven by government policy and environmental concerns. In the global context, 37 industrialized countries and the European Community legally committed to reducing greenhouse gas (GHG) emissions under the Kyoto Protocol. The first commitment period of the Kyoto Protocol covered 2008 until 2012. In addition, developing countries were indirectly involved as industrialized countries were allowed to comply with the GHG reduction commitment by

[1] Estimated data as of January 10, 2020 by United States Department of Agriculture (USDA).

investing in emission-reducing projects in developing countries. As a result, the government of many countries, such as Canada, European Union member countries, India, and Brazil, have launched policies to stimulate ethanol and biofuel use and production in their countries. In the meantime, the U.S. renewable fuel standard, which sets the volume requirement of ethanol that blends in fuel used in the transportation sector, became effective in 2008. Both would increase global demand for ethanol and demand for corn, implying a potential increase in demand for nitrogen fertilizer. The second factor is the change in fertilizer market structure, specifically the horizontal mergers between CF and Terra Industries in March 2010 and between Potash Corp and Agrium in January 2018. The mergers create the potential for less price competition in the industry, possibly leading to a higher price, lower consumer surplus, and greater deadweight loss (Mortan, 2019). In addition, there are other factors that are likely to affect nitrogen prices, for instance, shifts in production capacity, changes in government regulation, and increases in storage and transportation costs.

Huang (2007) indicated that the prices of nitrogen fertilizers were closely correlated with natural gas prices during the period of 2000-2005. In contrast, more recent studies have shown that the movement of fertilizer prices has been driven by demand pressure rather than natural gas prices (Beckman and Riche, 2015; Etienne et al., 2016). The presence of a structural change in the U.S. fertilizer industry was also stressed by prior literature. From January 2001 to December 2013, Beckman and Riche (2015) found a structural change occurring in June 2008, potentially because of an increase in demand for corn. Meanwhile, Bushnell and Humber (2017) examined the data from January 1998 to January 2016 and discovered a break occurring in January 2010, the year that CF and Terra Industries combined. The inconsistent outcomes of these studies indicate that there may exist more than one structural change. To my knowledge, the prior related research has considered at most one structural break in the relationship between the prices of U.S. nitrogen fertilizer and natural gas.

This study examines two research questions. The first question is whether the relationship between natural gas and nitrogen prices changes over time? If it does, what are the major causes? Secondly, how much do natural gas and corn prices pass through to nitrogen fertilizer prices? Furthermore, how has the relationship evolved over the last two decades?

Understanding the structure of the U.S. fertilizer industry is crucial for farmers and policymakers since fertilizer is the main input of crops to improve yields. If nitrogen fertilizer and natural gas prices are not strongly correlated, the hedging of natural gas futures on nitrogen prices would be ineffective. It suggests that natural gas futures cannot be used to reduce the risk of volatile fertilizer prices. Additionally, lower natural gas prices are likely to benefit fertilizer producers in the presence of market power, rather than farmers. Higher nitrogen prices might cause higher food prices and higher transportation costs via higher corn and ethanol costs, potentially resulting in higher prices of other goods.

To examine the stability of the relationships among natural gas, nitrogen, and corn prices, I apply the tests for multiple structural changes introduced by Bai and Perron (1998, 2003). In the study, I use monthly data of anhydrous ammonia, granular urea, Henry Hub natural gas, international natural gas, and corn price series during the period of February 1997 – January 2020. Three structural changes are found: (i) October 2006; (ii) March 2010; and (iii) October 2016. The first break is partly the result of the combination of technological progress in shale gas production and an increase in global demand for corn. The second break is related to the consolidation between CF Industries and Terra Industries. Lastly, the break occurring after the third quarter of

2016 likely occurs because of high supply of corn, the merger between Agrium and Potash Corp., and increases in domestic production capacity of nitrogen fertilizers.

Then, the pass-through rates of domestic natural gas, international natural gas, and corn prices to fertilizer prices are calculated by using the seemingly unrelated regression. The results suggest that the Henry Hub natural gas price was the most influential factor on the nitrogen prices before March 2010, but it is no longer the main factor. Instead, nitrogen prices depend more on international natural gas price afterward, potentially because of relatively high prices of international natural gas prices and a domestic production capacity constraint that restricts lower cost to not pass through to final products.

The pass-through rates of the shift in input prices to anhydrous ammonia prices are highly volatile over the sample period with the highest pass-through rate at 112% during October 2006 – February 2010 and the lowest rate at 25.4% between March 2010 and September 2016. The shift in ammonia prices depends less on supply side after March 2010 possibly due to high corn prices and the merger between CF and Terra Industries. Similarly, the pass-through of input price changes to granular urea price is volatile with a high at 77% in the second period and a low at 5.3% in the latest regime. The impact of corn price changes on both ammonia and urea prices are positive during October 2006 – September 2016, reflecting increasing global demand for fuel ethanol. However, from the fourth quarter 2016, the shift in corn prices negatively affects both nitrogen prices, in part, due to a stable demand for biofuel and high maize supply that put downward pressure on corn prices.

The outcomes support the argument of more than one structural break in the relationship among anhydrous ammonia, its main input, and output prices. The incomplete and negative total pass-through to ammonia and urea prices, especially in the last regime, suggests that the presence of many other factors that likely affect the nitrogen industry, including the merger between Agrium and PotashCorp in January 2018, completion of many capacity expansion projects, the change in government regulation, and increasing costs of transportation and storage.

The remainder of this study is organized as follows. The next section provides background on the U.S. nitrogen market and related factors. Section 3 reviews the literature, and methodologies are described in section 4. Furthermore, data and summary statistics are shown in section 5. Section 6 reports empirical results, and section 7 concludes.

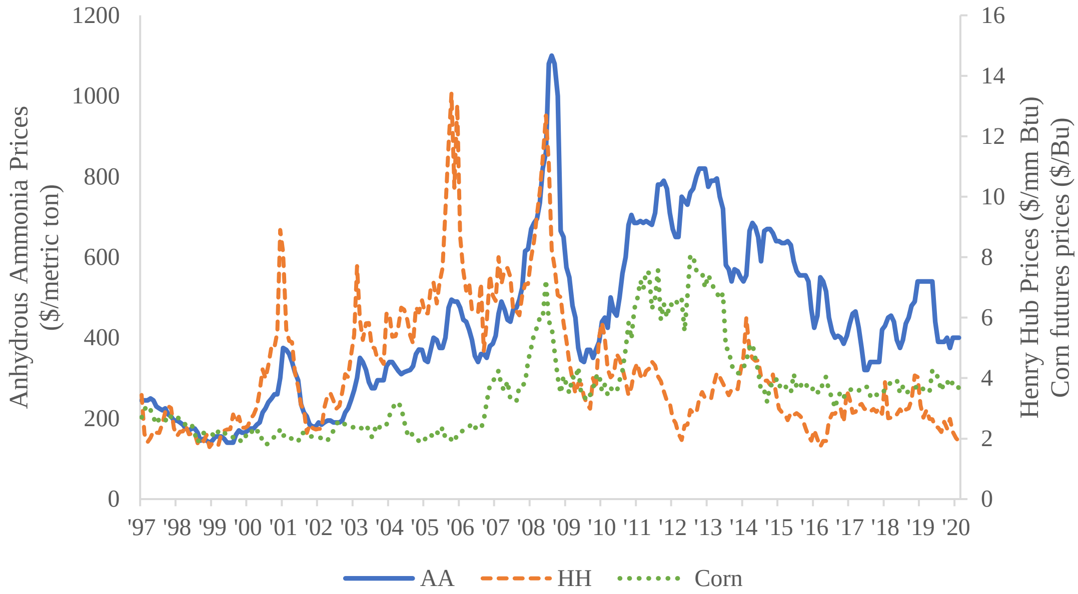
2. Background

Fertilizers are classified by their content of three principal nutrients: nitrogen, phosphorus, and potassium. In this study, I solely focus on nitrogen-based fertilizers that are intensively used in corn production, accounting for about 15-20 percent of the total operating costs of corn production.

