12-2016

Pulsating Market Boundaries in Supply Chain Network of Nitrogenous Fertilizers

Sumadhur Shakya
California State University, Monterey Bay, sshakya@csumb.edu

William Wilson
North Dakota State University--Fargo, william.wilson@ndsu.edu

Bruce Dahl
North Dakota State University--Fargo, Bruce.dahl@ndsu.edu

Recommended Citation

Shakya, Sumadhur; Wilson, William; and Dahl, Bruce, "Pulsating Market Boundaries in Supply Chain Network of Nitrogenous Fertilizers" (2016). *2016 Proceedings*. 1.
http://aisel.aisnet.org/siggis2016/1

Pulsating Market Boundaries in Supply Chain Network of Nitrogenous Fertilizers

Completed Research Paper

Sumadhur Shakya
California State University Monterey Bay
100 Campus Center, Seaside, CA 93955
sshakya@csumb.edu

William Wilson
North Dakota State University
NDSU Dept. 7610 PO Box 6050, Fargo, ND 58108-7441
William.wilson@ndsu.edu

Bruce Dahl
North Dakota State University
NDSU Dept. 7610 PO Box 6050, Fargo, ND 58108-7441
Bruce.dahl@ndsu.edu

Abstract

All the market boundary for a fertilizer plant is function of natural-gas prices (henry-hub), demand of nitrogen based fertilizer at county level, and transportation cost by mode (rail, truck and barge). The demand for nitrogenous fertilizers is largely driven by agriculture, wherein, the composition and pattern of crops varies widely with time and region. Variation and uncertainty in natural-gas prices and transportation cost results in pulsating market boundaries, the area that is served by a fertilizer plant. A combined approach of statistical analysis and geographic information systems (GIS) is used to build a spatial equilibrium model representing structure of supply chain network for United States comprising origins (fertilizer plant, point of imports), destinations (counties), and various mode of transportation (truck, rail and barge). Such approach helps in (a)visualizing the market boundaries, (b) structure of supply chain network of nitrogen based fertilizers, (c)analysis of potential impacts due changes in natural-gas prices.

Keywords: Spatial equilibrium, Fertilizer, Visualization, GIS, Natural Gas.

1 Introduction

Fertilizer industry has gone through major changes in the past decade. As per the recent report (USDA-ERS, 2013), annual nitrogen fertilizer use increased more rapidly due to development of the seed varieties with better response to application of the nitrogenous fertilizers. Non-agricultural industry consumption in United States (U.S.) has experienced more volatility since 2004 (Figure 1). Driven by the rising energy and the input material cost (mainly natural-gas), consumption varied from 18 million tons during record high fertilizer prices in 2009 to 24 million tons in 2011, and then again down to 21 million tons in 2010. Efficient intensive farming requires farmers to apply high grade and single nutrient fertilizers. With fixed production capacity of nitrogen based fertilizers plants in United States, the increase in consumption leads to increased imports, with net share of imports going up from 19 percent in 2002 to 50 percent in 2011. During calendar year of 2012 U.S. imported 10.74-million-ton nitrogen, and exported 1.75 million ton on nitrogen. Usually, the nitrogen imported in July to December of a year is expected to be used for crops in next year.

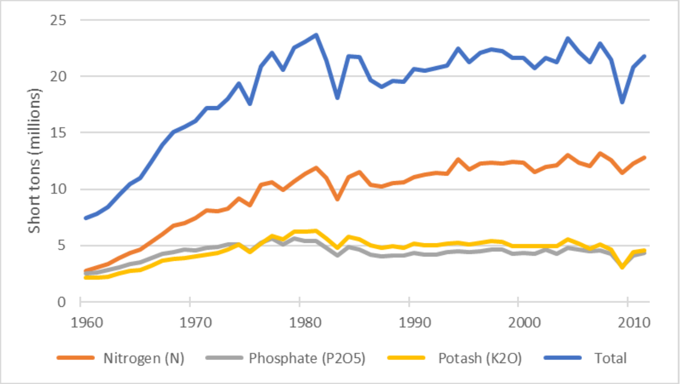


Figure 1 Fertilizer use in U.S. agriculture, 1960 – 2011. Source: (USDA-ERS, 2013)

The economic contribution of nitrogenous fertilizer (N-F) in 2009 is valued at 23.7 billion and 80,000 jobs (Plewes & Smith, 2009). Most of purchases were made from domestic natural gas production and pipeline sector predominantly in state with ammonia plants. Nitrogenous fertilizer industry is one of the three major industry (others being phosphorus and potassium). It is added to soil for intake by plants to promote vegetative growth in various forms. Anhydrous ammonia is the primary source of all nitrogenous fertilizers used in Untied States. During production of ammonia, nitrogen is used from air, and hydrogen is used from natural gas. Anhydrous ammonia is then later utilized directly in agriculture or industry sectors or converted into urea, nitrogen solutions and ammonium, sulfate. Apart from high fixed costs in fertilizer industry, natural gas is primary input for fertilizer manufacturing. Changes in natural gas prices have significant impact on the cost of production for nitrogenous fertilizer. Natural gas prices have reduced drastically in past decade. Natural gas prices also vary geographically at any one given point in time. Average wholesale spot prices for natural gas (Figure 2) in United States at Henry Hub in Erath, Louisiana, a key benchmark location, fell from $4.02 per million British thermal units (MMBtu) in 2011 to $2.77 per MMBtu in 2012. Such a price is lowest average annual price at Henry Hub since 1999 (U.S.- EIA, 2013).

The purpose of this study is to derive a spatial network flow model equilibrium model for nitrogenous fertilizer industry that is representative of spatial distribution and structure of supply chain network (SCN) in United States. Recent advances in technology in geographic information systems (GIS) is utilized to visualize the model for stochastic optimization model, something that would otherwise would not have been possible few years in the past. Stochastic market boundaries are derived for given historical natural gas price distribution for each fertilizer location, and the results from optimization model are represented in GIS. This is significant, as slight change in natural gas prices affects the competitiveness of a fertilizer plant to supply various destination regions. A comprehensive repeated optimization process helps in accounting for expected changes while deducing the structure of supply chain and most likely market boundary. As the natural gas prices change, so does the market boundaries. This paper refers to this phenomena as pulsating market boundaries. In order to represent pulsating market boundaries, only positive flows from any origin to any destination points are mapped in GIS. Mapping and visualization GIS helps in getting the overview of network of supply chain in United States, rather than a tabular data presented to reader for each individual fertilizer plant, which is usually in millions of rows of data. In this paper, all nitrogenous fertilizers are categorized into anhydrous ammonia, ammonia (dry), and (nitrogen solutions (UAN). All fertilizer plants and import locations in U.S.-gulf are treated as origin nodes, all county centroids (geometric center) are treated as destination nodes. Transshipment (change in mode of transport occurs at this point, such as from barge to truck or rail) points are kept true for conservation of flow in statistical model and represented as set of both origins and destination points depending on mode of transport. Selected results are presented in this paper in map/graphical form due to space constraints. This paper focuses on the transportation aspect of supply chain network and its structure for the purpose of visualization from the perspective of data analytics.

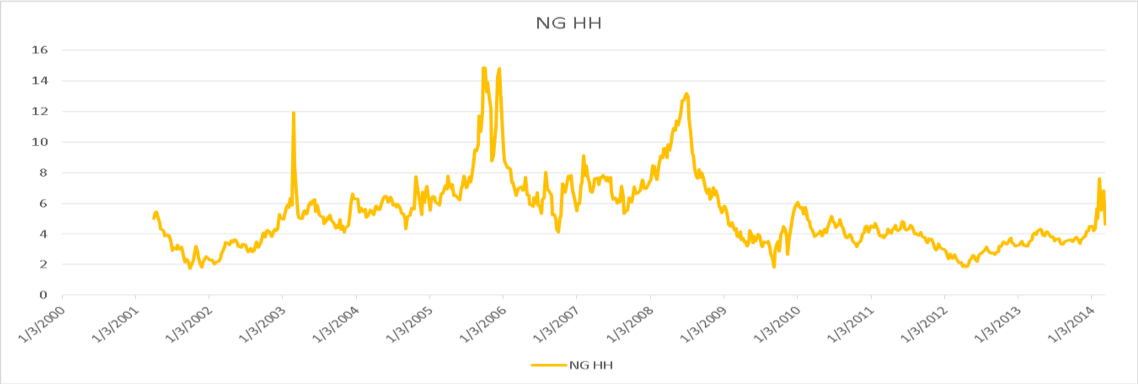


Figure 2 Natural-Gas Prices at Henry-Hub in $ per MMBtu (million British thermal units)

2 Industry Background

Nitrogen, phosphorus and potassium fertilizers are important inputs that impact crop productivity. Fertilizer demand varies across crops and regionally. Nitrogen fertilizer use has increased rapidly due to the development of high yielding seed varieties under intensive fertilizer application. Nitrogen fertilizers accounts for around 40 percent of the total U.S. fertilizer consumption (USDA ERS, 2016). The United States is one of the major users of nitrogen-based fertilizer, and use of N-F in other countries is on the rise as well. The most N-F intensive crops are corn, potatoes, and rice, with moderate use in sorghum, canola, wheat, cotton, and barley, while crops such as peanuts and soybeans use substantially less or no added nitrogen fertilizer. Any change in the crop composition thus causes change in demand of N-F. Expanded corn production in the mid-west U.S. is a major source of new demand for N-F. Fertilizer use has risen substantially over past few decades, increasing from 2 t/sq. km in 1961 to 11 t/sq. km in 2010 (Parker, 2011).

2.1 Fertilizer Demand

Anhydrous ammonia is primary input for N-F in U.S. Use of N-F varies geographically and has important implications for spatial distribution SCN. There are three primary types of nitrogen: anhydrous ammonia (Anhy), urea (dry), and UAN (UAN).[1] There are substantial differences in demand for each type across states. Some states make extensive use of urea and data (comparing 2006 and 2007, and 2011) do not suggest that fertilizer use by type changes between years, although variations in future cropping patterns and production practices may induce changes.

