Journal of Commodity Markets 30 (2023) 100326

Contents lists available at ScienceDirect

Journal of Commodity Markets

journal homepage: www.elsevier.com/locate/jcomm

Regular article

Quantifying impacts of competition and demand on the risk for fertilizer plant locations

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ARTICLE INFO

Keywords:
Spatial optimization
Risk
Market boundary
Monte-carlo
Spatial competition
Fertilizer

ABSTRACT

Fertilizer is an essential commodity traded in international and domestic markets and spatial competition is important feature impacting interfirm rivalry. In the case of North American fertilizer, numerous plants have been announced to either expand or open new plants (nitrogen-based fertilizer plants), exerting competitive pressures on an industry with surplus capacity but highly competitive in terms of production costs and technology. Proposed new plants and expansions are being induced by changes in the composition of crops, changes in the price of natural gas which affects the cost of producing domestic anhydrous ammonia. Developments in the fertilizer industry have become more volatile in the post-COVID period, and concurrent with the escalation in fuel prices, the Ukraine invasion, related embargoes on Russian trade, the world's largest exporter, and operations of the Grain Corridor. The purpose of this study is to quantify risks for plant expansion (brownfield and greenfield) of nitrogen fertilizer plants in North America, given the spatial competition and the corresponding dynamic market boundaries. Specifically, we quantify risks associated with fertilizer plant expansions, identify the optimal locations of new plants, and characterize spatial competition as a result of new entrants. A model is specified that integrates Geographical Information Systems (GIS) data into a stochastic mixed-integer network spatial optimization model using Monte Carlo simulations to account for risk in the random variables. The results are reprocessed into GIS for interpretation. The impact of risk in these variables results in market boundaries that are random. Specifically, competition for these new plants has embedded risks for new entrants on the probability of production and market penetration.

1. Introduction

Fertilizer is an essential commodity traded in international and domestic markets and spatial competition is an important feature impacting interfirm rivalry (Dutkowsky et al., 2014a, 2014b). In fact, spatial competition is important for many firms in agricultural input and output processing. Important strategic characteristics in fertilizer manufacturing, include substantial economies of scale, excess capacity, incumbents, and changing geography of agricultural production (Yara, 2010, 2012). In addition, there are numerous geopolitical interventions including restriction on Chinese exports, embargoes placed on Russian exports, the world's largest exporter, due to the invasion of Ukraine. Each of these characteristics is important in spatial competition among geographically dispersed plants

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https://doi.org/10.1016/j.jcomm.2023.100326
Received 31 March 2021; Received in revised form 25 February 2023; Accepted 8 March 2023
Available online 15 March 2023

and firms. In the case of fertilizer, any new plant would result in changes in market boundaries and disrupt the structure of spatial competition (Brester and Bekkerman, 2020). Variables impacting spatial market boundaries are highly volatile, including changes in production patterns (consumption of fertilizer), natural gas prices (major cost input) (EIA, 2021, 2022; FERC, 2013) and world fertilizer prices given that imports are a source of competition. The impact of the volatility of these variables leads to 'random market boundaries,' causing significant risk to entrants in locating a new fertilizer plant. Despite the importance of fertilizer and of spatial competition, there have been few studies on spatial competition and supply chains in North American fertilizer.

The purpose of this study is to quantify risks for new plants (greenfield) or expansions (brownfield) of nitrogen fertilizer plants in North America, given spatial competition and the corresponding dynamic market boundaries. A model is specified that integrates Geographical Information Systems (GIS) data into a stochastic mixed-integer network spatial optimization model using Monte Carlo simulations to account for risk in important random variables. The results are reprocessed into GIS for interpretation. The model is used to simulate changes in competition and to measure risks that new plants confront.

This study makes several contributions. It provides a novel methodology to capture stochastic variables impacting spatial competition, which is important in many agricultural sectors. Specifically, it provides a detailed analysis of the supply chain for fertilizer which is highly spatially interdependent. Second, the stochastic spatial mixed-integer optimization model extends traditional spatial analytical methods in several dimensions. It integrates spatially dependent input and output data using GIS methods. It measures risk in critical variables and evaluates their impacts on important output variables, notably, probability distributions of output and shipments. Finally, the output provides insight to this industry which is undergoing substantial pressures for new-entry and/or expansion, specifically, as it relates to potential fertilizer plant locations.

2. Background and previous studies

World trade in fertilizer is substantial. In 2020, world trade in Nitrogenous Fertilizers was valued at $22.5 B (OEC, 2020). In North America, fertilizer demand is met through domestic production as well as from imports from Canada and other countries through the U.S. Gulf. Four factors are pressuring changes (Yara, 2010, 2012). One is the change in the composition of crops within the United States which is being impacted by a number of factors. These include the RFS (Renewable Fuels Standards), and related biofuels policies. In addition, others include (without enumeration, but similarly important): development and adoption of GM corn (1996), climate change, Chinese growth in imports of soybean and corn (USDA projected in 2011, growth to 25 mmt); FSU growth in exports of wheat and corn, and extensive interventions causing volatility and changing price relations; among many other changes including the recent development of renewable diesel and sustainable aviation fuels. All of these have and are impacting the composition of crops and their spatial distribution.

Second is that the industry was dominated by a few major firms (Brester and Bekkerman, 2020) which have to confront a number of new entrants. Indeed, there were at least 12 to 15 plants (actually, up to 25) proposed, each at costs of about $1.5 to $3 billion. Characteristics of the new entrants are important.[1] Some are incumbents that are expanding (CF Industries, Agrium and Koch)[2]; some are established cooperatives (e.g., CHS),[3] or newly-formed cooperatives (e.g., Northern Plains Nitrogen); some are regional energy firms (Dakota Gasification; Mississippi Power); and some are off-shore firms expanding into the US market (e.g., Eurochem). Aside from the structural changes giving rise to opportunities of new plants and firms, each has differing goals. Incumbents would seek to expand and pre-empt new entrants. The cooperatives view this as a means to better serve their grower customers in a more vertically integrated system. Energy companies are looking for a use of their outputs. And offshore entrants are looking for opportunity, and several are looking for exports potentially to China. The third factor was the dramatic change in natural gas prices in the early 2000s, a primary input for fertilizer manufacturing. This change is spatially heterogeneous and has the impact of creating spatial advantages for plants located in states with lower-cost natural gas prices.

The fourth set of factors impacting the fertilizer industry are the dramatic events following COVID-19. These events include Covid related supply chain issues, Chinese restrictions on fertilizer and chemical manufacturing and exports, increased volatility of energy prices (from negative values in April 2020), and developments surrounding the Ukraine invasion and related embargoes in early 2022.[4] In response, embargoes and sanctions were imposed on Russia, the world's largest exporter. More recently, Russian export revenue from fertilizer surged by 70% (Terazono, 2023) and developments in the Black Sea made industry participants to claim that the Kremlin is 'weaponizing food' through its control over natural gas prices (Islam and Nanji, 2023). Further, while globally important, Russian restrictions impacted US fertilizer to a lesser degree due to the US having its own large domestic supply (Colussi et al., 2022). However, the combined impact of these developments was for an increase in fertilizer prices. In addition, these events are thought to prospectively cause dramatic food price inflation and potential starvation. Dawson (2022) indicated these problems would persist until new plants are developed. In response, the USDAto put out a grant program to develop alternatives.

[1] Greenmarkets (2013) provides an indicator of each proposed plants status. Craymer and Hoyle (2017)provide a detailed description of the expansions in U.S. fertilizer capacity, and its reduced imports.

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

[3] The CHS project was headed by Brian Schouvieller and was summarized by Debertin (2012). The CHS Board approved the Spritwood plant in 2014 (CHS Inc, 2014). The CHS project was ultimately abandoned and replaced with a minority investment in CF industries along with a long-term supply agreement, as described in Chakravorty and Kalluvila (2015) and in CHS Inc., & CF Industries Holdings, Inc., 2016.

[4] Numerous articles describe these events including (Dawson, 2022; Dizard, 2021; Foroohar, 2022; Smith, 2022).

Natural gas comprises more than 50% of the input cost for nitrogen-based fertilizer production, with availability and volatility in natural gas prices being an important factor affecting expansion/new plants. Production costs depend on natural gas and electricity costs which vary spatially, economies of scale (operational costs), and surplus capacity in the industry. There is uncertainty in demand due to increased yields, as well as changes in the spatial distribution of crops planted, thereby leading to different spatial quantities of demand for various types of nitrogen fertilizer.

Traditionally, the industry imports significant amounts of fertilizer to meet its needs with nitrogen fertilizer imports in the area of 57% of consumption (EIA, 2021, 2022). A large amount of urea is imported through Galveston. These shipments are distributed predominantly by rail and barge throughout the United States and are some of the dominant flows. Imports are also made from Canada. Imports and domestic prices are volatile, and impact domestic plant utilization. Urea prices at the US Gulf have ranged from $100–200/ton in the early 2000's to a peak of over $800 in 2008 and nearly that level again in 2012, and then declined to the $300 level. In 2022, prices escalated (e.g., as illustrated in MyDTN.com).[5] There are three types of nitrogen including anhydrous ammonia (Anhy), urea (Dry) and UAN (Liquid). Fertilizer demand varies geographically, and this has implications for spatial competition (ERS, 2013; USDA-ERS, 2013b).