In this paper, I consider two main types of nitrogen fertilizers: (i) anhydrous ammonia, which is a gas that is stored as a liquid under pressure; and (ii) granular urea, which is a solid product. Ammonia is the primary raw material to produce all other nitrogen fertilizers. It is also directly applied as a fertilizer due to its low production cost, high nitrogen content (82.2% nitrogen), and relative stability in soils. Anhydrous ammonia can be directly injected into the ground. Liquid ammonia then expands into a gas and is absorbed in the soil. Since anhydrous ammonia is a dangerous chemical, special equipment is required and often adds to the expense. Anhydrous ammonia is usually applied during both spring and fall.

Urea, which has the highest nitrogen content among solid nitrogen fertilizers (46.6% nitrogen), is the world's most popular nitrogen fertilizer. Granular urea is dry and highly resistant to moisture, so it is easy to transport and store. The usage of urea has surpassed and nearly replaced ammonium nitrate as fertilizer over the past decade. Unlike ammonia, granular urea is applied to the soil's surface, then combines with water to form ammonia. Nitrogen from urea, however, can be significantly lost to the atmosphere if urea remains on the soil surface during warm weather. As a result, applying urea in the fall is generally not as effective as ammonia. Typically, farmers use anhydrous ammonia during the pre-plant season, while urea is more preferred for in-season fertilizer applications.

Natural gas is the primary input for both anhydrous ammonia and urea. Due to the substantial increase in shale gas production in the U.S., the annual average domestic natural gas prices were between $2.52-4.39 per million Btu during the period of 2009 – 2019, compared to $8.86 per million Btu in 2008. Theoretically, if other factors are unchanged, a decline in natural gas prices will increase fertilizer production, and therefore, reduce fertilizer prices. Practically, however, falling domestic natural gas prices seem to have limited impacts on fertilizer prices. Figure 2.1 indicates the divergence between domestic ammonia and natural gas prices starting around 2009. Specifically, while the prices of natural gas have become lower because of the shale gas development, ammonia prices have increased. Thus, there are other factors driving the fertilizer price volatility, such as a shift to a global supply chain, an increase in crop production driven by feed and fuel needs, the volatility of prices of raw materials, and the volatility in exchange rates (Beckman, Borchers, and Jones, 2013).

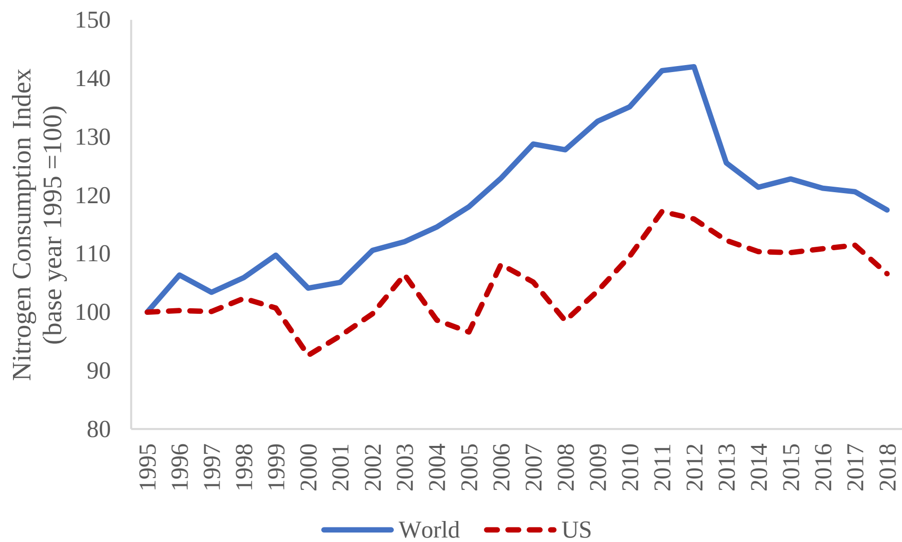


Source: EIA, Green Markets, Bloomberg

Figure 2.1 U.S. ammonia, Henry Hub natural gas, and corn prices between January 1997 – February 2020

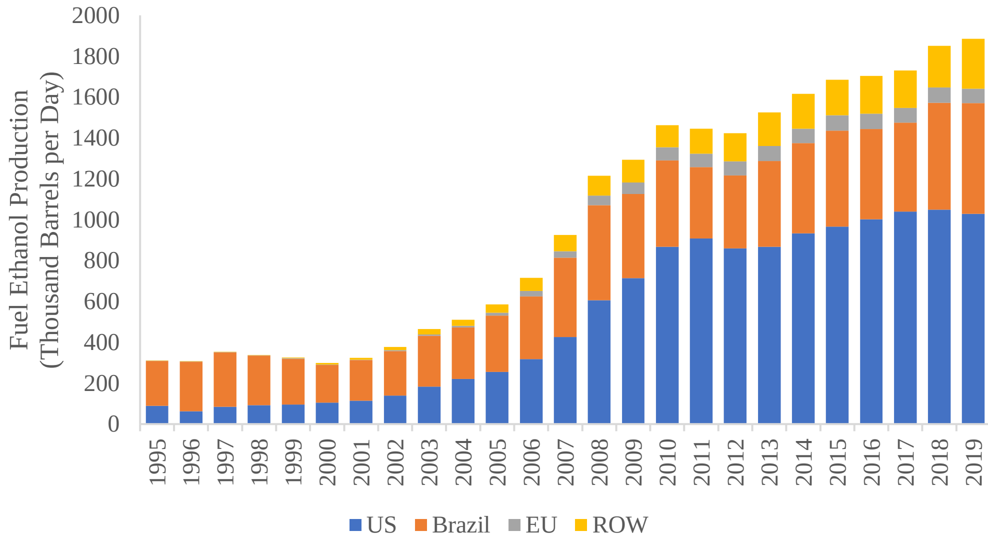
One of the most mentioned factors explaining the recent fluctuation in fertilizer prices is the expansion of fuel ethanol production, which requires higher maize and sugar cane production, leading to greater fertilizer usage. The 1990 Clean Air Act Amendments were the first U.S legislation that considered emission reductions from vehicles. U.S. ethanol production was intensified due to the U.S. renewable fuel standard (RFS) program under the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007. Starting from 2008, the U.S. Environmental Protection Agency (EPA) has set yearly volume requirements of renewable fuels to blend in automobile fuel. However, the level of U.S. nitrogen consumption barely changed due to increasing efficiency of fertilizer use. Comparing 7-year averages, the nitrogen consumption levels before and after RFS implementation were not significantly different, 12,320 thousand tons (between 2001-2007) and 12,764 thousand tons (between 2008-2014).

Compared to U.S. nitrogen consumption, the global demand for fertilizer has increased more aggressively over time. Global consumption of nitrogen had spiked since 2002 and peaked in 2012 (see figure 2.2). The move of substituting fossil fuel with ethanol globally significantly increased in the early 2000s. Accordingly, fuel ethanol production has strongly grown since 2001 with slight declines in 2011-2012 (see figure 2.3). Furthermore, the Kyoto Protocol's first commitment (2008-2012) is an international agreement that aims to reduce greenhouse gas (GHG) emissions. During the first commitment period, only 37 industrialized countries and the EU-15 agreed to reduce their emissions by an average of 5 percent compared to 1990 levels. The EU Member States adopted the Renewable Energy Sources Directive in early 2009. The Directive aimed to increase the share of renewable energy in the EU to 20% of gross final energy consumption in 2020. Additionally, it also required that at least 10% of all energy used in the transportation sector comes from renewable sources in 2020. This mainly involved biofuels, such as ethanol and biodiesel.



