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by

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Paper prepared for the NCCC-134 Conference on Applied Commodity Price Analysis, Forecasting, and Market Risk Management, 2024.

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The findings and conclusions in this presentation are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy. This research was supported by a Cooperative Agreement from the U.S. Department of Agriculture, Economic Research Service. This work was also supported by the A.J. and Susan Jacques Chair, the Oklahoma Agricultural Experiment Station, and USDA National Institute of Food and Agriculture [Hatch Project number OKL03170].

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The recent high fluctuations in fertilizer prices raise the desirability of better understanding fertilizer markets and estimating elasticities to include in large structural models for policy analysis. This paper aims to estimate demand and supply functions for nitrogen fertilizer in the United States. However, it is widely recognized that specifying an annual structural demand and supply model to estimate elasticities is challenging. An annual structural model must address issues such as endogeneity from simultaneity, frequent structural change, limited observations and highly aggregated data. To address these issues, we use a graphical approach to select time periods for estimating econometric models. Additionally, two-stage least squares is employed in an attempt to overcome endogeneity. Our finding indicates that the demand and supply of nitrogen fertilizer are inelastic, which means price spikes are going to happen and difficult to predict. Furthermore, the result shows that the international market might be more elastic than the domestic market. If so, international markets can provide a moderating effect on prices during domestic market shocks. However, shocks to the international market could result in the high price spikes, as observed historically.

Key word: demand and supply, nitrogen fertilizer, three panel diagram, 2SLS

Introduction

The 2022 spike in fertilizer prices raised concerns among farmers and policymakers, as the cost of fertilizers is a large component of production costs. This price rise was similar to what occurred during the Great Recession, when prices nearly doubled across all major fertilizer categories at the end of 2007. Since fertilizer costs make up almost 20% of the cash expenses for farming in the United States, it is important to better understand the fertilizer market and provide information to prepare for future crises (Jones and Frank, 2022). Globally, nitrogen fertilizer accounts for the largest share of fertilizer use at 56%, with urea being the most commonly used nitrogen fertilizer, making up more than 50% of the nitrogen fertilizers (IFA, 2024; Aftab and Hakeem, 2022).

World fertilizer consumption increased from 103.7 kg/ha in 2001 to 146.4 kg/ha in 2020 (World Bank 2023), an average annual rate of 1.89%. In 2022, the price of urea surpassed the 2008 peak, and phosphate and potash prices were close to 2008 peak prices. These price increases were affected by various market factors such as increases in demand, slow adjustments in production, and the Russia-Ukraine war. Russia's 2022 invasion of Ukraine limited fertilizer supply and import-export restrictions drove up prices for fertilizer and natural gas, which is a primary input in the production of nitrogen fertilizer. The spike in prices was also driven from supply chain disruptions caused by the COVID-19 pandemic, combined with several other factors. The surge in natural gas prices in Europe during mid-2021 caused a decrease in ammonia production, a key component in nitrogen fertilizer production. Additionally, coal price increases in China led to electricity rationing, resulting in some fertilizer production plants decreasing output. Since the United States imports a significant amount of fertilizer, increasing demand kept fertilizer prices elevated in the United States. The high fluctuations in fertilizer price and production raise the desirability to better understand demand and supply for fertilizer to better respond to future shocks.

The difficulty of using an annual structural supply/demand model to estimate elasticities, however, is widely recognized. An annual structural model must deal with endogeneity from simultaneity, frequent structural changes, limited observations and highly aggregated data. Due to the limited observations, it is often necessary to use restrictively simplistic functional forms, which may not well represent the actual data-generating process (Alston and Chalfant 1991). Understandably, the agricultural economics profession has wandered off to study problems that can use intraday data (Ma and Serra 2024) or differences in differences and large datasets (Janzen et al. 2024) where estimates can be precise enough to obtain statistical significance.

Despite the difficulties of constructing a demand/supply system, the need for elasticities to include in large structural models for policy analysis has not gone away. Examples of large structural models include the USDA baseline models (Maples et al. 2022; Fang and Katchova 2023), the Aglink-Cosimo model (OECD 2021), and the Food and Agricultural Policy Research Institute (FAPRI) models (Meyers et al. 2010). These models use various combinations of econometric estimates and expert opinion in deriving the elasticities used in the models.