A number of industry studies provide perspective on these emerging changes. Prud'homme (2005), discusses trends and outlooks for nitrogen fertilizer production, use and trade. Yara (2010, 2012) provides a detailed description of the underlying demand, pricing and costs for nitrogen fertilizer. Debertin (2012) and Lamp (2013) explained the logic of the plant that was proposed to be built by CHS (Kelleher, 2013). indicated returns to their new plants ranged from 14 to 20% depending on natural gas and urea prices. The World Bank (Baffes and Ćosić, 2013) pointed to the easing of world fertilizer prices in part due to the expansion of production in regions with lower natural gas prices.

There have been fewer academic or public studies on this industry. Huang (2007) analyzed the impacts of rising natural gas prices (at that time) on fertilizer price and described the industry structure and geography. Casavant et al. (2010) reviews the fertilizer industry and the importance of transportation. Rosas (2011) developed a model of world fertilizer demand tied into the world FAPRI projections model. Olson et al. (2010) examined factors affecting plant input supply industries. Zilberman et al. (2013) analyzed the future demand for food and point to the need for increased fertilizer requirements. Wilson et al. (2015) describe the changing industry structure of this industry and analyzed the industry using linear programming in a non-stochastic specification. More recently Bekkerman et al. (2020) analyzed the spatial relationship among fertilizer and corn prices, the dynamics of the fertilizer price transmission among regional markets, and the impacts of the biofuels policy. Results showed that the structural relationships changed following the biofuels policies in the early 2000s, and that the fertilizer market was relatively efficient. Finally, Brester and Bekkerman et al. (2020) described the announcements of new plants in the 2013–2018 and sought to provide an explanation as to why so few (if any) of these would be actualized. They suggest that this may be due to the Stackelberg strategic behavior, and the announcements may be a signal to competitors about their intentions. Since then, as described below nd shown in our empirical model, the vast majority of the 'announced' plants were in fact developed.

Spatial competition has always been an important feature in agricultural markets. Some of the origins of this literature evolved from Hotelling (1929) and later by Bressler and King (1970), and covered in (Greenhut et al., 1987). Spatial market areas were recently analyzed for handling grain catchments in Australia by Kingwell (2017). With increase in digital information processing and hardware capabilities, the fields of geographic information systems (GIS), transportation, and spatial analysis are intertwined to an extent of being inseparable (Fotheringham and Rogerson, 1993; Miller, 1999).

3. Empirical model

A detailed model was specified that integrates Geographical Information Systems (GIS) data into a stochastic mixed-integer network spatial optimization model using Monte Carlo simulation to account for risk in important random variables. The results are reprocessed into GIS for interpretation. The base case model was specified as a non-stochastic spatial network model to illustrate the market boundaries and the product flows. Then, a stochastic optimization model is specified and solved with projected exogenous variables to 2018 and solved as a mixed integer problem. The model includes the most important spatially dependent supply chain costs: processing costs for each fertilizer plant and by type of fertilizer; and shipping costs of products by rail, truck and/or barge/truck or barge-rail combinations and pipeline. Imports from Canada and the US Gulf were modeled endogenously. A geographic depiction of this model is shown in Fig. 1.

The data period for most variables was from 2000 to 2012 and were used to derive distributions. The base case was specified to be reflective of the market conditions in the period 2010–2012 which is concurrent when many of the structural changes were being occurring. A future case was specified for 2018 and simulated.

Nitrogen based fertilizer plants are allowed to produce at current known production capacities by type. Production cost is a function of natural gas prices and electricity cost each of which vary by state, and size of plant. There were 29 US plants operating and three in Canada. Output from Texas plants by rail was limited to be less than 721,000 tons. In order to account for the seasonal nature of barge service to Minneapolis, a limit of 20,000 tons was applied on this flow.[6] Transportation costs were applied from origin to transshipment (if applicable) and to county demand points, by mode (rail, truck, barge, and pipeline) and by type (anhydrous, Dry, and liquid). Finally, world market prices were used for US Gulf imports and averaged over this period.

[5] The Economist (2022)provides a detailed explanation of potential reasons causing increases in fertilizer prices.

[6] Industry experts provided input on these two issues and adopted to better reflect the current scenario.

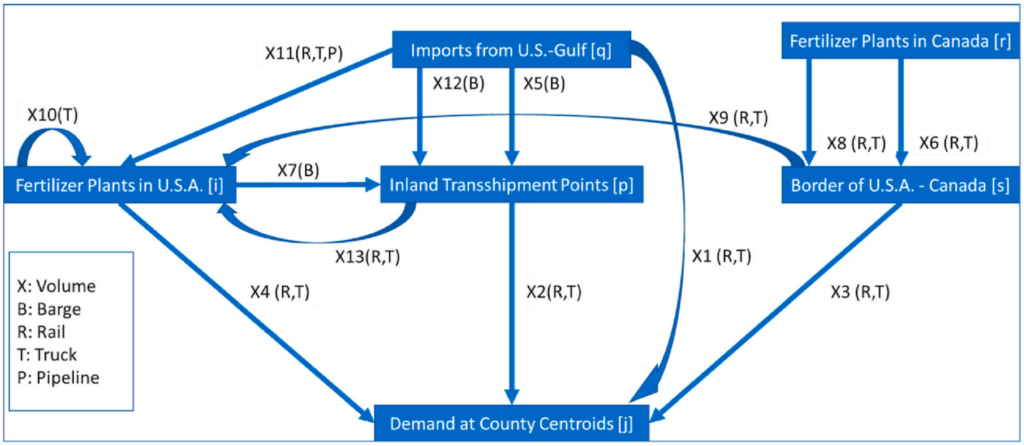

Fig. 1. Spatial fertilizer model: nodes, flows between nodes, and type of modes allowed between nodes, and name of flows representing quantity of fertilizer shipped. (R = Rail, T = Truck, B=Barge, P=Pipe; blue solid arrows represent normal shipments of anhydrous; X8, X9, X11, X12, and X13, anhydrous only shipments for conversion into urea or UAN at destination. All other X_i represent normal shipments of anhydrous ammonia, urea and UAN. For inland transshipment and U.S.-Canada border points, all input flows equal all output flows. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)[11]

Stochastic outputs of particular interest are production of fertilizer by type at each plant, imports, and modal shipments from origins to destinations. The model was specified to account for changes in market boundaries due to random variables including demand, production cost by state (due to price of natural gas) and import prices. In order to account for the randomness of these variables, the base case was expanded to a stochastic mixed integer model for a future case in year 2018. The results were reviewed with industry representatives, and a number of assumptions or restrictions were imposed to calibrate the model to reflect market flows and operations in recent years. The models were used to quantify the risks (probability distribution from stochastic optimization simulations) associated with each potential plant.

Stochastic Mixed Integer Case for 2018 A large number of variables are random and treated as stochastic. These include natural gas prices, fertilizer demand at the county level, by type (anhydrous ammonia (anhy), dry (urea) and liquid (UAN)) and world import prices of fertilizer. The data were evaluated to determine an appropriate distribution for each of these variables.[7]

Fertilizer plants in the United States and Canada are allowed to operate up to current known production capacities by type of fertilizer. In addition, each newly announced plant is allowed to operate in the model. There are 12 new/proposed plants (greenfield) in addition to those in base case and five expansions (brownfields). Processing costs were determined for each individual plant and fertilizer type. The model was specified as mixed integer given the large number of proposed or prospective new entrant plants. If this were not the case, a large number of new plants would enter, and operate at a low level of capital utilization level. To restrict these and based on discussions with industry, the larger 9 proposed plants (for others, the restriction was not imposed) were allowed to operate in the model as a binary variable, and if they operate, they operate at least 70 percent of production capacity. The value of 70% is conservative, as industry statistics indicated capacity utilization in 2018 and 2019 at 75% and 85% respectively (National Minerals Information Center, 2019, National Minerals Information Center, 2021) and Brester and Bekkerman (2020) suggested that 80 or 88 percent utilization rate were commonly observed for existing and newly announced plants. The capital cost (return) necessary to trigger development of a new plant was 8 percent.

Adjustments were made to reflect 2018 EIA projections for Henry Hub (HH) NG values, electricity costs and plant size. These were adjusted for each individual state using current state level differentials from EIA relative to HH. Henry-Hub is treated as random and fit to a distribution of historical values. The fit for HH for the last four years was used to generate distributions, in order to better reflect recent changes affecting the industry. These changes are a major factor behind the expansion of existing fertilizer plants or announcement for new plants. Simple linear Spearman correlations among demand by type, import costs at US-Gulf by type, and Henry-hub were used to generate random variables used in solving the spatial model.

Import costs are random, and the distribution for costs is based on fit of historical observed values. Transportation costs are applied from origin to transshipment (if applicable) and to final demand by mode (rail, truck, and barge) and by type (anhydrous, Dry, and liquid).