Source: International Fertilizer Association

Figure 2.2 U.S. and world nitrogen consumption between 1995-2018 (the base year 1995 = 100)



Source: Energy information Administration

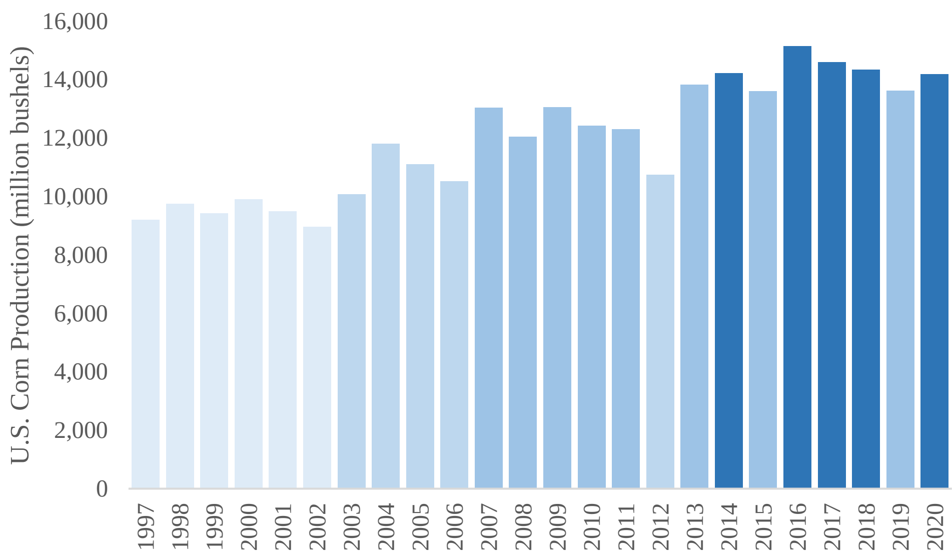
Figure 2.3 Fuel Ethanol Production by Country during 1995 – 2019

Developing countries were indirectly involved through the Clean Development Mechanism projects that allowed industrialized countries with a GHG reduction commitment to invest in emission-reducing projects in developing countries as an alternative. Many countries, such as Canada, India, and Brazil, have launched policies to stimulate ethanol and biofuel usage and production in their countries. Even though Brazil was not legally bound to cut its emission under the accord, Brazil has been one of the top ethanol producers for decades alongside the U.S., as seen in figure 2.3.

Another attempt to deal with greenhouse gas emissions internationally is the Paris climate agreement, signed on November 4, 2016, by 90 countries, including the U.S. The accord aims to keep the global average temperature rise in the 21st century well below 2 degrees Celsius above pre-industrial levels. During Trump's presidency, the U.S. withdrew from the Paris agreement, which now has 187 members. Then, on February 19, 2021, President Joseph Biden signed an executive order to rejoin the Paris agreement.

Corn-based ethanol is widely used in the U.S., while the main feedstock for ethanol in Brazil is sugarcane, which is also a heavy nitrogen user. For the EU, the primary feedstocks for ethanol production are sugar beet, wheat, and corn. Consequently, demand for nitrogen in these countries likely increases as they produce more ethanol to meet the rising demand. Consequently, higher international nitrogen prices are expected.

Figure 2.2 shows the apparent relationship between anhydrous ammonia and corn prices during 2007 – 2014 when corn prices were relatively high. The crop price surges in 2007-08 and 2010-12 were partly due to weather shocks, leading to tightening supply. Meanwhile, the relatively stable corn prices in 2015-2019 reflected the abundance of maize supply.



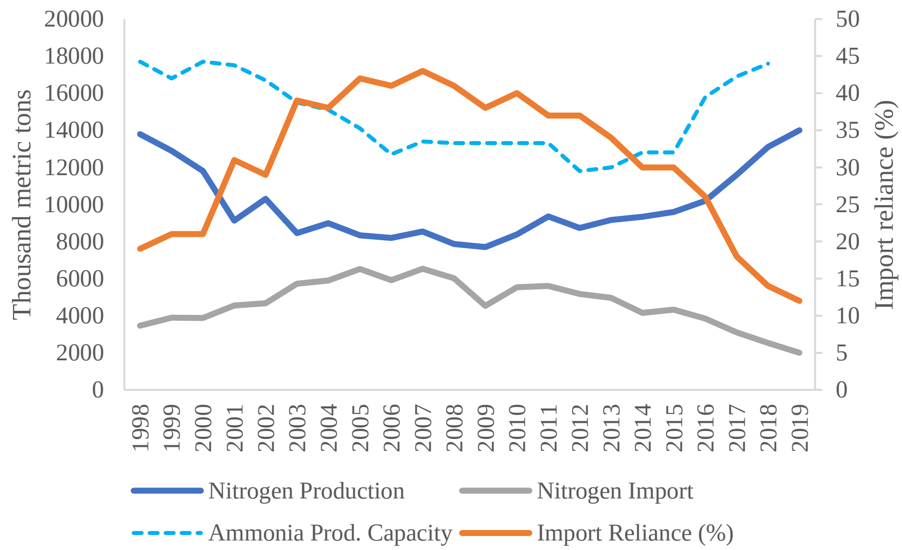
Source: USDA QuickStat

Figure 2.4 U.S. Corn production between 1997 – 2020

According to United States Geological Survey (USGS) statistics, more than 35% of U.S. nitrogen consumption had relied on imports between 2003 – 2012, with a peak at 43% in 2007. In addition, the U.S. has been one of the top importers of nitrogen fertilizer since the 1990s. In 2018, the U.S. was the largest importer of ammonia and the third-largest importer of urea. The dependency on imported nitrogen fertilizers indicates that domestic nitrogen prices may also rely on international natural gas prices.

Before 2000, U.S. ammonia production capacity had increased to 17.7 million tons. However, relatively high natural gas prices during the 2002-08 period attributed to U.S. nitrogen plant closures, resulting in declining domestic production capacity. The total production capacity of ammonia was lowest at 11.8 million tons in 2012. While domestic production of nitrogen dropped, imports increased to meet demand as seen in figure 2.5. As a result of capacity constraints of domestic producers, lower domestic natural gas prices due to the shale gas revolution seem to not translate to lower fertilizer prices in the short term, as there was strong demand for imported fertilizers (Ruder and Bennion, 2013).

Prolonged low prices of domestic natural gas due to technological progress in natural gas production led to an increase in nitrogen production capacity. In 2013, there were 14 ammonia plants proposed in the U.S., with nearly 12 million tons of new capacity. CF Industries' new urea plant in Donaldsonville, LA was completed in the third quarter of 2015, and then new ammonia and urea plants in Port Neal, IA, as well as new ammonia plants in Donaldsonville, LA, have become operational since the fourth quarter of 2016. Additionally, Koch's new 900,000 ton-per-year urea plant and a capacity increase to the existing ammonia plant in Enid, OK have started in 2017. Agrium (now Nutrien)'s capacity increased by 145,000 tons/year at their ammonia plant and a new 610,000 ton-per-year urea plant in Borger, TX, was completed in 2017. In April 2018, Iowa Fertilizer Company's new greenfield nitrogen fertilizer production facility in Wever, IA officially operated with an annual production of up to 2 million metric tons of nitrogen fertilizer products. The capacity of anhydrous ammonia production in the U.S. sharply increased to 15.8 million tons in 2016, up from 12.8 million tons in 2015. As shown in figure 2.5, nitrogen production has accordingly increased since 2016, while the imports of nitrogen have decreased, implying lower U.S. import reliance over time.



Source: United States Geological Survey

Figure 2.5 U.S. nitrogen production, import, and import reliance during 1998 – 2019

There are signs of increasing concentration in the U.S. nitrogen fertilizer market over time. The number of companies in the U.S. anhydrous ammonia industry declined from 58 firms in 1976 to 27 firms in 2000 and the total number of plants reduced to 39, from 113 plants during the same period. In March 2010, CF Industries and Terra, who were previously the second and first largest U.S. firms by production capacity, were successfully combined. 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 U.S. 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, called Nutrien, is the largest producer of potash, as well as the second largest producer of nitrogen fertilizer in the U.S. In the North American marketplace, Nutrien controls nearly two-thirds of the potash capacity, 30 percent of phosphate production, and 29 percent of nitrogen capacity.

Other factors that would affect retail nitrogen prices are transportation and storage costs. Anhydrous ammonia is required to transport under pressure, while dry urea is easier to transport. Truck, rail, barge, and ocean vessels can be used to ship nitrogen products. In addition, anhydrous ammonia can also be transported via pipeline. Fertilizer producers usually sign a long-term contract with minimum volume commitments of ammonia shipped via pipeline. Therefore, the pipeline tariff is relatively fixed over the contract period. Rail was one of the main modes of anhydrous ammonia transportation. In 2007, 3.9 million tons of it was shipped by rail, whereas 1.7 million tons by barge. According to U.S. Bureau of Labor Statistics, the changes in producer price indices of rail and truck transportation between 2004 – 2019 were in the same direction. However, the change for rail freight rate was more aggressive, relative to truck rate change. Compared to the 2004 price, rail carriers increased their charge 74.5% by 2019, while truck only charged 42.2% more. Unlike transportation costs, the price of warehousing and storage only increased 6.1% in 2019 from the price in 2007.