Adenauer et al. (2023) use Bayesian methods to estimate supply/demand elasticities. The Bayesian approach can impose theoretical restrictions such as homogeneity and symmetry as well as sign restrictions. The drawback of the Bayesian approach is that if the priors of the Bayesian approach are too tight, then the models differ little from the priors. Also, imposing inequality restrictions will introduce bias. Further, if the econometric models are misspecified due to not considering structural change, the Bayesian methods do not address the reason that the econometric estimates are poor.

The recognition that simple time series models can produce better forecasts than large scale econometric models (Just and Rausser 1981) also reduced the interest in supply and demand models. The knowledge that regressing one trending time series on another can lead to spurious regressions (Granger and Newbold 1974) also reduced the interest in structural models. Time series methods provide an alternative to structural models. Unfortunately, in the case of nitrogen fertilizer such models lead to the unlikely conclusion of no connection between natural gas prices and nitrogen fertilizer prices (Yang et al. 2022). While there are models labeled as structural vector autoregressions, these models are not really structural when estimated using only price data.

Purcell and Koontz (p. 88, 1991) use a graphical approach to study demand shifts. We follow their graphical approach and use it to select time periods to estimate econometric models. Thus, the approach we use considers the structural change that can be missed using other methods. The drawback is that it is a subjective method and so it is subject to the whimsy of the researchers. Note that the approach we use is consistent with Wang and Tomek (2007) who argue that commodity prices do not have unit roots and that the failure to reject the null hypothesis of a unit root results from not fully capturing the structural changes that have occurred.

The purpose of this paper is to estimate demand and supply functions for nitrogen in the United States. Supply is separated into domestic supply and an excess supply from the international market. Two-stage least squares is used in an attempt to overcome endogeneity, but does not prove successful in all cases. We would argue that there is a need for more research like this in spite of the inexactness of the answers that we are able to obtain.

Theory

The three functions estimated here, domestic demand, domestic supply and international excess supply of nitrogen fertilizer can be considered conceptually as estimating three of the curves in the three-panel diagram of Figure 1. The three curves estimated are the demand and supply in the first panel (U.S. Market) and the curve labeled ES in the international market. One important item to note from the figure is that the excess supply from the rest of the world depends on both supply and demand in the rest of the world and as a result it can be difficult to estimate since it can be influenced by so many different variables.

Note that fertilizer demand is a derived demand and so it is an input demand based on profit maximization for the final product, which are agricultural crops in this case. Input demands are a function of input and output prices. So, the variables affecting nitrogen quantity demanded included fertilizer price and crop price. The demand equation to be estimated is specified in general functional form as

(1) $$Q^D = f_1(P^D, r_1)$$

where Q^D is fertilizer consumed, P^D is the price of fertilizer, and r_1 is the output prices. The four primary crops in the U.S.-corn, cotton, soybeans, and wheat- account for approximately 60% of crop acreage. Given that estimated nitrogen use for corn makes up 65 to 70 % of the nitrogen usage among these crops, this study uses corn price as output price (r_1) to estimate the demand of the nitrogen fertilizer (USDA, 2019). Due to the limited data available, the prices of inputs other than nitrogen fertilizer are not included.

The domestic supply of fertilizer is a derived supply hinging on the price of fertilizer and the price of raw materials such as natural gas. Therefore, the supply function for fertilizers was be defined by

(2) $$Q^S = f_2(P^S, r_2)$$

where Q^S is the U.S. production of nitrogen fertilizer, P^S is the fertilizer price received by producers, and r_2 is the main input price. Natural gas is the main input for nitrogen fertilizer production, representing approximately 70 to 80% of the cost of producing ammonia, which can then be developed into urea (Sands et al. 2011). Therefore, the natural gas price is used as the primary input price (r_2) for nitrogen fertilizer production.

