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Nitrogen Fertilization of Growing Wheat Based upon Site-Specific Optical Sensing

Abstract

A site-specific fertilizer application system that uses optical reflectance measurements of growing plants to estimate fertilizer requirements and that can apply liquid nitrogen fertilizer at a grid level of four square feet is under development. The objective is to determine if the site-specific system is more economical than alternative systems.

Key Words: optical sensing, nitrogen fertilizer, precision farming, site specific, wheat

Introduction

A number of precision and site-specific technologies have been developed and introduced to the farming community, including global positioning systems, geographic information systems, yield monitoring sensors, and computer controlled within-field variable rate application equipment. Many agronomists, engineers, and economists posit that precision technology will be a driving force behind production agriculture in the future. Even though the profitability of some precision technologies appears promising, widespread adoption has been slow.

Nitrogen fertilizer is a primary nutrient that is typically applied each year in the fall prior to planting wheat in the southern Great Plains, and accounts for 20 to 30% of the per acre cash expenses, depending on the size of farm and location. Precision technologies for fertilizer application on wheat have relied on grid soil sampling, soil testing, and mapping on a three-acre grid basis. Haneklaus, Shroeder, and Schnug evaluated different decision-making processes governing variable rate fertilizer application. They concluded that to accurately describe the variability of nitrogen, phosphorus, and other plant nutrients in the soil, small grids are preferred to large grids. They found that 108 square foot grids (10 square meters) are more appropriate than the three-acre average grid size normally used as sample sites. Others report similar findings. For example, extensive soil testing, optical reflectance measurements of plants, and yields collected on very small plots, have shown that the spatial scale of nitrogen availability to winter wheat can be as small as a four square feet grid, and that economically optimal levels of nitrogen fertilizer may differ on adjacent four-square-foot grids (Raun et al., 1998; Solie, Raun and Stone.).

Practical implementation of a management strategy to sense growing wheat and apply nitrogen at a grid level of four-square-feet (10,890 square grids per acre) is challenging. A prototype site-specific variable rate nitrogen application system that uses optical reflectance information obtained from growing winter wheat plants has been developed. The system does not require mapping of soils, soil testing, or yield monitors. However, it does require several steps. First, in the late summer, or early fall, nitrogen is applied to a narrow strip of the field prior to planting. The level of nitrogen applied to the strip must be sufficient so as not to limit plant growth throughout the growing season. In other words, a non-limiting amount of nitrogen is applied to a strip across the field such that in the strip, yield will reach its plateau level (Frank, Beattie and Embleton; Grimm, Paris, and Williams; Waugh, Cate, and Nelson). This is referred to as a nitrogen rich strip (NRS). Wheat is planted in the fall after the NRS has been fertilized. Second, in late winter after the crop is well established, optical reflectance readings are taken from the NRS area of the field. These measurements provide information that enable comparing nitrogen uptake from plants growing in the area of the field where nitrogen is not yield limiting to plants growing elsewhere in the field.

Third, the system uses a self-propelled boom sprayer equipped with optical reflectance sensors, computers, and a global positioning device that is used to assist with steering the sprayer to prevent repeated applications on individual grids throughout the field. An algorithm programmed into the system's computers uses the sensor information from the NRS and sensor information from each four-square-foot grid of the field to determine the nitrogen treatment levels. The intent of the algorithm is to determine the quantity of nitrogen to apply to each individual four-square-foot grid necessary to achieve the plateau yield (Solie et al. 1996, 2002). As the applicator moves across the field, the machine optically senses, computes the level of nitrogen, and treats individual four-square-foot grids with 28% liquid nitrogen solution on the go.

The prototype does not consider either the price of nitrogen or the price of wheat. The objective of the research is to determine if the system is more economical than alternative nitrogen fertilization strategies. The system is in commercial production, but few sales have been made. Given the substantial investment needed to further develop the system, and the potential environmental benefits from lower nitrogen applications, estimates of its relative economic value are considered necessary to understand what is needed for the system to be adopted. Economic information would also provide engineers and manufacturers with a target cost to deliver the technology, would be of value to fertilizer distributors who must decide whether or not to purchase and promote the new equipment, and would be useful to agricultural extension specialists who may be confronted with questions regarding the system.

Economics of Variable Rate Precision Technology (VRPT)

Several studies have focused on estimating the economic feasibility of precision technologies for agricultural production. Lambert and Lowenberg-DeBoer reviewed 108 studies that provided estimates of the economics of site-specific variable rate precision technologies for agriculture. They found that 63% of the studies reported positive economic benefits. However, Bullock, Lowenberg-DeBoer, and Swinton found that of those 63% reporting economic benefits, many had omitted important costs, made unrealistic yield advantage estimates, or used simulation methods that might overestimate the value. The economics of variable rate fertilizer application are driven by three elements: (1) increased cost of sampling information and variable rate application; (2) change in cost of fertilizer applied; and (3) change in revenue from crop yield. The cost of information that is provided by precision technologies is central to analyzing profitability. However, cost estimates are not included in some studies (Bullock, Lowenberg-DeBoer, and Swinton).