3. Literature Review

Early research has found that historical prices of nitrogen fertilizers were closely related to natural gas prices during the period of 2000-2005 (Huang, 2007). However, more recent studies have shown that the movement of fertilizer prices has been driven by the changes in fertilizer demand, particularly increasing demand for corn, rather than natural gas prices. Li (2016) examined the change in market competitiveness of the North American nitrogen fertilizer industry during the period of 1999 – 2011. By using a Bayesian-based time-varying parameter approach, he found that the changes in nitrogen price followed its marginal productivity closer than its marginal cost and this tended to be stronger over the post-2006 period. Moreover, the impact of capacity utilization on nitrogen price increased over time, implying the potential for higher market power in the industry caused by the capacity constraint.

Beckman and Riche (2015) have found the presence of a structural change occurring in June 2008 by using a Quandt likelihood ratio test. Particularly, the relationship between fertilizer and corn prices significantly increased after the break point. Furthermore, Bushnell and Humber (2017) have analyzed the pass-through of U.S. natural gas prices to anhydrous ammonia prices during the period of January 1998 – January 2016 by using a distributed lag regression. They found a significant shift of pass-through rate around 2010, potentially resulting from a merger of two leading producers in the fertilizer industry. The short-run pass-through of Henry Hub natural gas price changes changed from 55% in the pre-2010 period to no pass-through after 2010. Meanwhile, the pass-through of the changes in corn price increased from an insignificant number before January 2010 to 41% during the post-2010 period. The results of these studies suggested that there may exist more than one structural break in nitrogen-based fertilizer prices, caused by a decline in input prices, an increase in demand, and/or a shift in market concentration. The earlier studies have focused on at most one structural break in the U.S. fertilizer market. Moreover, some articles did not consider the potential structural break in price series when testing for unit root, as well as cointegration.

Prior literature has studied the relationships among energy, fertilizer, and corn prices using a time series approach. Humber (2014) estimated the impact of the 2010 merger by adopting a structural vector autoregressive model. The results showed that the presence of a merger increased fertilizer prices by 75 percent. In addition, the impulse response functions indicated the unidirectional causality from natural gas prices to fertilizer price and bidirectional causality between corn futures and fertilizer prices. The error correction model is the method that is often used to investigate both short- and long-run relationships among natural gas, fertilizer, and corn prices (Beckman and Riche, 2015; Etienne et al., 2016). Beckman and Riche (2015) have found that before June 2008, ammonia and corn prices had no significant relationship, while no linkage between natural gas and ammonia prices was found after June 2008. Without consideration of a structural change, Etienne et al. (2016) found that a 1% increase in the long-run average natural gas price reflects a 0.6% increase in the ammonia price, while the cross-price elasticity between ammonia and corn was close to unity during the period of 1994-2014. In the short run, a change in natural gas price has a significant impact on ammonia price, but demand pressures from the corn market failed to significantly affect ammonia prices.

In addition, there exist asymmetric volatilities in food and fertilizer prices. Specifically, when energy prices increase, commodity and fertilizer prices also rise, whereas energy prices decrease, those prices did not move together (Ott, 2012). Hernandez and Torero (2013) have shown a 10-percentage point increase in level of concentration in a fertilizer market causes urea prices to increase 8.2-16.5 percent by using a dynamic panel approach. In addition, a study of the impact of mergers on productivity and market power found little evidence of an increase in productivity, while average price markups substantially increased following a horizontal merger (Blonigen and Pierce, 2016).

These outcomes indicate the potential existence of market power in the U.S. nitrogen fertilizer industry. However, market power is not the sole reason of the unexplained divergence between nitrogen and natural gas prices. As mentioned earlier, farmers' decision of nitrogen use can be also affected by shifts in other factors, such as the cost of transportation and storage, which are usually not included in regressions due to limited data.

4. Methodologies

4.1 Tests for Structural Breaks

U.S. natural gas and corn prices are likely to experience structural changes resulting from the shale gas revolution and increasing demand for ethanol, respectively, which could chain to domestic fertilizer prices. To test for stationarity of individual price series, I adopt the GLS-based unit root test with multiple structural breaks under both the null and the alternative hypotheses proposed in Carrion-i-Silvestre et al. (2009). Since the number of breaks in each price series is also unknown, I identify the number of breaks by applying a sequential testing procedure proposed in Kejriwal and Perron (2010).

The next step is to investigate whether the relationship between nitrogen and natural gas prices has been stable over time. Based on the stationary test results (shown in section 6), all price series are cointegrated of order 1. Therefore, I apply the tests for multiple structural breaks in linear models suggested by Bai and Perron (1998, 2003). The tests endogenously determine the number of structural changes and estimate the breakpoints. Another advantage of these methods is that they allow for serial correlation and heterogeneity in the errors when no lagged dependent presents as a regressor. The linear regression with m structural break ($m + 1$ regimes) can be expressed as:

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

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 breakpoint $(T_1, \ldots, T_m)$ are treated as unknown. y_t denotes the dependent variable (the first difference of nitrogen prices). $\boldsymbol{x}_t$ $(p \times 1)$ and $\boldsymbol{z}_t$ $(q \times 1)$ are the vector of explanatory variables, while $\boldsymbol{\beta}$ and $\boldsymbol{\delta}_j$ $(j = 1, \ldots, m + 1)$ are the corresponding vectors of coefficients, where the parameter $\boldsymbol{\beta}$ does not vary across regimes. In this study, the regressors $\boldsymbol{z}_t$ consist of the first differences of U.S. natural gas, international natural gas, and corn prices. Meanwhile, $\boldsymbol{x}_t$ contains constant and seasonal dummy variables in the case of homogeneous error distributions. I exclude $\boldsymbol{x}_t$ in the least squares regression in the tests that allow heterogeneity in error distributions across the breaks. The associated estimates of the parameters $\hat{\boldsymbol{\delta}}_j$ are estimated by minimizing the global sum of squares residuals of the objective function:

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

Denote $S_T(T_1, \dots, T_m)$ as the sum of squares residual with the estimated parameters. Then the estimates of break points are obtained by a global minimization of the sum of squared residuals:

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

I adopted 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 M ($0 < m \leq M$). 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 found to be highly sensitive the kind of tests, the assumption on the number of breaks, and trimming parameters (Muthuramu and Uma Maheswari, 2019).

4.2 Pass-through Estimation

After identifying the number of breaks and break dates in the cointegrated regression, I 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. Dummy variables representing different regimes are included (the first regime is the base group). The system of regressions on nitrogen prices with four regimes is expressed as:

$$\Delta F_t = \alpha + d_2 + d_3 + d_4 + \sum_{l=0}^{L} \beta_l^1 \Delta X_{t-l} + \sum_{l=0}^{L} \beta_l^2 \Delta X_{t-l} d_2 + \sum_{l=0}^{L} \beta_l^3 \Delta X_{t-l} d_3 + \sum_{l=0}^{L} \beta_l^4 \Delta X_{t-l} d_4 + \phi_1' W_t + \phi_2' W_t d_2 + \phi_3' W_t d_3 + \phi_4' W_t d_4 + \varepsilon_t \quad (3)$$

where F_t denotes a vector of anhydrous ammonia and urea prices, $[P_t^{AA}, P_t^{Urea}]'$, at time t, X_t represents a set of explanatory variables, W_t is quarterly dummy variables controlling for seasonality, and ε_t represents error terms, $[\varepsilon_t^{AA}, \varepsilon_t^{Urea}]'$. d_2, d_3, and d_4 are dummy variables for second, third, and fourth regimes, respectively. The summation of the distributed lag coefficients, $\beta_{PT}^1 = \sum_{l=0}^{L} \beta_l^1$, is the cumulative pass-through to nitrogen prices in the first regime. The pass-through rates of other regimes are computed by $\beta_{PT}^j = \sum_{l=0}^{L} \beta_l^1 + \sum_{l=0}^{L} \beta_l^j$, where $j = 2, 3$, and 4. If a pass-through is complete after L periods, then $\beta_{PT} = 1$.