As shown in Figure 1, excess supply is defined as the quantity of exportable surplus, which is $Q^{WS} - Q^{WD}$ where, at price P_w, the quantity supplied exceeds the quantity demanded, resulting in excess supply. The excess supply can be represented as

(3) $$Q^{ES} = f_3(P_w, X^{WS}, X^{WD})$$

where Q^{ES} is the excess supply in international market, X^{WS} are the shifters of world quantity supplied and X^{WD} are the shifters of the world quantity demanded for fertilizer. Then, the equilibrium in the U.S. market at price P_w can be formulated as

(4) $$Q^{DD} = Q^{ES} + Q^{DS} .$$

Data

The data used to construct the demand, supply and excess supply functions for nitrogen are annual data from 1990 to 2021. The primary sources of data are from the Food and Agricultural Organization (FAO) and the World Bank. The demand quantity for nitrogen fertilizer use in the U.S. is obtained from FAOSTAT statistical database, which is released by FAO, called agricultural use of fertilizer. The calendar year prices for urea are the spot prices of U.S. Gulf New Orleans obtained from IMF (International Commodity Prices) “Primary Commodity Prices” database, which are used for the price of nitrogen fertilizer. The marketing year price for corn is obtained from the “Agricultural Prices” report, which is released by USDA National Agricultural Statistical Service (NASS).

Regarding the supply function, we choose the production quantity from FAOSTAT statistical database at FAO, as the measure of supply quantity for nitrogen fertilizer. The calendar prices of natural gas are the spot price at the Henry Hub in Louisiana obtained from the World Bank Commodity Market “Pink Sheet” Database.

Lastly, this study analyzes excess supply in the global fertilizer market, using data from various sources. We use the natural gas in Europe obtained from the World Bank Commodity Market “Pink Sheet” Database, as the measure of the world natural gas prices. Given that Russia is the world's largest natural gas exporter and the European Union in 2021 received over 50% of its natural gas from Russia, we employ the natural gas price in Europe as a proxy for world natural gas price. Additionally, we add the world urea price to the model obtained from UN Comtrade to estimate the excess supply. To obtain the world urea prices, we gather annual urea import data (HS 310210) from UN Comtrade for all importing countries from 1990 to 2021. Then, we calculate a "world" price for urea imports by constructing the median unit value across these countries for each period. The imported quantity for nitrogen fertilizer is also obtained from FAOSTAT statistical database, which is released by FAO, called import quantity. About 99% of U.S. total annual natural gas imports were from Canada and nearly all by pipeline (EIA 2023). Therefore, CAD/USD exchange rate is employed as the main import shifter. The data of the exchange rate (Canadian dollar to U.S. dollar) is obtained from FAOSTAT statistical database, which is released by FAO. All prices data in this study were deflated using the U.S. Consumer Price Index (CPI).

Procedure

Demand and Supply Functions

Two-stage least squares

One primary challenge in estimating demand and supply is the endogeneity of prices. Two-stage least squares (2SLS) regression analysis is a common method to obtain consistent estimates in the presence of endogeneity. In equilibrium, the quantity supplied is equal to the quantity demanded

$$Q^D = Q^S \tag{5}$$

Using equations (1) and (2), the reduced forms for the equilibrium prices can be expressed as

$$P^D = g_1(Q^D, r_1, r_2) \tag{6}$$

$$P^S = g_2(Q^S, r_1, r_2) \tag{7}$$

These functional forms allow to use r_2 as an IV (instrumental variable) in the estimation of the demand function and r_1 as an IV in the estimation of the supply function. For instance, in equation (1), the endogenous variable (P^D) is regressed on selected instrumental variables (r_2)

using OLS in the first stage. Then, equation (1) is estimated with the endogenous variables replaced by the fitted value from the first stage.

The demand function of nitrogen is defined as

(8) $$\ln Q_t^D = \alpha_0 + \alpha_1 \ln P_t^D + \alpha_2 \ln CP_t + \alpha_3 \ln T + +v_t$$

where Q_t^D is the agricultural uses of total nitrogen fertilizer, P_t^D is the price of urea, CP_t is the corn price of tth year, T is a time trend variable, and v_t is the error term is independently, identically as a normal variable with $v_t \sim N(0, \delta_v^2)$. To address the price endogeneity in the model, we use 2SLS. In the first stage, the endogenous variable, urea price, is regressed on selected instrumental variables, specifically the natural gas price, using Ordinary Least Squares (OLS). Then, the fitted value ($\ln \hat{P}_t^D$) is represented by

(9) $$\ln \hat{P}_t^D = f(\ln CP_t, \ln T, \ln NG_t)$$

where NG_t is the price of natural gas in the United States, which is used as the instrumental variable to address endogeneity concerns. In the second stage, equation (8) is estimated with the endogenous variables replaced by the fitted values from equation (9). Then, the original equation can be rewritten as

(10) $$\ln Q_t^D = \alpha_0 + \alpha_1 \ln \hat{P}_t^D + \alpha_2 \ln CP_t + \alpha_3 \ln T + \mu_t$$

where μ_t is an error term that is uncorrelated with the explanatory variables.