Demand for fertilizer was constructed at the county level using data on nitrogen use by crop type and acres planted. Acres planted were for barley, canola, corn, cotton, peanuts, rice, sorghum, soybeans, wheat (treated separately for hard red spring, durum and hard red winter) and potatoes for 2010-1012 (USDA-NASS, 2013b). Nitrogen use by crop type was obtained from (USDA-ERS, 2013) and (USDA-NASS, 2013a) on a state level basis and applied to all counties within the state. Total demand for Nitrogen by type anhydrous ammonia Figure 3, urea Figure 4, UAN Figure 5was obtained by taking county level demands

---

[1] In addition, other sources of nutrients include phosphorus, potassium, and micronutrients. None of these sources are included in this study.

and multiplying these with the proportion of state level demands by type (AAPFCO Publications & Programs, 2013).

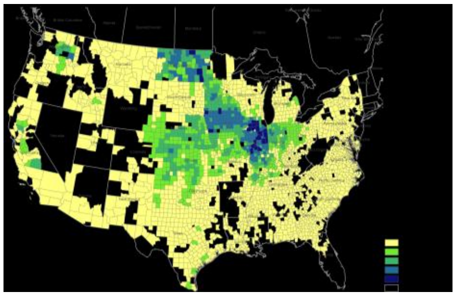


Figure 3 Demand across region for anhydrous ammonia in U.S.

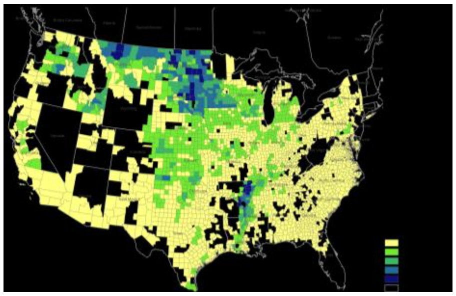


Figure 4 Demand across region for urea in U.S.

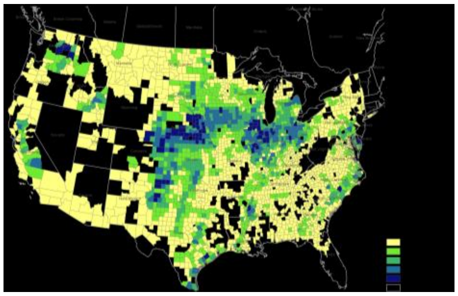


Figure 5 Demand across region for UAN in U.S.

2.2 Natural-Gas Prices

Domestic prices of natural gas price (as traded at Henry Hub) and imports are extremely volatile, impacting domestic-plant utilization (Figure 2). The industry of fertilizer manufacturing has tremendous economies of scale. The N-F industry has high fixed costs of $1.5 to $3.0 billion (Midwest Fertilizer, 2013; Wiser, 2013), with low marginal costs. The marginal costs decline with increase in output. The dominant input cost is natural gas which comprises 50% or more of the manufacturing costs. Thus, access to low-cost natural gas provides an important competitive advantage. Indeed, competitive advantage is partly the escalation in U.S. domestic oil output that results in increased spatial heterogeneity for natural-gas prices. Prices are lower in U.S. Gulf states (such as Louisiana, Texas, Oklahoma. and North Dakota).

Recent changes in natural gas prices prompted potential new entrants to the industry and the. Since 2011, a total of about 25 new plants have been proposed throughout the United States (Midwest Fertilizer, 2013; Wiser, 2013); each one proposed production in the area of 1.1 to 3.7 million tons/year and costing $1.5billion or more. Some announcements to open new plants have reportedly been put on hold or cancelled (Taylor, 2015). Characteristics of the new entrants are important.[2] Some companies are incumbents that are expanding (CF Industries, Agrium, and Koch);[3] some are established cooperatives (e.g., CHS), or, newly formed cooperatives (e.g., Northern Plains Nitrogen); some are regional energy firms (Dakota Gasification or Mississippi Power); and some are off-shore firms expanding into the U.S. market (e.g., Eurochem). Energy companies are looking to use their outputs. Off-shore entrants are looking for opportunity, and several are looking for exports, potentially to China.

Supply chain network for nitrogenous fertilizer in United States as included in this paper starts from the location of imports, to the location of fertilizer plant, and then from fertilizer plant to finally point of consumption at county level. SCN also includes transshipment between import location and fertilizer plant or consumption point wherein mode of transport changes from barge to rail/truck or from rail to rail/truck. Given the comprehensive nature of actual supply chain network, wholesale dealers and distributors, and retailers of N-F which would be subject to same forces of demand and supply as any other locations of imports, fertilizer plants, and county points. This paper focuses on the transportation aspect of supply chain network and its structure for the purpose of visualization from the perspective of data analytics.

3 Previous Studies in Spatial Analysis, Use of GIS in Transportation, and Spatial Arbitrage

Location of plants was first focused studies suggesting that consumers do not always buy from the least expensive supplier for the reason that firms are differentiated by their geographic locations or characteristics associated with product (Hotelling, 1929). Transportation costs and downward sloping average costs curves over a range of quantity sold was considered in a study much later (Capozza & Order, 1978).

Another spatial competition study was conducted in context of pricing in context of agricultural chemical industry (Hall, Dorfman, & Gunter, 2003). In this study, three spatial competition models were tested on retail price data for agricultural chemical industry that included insecticides, pesticides and herbicides. Study was based on 552 prices from 65 dealers. The authors collected the data for distance between closest competitor and number of competitors using 'Microsoft Map Quest' and the firm as listed with Georgia Department of Agriculture. The fifteen mile radius was chosen as approximate distance farmer was willing to travel to purchase chemicals. The distance more than 15 miles was deemed too far to expect a farmer to travel, that too as direct (Euclidean) distance and not the distance travelled on road. Authors considered this distance reasonable based on demands of farm labor time and the transportation costs associated with bulky chemicals.

This paper uses actual geographic location of fertilizer plants and actual road and rail distances travelled. Model applied in this paper deals with supply chain at much large scale (complete transportation geography of United States and Canada). Other studies have been grouped in smaller subtopics to account for overlapping nature of topical sciences. There is high correlation between terms used in different areas of study, but still different.

GIS in agricultural transportation has been applied since late 1980s, specifically in commodity movement and mode of transportation. Studies for optimal flows of commodities and alternate mode of transportation were done using ArcGIS starting mid 1990s (Ellis, 1996). Transportation cost is indispensable for any spatial arbitrage to exist. The process of spatial arbitrage was formalized in nineteen fifties (Enke, 1951; Samuelson, 1952, 1957). In decades thereafter, a standard form of spatial price equilibrium model has been used for many commodity markets; the livestock-feed market (Bates & Schmitz, 1969), international trade (Bawden, 1966), spatial price fluctuations (Granger & Elliott, 1967), two spatial random markets model from perspective of describing at retail outlets . Work related with spatial fluctuations was highlighted for commodities in ninety seventies and eighties(Bressler & King, 1970; Bronars & Jansen, 1987).

---

[2] Report titled "Overview of Key Markets" (Greenmarkets, 2013) provides a current indicator of each proposed plant's status.

[3] See "The New Koch" (Leonard, 2014) for a recent description of Koch in the fertilizer industry and Kelleher (Kelleher, 2013) for a similar interpretation of the industry evolution by CF Industries.

This paper contributes by using not only the actual distance between markets but also the freight rates to the markets under consideration on a repeated basis in order to get the mostly likely market boundaries. Moreover, instead of treating the prices as discrete, they are treated as random, with certain distribution based on historic prices, so as to capture the temporal aspect of price movement. This is captured in stochastic repeated linear programming.

4 Importance of Mapping/Visualization of Supply Chain Network (SCN) of Nitrogenous Fertilizers (N-F) in United States

As observed from recent announcements (Midwest Fertilizer, 2013; Wiser, 2013) new entrants to the industry are confident about gaining from technological advantages coupled with recent reductions in the price of natural gas. Natural-gas prices have fallen drastically with a surge in oil production from states such as Texas and western part of North Dakota, the two largest oil-producing regions in the United States. The main problem is to analyze how viable the recently announced expansion plans or new fertilizer plants are, and if it would make the United States a potential net exporter of nitrogen-based fertilizers. In order to determine the viability of new plants, it is necessary to take into account the randomness and volatility factor of inputs such as natural-gas prices and import prices at the USG in addition to changes in demand by quantity and type. Other intermediate nodes, such as fertilizer warehouse or distribution centers, may be ignored because they are subject to the forces of supply and demand.

Growth in the demand for new fertilizer capacity is both a challenge and opportunity for investors and promoters of industry expansion. Dynamic changes with the elements impacting fertilizer demand and competition are important. However, they are highly uncertain, notably in terms of demand, import competition, and natural-gas prices. Each of these factors are not only uncertain, but also has important impacts on spatial competition. Hence, for developers of expanded capacity, having a better understanding about how these uncertainties impact the viability of new plants is important. Such knowledge is crucial for shipping industry (railroads, barges, and distributors). Finally, an enhanced grasp of future competitive behavior is important for inter-firm and spatial competition. Fertilizer use directly impacts agriculture and the food industry, thereby directly affecting the economy. Growing surplus capacity worldwide has the potential to change the viability of both old and new plants. Traffic patterns and the general supply chain structure are likely to change geographically, warranting policy and regulation changes. These adjustments can help make new plants competitive within the local and global supply chain of nitrogen-based fertilizer.