4. Data

Fertilizer demand is derived at the county level by crop and type and then multiplied by growth factor by type capturing projected

[7] Due to the volume of data and distributions, they are not reported in the paper. However, they are available as an open access document at (Shakya, 2014) or direct from the authors.

changes in county level planting of crops. Demand for each county is treated as random and the distribution is based on historical demand by type for each county. Crops included 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 2010–2012 (USDA-NASS, 2013b). Nitrogen use by crop type was from USDA-ERS, and USDA-NASS (USDA-ERS, 2013a; USDA-NASS, 2013a) on a state level basis and applied to all counties within the state. Demand for nitrogen was derived from county level demands and multiplying these with the proportion of state level demands by type (AAPFCO Publications and Programs, 2013). Forecasted demand for 2018 was estimated by assuming planted acres by crop within a county increase by the average annual rate of change for planted acres from 2000 to 2012. These were used to estimate the change in planted acres from 2012 to 2018.

Fig. 2 shows the geographic distribution of fertilizer demand, aggregated by type, across counties for illustration. The results indicate demand to increase by 4.7% from the base case to 2018. This would be attributed partly to the impact of greater yields (2%), and partly due to the shift in the composition of area planted (2.7%). These results indicated a 5.6% increase in anhydrous, 5.5% increase in Dry and 3.8% increase in liquid. The states with the largest increases are: Anhydrous: IL, IA, MN, ND; Dry: AR, MN, ND, SD, and Liquid: IL, IN., IA, NE, OH. These differences are due to state level preferences of fertilizer by type. There is no evidence in this data of changes in preferred N type.

The model includes production at 29 existing plants, and 12 proposed new plants and expansions. The plants produce different types of fertilizer and have capacity restrictions for each. Imports from Canada are modeled similar to US production. Imports of fertilizer by type at the US Gulf is based on import prices, and shipping costs to destinations. Import volumes from Canada to the U.S. were from Statistics Canada (2013). These were averaged for 2010/11 to 2011/12 and used to constrain maximum Canadian imports. Imports were from USDA-ERS (2013b). Prices were from Greenmarkets. Plant capacities were from IFDC (2013) by type (Anhydrous Ammonia, Urea, and Nitrogen Solutions) for North America and reported in (Shakya, 2014, p. 56). Data on new or prospective plants were from IFDC (2013), *Agweek*, press releases, Greenmarkets (2013), and other industry sources.

Cost of production is indexed by sets. Production costs by type were derived using the model developed by Maung et al. (2012) as a point of departure. The costs reflect the economies and input requirements for modern state-of-art plants, were re-engineered to develop costs functions for fertilizer manufacturing. Costs for Anhydrous, Dry and Liquid were derived as a function of costs of Natural gas, electricity, other costs, and total capacity to reflect economies of size. Costs for natural gas by state were from USEIA (2013b) and were the average of monthly Industrial Prices from 2010 to 2013. The natural gas spread for each state was estimated as the spread between Industrial Prices and Henry-Hub Futures for the current 2010–2012 period and for the future case. Spatial basis levels were assumed unchanged, while Henry-Hub prices were reflective of current estimates for 2018 H-Hub prices. Electricity costs were by state from USEIA (2013a) and reflect average cents/kw hour from for 2010–2012.

Transport modes were rail, truck, pipeline and barge. Network distances are derived from road, railroad and barge as reported by public agencies (U.S. Department of Transportation, 2013). GIS is used to determine the distance between origin and destination nodes, so that it can then be used to better determine the counties (demand nodes) that fall within the market boundary of a production (fertilizer plants as origin or supply points) node. Fertilizer can be shipped via different modes and thus different origination-destination matrices by mode are calculated along with corresponding distances for any pair of "origination – destination" (OD). Each OD pair uniquely identifies an origin and destination identification number. The OD pair has distance for each mode that may exist for any pair. The OD pair is further classified by type of fertilizer and mode. A separate set of transport costs was developed for each U.S.-Canada border points (set s), transshipment points in United States (set p), and import port locations (set q) is created. Another set is created for county points that stores demand (set j) at county level (by type of product Anhy, Dry and Liquid is also specified). Lastly, in order to derive shipping cost between all elements of origin sets to all elements of destination sets, origin-destination (OD) matrixes were obtained using GIS and imported into optimization model. The model summarizes various types of flows, mode, and origin-destinations sets as illustrated in Fig. 1.

Shipping costs were derived and/or estimated from each origin to the county destination for rail and truck and combinations of shipments with barge. Rail costs were derived on mileage-based relationships from current mileage based tariffs for rail (BNSF, 2013a, 2013b, 2013c). These were reviewed by industry participants to identify some shipments which deviated substantially from rates depicted in these functions. In these cases, the rates suggested by industry were used. Truck rates were collected from 3 major firms based on mileage and truck capacity. These were derived for each and the average across the three firm's quotes were used. Barge rates were used for northbound shipments by barge and the data was from River Transport News (2013).

The random variables include world import prices of fertilizer, natural gas prices, fertilizer demand at the county level, by type: anhy (anhydrous ammonia), dry (urea) and liquid (UAN). For each fertilizer type, the distributions were determined using historical data using BestFit procedures in @Risk (Palisade). In addition, the correlation matrix among these variables were imposed on the simulation optimization procedures.

5. Solution strategy

The analytical framework is a spatial network flow model of the U.S. fertilizer industry. The model is calibrated and used to analyze production, imports, and fertilizer flows by type from origins to destinations. Primary activities include producing nitrogen fertilizer in existing and proposed plants, importing fertilizer and shipping from origins to demand. Costs are derived for each of these activities. Fertilizer plants are at actual locations and proposed locations for new plants. Imports are through the US Gulf (Louisiana and Texas) and from Canada. Demand is modeled at the county level. And, each activity is modeled for the 3 types of nitrogen fertilizer, anhydrous ammonia, dry (urea) and liquid (UAN). The network flow problem is specified as a mixed integer model. The problem is solved for minimum cost to derive flows among nodes while allocating supply to demand nodes. Demand for each type is set to be met at demand

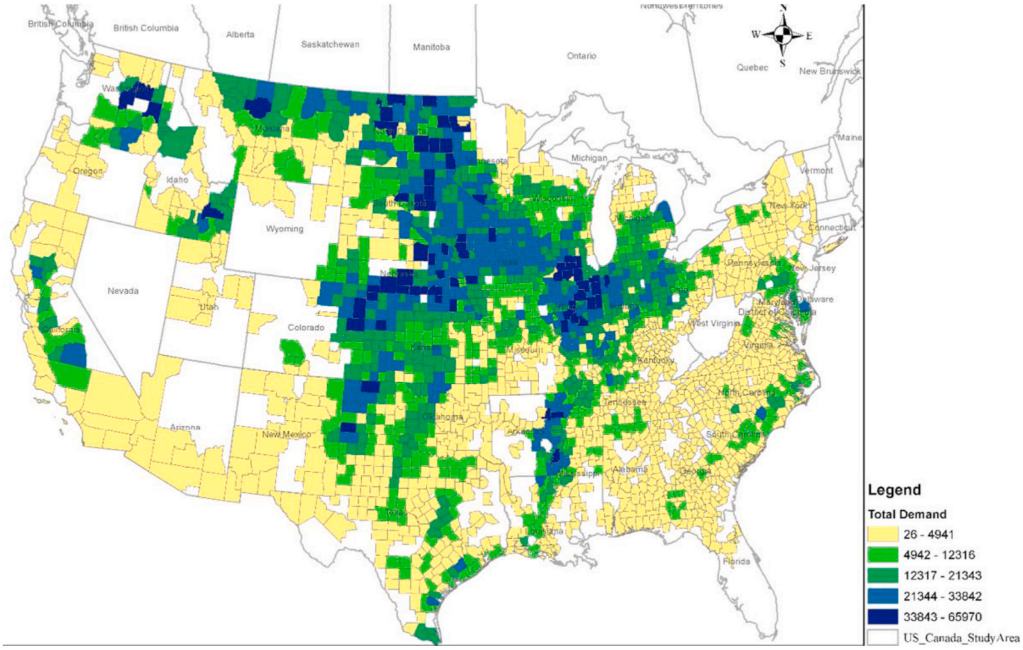

Fig. 2. Total demand for fertilizer by county (aggregated across fertilizer type) shown as graduating colors. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

nodes at cheapest cost from any of supply nodes.

The model was solved in SAS 9.3 which allows the integration of statistical tools, optimization, and data visualization in geographic information systems (GIS).[8] ArcMap 10.2 was used to capture the spatial nature of data including plant location, distances between fertilizer plants and the crop-growing counties as demand points. Origin-destination distance matrices calculated from GIS was used as one of the inputs for the optimization model in SAS. Fertilizer plant capacities, county demand and various costs were then used in the optimization model. The model was simulated 1000 iterations and outputs from repeated stochastic iterations were then used to plot the flows among all origins and destinations by type of fertilizer and by mode.

6. Results

Base case results are presented first to provide a description of the scope of fertilizer production, imports, and spatial flows. The results from the stochastic model are then presented to illustrate changes in market boundaries, and the risks of new plant development and/or expansion.

Base Case The base case results were mapped using GIS to show the overall structure of supply chain for anhydrous, dry, and liquid (Fig. 3). Each line represents a flow between a pair of origin and destinations for each mode, and the relative thickness represents volume of flow between the pair. Rail is the dominant mode for shipping. The majority of anhydrous imports from US-Gulf are via barge to transshipment points, particularly St. Louis and rail thereafter. Rail is the primary mode for Canadian imports. Truck constitutes a small portion mainly for short distances. These flows are consistent with current knowledge of the industry from experts.