The supply model of nitrogen is

(11) $$\ln Q_t^S = \beta_0 + \beta_1 \ln Q_{t-1}^S + \beta_2 \ln P_t^S + \beta_3 \ln NG_t + u_t$$

where Q_t^S means the production of total nitrogen fertilizer, P_t^S is the price of urea, NG_t is the industrial natural gas price of tth year, and u_t is the error term is independently, identically as a normal variable with $u_t \sim N(0, \delta_u^2)$. Following the approach used in the demand function, for the first stage, we regress the endogenous explanatory variable, which is the urea price, on the chosen IV, namely the corn price. The fitted value ($\ln \hat{P}_t^S$) is expressed by

(12) $$\ln \hat{P}_t^S = g(\ln Q_{t-1}^S, \ln NG_t, \ln CP_t)$$

where CP_t represents the corn price. In second stage, we estimate equation (11) by substituting the endogenous variable with the fitted values obtained from equation (12). Then, the original equation is transformed into

(13) $$\ln Q_t^S = \beta_0 + \beta_1 \ln Q_{t-1}^S + \beta_2 \ln \hat{P}_t^S + \beta_3 \ln NG_t + \tau_t$$

where τ_t represents an error term uncorrelated with the explanatory variables.

The excess supply model of nitrogen can be written as

(14) $$\ln Q_t^{IM} = \gamma_0 + \gamma_1 \ln Q_{t-1}^{IM} + \gamma_2 \ln P_t^W + \gamma_3 \ln EXR_t + \gamma_4 \ln WNG_t + \varepsilon_t$$

where Q_t^{IM} is the import quantity of total nitrogen, P_t^W is the price of urea for the world, EXR_t is the exchange rate for Canadian dollar to U.S. dollar, WNG_t is the world price of natural gas, and ε_t is the error term, which is independently, identically distributed as a normal variable with $\varepsilon_t \sim N(0, \delta_\varepsilon^2)$. In the first stage, the endogenous variable, world urea price, is regressed on the chosen instrumental variable, specifically the natural gas price, using OLS. Then, the fitted value $(\ln \hat{P}_t^W)$ is defined by

(15) $$\ln \hat{P}_t^W = h(\ln Q_{t-1}^{IM}, \ln EXR_t, \ln WNG_t, \ln NG_t)$$

where NG_t is the natural gas price in the United States, which is employed as the instrumental variable. For the second stage, we estimate equation (14) by substituting the endogenous variable with the fitted values obtained from equation (15). The original equation can be rewritten as

(16) $$\ln Q_t^{IM} = \gamma_0 + \gamma_1 \ln Q_{t-1}^{IM} + \gamma_2 \ln \hat{P}_t^W + \gamma_3 \ln EXR_t + \gamma_4 \ln WNG_t + \theta_t$$

where θ_t is an error term that is uncorrelated with the explanatory variables.

The graphical approach plots quantity versus price and then looks for clusters of data from the same time periods. Models are estimated separately for each cluster since the jumps in the curves are assumed to be due to structural changes that are not in the model.

Results and Discussion

The graphical approach proposed by Purcell and Koontz (p. 88, 1991) is used to construct the demand/supply system and find the structural change. For the demand function, one structural break is selected in the relationship between urea price and agricultural use of urea in 2006, as shown in Figure 2. The spike in demand is observed in 2006, and when the demand functions are plotted for the periods before 2006 and 2006 and thereafter, there is a significant change in the slopes. Given the difficulty in plotting a single demand curve from the plotted data in Figure 1, the sample is divided into two subsamples: (i) period 1: 1990-2005, (ii) period 2: 2006-2021. The structural break occurred in 2006, possibly because of a surge in ethanol production. Approximately 94% of ethanol in the United States is produced from corn and the introduction of the Renewable Fuels Standard (RFS) became law as part of the country's energy policy in 2005. It led to increased ethanol production of up to four billion gallons in 2006, resulting in increased fertilizer demand and a rightward shift in the demand curve (see Figure 2). Based on the identified structural break, we estimated demand functions for two periods. The estimated models are presented in Table 2. The signs of each variable are consistent with economic theory, although most coefficients were not statistically significant. The price elasticities of demand for nitrogen were estimated at −0.074 and −0.036 for the two periods, which are highly inelastic.