5 Approach to Mapping SCN of N-F in U.S.

The base case scenario for the year of 2012 year is considered as a static linear-optimization model that allocates flows of fertilizer from production origins to destinations consumption nodes, via transshipment points (if applicable) along the supply chains such that the total distribution cost in a model network is minimized. Production costs are known with certainty and treated as discrete values, along with the capacity at each node (plant) by type (Anhy, urea, or UAN). Demand, by type, is also known at the county level. During optimization, least-cost flows are distributed among the supply and demand nodes, while taking care of conservation of flows, supply and demand constraints, additional constraints to address specific limits of conversion, and capacity constraints, such as maximum import by type, by location, etc.

In order to model the structure of SCN for N-F in United States, a unique combination of spreadsheet (Microsoft Office 2016), SAS-OR (SAS 9.3), and geographic information systems (GIS) (ArcMap 10.2) is used (Figure 6). Spreadsheet data is converted imported in SAS, to be used in optimization model (Figure 6). Significant data, derivations, manipulation and transformation were done freely between SAS, spreadsheets and ArcGIS. There are a number of critical variables used in the model which are described in this section. These include the demand for fertilizer, import prices and volumes, plant locations and capacities by fertilizer type, and processing costs. Each set of nodes is represented by an ID number in the optimization model, so that volume of flow in arcs can be identified and assigned back in GIS post optimization. There are seven different basic types of flows in the basic model (Figure 8). In order to account for the fact that few fertilizer plants first produce anhydrous ammonia, and then act as supplier for anhydrous ammonia, or after conversion act as supplier for urea or UAN, separate set of origin-destination matrices are used (Figure 9, Table 1). A total of 24 different matrices are created in ArcMap and imported into optimization model in SAS. Eight additional dummy matrices are brought in optimization model to account for conversion and assign cost of conversion at fertilizer plants. Distance matrices are brought in from ArcMap into SAS as well (Figure 9, Table 1). Cost of transportation varies per unit of distance travelled, and by mode of transportation. The cost of transportation is treated as impedance in optimization for each set of arcs.

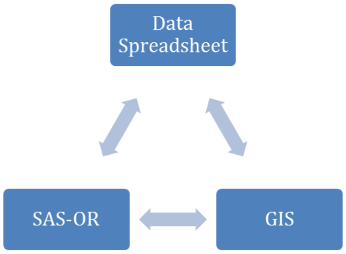


Figure 6 Combination of data manipulation and conversion used in mapping of SCN of N-F in United States

In practice, a static linear, optimized model may best represent the current structure of the fertilizer industry under the assumptions made in this paper. However, such assumptions would be limited to address the volatility and randomness of the input variables if only discrete known values are considered. Stochastic spatial optimization is, therefore, used to address the randomness for input variables such as the volatility of natural-gas prices, thereby affecting the fertilizer plant's cost of production. A linear, spatial, stochastic model helps address the randomness of input variables based on the historic fit of distribution for, say, fertilizer import prices at USG. Linear stochastic optimization allows all plants to work if and when required to meet the demand. There is no lower limit for plants to work, the fertilizer plant can work anywhere between zero and its production capacity. There is no minimum operating constraint for current and new plants either.

Transportation-network or spatial optimization involves the distances between nodes. In this paper, network distances are derived for road, railroad, and barge as reported by public agencies (U.S. Department of Transportation, 2013). Geographical information systems (GIS) are used to determine the distance between origin and destination nodes. The distance can then be used to better determine the counties (demand nodes) that fall within the market boundary of a production (fertilizer plant) node.

Demand is determined at the county level for all major crops and then aggregated by type of fertilizer (Figure 3, Figure 4, and Figure 5). County centroids act as demand nodes such that irrespective of type of fertilizer supplied to it in the analytical model does not exceed cumulative demand for nitrogen, for a total of 2600 demand points (Figure 8) with 6 attributes such 3 attributes are capacity are for current and future for anhydrous, urea and UAN each (Figure 8).

The model includes production at 29 existing fertilizer plants, and 12 proposed plants that acts as set of supply nodes in the model. Each node has 6 attributes, for capacities for anhydrous current, urea current, and UAN current, anhydrous future, urea future, and UAN future (Figure 8). Proposed plants include new plants as well expansion in capacity at existing plants. Each plant produces different types of fertilizer and has capacity restrictions for the various types of fertilizer. There is cost associated with location of fertilizer plants by state (due to different rate of electricity). Imports of fertilizer by type at the U.S. Gulf is based on import prices, and shipping costs to the destinations.

Node sets for imports from Canada and U.S. Gulf each are modeled similar in terms of attributes structure (6 attributes for capacities) to set of node for U.S. fertilizer plants for the fact that each node is assigned with capacities with 6 attributes. There are also two sets of transshipment points used in model. First set of transshipment is port of entry (POE) at U.S. Canada border (5 nodes), where in conservation of volume of flow by type of fertilizer is maintained as well as mode of transportation (total flow in is equal to total flow out by for each type of fertilizer by each mode of transportation). Second set of transshipment is inland transshipment (3 nodes) where in conservation of flow by type fertilizer is maintained, however, the change of mode of transportation is allowed at certain cost (unloading from barge, and loading onto rail or truck for further distribution). Details of nodes for import points for Canada, U.S. Gulf, U.S.-Canada border points, and inland transshipment points are presented in detail in Figure 8. A sample of supply nodes and demand nodes is also presented in Figure 8.

6 Theoretical Framework & Model

Agricultural prices and commodity markets are random and stochastic in nature due to associated volatility (Ferris, 2005). Population densities and production densities determine aggregate volume of products shipped and availability of back-hauls, thereby influencing the utilization of available capacity within existing transportation network. Consider a plant located in the middle of a large producing territory, representing a small market. To attract larger volumes, it will be necessary to offer higher prices for the product be supplied to it by neighboring producing region. So long as the plant is away from other competitor plants other plants, its supply or producing territory will take the form of a circle centered on the plant (Bressler & King, 1970, p. 141).

With entry of competing plants to serve an entire producing region, final equilibrium would determine the location size and number of plants as well as allocation of geographical territory among plants; just as in case of competing markets. A system of circular areas cannot fully all of the areas without either overlapping or leaving out some of the area. Overlapping areas would be eliminated by the case of producers towards most favorable market. In practice, however, this is not the case, as same region may be well within market boundary region of more than one market and producers supply to more than one market (stochastic representation of market boundaries present such case in stochastic models of this paper). The idealized solution to plant size and allocation of geographical boundaries appear to involve a regular system of hexagonal market boundaries for plants where in the plants are located at geometric center.

In this paper, market boundaries are derived from the perspective of fertilizer plants (supply points) such that with changes in cost of production (natural-gas price), such that fertilizer plants can supply the counties to meet their respective demand for anhydrous ammonia, urea, and UAN, at lowest cost. Instead of supply plant being located in center of a circular supply area, the fertilizer plants are located such that they supply to counties (as demand points) around them while balancing maximum supply at lowest cost of transportation and lowest average plant cost. Initially demand at counties, price of natural-gas (Henry-Hub), and import prices are treated as discrete, but later these are treated as random stochastic distribution to derive dynamic market boundaries (most likely under the any given market condition) for each of fertilizer plant. Lower transportation cost means a fertilizer plant can supply counties that are geographically farther away from it. Lower cost of production either due to lower natural-gas prices or electricity cost or better technology (operational cost) or larger size (better economies of scale) may also mean that one fertilizer plant can compete better than another fertilizer plant in same vicinity of geographical area.

6.1 Transportation Network Model

Graphical or network representation helps in analyzing many important optimization problem. A graph of network is defined by two set of symbols namely nodes and arcs. Nodes are set of points or vertices (set V). An arc consists of an ordered pair of vertices and represents a possible direction of motion that may occur between vertices (a set of A) (Winston, 2003). Also a sequence of arcs such that every arc has exactly one vertex in common with the previous arc is called a chain (Winston, 2003). Lastly a path is a chain in which the terminal node of each arc is identical to the initial node of the next arc (Winston, 2003).

This paper utilizes the approach of finding the flows through each arcs in the network that minimizes the total cost of flow for the network while meeting demand at each demand node, subject to the constraints of supplying nodes, demand nodes, arcs, and conservation of flow. These are elaborated in context as related to this paper. Constraints of supplying nodes include the maximum amount of production or supply that can be assigned to a supplying node such as import points and fertilizer plants. Such constraints are treated separately for each type of fertilizer. Constraints for demand nodes refer to amount of demand to be met at county nodes (geographic centroid) for each type of fertilizer. Constraints related to an arc is the minimum or maximum amount of flow allowed between a pair of nodes. For example, a maximum number of containers via barge between import points to Minneapolis can be set to a limit for the arc of Import to Minneapolis.

As an example, if a network contains an arc (j,k), then the possible motion for flow of quantity is from node j to node k. Lets say nodes, 1, 2, and 3 represents cities and each arc represents one-way road linking cities. For this network, V={1,2,3} and arc A = {(1,2),(2,3),(3,2),(3,1)}. For the arc (j,k), node j is the initial or origin node, and node k is the terminal or destination node. The arc (j,k) is said to go from node j to node k. thus arc (1,2) has origin node 1, and destination node 2 and it goes from node 1 to node 2. In (Figure 7) shows that travel is allowed between node 1 to node 2 for arc (1,2) and from node 2 to node 3 as well as from node 3 to node 2 for arc (2,3). In this example, (3,1)-(1,2), (3,2) is a chain but not a path whereas (1,2)-(2,3) is a chain and a path.

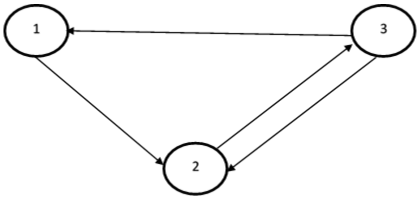


Figure 7 A hypothetical network showing flow between nodes and corresponding arcs showing direction of movement allowed.