VRPT for Wheat

Some studies have reported positive returns to VRPT for wheat. For example, Fiez, Miller, and Pan reported that managing nitrogen on wheat using VRPT was more profitable than a uniform management strategy, but they did not consider all costs associated with using VRPT, reported data from only one year, and did not consider risk. Long, Carlson and Nielsen also reported that net returns from VRPT were greater than the uniform rate strategy. Godwin et al. evaluated nitrogen application rates and systems for wheat and barley fields in a one-year three-site on-farm experiment located in the United Kingdom. They reported that net returns from VRPT across all sites were greater than uniform rate systems, and that net returns varied by site and method used. However, they did not consider the cost of information collection, fixed costs for application, and did not consider risk.

Other studies of VRPT for commercial wheat production have found that the economics is questionable. Wibawa et al., Lowenberg-DeBoer and Aghib, and Carr et al. found that whole field management strategies realized higher net returns than managing fertilizer using VRPT based on soil mapping information and grid soil sampling and testing information. The reasons for these findings are related to the high costs of implementing the precision technologies, such as consulting fees, costs of training, and costs of information gathering.

Wollenhaupt and Buchholtz summarized the results of four field trials that investigated the marginal returns of VRPT for wheat in Montana. They concluded that site-specific management techniques including grid and soil sampling tests, map-making, variable rate fertilizing, and data management were not profitable compared to conventional soil fertility management techniques. They found that special application equipment, additional soil sampling and analysis, data management and map making incurred higher costs than the benefits incurred from the site-specific management strategy.

Swinton and Lowenberg-DeBoer evaluated the profitability of VRPT on nine farms in the western United States. They found that VRPT was not profitable for wheat and barley. They concluded that high value, high yielding crops are more economically responsive to VRPT than lower value per acre crops such as wheat and barley. Hennessy, Babcock, and Fiez concluded that site-specific information is a low-value commodity, and that returns from VRPT did not outweigh implementation costs. For the conditions of their study they found little incentive for producers to adopt VRPT.

The majority of studies have concluded that VRPT such as grid mapping and intensive soil testing are not economical for wheat. However, to-date the economics of site-specific nitrogen fertilizer application to wheat using optical sensing technology has not been evaluated. This site-specific technology does not require soil mapping, soil sampling, or soil testing. The optical sensing technology samples (senses) the growing plant directly.

Procedures and Data

The annual per acre ownership and operating costs for the sensor and computer equipped nitrogen fertilizer applicator are estimated. The cost of implementing the NRS prior to planting wheat is also estimated. Net returns are computed for eight nitrogen fertilizer management systems, including two systems that use site-specific four-square-foot grid technology.

Yield data were obtained from a series of on-farm wheat experiments with alternative nitrogen treatments conducted during the 2001, 2002, and 2003 growing seasons across ten locations in Oklahoma. The farms were located near the communities of Altus, Blackwell, Chickasha, Covington, Haskell, Hennessey, Lahoma, Perkins, Perry, and Tipton. The nitrogen fertilization treatments were as follows: 0/0 is a check treatment that received no nitrogen prior to planting in September and no topdress nitrogen in March; 0/40 received no preplant and a 40-pounds per acre level of actual nitrogen as a topdress in March; 0/80 received no preplant and an 80-pounds per acre level of topdress; 40/40 received a 40-pounds per acre level of both preplant and topdress; 40/0 received a 40-pounds per acre level of preplant and no topdress; 80/0 included an 80-pounds per acre level of preplant with no topdress; 0/OS received no preplant nitrogen with the level of topdress determined by the optical sensing (OS) system; and 40/OS included a 40-pounds per acre level of preplant with topdress levels determined by the optical sensing system.

Treatment yield means for each location were averaged across all replications for each year. Treatments 0/OS and 40/OS are the two alternative treatments for managing nitrogen application to winter wheat using the prototype site-specific optical sensing applicator. For the experiments, preplant nitrogen was applied as 33% ammonium nitrate (AN) prior to planting wheat in the fall, and topdress nitrogen was applied as 28% urea-ammonium nitrate (UAN) during Feekes Physiological Growth Stages 4-6 in late winter or early spring (Large; Stone et al.; Solie et al., 1996). However, there are currently many wheat producers in the southern Great Plains who apply anhydrous ammonia (NH_3) prior to planting, primarily due to its lower cost. Net returns were estimated for each of the eight treatments under the assumption that AN was used as the source of preplant nitrogen and then again under the assumption that NH_3 was used as the source of preplant nitrogen. For the region under study it is assumed that wheat yield responds to the level but not the source of preplant nitrogen.