I estimate eq (3) using the seemingly unrelated regression (SUR), which allows error terms to be correlated across equations. Three explanatory variables X_t are included (i) U.S. natural gas prices; (ii) natural gas futures prices traded on the Intercontinental Exchange based in the United Kingdom (ICE natural gas prices hereafter); and (iii) corn futures prices. The ICE price is suggested by Bushnell and Humber (2017) to capture the impact of international natural gas prices as countries in Eastern European and Middle East regions are part of the top exporters of anhydrous ammonia. The corn price is added to capture the increasing demand for nitrogen fertilizers. Instead of spot prices, using corn futures prices is more reasonable as the planting decision occurs before corn prices are known due to the nature of agricultural products.

The U.S. and international natural gas prices are included to capture the shift in the supply side of nitrogen production, while corn futures represent the change in demand for nitrogen fertilizers. However, these explanatory variables cannot fully explain the variation in nitrogen prices. There are other factors that might affect nitrogen prices, for example, potential market power, government regulation and nitrogen'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 are positively related to corn prices. It would likely cause an overestimation of the pass-through of the changes in corn prices.

5. Data

The data used in this study are of monthly frequency during the period of February 1997 – January 2020 (276 observations), which covers the changes in the U.S. fertilizer industry discussed earlier. Henry Hub natural gas spot prices (HH) are obtained from the U.S. Energy Information Administration. Wholesale prices of anhydrous ammonia and granular urea sold within the U.S. Corn Belt are used to represent for nitrogen end user price, obtained from Green Markets/Bloomberg. The prices of No. 2 yellow corn futures traded on the Chicago Board of Trade are obtained from Bloomberg. Additionally, to capture the plausible impact of international natural gas prices, I adopt futures prices of natural gas traded on the Intercontinental Exchange (ICE), obtained from Bloomberg.

Table 5.1 reports that anhydrous ammonia prices are, on average, higher and more volatile than urea prices using the entire sample. Meanwhile, the mean of ICE natural gas prices is greater than the mean of HH prices. Table 5.2 shows that the correlations between international natural gas and nitrogen prices are substantially higher than those of domestic gas and nitrogen prices. Besides, corn prices are highly related to nitrogen prices.

Table 5.1 also illustrates the summary statistics of the data during four time periods based on the three structural breaks: (i) October 2006; (ii) March 2010; and (iii) October 2016[2]. The average prices of both types of nitrogen fertilizers are higher and more volatile between October 2006 to September 2016, compared to the prices before October 2006 and after the third quarter of 2016. The averages of corn future prices fairly followed the trend of nitrogen prices as they increased after the first break and slightly declined after the third structural break. Also, I notice that the volatility of nitrogen and corn prices dramatically dropped in the last time interval. Meanwhile, Henry Hub natural gas prices were high and volatile during the pre-March 2010 period, compared to the average HH prices at $3.45 per million Btu during March 2010 – September 2016, and at $2.9 per million Btu during October 2016 – January 2020. Unlike the HH gas prices, the mean of Intercontinental Exchange natural gas prices rose to $10 per million Btu during October 2006 – February 2010 and stayed relatively high afterward.

6. Empirical Results

Pass-through Estimations with Full Sample

To outline the analysis, I will explore pass-through rates with no structural break before moving to the models with structural breaks. The estimates of the pass-through to anhydrous ammonia and granular urea prices in eq (3) are computed using the seemingly unrelated regression. Bushnell and Humber (2017) used lag 3, 6, and 12 for explanatory variables to represent the short-, middle-, and long-run pass-through. In this paper, I select only lag 3 for explanatory variables to preserve degrees of freedom. Additionally, the coefficients of higher

[2] More details in section 6.

lags are more likely to be small and insignificant[3], reflecting that nitrogen producers are more likely to adjust their prices within 3-4 months of input price changes.

The estimates of pass-through rates for the whole sample are reported in table 6.1. The regression on ammonia prices is shown in the upper section of the table, while the lower section illustrates the regression on urea prices. Column (1) indicates that the pass-through rate of the change in domestic natural gas prices in the first model (HH only) is approximately 46.1% for anhydrous ammonia and 27.3% for urea, and the pass-through rate of the Henry Hub price changes declines as more control variables are added (see columns (2)-(4)). These results imply that the Henry Hub natural gas price is unlikely to be the sole factor influencing the shift in nitrogen prices. In regression (4), which adds both international natural gas and corn futures prices, the pass-through of the changes of HH natural gas, ICE natural gas, and corn prices to ammonia prices are 38.9%, 22%, and 20.8%, respectively, and to urea price are 17.6%, 24.1%, and 34.1%, respectively. In other words, 61% of the changes in anhydrous ammonia prices are explained by the changes in input prices (HH and ICE natural gas), while 20.8% are from the shift in output prices (corn). The estimated pass-through of the shift in HH prices to urea prices is notably lower (17.6%-27.3%), which is intuitive because urea contains less nitrogen content than anhydrous ammonia. Surprisingly, the changes in corn prices have more influence on urea prices than on anhydrous ammonia prices.

The outcomes indicate that the changes in domestic natural gas prices are not likely to be the sole factor affecting the fluctuation in anhydrous ammonia and urea prices. Thus, the primary model in this paper is the model with the first differences of HH natural gas, ICE natural gas, and corn prices and their lags as regressors.

[3] Based on the results on the models with one structural break in table A3-A6 in appendix

Tests for Multiple Structural Changes

Next, I test for the existence of structural changes in the relationship among nitrogen, its input, and its output prices. First, I check whether the price series are stationary. However, if there are structural breaks in the price series, the conventional unit root test may not provide an accurate outcome. Hence, I identify the number of structural breaks in individual price series proposed by Kejriwal and Perron (2010). Two structural changes are found in all price series over the sample period. Then, I employ the GLS-based unit root test allowing for multiple unknown structural breaks and both level and slope shifts developed by Carrion-i-Silvestre et al. (2009). Table 6.2 reports the results of the GLS-based and the augmented Dickey-Fuller (ADF) unit root tests. All GLS-based test statistics cannot reject the null hypothesis of a unit root at 5% significant level for all other series, indicating that these individual series are integrated. Meanwhile, the ADF tests show similar results except for both domestic and international natural gas price series, which are found to be trend stationary. These results indicate that the conventional unit root test would provide a misleading outcome in the presence of structural breaks.

The first differences of all individual price series are found to have no break within the series. Without a structural break, the ADF unit root test can be applied to the first difference of these series. The results show a strong rejection of the null hypothesis of a unit root in all series (see table A1 in appendix). Thus, I can conclude that all price series are integrated of order one or I(1), and their first differences are stationary.

Next, I adopt a method in Bai and Perron (1998, 2003) to test for the existence of structural breaks in the relationship between natural gas, corn, and ammonia prices. The least-squares regressions are in the forms of $\Delta P_t^{AA} = \alpha + \sum_{l=0}^{L} \beta_l \Delta X_{t-l} + \phi' W_t + \varepsilon_t$, where F_t denote anhydrous ammonia prices, X_t represents Henry Hub natural gas, ICE natural gas and corn prices, and W_t is quarterly dummy variables. Only the parameters β_l are tested for parameter stability. I apply the tests with 15% trimming, so the maximum number of breaks is 5.

Table 6.3 shows the results of the tests for multiple structural changes in the relationship among anhydrous ammonia, natural gas, and corn prices. In the model with only the first difference of domestic natural gas price and its lags as regressors, the outcomes strongly support the results of one break in April 2010, corresponding to the merger between CF Industries and Terra Industries. In the meantime, the tests detect 3-5 breaks in the regression with the first differences of Henry Hub natural gas, ICE natural gas, and corn prices and their lags. I also apply the tests on urea prices, the outcomes are entirely different with none or 4-5 structural changes (see table A2 in appendix).

Despite inconsistency between the results from the tests on ammonia and urea prices, ammonia prices are used to represent nitrogen prices since anhydrous ammonia is the main type of nitrogen fertilizers used for growing maize in the U.S. Corn Belt. Furthermore, three structural breaks can preserve more degrees of freedom in each subsample. Therefore, I estimate the pass-through rates in four regimes corresponding to the ammonia model results.

The first detected break occurred in October 2006, in part, because of the shale gas development and increasing global nitrogen consumption. The merger agreement between CF and Terra Industries finalized and is likely to be the main reason for the structural change in March 2010. Lastly, after the third break in October 2016, many production capacity expansion projects were completed, which increase domestic nitrogen production. In the meantime, high corn supply put downward pressure on the prices.