A general description of transportation problem as relevant to this paper, can be specified as follows (1) A set of m supply points from which fertilizer can be shipped. Supply point i can supply at most s_i units of shipped good (for example, this is the fertilizer plant capacity).(2)A set of n demand points from which fertilizer can be shipped. Demand point j must receive at least d_j units of shipped good (for example, this is the amount of a type of fertilizer a county must receive). (3) Each unit produced at supply point i and shipped to demand point j incurs a variable cost of c_{ij} (for example, tuck cost per mile times the distance between supply point i and demand point j). (4)Let X_{ij} is the number of units shipped from supply point i to demand point j then the general formulation of a transportation problem is

$$\sum_{i=1}^{i=m}\sum_{j=1}^{j=n} C_{ij}X_{ij} \qquad \textit{(Eq. 6.1)}$$

Subject to

$$\sum_{j=1}^{j=n} X_{ij} \leq S_i \quad (i=1,2,\ldots,m) \quad \textit{(Supply constraints)} \qquad \textit{(Eq. 6.2)}$$

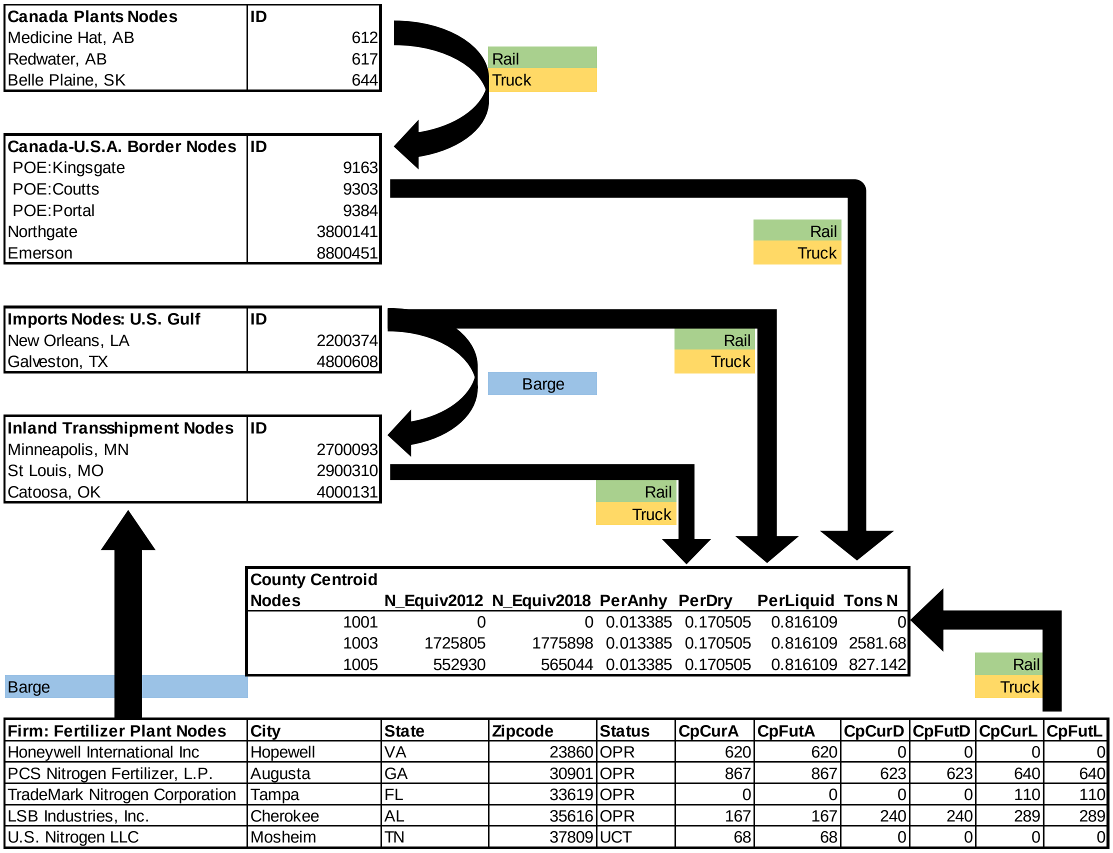
$$\sum_{i=1}^{i=m} X_{ij} \geq d_j \quad (j=1,2,\ldots,n) \quad \textit{(Demand constraints)} \qquad \textit{(Eq. 6.3)}$$

$$X_{ij} \geq 0 \quad (i=1,2,\ldots,m;\ j=1,2,\ldots n) \qquad \textit{(Eq. 6.4)}$$

In addition there can be also a transshipment point through which goods can be transshipped on their journey from supply point to a demand point., and it can both receive goods from other points and send goods to other points (Winston, 2003), and has no consumption or production of its own. In this paper, an example of the transshipment point considered is St. Louis, MO which can receive shipments from import points via barge, and can send fertilizer to destination points of counties via rail or truck with production or consumption of its own. At such transshipment nodes, additional costs like loading and unloading costs (if applicable) or change costs for changing of mode of transportation related costs are also considered.

6.2 Model Specification

The optimization model to allocate flow of volumes to arcs, under the constraints of supply and demand nodes are optimized for lowest cost for the base case period of 2010 to 2012. The model is calibrated and verified with visualization of supply chain structure. Each set of nodes are cross-verified with actual data available. Then projections are made for a number of the important exogenous variables to the year 2018. Comparisons are then made to outputs of interest between the base case and projection period. The variables of particular interest are demand, production of fertilizer by type at each plant, imports and shipments by model from origins to destinations. The model is later extended to account for changes in market boundaries under randomness of variables like demand, cost of production by state (due to price of natural-gas) and more importantly, the import prices. In order to account for such randomness, model for base case (year 2012, static) is expanded to stochastic repeated linear optimization programming for future case in year 2018. Some of the inputs variables are treated as random. The distribution of random variables represent the historical data as observed for eight to ten years for crop production at county level, and thus the dependent demand for N-F by type(anhydrous, urea, and liquid) and natural gas price as traded at Henry-Hub, and transportation costs (Figure 10) were used as stochastic variable in optimization model.



Canada Plants Nodes	ID
Medicine Hat, AB	612
Redwater, AB	617
Belle Plaine, SK	644

Canada-U.S.A. Border Nodes	ID
POE:Kingsgate	9163
POE:Coutts	9303
POE:Portal	9384
Northgate	3800141
Emerson	8800451

Imports Nodes: U.S. Gulf	ID
New Orleans, LA	2200374
Galveston, TX	4800608

Inland Transshipment Nodes	ID
Minneapolis, MN	2700093
St Louis, MO	2900310
Catoosa, OK	4000131

County Centroid Nodes	N_Equiv2012	N_Equiv2018	PerAnhy	PerDry	PerLiquid	Tons N
1001	0	0	0.013385	0.170505	0.816109	0
1003	1725805	1775898	0.013385	0.170505	0.816109	2581.68
1005	552930	565044	0.013385	0.170505	0.816109	827.142

Firm: Fertilizer Plant Nodes	City	State	Zipcode	Status	CpCurA	CpFutA	CpCurD	CpFutD	CpCurL	CpFutL
Honeywell International Inc	Hopewell	VA	23860	OPR	620	620	0	0	0	0
PCS Nitrogen Fertilizer, L.P.	Augusta	GA	30901	OPR	867	867	623	623	640	640
TradeMark Nitrogen Corporation	Tampa	FL	33619	OPR	0	0	0	0	110	110
LSB Industries, Inc.	Cherokee	AL	35616	OPR	167	167	240	240	289	289
U.S. Nitrogen LLC	Mosheim	TN	37809	UCT	68	68	0	0	0	0

Figure 8 Overview of basic model showing flow between pair of origins and destination by mode of transportation and structure of data used for each node.

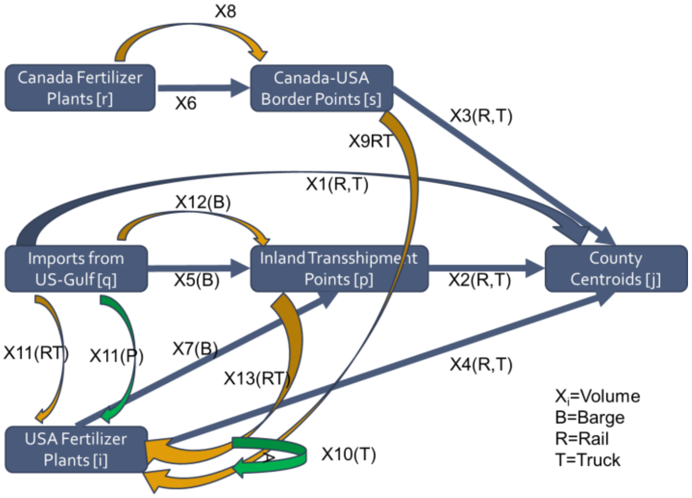
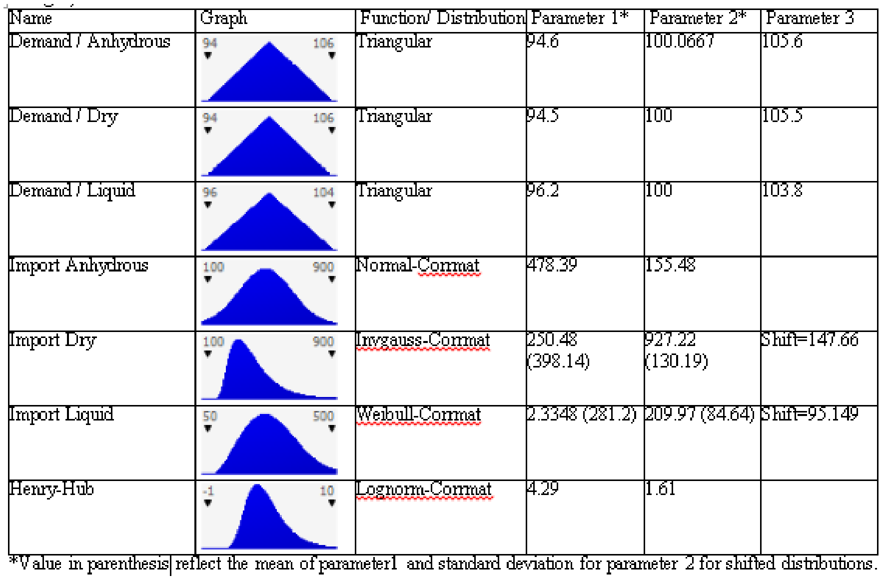


Figure 9 Detailed Full model showing nodes, flows between nodes, and type of modes allowed between nodes, and name of flows representing quantity of fertilizer shipped. (R=Rail, T=Truck, B=Barge, P=Pipe, blue solid arrows represent normal shipments of anhydrous ammonia, urea, and UAN, Brown colored arrows represent anhydrous only shipments for conversion into urea or UAN at destination nodes).