The model reflects capacity utilization during that period and only a few of the plants are at capacity. Shadow prices were derived and indicated that plants in Louisiana and western Iowa are more valuable than in central Iowa. Market boundaries were derived for each plant post optimization using the total volume for each county from a fertilizer plant. These are then joined to counties to derive a market boundary for the plant. For illustration, Fig. 4 shows the market boundaries for plants around Weaver and Port Neal, IA. These plants have large market boundaries, supplying more to counties closer to them (represented by a darker color in map) and lesser to counties farther away. Each plant has clearly defined market boundaries (shown in different color unique to the supplier plant). The anhydrous results show that plant 51,054 ships most of its product to the counties east of it, and plant 50,501 to northeast of it. Market boundaries for liquid are more widespread. Most of quantities are shipped nearby. The geographic area to which both plants serve is huge due to absence of any other plant that produces liquid.

Stochastic Mixed Integer Case for 2018. In the case above, any fertilizer plant was allowed to enter even if they operate only at small percentage of their production capacity. This results in a solution in which there are many new entrants, and each operates at a

[8] Due to its volume, the mathematical specification of the model is contained in the appendix. The model is explained in more detail in (Shakya, 2014; Wilson et al., 2014, 2015). The spatial optimization model is in SAS and the code is available in Mendeley Data (Shakya, 2023).

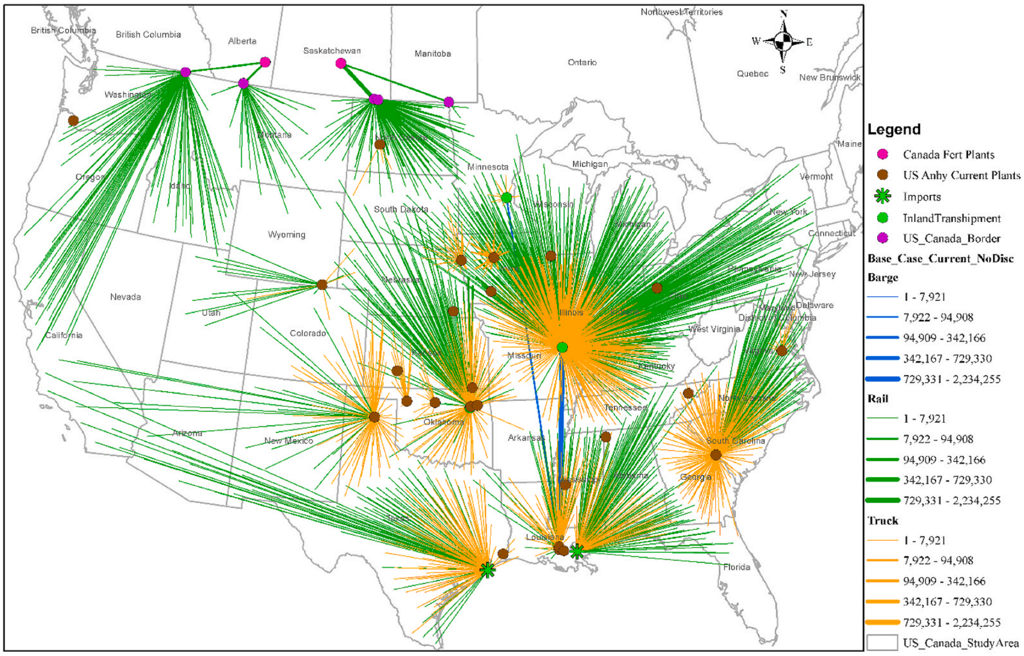

Fig. 3. Structure of supply chain for anhydrous for base case by mode (Rail = green, Truck = Orange, Barge = Blue). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

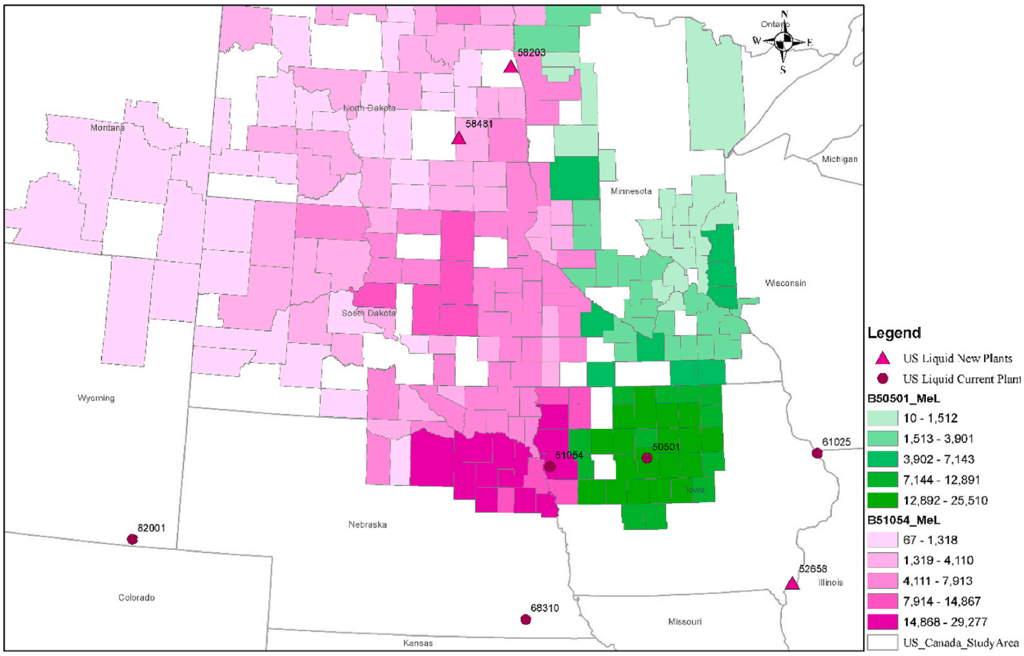

Fig. 4. Market boundaries for Ft Dodge and Port Neal, Ia. (plant i = 50,501, i = 51,054) for Liquid.

small portion of capacity. This is unlikely and for this reason a mixed integer model was specified which required that some of the large-scale new plants would have to operate at least at 70% capacity (by type). U.S. producers operated at about 75% and 85% of rated capacity in 2018 and 2020 respectively (National Minerals Information Center, 2019,2021). Specifically, a minimum capacity utilization of 70% was imposed as a constraint in the model, for five greenfield (new) and two brownfield (expansion of the current) plants to be viable and achieve economies of scale.

Tables 1 and 2 show a summary of these results for incumbent, new greenfield and brownfield plants respectively. Also shown are the quantity produced for each type of product and the percentages for each fertilizer type produced. As example, Augusta, GA. supplies most of its capacity devoted to liquid nitrogen (100%) and produces anhydrous (1%), and dry (3%), seldomly at minimal quantity. Of the existing plants there are a number that would not be included in a minimum cost solution including optimally located new entrants. The results suggest these plants would be subject to intense competitive pressures if new-entrants and other incumbents expanded as suggested in the results below.

The newly announced plants (Table 2) would operate at various capacities for anhydrous, dry, and liquid. The results indicate that six greenfield plants (American Falls ID, Grand Forks ND, Iberville LA, Jamestown ND, Rockport IN, Weaver IA) would enter the market. Another five Brownfield plants (Beulah ND, Donaldsonville LA, East Dubuque IL, Kennewick WA, Port Neal IA) would be utilized. Six of the seven plants with a 70% minimum operating capacity were included in the final solution. Only Penwell, Tx did not exceed the 70% operating rate hurdle.

The model performs well. The purpose of this paper was to quantify risks for plant expansion (brownfield and greenfield) of nitrogen fertilizer plants in North America, given the spatial competition and the corresponding dynamic market boundaries. These are represented as the distribution of output variables (as illustrated below). It is important that we are not seeking to generate point estimates, nor of estimates of a single dependent variable,[9] but, rather are deriving the risks, represented as probability distributions, associated with greenfield or brownfield plant expansions (i.e., the probability). Further, many of the intermediate inputs (e.g., fertilizer demand by commodity, modal shipments from origins to consumption, fertilizer operating rates, and type of fertilizer production by plant, etc.) are not observable, nor publicly reported. Hence, it was not possible to evaluate the values derived in the model. To assure the validity of the results, however we had the results reviewed by industry participants, and by a major railroad and they indicated these intermediate values seemed representative. Finally, as noted above, the model did predict that six of the seven proposed new plants are in fact being developed (see Table 2 footnotes). For these reasons, the results seem reasonable.

Market boundaries for the stochastic mixed integer model are calculated and presented in two formats; one uses the mean quantity shipped from 1000 iterations, and secondly using the probability where a plant is likely to ship. For anhydrous, the market boundary of the planned plant in Grand Forks (j = 58,203), penetrates the market boundary of plants 50,501 and 51,054 (as visible from Fig. 5). The most plausible market boundaries for each of the plants are shown. Grand Forks is 80 percent or more likely to ship east, and mostly to Minnesota, North Dakota, and South Dakota, thereby forcing the plant 51,054 to ship in the immediate vicinity of its location 80% of the time. The market boundary for Grand Forks is expansive and is detrimental to the competing plants. The market boundaries of plants in Beulah, Jamestown, and northern Iowa are overwhelmed when the Grand Forks plant operates in geographic regions where it ships with an 80 percent probability. The plant in Grand Forks covers a wide area in the Midwest which was earlier supplied by plants in Iowa and imports from Canada in the base case.