Pass-through Estimations with One Structural Break

Here, I assume one structural break occurring in January 2010, same as in Bushnell and Humber (2017). Table 6.4 shows the substantial decline in the estimates of the pass-through rate of domestic natural gas prices to nitrogen prices after January 2010. In particular, more than half of Henry Hub price changes contribute to the changes in anhydrous ammonia prices before January 2010, then the pass-through drops to 1.4%. Meanwhile, the transmission of the shift in HH prices on urea prices drops to a negative value between January 2010 and January 2020, from almost 40%. Prior to 2010, the changes in ICE natural gas prices have a low impact on nitrogen prices. Then, ICE price changes have become the dominant factor in nitrogen price changes during the post-2010 period, accounting for 38% of the anhydrous ammonia price changes and 61% of the urea price changes. In total, the contribution of the input price (HH and ICE natural gas) changes to the variation in anhydrous ammonia prices decreases to 40% after 2010, from 74%.

Before January 2010, the output price changes have greater effects on urea prices than on ammonia prices. These estimates are unexpected since anhydrous ammonia has been mainly used for growing corn in the U.S. Corn Belt for years. However, after January 2010, the impact of corn price changes on anhydrous ammonia prices more than double, but its effect on urea prices sharply subsides.

Compared to Bushnell and Humber (2017)'s article, the estimates of pass-through rate during the pre-January 2010 period are similar. Specifically, the pass-through of Henry Hub, ICE, and corn price changes to anhydrous ammonia prices were 0.55, 0.18, and 0.15, relative to 0.58, 0.16, and 0.13 in table 6.4. After January 2010, the estimates of the pass-through rate of HH price changes are approximately 1% in both studies. Nevertheless, the shift in international natural gas prices has greater impact and the changes in corn prices has lower effect on anhydrous ammonia prices in this paper. The input pass-through rate found in this paper is 39.6% versus 29% in their paper. Meanwhile, Bushnell and Humber (2017) found that the effect of corn price changes is more dominant with the pass-through rate of 41% versus 29.7% in this paper. The differences in outcomes are because the post-2010 period in Bushnell and Humber (2017) was between January 2010 and January 2016, implying that there may exist another structural change after January 2010.

Pass-through Estimations with Three Structural Changes

Now I consider three structural changes occurring in October 2006, March 2010, and October 2016. Table 6.5 shows a significant shift in the correlation coefficients among nitrogen fertilizer, natural gas, and corn prices across time periods. The correlation between HH natural gas and nitrogen prices considerably drops from 0.67-0.71 in October 2006 – February 2010 to 0.12-0.14 during March 2010 – September 2016. After the third quarter of 2016, the correlation between domestic natural gas and ammonia prices slightly regains to 0.22, while the correlation between HH and urea prices continues to decrease to 0.06. The correlation coefficients between international natural gas and nitrogen prices gradually decline over time. However, the correlations between ICE and nitrogen prices have been stronger than the correlations between HH and nitrogen prices since October 2006.

The correlation coefficients between nitrogen and corn prices are relatively high at 0.71-0.81 for anhydrous and at 0.67-0.77 for urea during October 2006 – September 2016. However, the correlations sharply fall to 0.22 for ammonia and 0.30 for urea after September 2016. These changes in correlation coefficients support the multiple structural breaks in the relationship between nitrogen fertilizer, its input and output prices.

Table 6.6 reports the results of the pass-through estimation of the full model with three breaks. In the first regime (before October 2006), Henry Hub price variation is the major factor that drives the changes in anhydrous ammonia prices, followed by ICE price changes. Similarly, the changes in HH and ICE prices dominantly transmit to urea prices during the same period. The pass-through rate of input price changes is approximately 65.5% to ammonia prices and 44.4% to urea prices. The fluctuation in demand-side did not have a positive impact on nitrogen prices in this period, indicating that nitrogen prices followed closer its marginal costs rather than relative low corn prices during the period.

In the second regime, during October 2006 – February 2010, increasing global ethanol demand likely increase the impact of corn price variation on ammonia and urea prices with the pass-through rates of 11.8% and 61.1%, respectively. The increase in shale gas production in the U.S. and higher average natural gas prices abetted a strong pass through of the input price changes with the pass-through rate of 112% in the ammonia case and 76% in the urea case.

The second structural break occurs in March 2010, coinciding with the merger between CF Industries and Terra Industries. In addition, high volatility of corn prices is observed during the third regime with a peak at $8.06 per bushel. Accordingly, the pass-through of corn price changes on ammonia prices rises to 35.2%. For the urea model, however, the transmission of corn price changes considerably diminishes to 11.9%. In contrast to the previous regimes, anhydrous ammonia and urea prices negatively respond to the changes in Henry Hub natural gas prices with the pass-through rates of -14.6% and -33.6%, respectively, during March 2010 – September 2016, corresponding to a decline in Henry Hub average price to $3.5 per MMBtu.

The fluctuation in ICE prices dominantly induces changes in the prices of both nitrogen types, rather than domestic natural gas price changes as in the previous two regimes, potentially because of relatively high international natural gas prices at $9 on average. Overall, the impact of input price variation on anhydrous ammonia prices plummets to 25.4% from 112% in the previous period, and the effect on urea prices drops to 39.8% from 76%.

In the fourth regime starting in the fourth quarter of 2016, many capacity expansions have been completed and started operation and the merger between Agrium and Potash Corp finalized in January 2018. The negative transmission of domestic natural gas price changes to ammonia and urea prices persists from the earlier time interval. Likewise, the transmission of ICE gas price changes stays strong at the pass-through rates of 44% for the ammonia case and 61% for the urea model. The total effect of input price changes slightly rises to 32.6% on anhydrous ammonia prices, while the effect on urea prices sharply drops to 5.2% due to strong negative effects of HH price changes. The demand pressure is unlikely to have a significant impact on nitrogen prices in this regime, indicated by negative pass-through of corn price changes to both nitrogen prices during the period. These results are partly due to stable demand for biofuel and high supply of corn, leading to decreases in corn prices and its volatility.

The transmission of input price changes on anhydrous ammonia prices is strongest during October 2006 – February 2010, when domestic natural gas production and prices were skyrocketing. The pass-through rate plummets during March 2010 – September 2016 and lightly regains afterward. The overall pass-through rates (HH, ICE, and corn price changes) of nitrogen prices are highly volatile throughout the sample period. The total pass-through rate to ammonia prices peaks at 124% during the second regime and hits the bottom at 12.3% after the third break.

The changes in the relationship among nitrogen, natural gas, and corn prices over time indicate that multiple factors have a great impact on nitrogen prices. Nitrogen prices are likely to adjust based on volatile factor prices. The sharp decline in pass-through rates of input price changes and the increase in pass-through of output price changes after March 2010 indicates a potential increase in market concentration as CF Industries and Terra Industries merged. However, the impact of merger in January 2018 is not clear partially due to insufficient observations. The incomplete pass-through reflects the effects of other factors, such as the changes in capital costs, the changes in government regulation, an increase in transportation and storage costs, especially rail rates. An average rail rate in 2010-2019 was 31.5% greater than the average in 2004-2009. Concurrently, the average truck rate increased 17.4%, and the average water transportation price increased 19.9% during the same period.

7. Conclusions

As the main input of anhydrous ammonia, natural gas price is expected to highly affect anhydrous ammonia and other nitrogen fertilizer product prices under perfect competition. Due to new innovations in natural gas extraction, domestic natural gas prices have dropped to a relative low level. Even though prior literature showed that anhydrous ammonia and Henry Hub spot prices were highly correlated during the period of 2000-2005, more recent data indicated that the impact of other factors may dominate.

This study examines the changes in the relationship between the prices of nitrogen fertilizer and its related factors. Three structural changes are found during February 1997 – January 2020: (i) October 2006; (ii) March 2010; and (iii) October 2016. The first structural change is likely to occur as a result of increasing natural gas production and demand for ethanol, while the second break is expected to occur due to the merger between two leading firms and the decline in domestic natural gas prices. The structural break in the fourth quarter of 2016 happens potentially because of increasing production capacity of U.S. nitrogen fertilizer and high corn supply.

I employ the seemingly unrelated regression to estimate pass-through rates of natural gas and corn prices to anhydrous ammonia and urea prices. Henry Hub natural gas prices is found as the dominant factor on nitrogen prices during the pre-March 2010 period. However, the results provide evidence that nitrogen prices instead depend more on international natural gas price after March 2010, possibly due to high import reliance and relatively high international natural gas prices. The pass-through rates of the shift in input prices to both ammonia and urea prices are highly volatile over the sample period. The highest pass-through rate of input price changes is in the second regime when natural gas prices were averagely high and highly volatile.