Table 1 List of all origin-destination matrices used in detailed model to calculate distances for the respective mode of transportation.

1	Border to Demand Rail	9	Inland to Demand Road	17	Imports to Demand Rail
2	Border to Demand Road	10	U.S. to Demand Rail	18	Imports to Demand Road
3	Canada to Border Rail	11	U.S. to Demand Road	19	Imports to Inland Barge
4	Canada to Border Road	12	U.S. to Inland Barge	20	Inland to Demand Rail
5	Imports to Demand Rail	13	Border to Demand Rail	21	Inland to Demand Road
6	Imports to Demand Road	14	Border to Demand Road	22	U.S. to Demand Rail
7	Imports to Inland Barge	15	Canada to Border Rail	23	U.S. to Demand Road
8	Inland to Demand Rail	16	Canada to Border Road	24	U.S. to Inland Barge



Name	Graph	Function/ Distribution	Parameter 1*	Parameter 2*	Parameter 3
Demand / Anhydrous	94 106	Triangular	94.6	100.0667	105.6
Demand / Dry	94 106	Triangular	94.5	100	105.5
Demand / Liquid	96 104	Triangular	96.2	100	103.8
Import Anhydrous	100 900	Normal-Cormat	478.39	155.48	
Import Dry	100 900	Invgauss-Cormat	250.48 (398.14)	927.22 (130.19)	Shift=147.66
Import Liquid	50 500	Weibull-Cormat	2.3348 (281.2)	209.97 (84.64)	Shift=95.149
Henry-Hub	-1 10	Lognorm-Cormat	4.29	1.61	

*Value in parenthesis reflect the mean of parameter1 and standard deviation for parameter 2 for shifted distributions.

Figure 10 Distribution for variables treated as random for Future cases (stochastic repeated linear optimization model).

6.3 *Objective Function*[4]

The model specified is based on spatial competition using simple transportation model with supply and demand nodes to account for changes in market boundaries. Market boundaries for a supply node (fertilizer plant) are the all the demand nodes supplied by it. It uses linear programing that is integrated with GIS data structure provides a description of the major features of the model. The mathematical model specification is described below:

$$\begin{gathered}
Min\ Cost = \left[\textstyle\sum_{r,s,T,M}^{n} X6_{r,s,T,M} \ * CostCim_{r,T} + \left(\textstyle\sum_{q,p,T,M}^{n} X5_{q,p,T,M} + \right.\right. \\
\left.\textstyle\sum_{q,j,T,M}^{n} X1_{q,j,T,M} \ \right) * CostIm_{T} + \left(\textstyle\sum_{i,j,T,M}^{n} X4_{i,j,T,M} + \textstyle\sum_{i,p,T,M}^{n} X7_{i,p,T,M} \ \right) \\
\left. * CostUS_{i,T} \right] + \left[\textstyle\sum_{r,s,anhy,M}^{n} X8_{r,s,anhy,M} * \left(CostCanBor_{r,s,anhy,M} \ \right) + \right. \\
\textstyle\sum_{s,i,anhy,M}^{n} X9_{s,i,anhy,M} * \left(CostBorUS_{s,i,anhy,M} \ \right) + \\
\textstyle\sum_{q,p,anhy,Barge}^{n} X12_{q,p,anhy,Barge} * \left(CostImpTrans_{q,p,anhy,Barge} \ \right) \ + \\
\textstyle\sum_{p,i,anhy,M}^{n} X13_{p,i,anhy,M} * \left(CostTransUS_{p,i,anhy,M} \ \right)
\end{gathered}$$

---

[4] More detailed information on inputs, additional outputs and the model are available (Shakya, 2014; Wilson, Shakya, & Dahl, 2015).

$$\begin{gathered}
\textstyle\sum_{q,i,anhy,M}^{n} \boldsymbol{X11}_{q,i,anhy,M} * \left(\boldsymbol{CostImpUS}_{q,i,anhy,M}\right) + \\
\textstyle\sum_{i,i,anhy,M}^{n} \boldsymbol{X10}_{i,i,anhy,M} * \left(\boldsymbol{CostUSUS}_{i,i,anhy,M}\right)\Big] \\
+\Big[\textstyle\sum_{r,s,T,M}^{n} \boldsymbol{X6}_{r,s,T,M} * \left(\boldsymbol{CostCanBor}_{r,s,M,T}\right) + \textstyle\sum_{s,j,T,M}^{n} \boldsymbol{X3}_{s,j,T,M} * \\
\left(\boldsymbol{CostBorDmd}_{s,j,M,T}\right) + \textstyle\sum_{q,p,T,Barge}^{n} \boldsymbol{X5}_{q,p,T,Barge} * \\
\left(\boldsymbol{CostImpTrans}_{q,p,T,Barge}\right) + \textstyle\sum_{p,j,T,M}^{n} \boldsymbol{X2}_{p,j,T,M} * \left(\boldsymbol{CostTransDmd}_{p,j,T,M}\right) \\
+ \textstyle\sum_{q,j,T,M}^{n} \boldsymbol{X1}_{q,j,T,M} * \left(\boldsymbol{CostImpDmd}_{q,j,T,M}\right) + \\
\textstyle\sum_{i,p,T,M}^{n} \boldsymbol{X7}_{i,p,T,M} * \left(\boldsymbol{CostUSTrans}_{i,p,T,M}\right) + \\
\textstyle\sum_{i,j,T,M}^{n} \boldsymbol{X4}_{i,j,T,M} * \left(\boldsymbol{CostUSDmd}_{i,j,T,M}\right)\Big]
\end{gathered} \qquad \textit{(Eq. 6.5)}$$

S.T.

Constraints of production at Fertilizer plants, both existing and proposed, by type of fertilizer.
Constraints of consumption of N-F at county centroid as demand points.
Constraints of transportation by mode (such as Barge is not operable in winter to Minneapolis, MN).
Constraints of transshipments points, import limits by type of N-F.
Cost of manufacturing by state.

Where:
T= Type of fertilizer namely: anhydrous ammonia, urea and UAN
M=Mode of transportation, namely: Rail, Truck, Pipe and Barge
i=fertilizer plants located within United States (USPlants)
j= County level demand points
p=Inland Trans-shipment locations (where Barge is incoming mode of flow and rail and truck is outgoing mode of flow).
q=Gulf Import port locations
r=Canadian fertilizer plant locations
s=Canada/USA cross-border points also called as port of entry (POE)
CostIm_{T}=Cost of procuring imports at Gulf port locations by type *T*.
$\text{CostCim}_{r,T}$=Cost of procurement at Canadian plant *r* by type *T*.
$\text{CostUS}_{i,T}$= Cost of Procurement at USA Plant *i* by type *T*.
CostCanBor= cost of shipping between Canada and border points
CostBorUS=cost of shipping between border points and USPlants.
CostImpTrans=Cost of shipping between import port locations to transshipment points.
CostTransUS=cost of shipping between transshipment points to USPlants
CostImpUS= cost of shipping between import port locations to USPlants.
CostUSUS=cost shipping between USPlants to USPlants.
CostTransDmd=Cost of shipping between transshipment to demand points (counties).
CostImpDmd=cost of shipping between import port locations directly to demand points.
CostUSTrans=Cost of shipping between USPlants (selective) to transshipment points.
CostUSDmd=Cost of shipping between USPlants to demand points.
$\text{USCap}_{i,T}$=USA capacity at plant *i* by type *T*.
CanCap= Canada capacity at plant *r* by type *T*.
$\text{Demand}_{j,T}$=Demand at county *j* by type *T*.

7 Results

7.1 Base Case Current

Results from optimization model were plotted in GIS to show the overall structure of supply chain for anhydrous, urea and UAN in Figure 11, Figure 13, and Figure 15 respectively. Each line represents a flow between a pair of origin and destinations where in different color represents different mode of transport and relative thickness represents volume of flow between the pair. This methodology of plotting helps in deciding the supply chain structure for anhydrous ammonia, urea and UAN and has tremendous advantage than looking at a large tabular. Rail dominates as mode of transport, which is expected. Moreover, majority of anhydrous imports from U.S.-Gulf are via Barge to transshipment points, especially St. Louis, MO and then Rail thereafter. Rail is primarily the mode from Canadian anhydrous imports.

Truck constitutes a small portion mainly for short distances. This is consistent with current knowledge of the industry from experts.

Market boundaries were also derived for each plant. This step is done post optimization in order to find out all the counties and the total volume for each of these counties from a fertilizer plant. These are then joined to counties to get a market boundary for a plant. This step was repeated for each plant. Market boundary for selective plants is presented here for highlighting the advantage of methodology and demonstration purpose. The market boundary is presented for plants j=50501, Fort Dodge, Iowa and j=51054, Port Neal, Iowa in Figure 17 (both current plants).