Shipment results were analyzed to determine where competition would be most intense and ruinous. This area comprises counties that are common to the market boundaries of more than one plant. In the case of anhydrous, regional competition would become increasingly intense with opening of the new plant for example in Grand Forks (58,203). Market boundaries for the same set of plants: Port Neal, IA (existing plant), Weaver, IA (existing plant) and Grand Forks, ND (planned plant) 50,501(anhydrous), 51,054(dry) and 58,203 (liquid) are also presented.

To highlight competition in counties where it would be most intense, spatial selection (same geographical regions overlaid on top of each other for comparison) in GIS was used to derive the common counties that are part of market boundaries where each of the three plants are most likely to ship (Fig. 6). During each of the 1000 iterations of solving the optimization problem, results are collated for every pair of origin and destination that was part of solution i.e. each county is identified along with the identity of the fertilizer by which is served by type of fertilizer, and mode of transportation. We refer to these counties as overlapping market boundaries for fertilizer. Specifically, if the market boundary (a set of counties) for Port Neal, IA (i = 51,054) is put on top of the market boundary of Grand Forks, ND (i = 58,203), a clear demarcation in form of market boundaries on Grand Forks is obtained in the form of over lapping market boundaries.

All the area shown in Fig. 6 is within the market boundary of the new plant in Grand Forks (5 for comparison). Fig. 6 shows market boundary of the dark colored area shows higher competition between plant 58,203 with the rest of the two (51,054 = pink, 50,501 = green). Darker areas represent higher probability for a county to be shipped by Grand Forks, ND in future year 2018, whereas pink color represents the market area of Port Neal, IA and Green represents the market boundary of Weaver, IA (i = 50,501) (Fig. 6). The most intense competition is in close periphery of Port Neal and Weaver plants. In other words, opening new plants results in increased competition with existing plants, as illustrated by the darker graduated colors by county.

In order to summarize the results from 1000 iterations of optimization, graduated colors (symbology) was used wherein a lighter color for a county signifies that county was utilized as destination fewer number of times. On the other hand, a darker color for counties means that county was used destination more often for a particular fertilizer plant. If a county is supplied by a different fertilizer. A different color is used for a county. Grand Forks provides competition to existing plants, far from its location. The market boundary of Grand Forks covers most of South Dakota, southwest Minnesota, north belt of North Dakota and eastern Montana, which were earlier supplied by imports from Canada by Rail and plant in Beulah, ND.

Distribution of Stochastic Output Parameters The output variables are random due to the specification of many of the input variables. Those of particular importance are production and utilization rates at existing and new plants, as well as shipments. CDFs

[9] In contrast to typical forecasting econometric models in which there would be one or a few dependent variables, our model contained 356,399 variables and 6014 constraints. For these reasons normal methods for back testing (as used in econometric models or trading strategies) is not commonly pursued in spatial optimization models.

Table 1
Stochastic Mixed Integer by type of fertilizer (Anhy, Dry and Liquid)[a]: Quantity Produced and Utilization rate of existing fertilizer plants.

ID Set(i)	City, state of fertilizer plant	Anhy	Urea	UAN	Anhydrous (%)	Urea (%)	UAN (%)
Zip code		Quantity Produced (tons)			Utilization Rate (%)		
30,901	Augusta GA	7059	18,455	640,000	1%	3%	100%
68,310	Beatrice NE		29	199,803	0%	0%	100%
77,627	Beaumont TX						
79,007	Borger TX	72,644	97,988		13%	90%	
35,616	Cherokee AL			239,733	0%	0%	83%
82,001	Cheyenne WY	1851	2574	140,558	1%	2%	67%
67,337	Coffeyville KS		19,403	146,438	0%	7%	14%
50,801	Creston IA						
67,801	Dodge City KS			237,544	0%	0%	93%
73,701	Enid OK	2005	52,691	79,768	0%	9%	89%
70,792	Faustina LA						
50,501	Fort Dodge IA	71,339	27,226	537,643	18%	14%	100%
70,734	Geismar LA		193,183	783,843	0%	43%	69%
23,860	Hopewell VA	785			0%		
45,804	Lima OH			224,933	0%	0%	90%
37,809	Mosheim TN						
45,052	North Bend OH						
74,362	Pryor OK						
97,051	St. Helens OR			53,246	0%	0%	86%
33,619	Tampa FL						
74,019	Verdigris OK	59,691		788,209	5%		40%
95,691	W. Sacramento CA						
73,801	Woodward OK	13,803	11,945	796,249	3%	48%	100%
39,194	Yazoo City MS			142,729	0%	0%	89%

[a] Note: Total quantity produced (in tons) for each fertilizer plant is comprised as 82% of Anhy, 46% of Dry and 30% of UAN.

Table 2
Stochastic Mixed Integer by type of fertilizer (Anhy, Dry and Liquid)[a]: Quantity Produced and Utilization rate of Greenfield and Brownfield fertilizer plants.

ID Set (i)	City, state of fertilizer plant	Anhy	Urea	UAN	Anhy (%)	Urea (%)	UAN (%)	Planned Plant-Type of N Fertilizer to be produced
Zip code		Quantity Produced (tons)			Utilization Rate (%)			
83,211	American Falls ID	23,376	60,590	230,688	13%	9%	44%	Greenfield, Anhy, Urea, UAN
58,523	Beulah ND[b]	5	314,387		0%	82%		Brownfield, ≥ 70% of plant capacity, Urea,
70,346	Donaldsonville LA[c]	2,049,186	2,197,451	2,828,489	48%	93%	68%	Brownfield, Anhy, Urea, UAN
61,025	East Dubuque IL			230,841	0%	0%	59%	Brownfield, Anhy,
58,203	Grand Forks ND[d]	956,565	800,000	395,480	43%	100%	79%	Greenfield, ≥ 70% of plant capacity, Anhy, Urea, UAN
70,765	Iberville LA	305,187	685,433	1,715,071	24%	100%	97%	Greenfield, ≥ 70% of plant capacity, Anhy, Urea, UAN
58,481	Jamestown ND	75,124	0	238,000	36%	0%	100%	Greenfield, ≥ 70% of plant capacity, Anhy, Urea, UAN
39,358	Kemper County MS							Greenfield, Anhy,
99,337	Kennewick WA[e]			85,174	0%		18%	Brownfield, Anhy,
50,164	Menlo IA							Greenfield, Anhy,
63,869	New Madrid MO							Greenfield, Urea, UAN
79,776	Penwell TX							Greenfield, ≥ 70% of plant capacity, Urea,
51,054	Port Neal IA[f]	381,171	1,026,292	800,000	31%	73%	100%	Brownfield, ≥ 70% of plant capacity, Anhy, Urea,
47,635	Rockport IN			392,087	0%		38%	Greenfield, Anhy, UAN
52,658	Weaver IA[g]	191,235		1,184,350	29%		81%	Greenfield, ≥ 70% of plant capacity, Anhy, UAN

[a] Note: Total quantity produced (in tons) for each fertilizer plant is comprised as 82% of Anhy, 46% of Dry and 30% of UAN.
[b] https://www.dakotagas.com/about-us/gasification/ammonia-process.
[c] https://www.cfindustries.com/who-we-are/locations/donaldsonville.
[d] https://www.agweek.com/business/work-on-fertilizer-plant-in-grand-forks-nd-could-start-as-early-as-2022.
[e] https://ecology.wa.gov/Regulations-Permits/Permits-certifications/Industrial-facilities-permits/Agrium-Kennewick-Fertilizer-Operations.
[f] https://www.cfindustries.com/who-we-are/locations/port-neal.
[g] https://www.oci.nl/operations/iowa-fertilizer-company/.

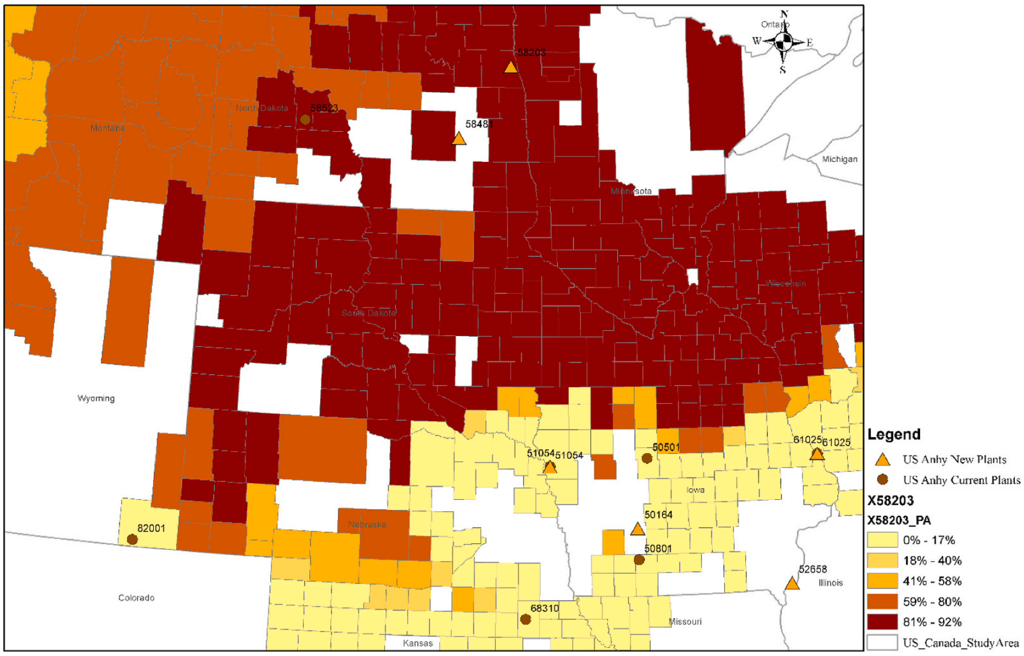

Fig. 5. Market boundaries for Grand Forks (plant i = 58,203) for Anhydrous (probability of shipping for 1000 iterations) in stochastic mixed integer model.