The impact of corn price changes on anhydrous ammonia prices sharply increases after October 2006, reflecting an increase in global demand for fuel ethanol. However, starting in the fourth quarter 2016, the shift in corn prices has lost its significance on ammonia prices and the pass-through rate drastically drop to a negative value, in part, due to a stable global demand for ethanol and high maize supply that put downward pressure on corn prices. Likewise, urea prices positively respond to corn price changes between October 2006 and September 2016, with a remarkably high pass-through rate during October 2006 – February 2010.

The changes in the estimates of pass-through for anhydrous ammonia price support the existence of more than one structural break in the relationship among nitrogen, natural gas, and corn prices. However, the outcomes for granular urea price are more ambiguous since the structural breaks are determined by using ammonia prices and urea contains lower percentage of nitrogen.

The incomplete total pass-through rate indicates that some influencing factors are missing from the estimation, especially in the post-September 2016 period. Other factors affecting the U.S. nitrogen fertilizer market include the merger between Agrium and PotashCorp in January 2018, the completion of many capacity expansion projects, the change in government regulation, and increasing costs of transportation and storage.

Table 5.1 Summary statistics

Variables	Mean	Std. Dev.	Min	Max
Full sample (276 Obs):				
Ammonia	397.03	182.14	127.01	997.91
Urea	303.58	137.28	105	880
HH	4.27	2.18	1.72	13.42
ICE	7.10	3.84	1.56	20.97
Corn	358.71	151.58	180.25	806.5
Feb 1997 – Sep 2006 (115 Obs):				
Ammonia	240.49	85.51	127.01	449.06
Urea	191.51	60.95	105	335
HH	4.49	2.45	1.72	13.42
ICE	4.77	3.73	1.56	16.38
Corn	228.24	30.10	180.25	320
Oct 2006 – Feb 2010 (41 Obs):				
Ammonia	507.14	194.78	308.45	997.91
Urea	422.07	151.34	260	880
HH	6.55	2.29	2.99	12.69
ICE	10	4.22	4.56	20.97
Corn	419.27	94.50	320.75	724.75
Mar 2010 – Sep 2016 (79 Obs):				
Ammonia	574.58	102.78	362.88	743.90
Urea	413.67	101.17	220	775
HH	3.45	0.88	1.73	6
ICE	9.08	2.20	4.51	12.60
Corn	513.22	153.36	301.5	806.5
Oct 2016 – Jan 2020 (40 Obs):				
Ammonia	385.33	58.53	290.30	489.89
Urea	287.88	37.84	210	395
HH	2.89	0.45	2.02	4.09
ICE	6.83	1.32	3.21	9.73
Corn	368.95	20.09	336.75	427

Note. This table 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 5.2 Correlation Coefficients

	Ammonia	Urea	HH	ICE	Corn
Feb 1997 – January 2020 (276 Obs):					
Ammonia	1				
Urea	0.93	1			
HH	0.28	0.33	1		
ICE	0.80	0.82	0.56	1	
Corn	0.83	0.80	-0.01	0.60	1

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

Table 6.1 The estimates of pass-through rate to nitrogen fertilizer prices: Full sample

	HH only	HH + ICE	HH + Corn	HH + ICE + Corn
	(1)	(2)	(3)	(4)
Anhydrous ammonia:				
HH	0.461	0.406	0.439	0.389
	(0.456, 0.466)	(0.40, 0.411)	(0.434, 0.444)	(0.383, 0.394)
ICE		0.224		0.22
		(0.218, 0.231)		(0.213, 0.226)
Corn			0.237	0.208
			(0.229, 0.245)	(0.20, 0.217)
Granular urea:				
HH	0.273	0.211	0.229	0.176
	(0.267, 0.28)	(0.204, 0.218)	(0.223, 0.236)	(0.169, 0.182)
ICE		0.262		0.241
		(0.254, 0.27)		(0.233, 0.249)
Corn			0.371	0.341
			(0.361, 0.382)	(0.33, 0.351)

Note. The number in parentheses reports 95% confidence interval.
HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas.

Table 6.2 Unit root tests

Test statistics	Ammonia	Urea	HH	ICE	Corn
P_T^{GLS}	18.89	22.86	8.06	10.68	9.05
MP_T^{GLS}	14.80	18.89	7.70	10.59	8.16
MZ_α^{GLS}	-14.14	-11.05	-28.31	-19.94	-26.52
MSB^{GLS}	0.19	0.21	0.13	0.16	0.14
MZ_t^{GLS}	-2.66	-2.34	-3.76	-3.14	-3.64
ADF	-2.74	-2.41	3.98*	-3.27	-3.84*

Note. * indicates the rejection of the null hypothesis of unit root at 5% critical level. The number of breaks detected is two in each series. HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas.

Table 6.3 The number of breaks and estimated break dates based on ammonia prices

	# of Breaks Determined	Estimated Break Dates
Regressors: Henry Hub natural gas prices		
Heterogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	1	2010M04
$WDMax\ F_T$	1	2010M04
Sequential test		
Sequential F	1	2010M04
Homogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	1	2010M04
$WDMax\ F_T$	0	-
Sequential test		
Sequential F	1	2010M04
Regressors: Henry Hub and ICE natural gas prices		
Heterogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	1	2007M06
$WDMax\ F_T$	5	2003M06, 2006M10, 2010M02, 2013M06, 2016M10
Sequential test		
Sequential F	1	2007M06
Homogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	1	2007M06
$WDMax\ F_T$	5	2003M04, 2006M09, 2010M02, 2013M06, 2016M10
Sequential test		
Sequential F	0	-
Regressors: Henry Hub natural gas and corn prices		
Heterogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	1	2010M04
$WDMax\ F_T$	5	2003M06, 2006M10, 2010M02, 2013M06, 2016M10
Sequential test		
Sequential F	2	2006M10, 2010M03
Homogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	1	2010M04
$WDMax\ F_T$	0	-
Sequential test		
Sequential F	1	2010M03

Table 6.3 (cont.) The number of breaks and estimated break dates based on ammonia prices

	# of Breaks Determined	Estimated Break Dates
Regressors: Henry Hub natural gas, ICE natural gas, and corn prices		
Heterogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	3	2006M10, 2010M03, 2016M10
$WDMax\ F_T$	5	2003M06, 2006M10, 2010M02, 2013M06, 2016M10
Sequential test		
Sequential F	3	2006M10, 2010M03, 2016M10
Homogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	5	2003M06, 2006M10, 2010M02, 2013M06, 2016M10
$WDMax\ F_T$	5	2003M06, 2006M10, 2010M02, 2013M06, 2016M10
Sequential test		
Sequential F	3	2006M10, 2010M03, 2016M10

Table 6.4 The estimates of pass-through rate to nitrogen fertilizer prices in one-break model

	Before Jan 10	After Jan 10
Anhydrous ammonia:		
HH	0.583	0.014
	(0.576, 0.589)	(0.005, 0.023)
ICE	0.159	0.382
	(0.151, 0.167)	(0.37, 0.393)
Corn	0.126	0.297
	(0.116, 0.137)	(0.285, 0.31)
Granular urea:		
HH	0.391	-0.26
	(0.383, 0.40)	(-0.272, -0.249)
ICE	0.091	0.609
	(0.081, 0.101)	(0.594, 0.625)
Corn	0.452	0.156
	(0.438, 0.466)	(0.139, 0.173)

Note. The number in parentheses reports 95% confidence interval.
HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas.