Regarding the supply function, two structural breaks are selected, one in 2000 and the other in 2017. Three periods are examined based on the structural changes: (i) period 1: 1990-1999, (ii) period 2: 2000-2016, and (iii) period 3: 2017-2021. The first structural break occurred in 2000 because of a reduction in the number of suppliers. During period 1, several nitrogen facilities were permanently closed, and the ammonia producers operated at about 50% of capacity, with some even filing for bankruptcy (USGS, 2000). These historical events led to a leftward shift in supply. The second structural change in 2017 coincides with a rebound in production capacity and the construction of new urea and ammonia plants, resulting in a rightward shift in supply, as illustrated in Figure 3. This shift may be a delayed effect of increased natural gas production due to horizontal drilling and fracking. Based on these structural breaks, three supply functions were estimated and their results are presented in table 3. While the signs of each variable are consistent with economic theory, most coefficients were not significant. In period 1, the price elasticity of supply for nitrogen was estimated at 0.208.

For period 2, all signs except urea price are consistent with economic theory, but most coefficients were not significant. The price elasticity of supply for nitrogen was -0.129, which is inelastic as expected, but has an unexpected sign. For period 3, every sign except for natural gas price was consistent with economic theory, but with the small sample size most coefficients were not significant. The price elasticity of nitrogen supply was estimated as 0.094 which is inelastic. Some results contradicted economic theory, and most results were not statistically significant.

This may be due to the limited dataset and that the elasticities are indeed close to zero. The inelastic supply and demand functions can explain the high price spikes that have occurred in fertilizer markets.

Regarding the excess supply function, one structural break is identified in the urea price and production in 2002. Two periods are examined based on the structural changes: (i) period 1: 1990-2001 and (ii) period 2: 2002-2021. Based on the results of structural break, excess supply functions are estimated for each period. The estimated models are summarized in Table 4. Several results of the model contradicted economic theory, and most results were not statistically significant. Specifically, the price elasticities of import for nitrogen were estimated at -0.557 and 0.150 for the two periods, which are inelastic. Note that there is a hint that the international market might be more elastic than the domestic market. If so, the international market can moderate the effects of shocks to domestic demand and supply. Shocks to the international market, however, could result in the high price spikes that have been seen historically.

Summary and Conclusions

The recent volatility of fertilizer prices demonstrated the need to better understand fertilizer markets and estimate elasticities to include in large structural models used in policy analysis. However, the challenge of specifying an annual structural supply and demand model to estimate elasticities is widely recognized. An annual structural model must address issues like endogeneity from simultaneity, frequent structural change, limited observations and highly aggregated data. To overcome these issues, several solutions are available. In this study, we adopt a graphical approach and use it to select time periods for estimating econometric models. This approach considers structural change that can be missed using other methods. As nitrogen fertilizer accounts for 56% of total fertilizer use, this study mainly examines nitrogen fertilizer. The purpose of this paper is to estimate demand and supply functions for nitrogen in the United States. Supply is separated into domestic supply and an excess supply function from the international market. Additionally, two-stage least squares is used in an attempt to overcome endogeneity.

Annual data from 1990 to 2021 are used. On the demand side, one structural change was identified in the relationship between price and agricultural use of nitrogen fertilizer using the graphical approach: 1990-2005 and 2006-2021. Based on the structural break, we estimated the demand functions for two periods. The price elasticities of demand for nitrogen were estimated at 0.074 and 0.0359 for the two periods, which are highly inelastic.

Regarding the supply, two structural breaks are found in the urea price and production in 2000 and 2017, resulting in the analysis of three periods: 1990-1999, 2000-2016, and 2017-2021. Based on these structural breaks, the price elasticity of supply for nitrogen was estimated at 0.208 for the first period. For the second period, the price elasticity of supply for nitrogen was estimated -0.129, which is inelastic as we expect, but the direction of sign is opposite. For the third period, the price elasticity of supply for nitrogen was estimated as 0.094, which is inelastic.

Some results contradicted economic theory, and most results were not statistically significant. This may be due to the limited dataset and that the elasticities are indeed close to zero. The inelastic supply and demand functions can help to explain the high price spikes observed in fertilizer markets.