7.2 Stochastic Linear Future Case 2018[5]

Instead of single set of optimized results for base case results, this scenario was simulated with 1000 iterations. Structure of supply chain looks very different from base and accounts for variation and randomness of variables like demand, cost of production (Henry-Hub), and import prices. And since all the fertilizer plants, current and new, were allowed to operate with no restriction on utilization of plant capacity, this scenario is most informative as to what is likely to be the structure of supply chain in year 2018. This scenario allows for all existing and all planned potential fertilizer plants to operate. Mean volume of fertilizer flow all 1000 iterations are shown for anhydrous, urea, and UAN in Figure 12Figure 14Figure 16 respectively. Base case current maps and linear case for future year 2018 presented simultaneously for the purpose of comparison, something that could not have been possible had either statistical or either GIS were to be used as standalone platform for analysis. None of the software (SAS or ArcMap) meet the requirements of addressing the problem of mapping SCN for N-F in United States.

Results when presented in pictorial form for anhydrous, urea, and UAN clearly suggest the potential change in structure of supply chain of N-F in United States. New plants are represented by triangular symbols, and existing plants are shown as circular symbols. Modes of rail, truck and barge are represented by lines of green, orange and blue. Current spatial equilibrium for anhydrous is dominated by rail in Midwest, while truck is limited to transshipment points and import points (Figure 11). The structure of supply chain for N-F for future case is significantly dominated by rail (Figure 12). Increased imports also impact cause increase in transportation of anhydrous ammonia by barge. Only some of the new fertilizer plants are being utilized. There is stiff competition expected between newly opened N-F plants in North Dakota with imports from Canada. Urea is more likely to be the choice of new N-F plants as final product, especially in Midwest (Figure 13, Figure 14) and is also transported by truck. The urea shipments by truck are under significant competition from rail shipments across the border from Canada. There is also significant increase in barge traffic from import nodes. For UAN, the N-F plants from Oklahoma loses market to the new plant in Idaho. There is increase in shipments by rail from Canada to east coast (). There is overall increase in truck shipments directly from import locations.

At the level of individual N-F plants, the market boundaries are likely to change as well, such that maximum price war is expected to be in the counties that are close to being indifferent to more than one N-F plant. Figure 17 shows such a market boundaries between two neighboring plants in Iowa, for current base case. Moving forward in future case (Figure 18), one of the plants in Port Neal, IA has very high probability of shipping in counties that are closer to itself, some of which overlap counties that were originally being shipped to by its competitors. Despite the high probability though, the Port Neal plant on an average ship more towards Iowa than to Nebraska. Such a graphic representation of market boundaries highlights the change in market boundaries, and the areas where stiff competition is likely going to occur.

Each line in the maps, represent a mean flow that occurred during one or more iterations out 1000 for which the optimization results were collected. It is to be noted that Midwest is dominated by imports from Canada by rail and shipments from transshipment points at Minneapolis, St Louis, MO and Catoosa, OK. When compared with anhydrous flows in base case, there are numerous flows from St. Louis, MO, Catoosa, OK and imports from Canada and U.S.-Gulf. In market boundary graphs are helpful in analyzing

---

[5] More detailed information on inputs, additional outputs and the model are available (Shakya, 2014; Wilson et al., 2015).

changes in market boundaries for a fertilizer plant from current base case (Figure 17), and linear future case operating at full capacity such that darker area represents counties the fertilizer plant is most likely/probability to ship its product to, (Figure 18) , and the counties where most of the volume of output from the fertilizer plant is likely to be shipped to which counties (Figure 19).

7.3 Contribution

The major contribution of paper is the stochastic representation of the problem and its impact on the structure of the supply chain for the nitrogen-based fertilizer industry. The model provides flexibility and multiple options to assess the impact of changes in the fertilizer industry through variations in the market boundary, shadow prices, the utilization rate of fertilizer plants, the likely probability distribution for production at fertilizer plants, and the distribution fit for output production parameters. This dissertation in essence, provides a feasibility study for expanding existing plants or opening new plants. Had such feasibility study conducted on smaller geographic level as part of an individual study, market forces at play for the larger geographical level would have been ignored. Data manipulation and processing with post-optimized results provides significant insight that would have been ignored in the absence of GIS techniques. Optimized results, when presented with slight analytical steps of the GIS itself, lead to a quicker and clearer picture than a tabular data.

The study helps understand the economic viability of newly announced nitrogen based fertilizer plants. There is sufficient surplus capacity for production of nitrogen based fertilizers. Therefore, out of all the thirteen N-F plants announced, only few are likely to be viable. The factors that might make the new N-F plants viable are if there exists significant technology advantage, and the cost of natural gas stays low. Additionally, N-F plants that are located farther away from import routes (away from barge transportation) are more at risk decline in natural gas supply as when there would be fluctuation in shale oil production in states like North Dakota. This is viewpoint of not all N-F plants being viable is also corroborated by the fact that N-F plants, if built, need to work at certain utilization rate to recover construction costs (Shakya, 2014; Wilson, Shakya, & Dahl, 2015). Since the time of this study was modelled and analyzed, some of the recent developments support this viewpoint (Taylor, 2015), where in CHS Inc. backed out of proposed construction of N-F plant in Spiritwood, North Dakota. This is clearly visible in future cases presented in Figure 12, Figure 14and Figure 16.

7.4 Future Work

It may be useful to extend this study to further analyze the effect of change with one parameter or in combination to discover which random variables affect the market boundaries of fertilizer plants and by what extent. A similar approach may also be used to determine which random parameters affect the total miles traveled (or the last miles traveled) for each fertilizer type. It may be interesting to first derive the total average distance traveled for a ton of anhydrous to reach its destination. Such analysis can provide greater insight about which counties consume fertilizer from faraway places (Farmers in such areas would be paying more for their transportation cost.), thus is there an incentive for closer fertilizer plants to lower their price? If yes, then by how much?

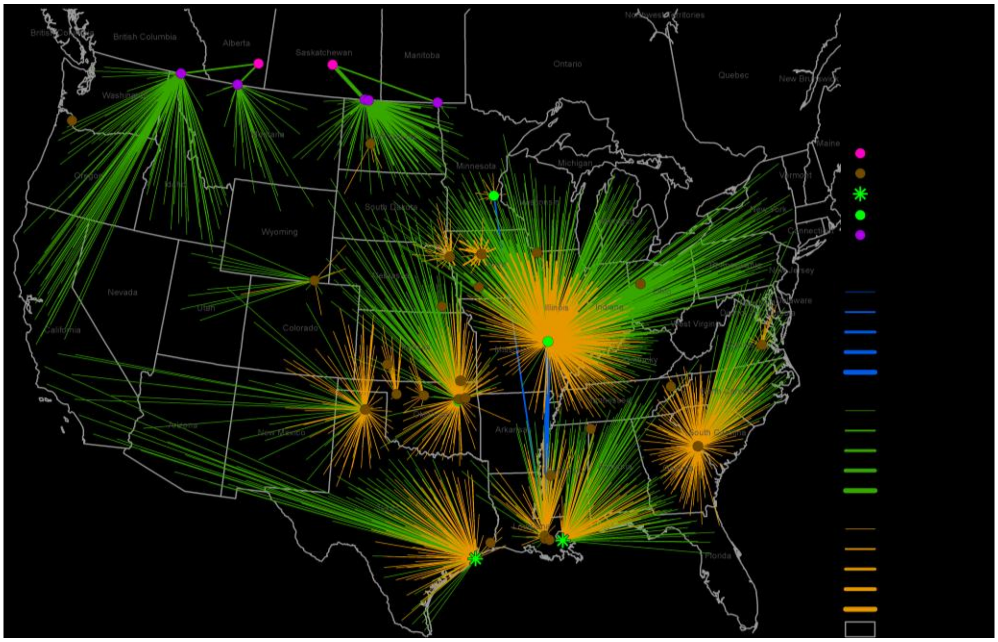


Figure 11 Structure of supply chain for anhydrous ammonia for base case by mode (Rail=Green, Truck=Orange, Barge=Blue).

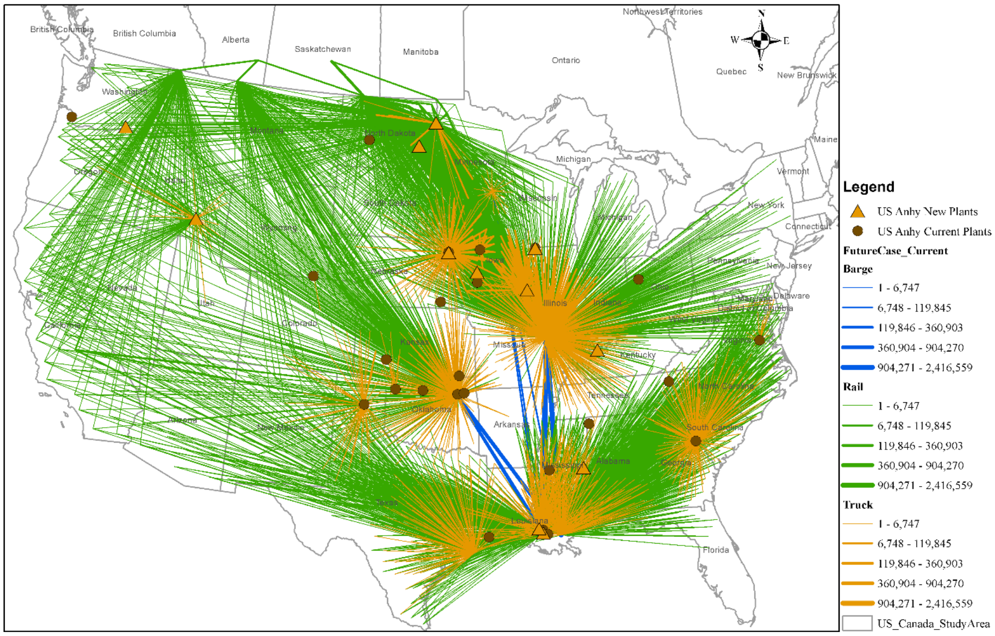


Figure 12 Structure of supply chain for anhydrous ammonia for future case linear by mode (Rail=Green, Truck=Orange, Barge=Blue).