Table 6.5 Correlation coefficients

	Ammonia	Urea	HH	ICE	Corn
Feb 1997 – Sep 2006 (115 Obs):					
Ammonia	1				
Urea	0.96	1			
HH	0.91	0.86	1		
ICE	0.82	0.85	0.76	1	
Corn	-0.003	-0.01	-0.13	-0.07	1
Oct 2006 – Feb 2010 (41 Obs):					
Ammonia	1				
Urea	0.91	1			
HH	0.67	0.71	1		
ICE	0.89	0.89	0.80	1	
Corn	0.71	0.77	0.78	0.83	1
Mar 2010 – Sep 2016 (79 Obs):					
Ammonia	1				
Urea	0.77	1			
HH	0.14	0.12	1		
ICE	0.70	0.71	0.49	1	
Corn	0.81	0.67	0.13	0.69	1
Oct 2016 – Jan 2020 (40 Obs):					
Ammonia	1				
Urea	0.66	1			
HH	0.22	0.06	1		
ICE	0.30	0.51	0.41	1	
Corn	0.22	0.30	-0.33	-0.12	1

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

Table 6.6 The estimates of pass-through rate in three structural breaks model

	Before Oct 06	Oct 06 – Feb 10	Mar 10 – Sep 16	Oct 16 – Jan 20
Anhydrous ammonia (Adjusted R^2 = 0.45)				
HH	0.50	1.04	-0.146	-0.118
	(0.493, 0.506)	(1.025, 1.056)	(-0.156, -0.136)	(-0.138, 0.098)
ICE	0.186	0.081	0.40	0.444
	(0.175, 0.197)	(0.07, 0.092)	(0.386, 0.415)	(0.425, 0.463)
Corn	-0.273	0.118	0.352	-0.203
	(-0.287, -0.258)	(0.101, 0.134)	(0.34, 0.365)	(-0.247, -0.16)
Granular urea (Adjusted R^2 = 0.22)				
HH	0.212	1.04	-0.336	-0.557
	(0.204, 0.221)	(1.018, 1.062)	(-0.35, -0.322)	(-0.585, -0.529)
ICE	0.272	-0.27	0.734	0.61
	(0.257, 0.287)	(-0.285, -0.255)	(0.714, 0.754)	(0.583, 0.636)
Corn	-0.232	0.611	0.119	-0.679
	(-0.252, -0.212)	(0.589, 0.634)	(0.102, 0.136)	(-0.739, -0.618)

Note. The number in parentheses reports 95% confidence interval.
HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas.
Breushch-Pagan (1980) test statistics is 48.9 (p-value = 0.00), indicating correlated errors terms across equations.

Appendix

Table A1. Unit root rest of first difference variables

Test statistics	Ammonia	Urea	HH	ICE	Corn
ADF	-8.67*	-9.69*	-17.03*	-15.324*	-17.25*
number of lags	1	3	0	0	0

Note. * indicates the rejection of the null hypothesis of unit root at 1% critical level. The number of lags is chosen by SBIC. HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas.

Table A2. The number of breaks and estimated break dates based on urea prices

	# of Breaks Determined	Estimated Break Dates
Regressors: Henry Hub natural gas prices		
Heterogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	0	-
$WDMax\ F_T$	3	2001M02, 2006M09, 2010M01
Sequential test		
Sequential F	2	2006M09, 2010M01
Homogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	2	2006M09, 2010M01
$WDMax\ F_T$	2	2006M09, 2010M01
Sequential test		
Sequential F	2	2006M09, 2010M01
Regressors: Henry Hub and ICE natural gas prices		
Heterogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	1	2008M04
$WDMax\ F_T$	1	2008M04
Sequential test		
Sequential F	1	2008M04
Homogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	1	2008M04
$WDMax\ F_T$	1	2008M04
Sequential test		
Sequential F	1	2008M04

Table A2. (cont.) The number of breaks and estimated break dates based on urea prices

	# of Breaks Determined	Estimated Break Dates
Regressors: Henry Hub natural gas and corn prices		
Heterogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	0	-
$WDMax\ F_T$	0	-
Sequential test		
Sequential F	0	-
Homogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	0	-
$WDMax\ F_T$	2	2008M04, 2012M07
Sequential test		
Sequential F	0	-
Regressors: Henry Hub natural gas, ICE natural gas, and corn prices		
Heterogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	4	2001M03, 2008M04, 2011M10, 2016M02
$WDMax\ F_T$	5	2000M10, 2004M02, 2008M04, 2011M10, 2016M02
Sequential test		
Sequential F	0	-
Homogeneous error distributions		
Double Maximum test		
$UDMax\ F_T$	4	2003M12, 2008M04, 2011M09, 2016M02
$WDMax\ F_T$	5	2000M10, 2004M02, 2008M04, 2011M09, 2016M02
Sequential test		
Sequential F	0	-

Table A3. The estimates of pass-through rate to nitrogen fertilizer price (L=6): Before Jan 2010

	HH only	HH + ICE	HH + Corn	HH + ICE + Corn
	(1)	(2)	(3)	(4)
Anhydrous ammonia:				
HH	0.725	0.644	0.673	0.608
	(0.71, 0.739)	(0.627, 0.661)	(0.66, 0.686)	(0.593, 0.623)
ICE		0.19		0.17
		(0.169, 0.21)		(0.153, 0.188)
Corn			0.379	0.335
			(0.348, 0.409)	(0.304, 0.366)
Granular urea:				
HH	0.435	0.427	0.372	0.376
	(0.414, 0.456)	(0.404, 0.45)	(0.353, 0.391)	(0.355, 0.396)
ICE		-0.012		-0.027
		(-0.04, 0.015)		(-0.049, -0.005)
Corn			0.438	0.415
			(0.394, 0.482)	(0.376, 0.454)

Note. The number in parentheses reports 95% confidence interval.
HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas.

Table A4. The estimates of pass-through rate to nitrogen fertilizer price (L=6): After Jan 2010

	HH only	HH + ICE	HH + Corn	HH + ICE + Corn
	(1)	(2)	(3)	(4)
Anhydrous ammonia:				
HH	0.089	-0.112	0.111	-0.034
	(0.046, 0.132)	(-0.158, -0.067)	(0.068, 0.155)	(-0.075, 0.006)
ICE		0.602		0.53
		(0.551, 0.653)		(0.493, 0.567)
Corn			0.322	0.238
			(0.289, 0.355)	(0.203, 0.273)
Granular urea:				
HH	-0.141	-0.228	-0.131	-0.203
	(-0.191, -0.091)	(-0.275, -0.182)	(-0.184, -0.077)	(-0.242, -0.165)
ICE		0.475		0.521
		(0.416, 0.534)		(0.471, 0.57)
Corn			0.043	-0.117
			(-0.018, 0.104)	(-0.169, -0.065)

Note. The number in parentheses reports 95% confidence interval.
HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas.

Table A5. The estimates of pass-through rate to nitrogen fertilizer price (L=12): Before Jan 2010

	HH only	HH + ICE	HH + Corn	HH + ICE + Corn
	(1)	(2)	(3)	(4)
Anhydrous ammonia:				
HH	0.84	0.811	0.807	0.778
	(0.821, 0.859)	(0.79, 0.833)	(0.791, 0.823)	(0.756, 0.801)
ICE		-0.0005		-0.04
		(-0.03, 0.03)		(-0.067, -0.013)
Corn			0.48	0.54
			(0.437, 0.523)	(0.499, 0.581)
Granular urea:				
HH	0.473	0.503	0.496	0.525
	(0.449, 0.497)	(0.473, 0.533)	(0.474, 0.518)	(0.488, 0.562)
ICE		-0.154		-0.228
		(-0.192, -0.117)		(-0.271, -0.186)
Corn			0.446	0.498
			(0.391, 0.502)	(0.448, 0.547)

Note. The number in parentheses reports 95% confidence interval. HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas.

Table A6. The estimates of pass-through rate to nitrogen fertilizer price (L=12): After Jan 2010

	HH only	HH + ICE	HH + Corn	HH + ICE + Corn
	(1)	(2)	(3)	(4)
Anhydrous ammonia:				
HH	0.015	-0.276	-0.005	-0.398
	(-0.042, 0.071)	(-0.339, -0.212)	(-0.08, 0.069)	(-0.451, -0.345)
ICE		0.596		0.792
		(0.548, 0.644)		(0.737, 0.846)
Corn			0.129	-0.241
			(0.068, 0.19)	(-0.293, -0.188)
Granular urea:				
HH	-0.064	-0.25	-0.15	-0.627
	(-0.141, 0.012)	(-0.324, -0.176)	(-0.226, -0.074)	(-0.676, -0.577)
ICE		0.677		1.106
		(0.595, 0.76)		(1.038, 1.174)
Corn			-0.069	-0.659
			(-0.172, 0.033)	(-0.747, -0.57)

Note. The number in parentheses reports 95% confidence interval. HH = Henry Hub natural gas; ICE = Intercontinental Exchange natural gas.

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