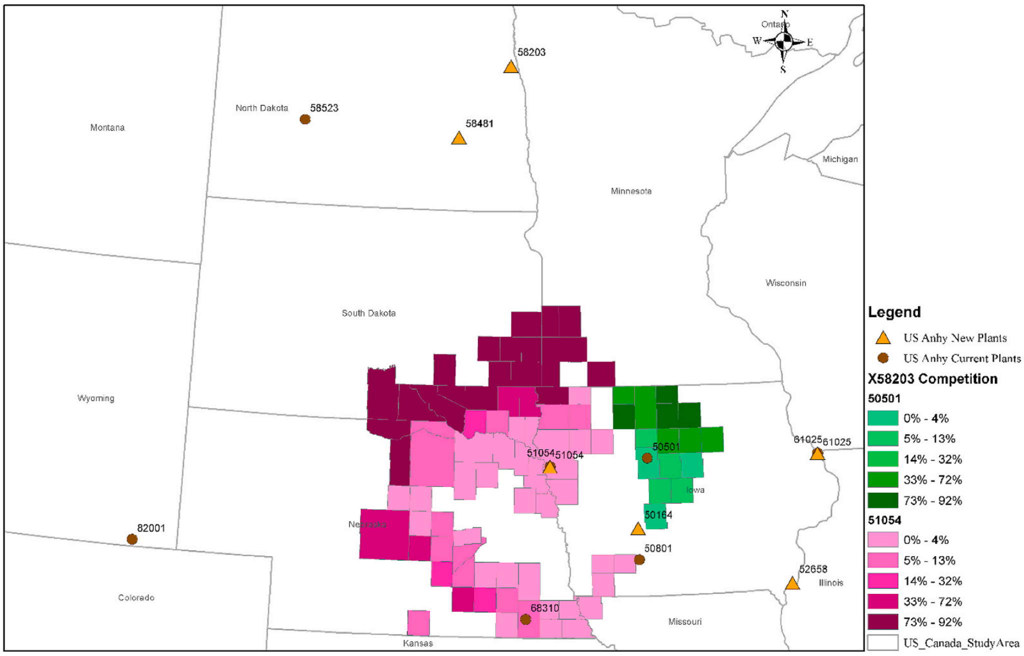

Fig. 6. Counties for Grand Forks (plant 58,203) anhydrous production that are also served by Ft Dodge and Port Neal, Ia. (plants 50,501 and 51,054). Darker region represents higher likelihood of being served. (51,054 = pink color, 51,054 = green). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

were derived for each output distribution using the simulated output data, resulting in a large number of distributions. Below we illustrate the distributions of some selected output variables of interest to this industry. Comparisons are also shown across scenarios.

Fig. 7 shows the CDFs for Grand Forks (j = 58,203). That plant would produce Dry with certainty. There is greater risk of producing anhydrous, less for liquid, and almost none for Dry. Grand Forks is interesting for the fact that there is 20 percent chance that the

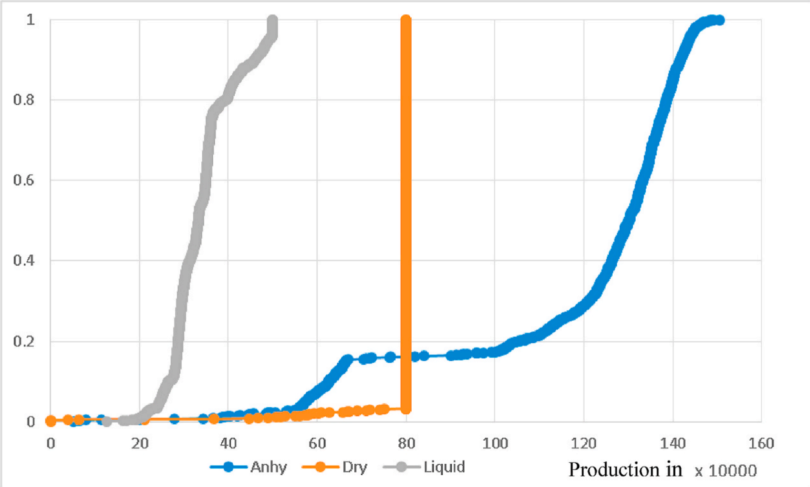

Fig. 7. Probability of production (in tons) at Grand Forks in the case of Stochastic Linear model.

production would be less 1000 thousand tons. Grand Forks, ND (58,203) has a variability of production between one to 1.4 million tons for anhydrous, while between 200,000 and 490,000 tons for UAN, with dry at 800,000 tons.

Comparison across scenarios, the plant in Weaver, IA (i = 52,658) produces anhydrous ammonia between 441,000 tons and 661,000 tons with cumulative probability of 28–68 percent (Fig. 8). There is a probability of .08–.28 that it would produce 441,000 tons. In the stochastic linear case, there is 1 in 1000 chance the plant does not produce anything. For comparison, in the stochastic mixed integer case there is a probability of .03–.46 percent, that it would produce 462, 000 tons. Thus, there is a higher range for producing at 70 percent of plant capacity. There is variability between probability of .46–.72 percent for producing anywhere between 462,000 tons and 661,000 tons. There is 75 percent or more chance that the plant in Weaver would produce at its capacity in both stochastic linear and stochastic mixed integer case.

Sensitivity for Natural Gas Prices: Prices of natural gas have an important impact on import volumes. A one-unit increase in Henry Hub prices increases import volume for anhydrous, dry, and liquid shipments by 57,530, 10,955 and 3432 tons respectively. Increases in Henry Hub prices also increased the production cost at Canadian plants. For this reason, increases in HH resulted in lower imports to the U.S. from Canada. Increases in import prices, tended to reduce import volumes, however the effect was minimal. Increases in import costs at the Gulf generally resulted in higher values for Canadian imports. Further, increases in U.S. demand generally increased Canadian imports (995 for anhydrous, 3811 for dry and −89 for liquid). For the two U.S. plants in Weaver, IA and Grand Forks, ND, the effects of the random variables were similar, except for liquid. The size of the beta's[10] were larger for Grand Forks than for Weaver. In addition, all betas were positive for Weaver, IA, while increases in demand for liquid for Grand Forks was negative, thus, an increase in U.S. demand for liquid, reduced production in Grand Forks of liquid nitrogen. This indicates that the plant at Grand Forks would be more sensitive to natural gas prices, import costs and demand, than the Weaver, IA plant.

7. Summary

Fertilizer is an important commodity traded domestically and internationally, and spatial competition is an important feature of this and many agricultural industries. Compounding analysis about spatial competition is the stochastic nature of many of the variables that impact these industries. This study analyzes spatial competition in the North American fertilizer industry which is confronting a number of structural changes and recent events have highlighted the limitations of the supply chains in this sector. The purpose of this study is to quantify risks for plant expansion (brownfield and greenfield) of nitrogen fertilizer plants in North America, given the spatial competition and the corresponding dynamic market boundaries. A model is specified that integrates Geographical Information Systems (GIS) data into a stochastic mixed-integer network spatial optimization model using Monte Carlo simulations to account for risk in important random variables. The model was integrated with GIS procedures for both the input and output variables. The model included production of fertilizer for individual plants, imports and shipments to final demands at the county level by crop and fertilizer type. Many of these variables are random including import prices, natural gas and electricity which vary spatially and have important impacts on processing costs and demands (are there other random variables). Each of these are risky and were characterized by

[10] Beta's were defined as the average shadow price over the full distribution of random variable across the simulated optimization runs of the model thousand times.

[11] For more details, See Appendix: Mathematical Specification. [] represents sets of similar nodes, for example [i] represents all fertilizer plants in the U.S (existing, greenfield, and brownfield) acting as origin points with respective capacities of production by type of fertilizer, while [j] represents all the counties in the U.S. that have any demand for a various type of nitrogenous fertilizer.