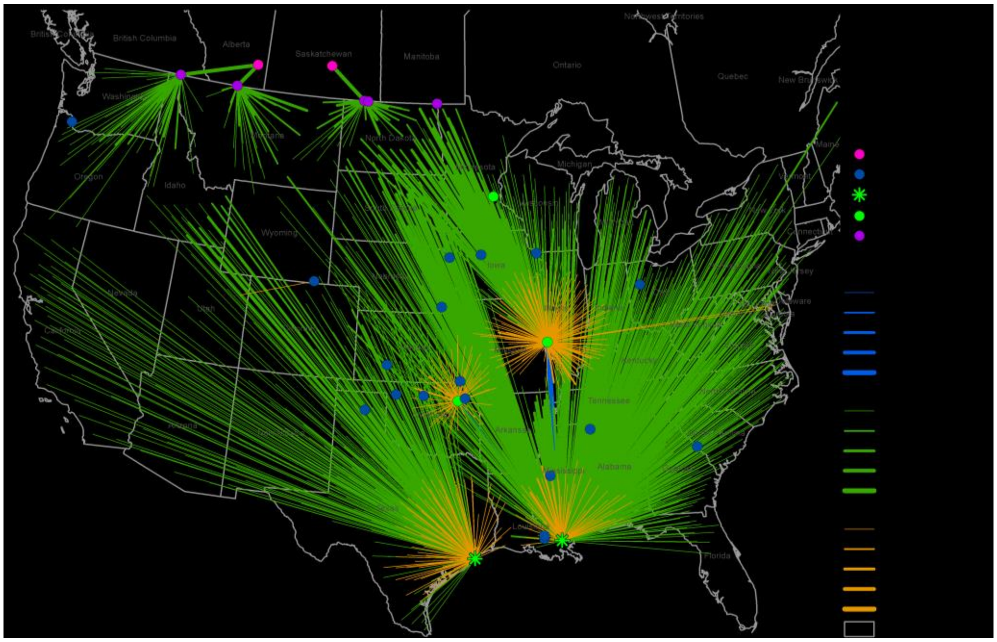


Figure 13 Structure of supply chain for urea for base case by mode (Rail=Green, Truck=Orange, Barge=Blue).

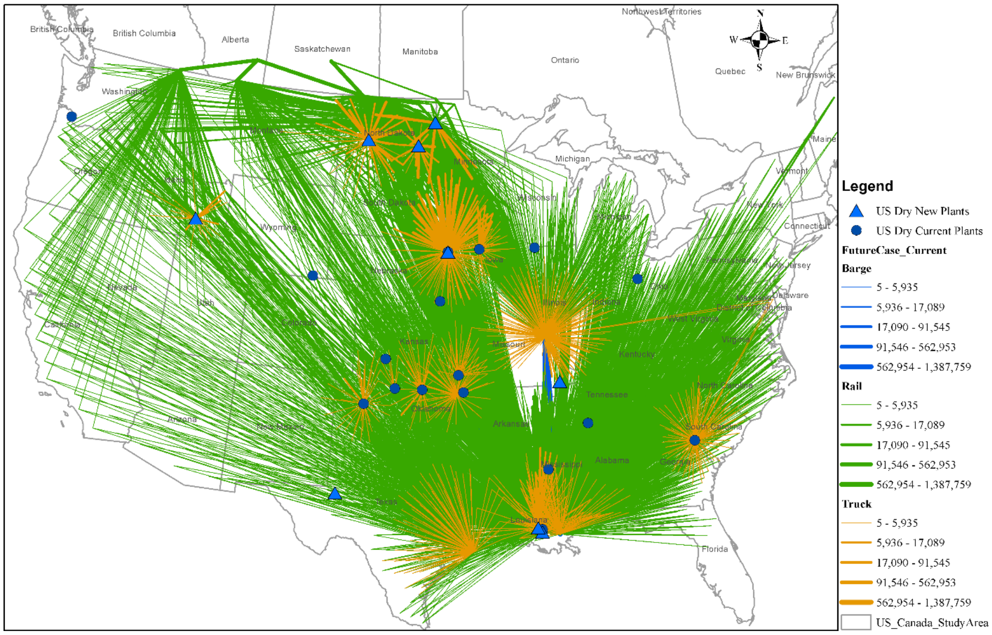


Figure 14 Structure of supply chain for urea for stochastic linear future case 2018 by mode (Rail=Green, Truck=Orange, Barge=Blue).

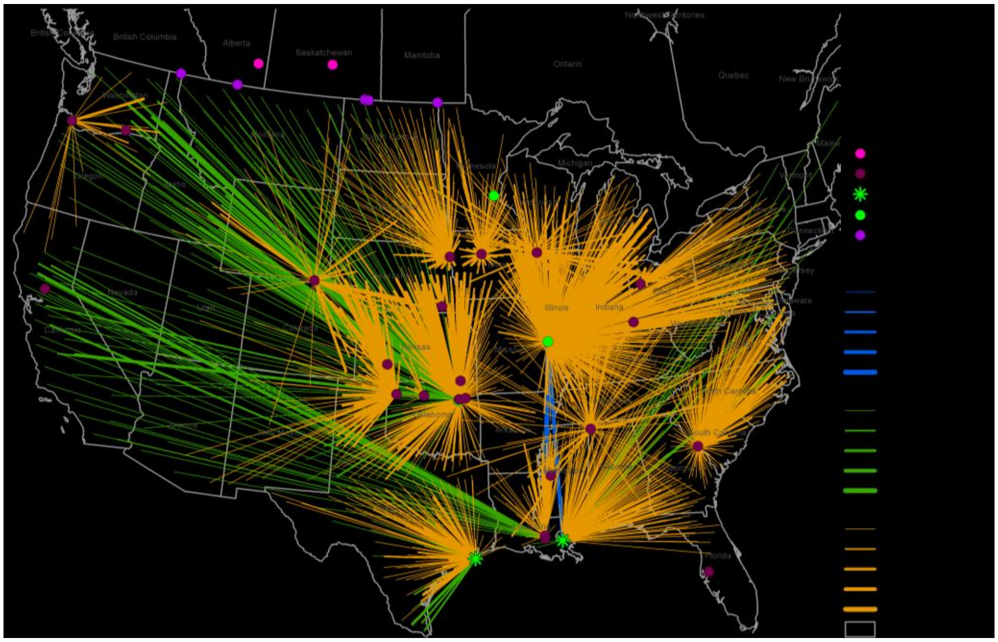


Figure 15 Structure of supply chain for UAN for base case by mode (Rail=Green, Truck=Orange, Barge=Blue).

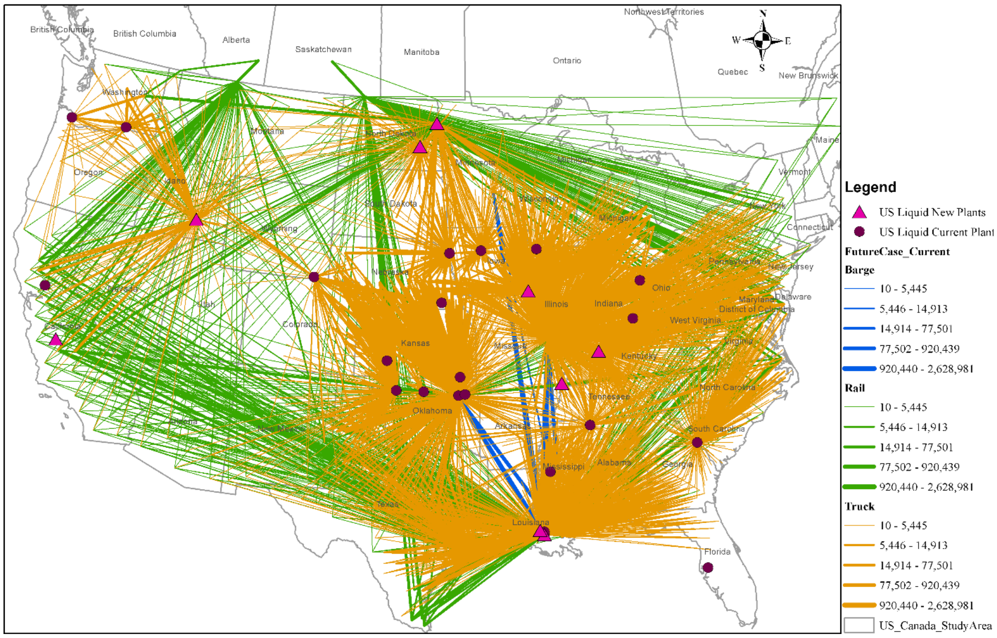


Figure 16 Structure of supply chain for UAN for stochastic linear future case 2018 by mode (Rail=Green, Truck=Orange, Barge=Blue).