On the import side, one structural break is identified in the urea price and production in 2002. Two periods are examined based on the structural changes: 1990-2001 and 2002-2021. The price elasticities of nitrogen imports were estimated at -0.557 and 0.150 for these periods, which are inelastic.

What the results show is that the demand and supply of nitrogen fertilizer is inelastic. Thus, like many agricultural commodities, small shifts in supply or demand can create large movements in price. This means that price spikes are going to happen and they are going to be hard to predict. International markets are generally expected to be more elastic than domestic markets and there is a hint of that being true here. If so, international markets can provide a moderating effect on prices when the shocks are in the domestic market. Shocks to the international market do not have such a buffer and thus are more likely to create the price spikes that have been seen historically.

Table 1. Summary Statistics

Variable	Mean	Std. Dev.
World urea price ($/mt)	276.53	123.08
US gulf NOLA urea price ($/mt)	197.15	80.52
Urea production (ten thousand tons)	1,099.43	249.95
Urea agricultural use (ten thousand tons)	1,133.26	58.54
World natural gas ($/mcf)	6.00	3.75
Natural gas price ($/mcf)	4.00	2.16
Imported urea quantity (ten thousand tons)	437.78	114.18
Corn price ($/bu)	3.30	1.34
Exchange rate (CAD/USD)	1.26	0.16

Table 2. Demand Function for Nitrogen Fertilizer in U.S. The dependent variable is U.S. agricultural consumption (10,000 tons/ year)

Variables	Coefficient	Standard error
Period 1 (1990-2005)		
Urea price ($/mt)	-0.074	0.052
Corn price ($/bu)	0.074	0.052
Time	0.006*	0.002
Constant	2.692	4.341
Period 2 (2006-2021)		
Urea price ($/mt)	-0.036	0.403
Corn price ($/bu)	0.036	0.403
Time	0.0004	0.001
Constant	15.598	3.912

Note: ***, ** and * indicate significance at 1%, 5%, and 10% level.

Table 3. Domestic Supply of Nitrogen Fertilizer in U.S. The dependent variable is U.S. production (10,000 tons/year)

Variables	**Coefficient**	**Standard error**
Period 1 (1990-1999)		
Lagged quantity (ten thousand tons)	0.638	0.370
Urea price ($/mt)	0.208*	0.093
Natural gas price ($/mcf)	-0.131	0.153
Constant	-0.565	0.631
Period 2 (2000-2016)		
Lagged quantity (ten thousand tons)	0.379**	0.268
Urea price ($/mt)	-0.129	0.145
Natural gas price ($/mcf)	-0.039	0.027
Constant	-0.116	0.154
Period 3 (2017-2021)		
Lagged quantity (ten thousand tons)	0.762	0.327
Urea price ($/mt)	0.094	0.236
Natural gas price ($/mcf)	0.480	0.147
Constant	2.103	1.623

Note: ***, ** and * indicate significance at 1%, 5%, and 10% level.

Table 4. Imports of Nitrogen Fertilizer (ten thousand tons/year) in U.S.

Variables	**Coefficient**	**Standard error**
Period 1 (1990-2001)		
Lagged quantity (ten thousand tons)	0.142	0.316
World urea price ($/mt)	-0.557	0.528
World natural gas price ($/mcf)	-0.243	0.452
Exchange rate (CAD/USD)	1.196	0.786
Constant	12.544**	5.273
Period 2 (2002-2021)		
Lagged quantity (ten thousand tons)	0.029	0.260
World urea price ($/mt)	0.150	0.415
World natural gas price ($/mcf)	-0.106	0.187
Exchange rate (CAD/USD)	-0.720	0.883
Constant	14.453***	4.132

Note: ***, ** and * indicate significance at 1%, 5%, and 10% level.