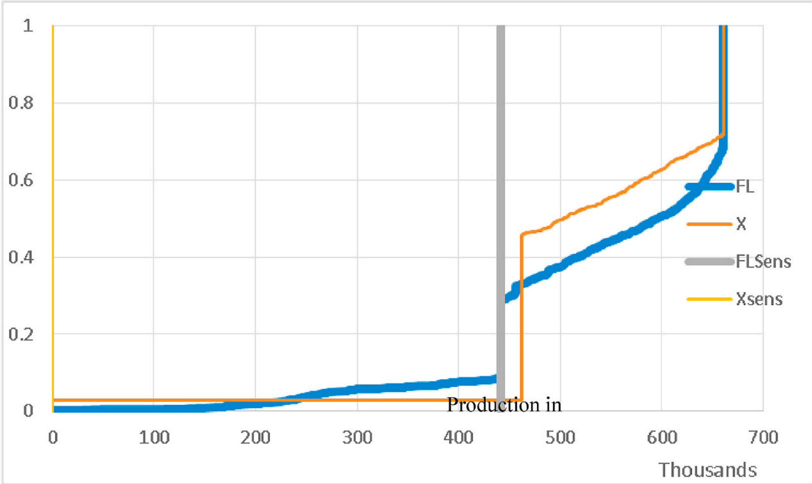

Fig. 8. Probability of production for anhydrous at weaver, Ia across scenarios of stochastic linear (FL), mixed integer (X), linear sensitivity (FLSens) and mixed integer sensitivity (xsens).

distributions and included in the stochastic spatial optimization model.

The results characterize supply chain and spatial competition well. There are a number of interesting impacts of the stochastic analysis. One is that market boundaries change significantly with changes in random variables including import prices, natural gas prices, and demand. Location of fertilizer plants and costs determine their market boundaries and provides great insights as to where the competition is intense. Second, any new fertilizer plant would penetrate markets only due to lower input cost and changes in demands. Third, not all fertilizer plants that have been announced would be competitive. These results indicate which new plants would be most likely to succeed. Some of the proposed plants in Louisiana and North Dakota have higher probability in successfully entering the market. These new plants would have a significant impact on market boundaries of existing fertilizer plants which we refer as 'overlapping market boundaries." Fourth, competition between fertilizer plants varies regionally. Finally, imports remain competitive, and only a few of newly announced fertilizer plants would reach minimal efficient scale of output. These results support findings of recent literature describing the projects under development.

These results have several implications. Private firms are confronted with the dilemma to invest in expansion of a current plant. If they decide to invest in a new plant, there are a number of issues management confronts: what is the probability that fertilizer plant would be viable by the time the fertilizer plant reaches operational stages? What is the market size or market boundary that new expansion or new fertilizer plant will be able to serve? Who would be the competitors? All of these questions are captured in the results of this study. It is of interest that since the analysis in this study was complete, most (Table 2) of the proposed new plants are in the process of being developed. This suggest and confirms the tendency for firms with substantial economies of scale and volatile demand to over-build and ultimately compete with excess capacity.

Public agencies are also impacted by developments in this industry. Many state agencies provide incentives for new entrants which provide incentives for new entrants and the succeeding spatial competition. New plants of this size impact transportation demands and infrastructure. Some agencies impose regulations on manufacturing and on shipping of products included in the fertilizer sector. Finally, changes in structure of supply chain may warrant changes in the configurations of warehouses used to distribute the product. Indeed, this is the case of at least one major railroad serving the relevant region.

This paper makes several contributions in the topic of modeling spatial competition. Existing literature in commodity trading typically have not used GIS based data analytics and spatial optimization, despite its importance in many other sectors. The model developed in this paper integrates a stochastic spatial optimization model with repeated mixed integer modelling to account for risk associated with changes in transportation cost, fertilizer consumption and changes in natural gas import prices (there by affecting spatial distribution of supply chain networks by various modes of transportation). If greenfield fertilizer plants are to be developed, they would need to operate at a minimum capacity which was captured in this model. Traditional spatial models rarely account for random variables.

The model developed in this paper has limitations in that it is very data and computationally intensive. However, the model demonstrates a spatial stochastic mixed-integer model that can directly be used to explain the network and distribution of supply chain for nitrogen-based fertilizer in the United States with an example of Mid-west region. The paper also demonstrates the feasibility of greenfield and brownfield fertilizer plants and the risk associated given the random nature other variables that not only affects the plants but also the distribution of flows (quantity flows). Lastly, the paper demonstrates how spatial competition can be quantified in terms of probabilities derived from repeated optimization instead of single static optimum solution potentially with many discrete sensitivities.

Credit author statement

Wilson: conceptualizing, funding acquisition, projected administration, supervision, writing. Shakya: data curation, formal analysis, methodology, software.

Data availability

Data will be made available on request.

Appendix. Mathematical Specification

The model specified is based on spatial competition using a 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. Fig. 1 provides a description of the major features of the model. The mathematical model specification is described below:

$$Min\ Cost = \left[\sum_{r,s,T,M}^{n} X6_{r,s,T,M} * CostCim_{r,T} + \left(\sum_{q,p,T,M}^{n} X5_{q,p,T,M} + \sum_{q,j,T,M}^{n} X1_{q,j,T,M} \right) * CostIm_T + \left(\sum_{i,j,T,M}^{n} X4_{i,j,T,M} + \sum_{i,p,T,M}^{n} X7_{i,p,T,M} \right) * CostUS_{i,T} \right] + \left[\sum_{r,s,anhy,M}^{n} X8_{r,s,anhy,M} * \left(CostCanBor_{r,s,anhy,M}\right) + \sum_{s,i,anhy,M}^{n} X9_{s,i,anhy,M} * \left(CostBorUS_{s,i,anhy,M}\right) + \sum_{q,p,anhy,Barge}^{n} X12_{q,p,anhy,Barge} * \left(CostImpTrans_{q,p,anhy,Barge}\right) + \sum_{p,i,anhy,M}^{n} X13_{p,i,anhy,M} * \left(CostTransUS_{p,i,anhy,M}\right) + \sum_{q,i,anhy,M}^{n} X11_{q,i,anhy,M} * \left(CostImpUS_{q,i,anhy,M}\right) + \sum_{i,i,anhy,M}^{n} X10_{i,i,anhy,M} * \left(CostUSUS_{i,i,anhy,M}\right) \right] + \left[\sum_{r,s,T,M}^{n} X6_{r,s,T,M} * \left(CostCanBor_{r,s,M,T}\right) + \sum_{s,j,T,M}^{n} X3_{s,j,T,M} * \left(CostBorDmd_{s,j,M,T}\right) + \sum_{q,p,T,Barge}^{n} X5_{q,p,T,Barge} * \left(CostImpTrans_{q,p,T,Barge}\right) + \sum_{p,j,T,M}^{n} X2_{p,j,T,M} * \left(CostTransDmd_{p,j,T,M}\right) + \sum_{q,j,T,M}^{n} X1_{q,j,T,M} * \left(CostImpDmd_{q,j,T,M}\right) + \sum_{i,p,T,M}^{n} X7_{i,p,T,M} * \left(CostUSTrans_{i,p,T,M}\right) + \sum_{i,j,T,M}^{n} X4_{i,j,T,M} * \left(CostUSDmd_{i,j,T,M}\right) \right] \tag{1}$$

S.T

$$\sum_{r,anhy} \left(\sum_{s,M}^{n} X6_{r,s,anhy,M} + \sum_{s,M}^{n} X8_{r,s,anhy,M} \right) \le CanCap_{r,anhy} \tag{2}$$

$$\sum_{i,anhy} \left(\sum_{j,Barge}^{n} X7_{j,p,anhy,Barge} + \sum_{j,M}^{n} X4_{i,j,anhy,M} + \sum_{i,M}^{n} X10_{i,i,anhy,M} \right) \le USCap_{i,anhy} \tag{3}$$

$$\sum_{i} \left(\sum_{s,M}^{n} X9_{s,i,anhy,M} + \sum_{q,M}^{n} X11_{q,i,anhy,M} + \sum_{p,M}^{n} X13_{p,i,anhy,M} + \sum_{i,M}^{n} X10_{i,i,anhy,M} \right) = \sum_{i} \left(\sum_{j,M}^{n} X4_{i,j,Dry,M} + \sum_{p,M}^{n} X7_{i,p,Dry,M} \right) * .58 + \sum_{i} \left(\sum_{j,M}^{n} X4_{i,j,Liquid,M} + \sum_{p,M}^{n} X7_{i,p,Liquid,M} \right) * .302 \tag{4}$$

$$\sum_{i} \left(\sum_{i,M}^{n} X10_{i,i,anhy,M} \right) = \sum_{i} \left(\sum_{j,M}^{n} X4_{i,j,Dry,M} + \sum_{p,M}^{n} X7_{i,p,Dry,M} \right) * .58 + \sum_{i} \left(\sum_{j,M}^{n} X4_{i,j,Liquid,M} + \sum_{p,M}^{n} X7_{i,p,Liquid,M} \right) * .302 \tag{5}$$

$$\sum_{r,Dry}^{n} \sum_{s,M}^{n} X6_{r,s,Dry,M} \le CanCap_{r,Dry} \tag{6}$$

$$\sum_{r,Liquid}^{n} \sum_{s,M}^{n} X6_{r,s,Liquid,M} \le CanCap_{r,Liquid} \tag{7}$$

$$\sum_{i,Dry} \left(\sum_{j,M}^{n} X4_{i,j,Dry,M} + \sum_{p,Barge}^{n} X7_{i,p,Dry,Barge} \right) \le USCap_{i,Dry} \tag{8}$$