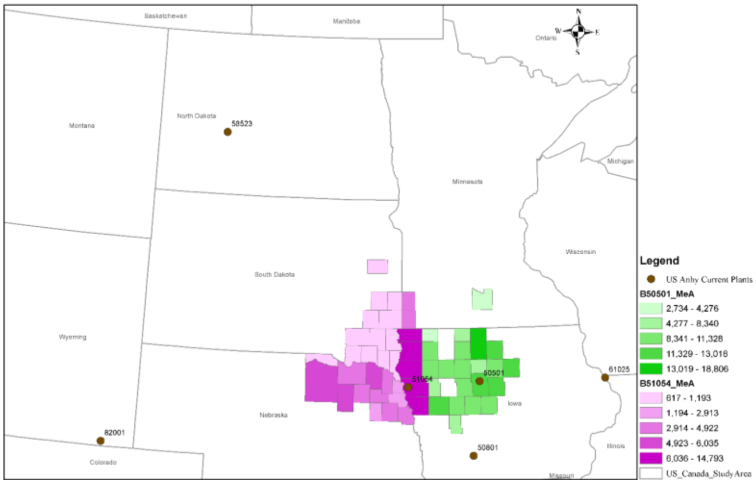


Figure 17 Market boundaries for plant j= 50501, Fort Dodge, Iowa and j= 51054 Port Neal, Iowa for anhydrous ammonia

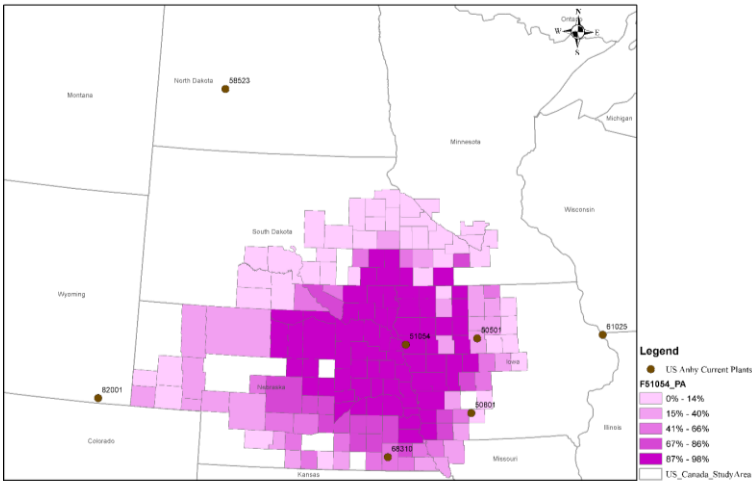


Figure 18 Market boundaries for plant j= 51054 Port Neal, Iowa for anhydrous ammonia (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

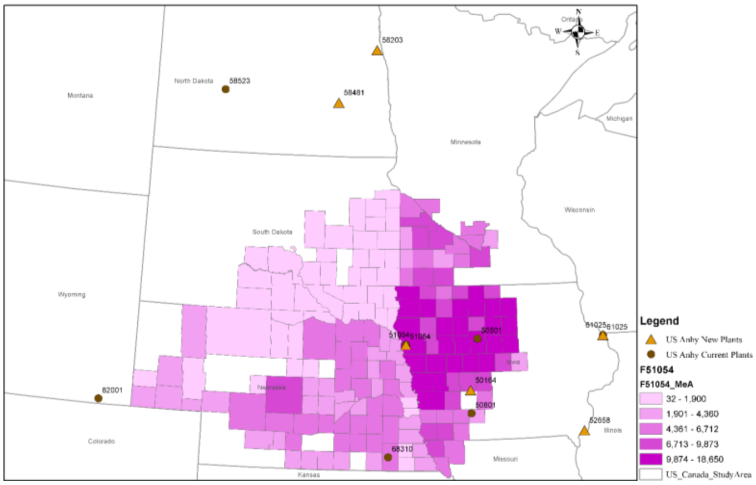


Figure 19 Market boundaries for plant j=51054 Port Neal, Iowa for anhydrous ammonia (mean quantity of shipping for 1000 iterations) in stochastic linear future case 2018.

8 References

AAPFCO Publications & Programs. (2013). Commercial Fertilizers 2011. Retrieved June 17, 2014, from http://www.aapfco.org/publications.html

Bates, T. H., & Schmitz, A. (1969). *A spatial Equilibrium analysis of the world sugar economy*. Giannini foundation monograph. Retrieved from http://giannini.ucop.edu/Monographs/23-Sugar%20Economy.pdf

Bawden, D. L. (1966). A Spatial Price Equilibrium Model of International Trade. *Journal of Farm Economics*, *48*(4), 862.

Bressler, R. G., & King, R. A. (1970). *Markets, Prices and Interregional Trade*. John Wiley & Sons Inc.

Bronars, S. G., & Jansen, D. W. (1987). The geographic distribution of unemployment rates in the U.S.: A spatial-time series analysis. *Journal of Econometrics*, *36*(3), 251–279. https://doi.org/16/0304-4076(87)90002-9

Capozza, D. R., & Order, R. V. (1978). A Generalized Model of Spatial Competition. *The American Economic Review*, *68*(5), 896–908.

Ellis, J. (1996). *A GIS and transportation optimization model approach to determining highway and rural road commodity flows*. Washington State University.

Enke, S. (1951). Equilibrium among Spatially Separated Markets: Solution by Electric Analogue. *Econometrica*, *19*(1), 40–47. https://doi.org/10.2307/1907907

Ferris, J. N. (2005). *Agricultural Prices and Commodity Market Analysis* (2nd ed.). Michigan State University Press.

Granger, C. W. J., & Elliott, C. M. (1967). A Fresh Look at Wheat Prices and Markets in the Eighteenth Century. *The Economic History Review*, *20*(2), 257–265. https://doi.org/10.2307/2592156

Greenmarkets. (2013). Fertilizer News, Pricing, Regulation and Supply Chain. Retrieved June 17, 2014, from http://www.fertilizerpricing.com/Research/urea-cost-curve

Hall, R. L., Dorfman, J. H., & Gunter, L. F. (2003). *Spatial Competition And Pricing In The Agricultural Chemical Industry: Empirical Evidence From Georgia* (2003 Conference, April 21-22, 2003, St. Louis, Missouri No. 18984). NCR-134 Conference on Applied Commodity Price Analysis, Forecasting, and Market Risk Management. Retrieved from http://ideas.repec.org/p/ags/ncrthr/18984.html

Hotelling, H. (1929). Stability in Competition. *The Economic Journal*, *39*(153), 41–57. https://doi.org/10.2307/2224214

Kelleher, D. (2013, December 3). CF Industries Holdings, Inc. Citigroup 6th Annual Basic Materials Symposium. Retrieved June 17, 2014, from http://phx.corporate-ir.net/phoenix.zhtml?c=190537&p=irol-presentations

Leonard, C. (2014). The New Koch. *Fortune*, *169*(1), 60.

Midwest Fertilizer. (2013, October 17). Midwest Fertilizer picks Indiana for $2.1 billion project. Retrieved June 25, 2014, from http://www.agprofessional.com/news/Midwest-Fertilizer-picks-Indiana-for-21-billion-project-228181211.html

Parker, J. (2011, February 24). The 9 billion-people question. *The Economist, Special report: Feeding the world*(Print). Retrieved from http://www.economist.com/node/18200618

Plewes, J., & Smith, A. (2009). *Economic Contributions of the U.S. Fertilizer Manufacturing Industry* (CRA International) (p. 39). Washington, DC: The Fertilizer Institute. Retrieved from https://www.tfi.org/sites/default/files/images/CRAreport.pdf

Samuelson, P. A. (1952). Spatial Price Equilibrium and Linear Programming. *The American Economic Review*, *42*(3), 283–303.

Samuelson, P. A. (1957). Intertemporal Price Equilibrium: A Prologue to the Theory of Speculation. *Weltwirtschaftliches Archiv*, *79*, 181–221.

Shakya, S. (2014). *Structural Changes in North American Fertilizer Logistics* (Dissertation). North Dakota State University, North Dakota, United States. Retrieved from http://pqdtopen.proquest.com/doc/1564228817.html?FMT=ABS&pubnum=3630982

Taylor, M. Z. (2015, August 13). CHS Backs Out on Building Fertilizer Plant in North Dakota. *NorthernAg*. Haddonfield, N.J. Retrieved from http://www.northernag.net/AGNews/AgNewsStories/TabId/657/ArtMID/2927/ArticleID/5019/CHS-Backs-Out-on-Building-Fertilizer-Plant-in-North-Dakota.aspx

U.S. Department of Transportation. (2013). *National Transportation Atlas Database (NTAD)* (Bureau of Transportation Statistics). Research and Innovative Technology Administration. Retrieved from http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/subject_areas/geographic_information_services/index.html

U.S.- EIA. (2013). *Average wholesale natural gas prices fell 31% in 2012 - Today in Energy - U.S. Energy Information Administration (EIA)* (2012 Brief). U.S. Energy Information Administration. Retrieved from http://www.eia.gov/todayinenergy/detail.php?id=9490

USDA ERS. (2016). *Chemical Inputs: Fertilizer Use & Markets* (Farm Practices & Management/ Chemical Inputs). United States Department of Agriculture - Economic Research Service. Retrieved from http://www.ers.usda.gov/topics/farm-practices-management/chemical-inputs/fertilizer-use-markets.aspx

USDA-ERS. (2013). Fertilizer Use and Price. Retrieved May 17, 2013, from http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#.U7ET_bFLvuy

USDA-NASS. (2013a, May). Agricultural Chemical Use Program Agricultural Chemical Use Program Survey Data on Fertilizer Use by Crop. Retrieved from http://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/index.asp#description

USDA-NASS. (2013b, May). Planted Acres by Crop by County. Retrieved May 16, 2013, from http://quickstats.nass.usda.gov/

Wilson, W. W., Shakya, S., & Dahl, B. (2015). Dynamic changes in spatial competition for the nitrogen fertilizer industry in the United States. *Agricultural Systems*, *135*, 10–19. https://doi.org/10.1016/j.agsy.2014.11.006

Winston, W. L. (2003). *Operations Research: Applications and Algorithms* (4 edition). Belmont, CA: Cengage Learning.

Wiser, M. (2013, March 30). Why fertilizer plants target Iowa, Midwest. *The Quad-City Times*. DES MOINES, Iowa. Retrieved from http://qctimes.com/news/local/why-fertilizer-plants-target-iowa-midwest/article_f01b9eee-99b1-11e2-99db-0019bb2963f4.html