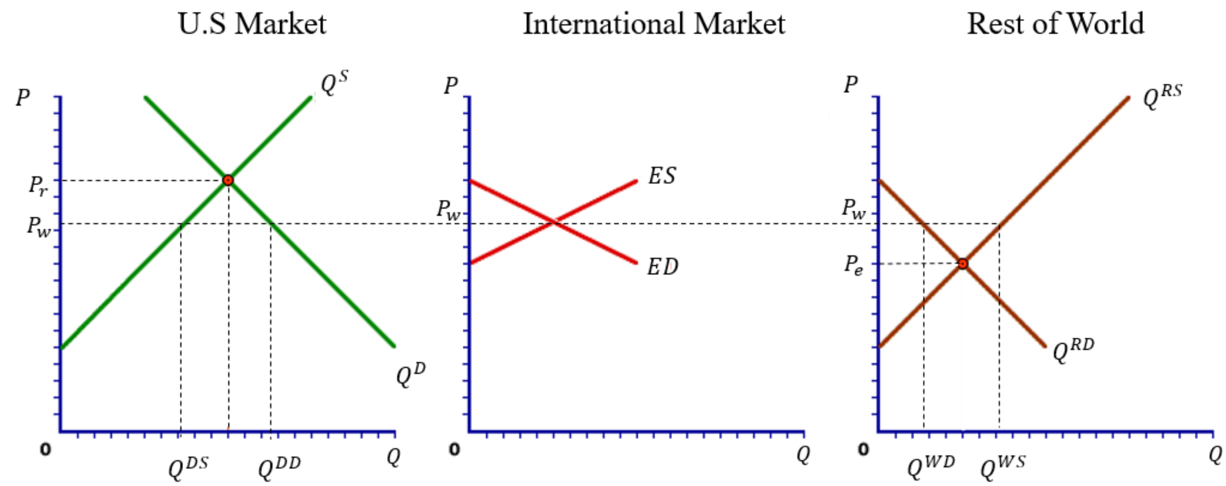

Figure 1. Example three panel diagram

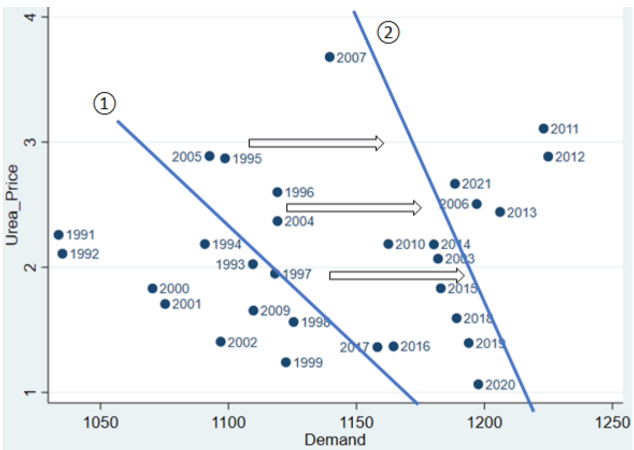

Figure 2: Structural change of urea demand

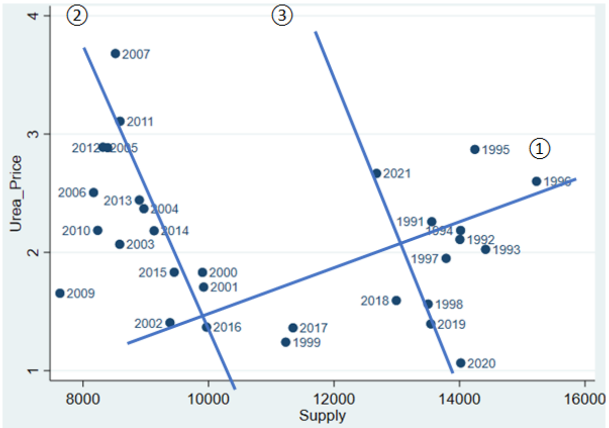

Figure 3: Structural change of urea supply

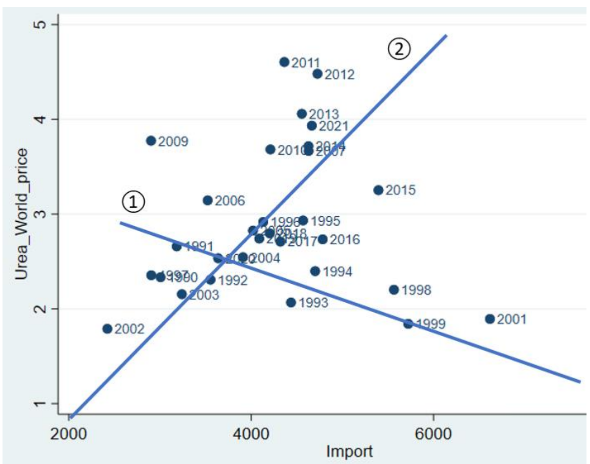

Figure 4: Structural change of urea excess supply

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