$$\sum_{i,Liquid}\left(\sum_{j,M}^{n} X4_{i,j,Liquid,M} + \sum_{p,Barge}^{n} X7_{i,p,Liquid,Barge}\right) \le USCap_{i,Liquid} \tag{9}$$

$$\sum_{s,anhy}\left(\sum_{r}^{n} X8_{r,s,anhy,M}\right) = \sum_{s,anhy}\left(\sum_{i}^{n} X9_{s,i,anhy,M}\right) \tag{10}$$

$$\sum_{s,T,M}\sum_{r}^{n} X6_{r,s,T,M} = \sum_{s,T,M}\sum_{j}^{n} X3_{s,j,T,M} \tag{11}$$

$$\sum_{p,anhy}\left(\sum_{q}^{n} X12_{q,p,anhy,Barge}\right) = \sum_{p,anhy}\left(\sum_{i}^{n} X13_{p,i,anhy,M}\right) \tag{12}$$

$$\sum_{p,T}\left(\sum_{q}^{n} X5_{q,p,T,Barge} + \sum_{i}^{n} X7_{i,p,T,Barge}\right) = \sum_{p,T}\left(\sum_{j}^{n} X2_{p,j,T,M}\right) \tag{13}$$

$$\left(\sum_{j,T}\sum_{s,M}^{n} X3_{s,j,T,M} + \sum_{j,T}\sum_{q,M}^{n} X1_{q,j,T,M} + \sum_{j,T}\sum_{p,M}^{n} X2_{p,j,T,M} + \sum_{j,T}\sum_{i,M}^{n} X4_{i,j,T,M}\right) = Demand_{j,T} \tag{14}$$

$$\sum_{r,s,anhy,M}^{n} X1_{r,s,anhy,M} + X5_{r,s,anhy,Barge} + X11_{r,s,anhy,M} \le 4,978,890 \tag{15}$$

$$\sum_{r,s,Dry,M}^{n} X1_{r,s,Dry,M} + X5_{r,s,Dry,Barge} \le 5,163,843 \tag{16}$$

$$\sum_{r,s,anhy,M}^{n} X1_{r,s,anhy,M} + X5_{r,s,anhy,Barge} \le 2,626,192 \tag{17}$$

$$\sum_{r,s,anhy,M}^{n} X6_{r,s,anhy,M} + X8_{r,s,anhy,M} \le 1,022,944 \tag{18}$$

$$\sum_{r,s,Dry,M}^{n} X6_{r,s,Dry,M} \le 1,774,719 \tag{19}$$

$$\sum_{r,s,Liquid,M}^{n} X6_{r,s,Liquid,M} \le 619,498 \tag{20}$$

$$\sum_{j,T,M}^{n} X1_{Galveston,j,Dry,Rail} \le 721,000 \tag{21}$$

$$\sum_{p,T,Barge}^{n} X2_{p,MNBarge,T,Barge} \le 20,000 \tag{22}$$

where:

T = Type of fertilizer namely: Anhydrous, Urea and Liquid.
M = Mode of transportation, namely: Rail, Truck, Pipe and Barge
I = fertilizer plants located in United States (USPlants) Locations
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*.
$CostCim_{r,T}$ = Cost of procurement at Canadian plant *r* by type *T*.
$CostUS_{i,T}$ = 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.
$\mathrm{USCap}_{\mathrm{i,T}}$ = USA capacity at plant *i* by type *T*.
CanCap = Canada capacity at plant *r* by type *T*.
$\mathrm{Demand}_{\mathrm{j,T}}$ = Demand at county *j* by type *T*.

The objective function contains three main parts. The first is the procurement cost which is defined as the cost of production at US and Canadian plants and import prices for imports at the US Gulf. The second part of the objective function includes the shipping cost for anhydrous as intermediate product referred to as 'Anhy-only.' The last part is the shipping cost for final products (Anhydrous Ammonia, Urea and Liquid) from plants to consumption points.

The model was solved subject to several constraints. The constraints included capacity constraints at Canadian (equation (2)) and U.S. Plants (equation (3)) which limit the production of anhydrous as an intermediate product to less than the physical capacities of individual plants. Equations (4) and (5) are balance equations for the conversion of anhydrous as an intermediate product to urea and liquid nitrogen fertilizers, respectively. It is assumed it takes 0.58 tons of anhydrous ammonia to produce 1 ton of urea and 0.302 tons tom make 1 ton of UAN solution. Equations (6) and (7) are supply constraints for Canadian plants production of Dry (Eq. (6)), Liquid (Eq. (7)), and U.S. plants production for Dry (Eq. (8)), Liquid (Eq. (9)) which limits production of that type of fertilizer to be less than or equal to the plant capacity for each plant, type, and country.

Equation (10) is a balance equation for shipment of anhydrous to the U.S. from Canada as an intermediate product. This forces shipments from Canadian plants to border points to equal shipments from border points to U.S. plants. This equation allows the production of anhydrous at Canadian plants to be converted into Dry or Liquid at fertilizer plants in United States. Equation (11) is another balance equation that forces shipments of dry and liquid fertilizer from Canadian plants to border points to equal flows from border points to demand areas. Equation (12) is a balance equation for inland transshipments points within the United States, such that what comes in equals to transshipment points equals the flows out for anhydrous as an intermediate product. The balance equation for inland transshipments points in the United States for final products is such that sum of production at U.S. Plants and imports, for Anhy, Dry and Liquid, is equal to total flow out from transshipment points s to demand points is represented by (Equation (13)). Equation (14) forces the total fertilizer shipped to be equal to the demand by type for each county. Equations (15)–(17) limit total imports from the U.S. Gulf to inland transshipment points to be less than the maximum import volume in 2012, by type. Equations (18)–(20) limit total imports from Canada to a maximum of 2012 vol by type. Equation (21) limits rail shipments of dry fertilizer originating out of Galveston, TX to a maximum of observed values as in December 2013. To account for seasonality in barge traffic to Minnesota, shipment volume to the trans-loading point was limited to 20,000 tons (Equation (22)).

To specify the mixed integer problem, a binary variable to control the operating capacity for a few of the new plants is applied. If the binary variable allows these plants, then the plant is allowed to work at least 70 percent of its capacity. This is to account for initial break even cost of plants to realize economies of scale. These plants are Spiritwood (j = 58,481), GrandForks (j = 58,203), Russian (j = 70,765), Beulah (j = 58,523), Ector (j = 79,776), PortNeal (j = 51,054), and Weaver (j = 52,658).

$$\sum_{i\in FutSel_{Anhy},Anhy}\left(\sum_{p,Barge}^{n} X7_{i,p,Anhy,Barge}+\sum_{j,M}^{n} X4_{i,j,Anhy,M}+\sum_{i,M}^{n} X10_{i,i,Anhy,M}\right)\leq USCap_{i,Anhy}*Bin_{i,Anhy} \tag{23}$$

where $\mathrm{FutSel}_{\mathrm{Anhy}}$ = {58,481, 58,203, 70,765, 52,658} for Spiritwood-ND, Grand Forks-ND, Iberville-LA, and Weaver-IA respectively.

$$\sum_{i\in FutSel_{Dry},Dry}\left(\sum_{p,Barge}^{n} X7_{i,p,Dry,Barge}+\sum_{j,M}^{n} X4_{i,j,Dry,M}\right)\leq USCap_{i,Dry}*Bin_{i,Dry} \tag{24}$$

where $\mathrm{FutSel}_{\mathrm{Dry}}$ = {58,481, 58,203, 70,765,58,523,79,776,51,054} for Spiritwood-ND, Grand Forks-ND, Iberville-LA, Beulah-ND, Ector-TX, and Port Neal-IA respectively.

$$\sum_{i\in FutSel_{Liquid},Liquid}\left(\sum_{p,Barge}^{n} X7_{i,p,Liquid,Barge}+\sum_{j,M}^{n} X4_{i,j,Liquid,M}\right)\leq USCap_{i,Liquid}*Bin_{i,Liquid} \tag{25}$$

where $\mathrm{FutSel}_{\mathrm{Liquid}}$ = {58,481, 58,203, 70,765, 52,658} for Spiritwood-ND, Grand Forks-ND, Iberville-LA, and Weaver-IA respectively.

$$\sum_{i\in FutSel_{Anhy},Anhy}\left(\sum_{p,Barge}^{n} X7_{i,p,Anhy,Barge}+\sum_{j,M}^{n} X4_{i,j,Anhy,M}+\sum_{i,M}^{n} X10_{i,i,Anhy,M}\right)\geq USCap_{i,Anhy}*Bin_{i,Anhy}*.7 \tag{26}$$

$$\sum_{i \in FutSel_{Dry}, Dry} \left(\sum_{p,Barge}^{n} X7_{i,p,Dry,Barge} + \sum_{j,M}^{n} X4_{i,j,Dry,M} \right) \geq USCap_{i,Dry} * Bin_{i,Dry} * .7 \tag{27}$$

$$\sum_{i \in FutSel_{Liquid}, Liquid} \left(\sum_{p,Barge}^{n} X7_{i,p,Liquid,Barge} + \sum_{j,M}^{n} X4_{i,j,Liquid,M} \right) \geq USCap_{i,Liquid} * Bin_{i,Liquid} * .7 \tag{28}$$

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