The levels of 28% UAN applied with treatments 0/OS and 40/OS in the on-farm experiments were determined using a nitrogen fertilizer optimization algorithm that compares optical reflectance information obtained from the NRS with information from a four-square-foot grid. The algorithm is programmed into the computers on the prototype machine. Sensors mounted at the front of the machine sense the growing plants and provide a reading to the onboard computers. The information is used to determine the level of nitrogen to apply. As the rear of the machine travels across the sensed grid it is fertilized. A description of the algorithm used for the on-farm trails used in this research is presented in Raun et al. 2002.

Machine Costs

Custom application charges for applying 28% UAN fertilizer in the southern Great Plains in the spring is, on average, \$2.90 per acre (Kletke and Doye). This includes ownership and operating costs including the cost of transporting fertilizer and applicator to and from the field. The ownership and operating expenses associated with equipping a field applicator with optical sensing technology is computed using MACHSEL (Kletke and Sestak). The cost of modifying and equipping a self-propelled fertilizer applicator with optical reflectance technology is \$60,000. The expected useful life of the equipment is five years. This is assumed because of the rapid rate of obsolescence and wear and tear of the many computers that are included with the technology. The applicator equipped with optical sensing technology is expected to have a field operating speed of 15 miles per hour with 70% field efficiency. By these measures, the applicator can cover 82.7 acres per hour for a total of 827 acres per day when used 10 hours per day. The window of opportunity for applying liquid nitrogen to winter wheat during the optimal application time may be relatively small due to weather conditions, so machine managers could be expected to use the machine as many hours per day as possible.

Workers in the region earn, on average, ten dollars per hour to operate a self-propelled boom-sprayer. However, with the enhanced site specific applicator the operator is expected to have additional interaction with the machine's computers that will require additional training. The cost of this additional training is reflected in the wage rate. To reflect this cost of additional training, a wage rate of $12 rather than $10 per hour was assumed. This two-dollar difference is considered when determining the ownership and operating cost of the optical sensing technology. An annual interest rate of eight percent is assumed.

Cost of Nitrogen Rich Strip

Implementing the NRS is an essential part of the technology. The NRS is placed in the center of the field. Its size is a function of the applicator boom width and the length of the field. For this study the width of the NRS is assumed to be 65 feet, which is the width of the UAN applicator assumed for this analysis. Field area is assumed to be 160 acres (0.5 square mile). Hence, NRS length is assumed to be 2,640 feet. This gives a total area of 171,600 square feet, which translates into a NRS equal to 3.94 acres. For the 0/OS treatment, the applicator is assumed to make one pass across the center of the field applying 120 pounds of nitrogen in the form of 28% UAN per acre. For the 40/OS treatment the applicator will make one additional pass across the center of the field and apply an additional 80 pounds of nitrogen. The NRS encompasses approximately two percent of the 160-acre field. To account for the cost of the NRS, the per-acre machine ownership and operating cost are multiplied by 1.02.

Net Return

Net return is calculated for each treatment and year as the difference between gross revenue from the sale of wheat grain and the cost of nitrogen fertilization. Average prices for wheat grain and nitrogen fertilizer sources are based on long-term (32-year) averages (USDA). The budgeted price of wheat grain is $3 per bushel, anhydrous ammonia (82-0-0) is $0.15 per pound of nitrogen ($246 per ton), ammonium nitrate (33-0-0) is $0.25 per pound of nitrogen ($170 per ton), and UAN liquid solution (28-0-0) is $0.25 per pound of nitrogen ($140 per ton). In addition to using the 32-year average price of $0.15 per pound for anhydrous ammonia, net returns for each treatment that requires preplant nitrogen were also calculated using the 2002 price of anhydrous ammonia of $0.22 per pound ($361 per ton) to reflect a possible structural change in the production and marketing of this type of nitrogen fertilizer.

Results

Wheat grain yields for each treatment, year, and location and levels of 28% UAN applied for the two treatments using site-specific technology are presented in Table 1. Across all locations and years of the study, the average amount of nitrogen applied as 28% UAN as a topdress in the spring with the 0/OS treatment was 24.3 pounds per acre, and the average response to nitrogen for this treatment was 4.3 bushels per acre. For the 40/OS treatment, an average of 19.3 pounds of nitrogen as 28% UAN was applied as a topdress in the spring that resulted in an average response of 7 bushels per acre.

During the 2002 season, the average yield from the 0/0 treatment was 42 bushels per acre. In the same year, the 0/OS treatment applied, on average, eight pounds per acre of nitrogen as UAN in the spring and also yielded 42 bushels per acre. The 40/OS treatment received 40 pounds of actual nitrogen preplant and ten pounds of nitrogen topdressed as UAN and also yielded 42 bushels per acre. During 2002, it would have been more economical not to apply any nitrogen in the spring.

In 2003, the average yield obtained from the 0/0 treatment was 38 bushels per acre. The 0/OS treatment received an average of 23 pounds per acre of nitrogen in the spring and yielded 43 bushels per acre. The 40/OS treatment received 40 pounds per acre of nitrogen preplant and an average of 25 pounds per acre in the spring and yielded 53 bushels per acre. These data suggest that for 2003 the site-specific system did not apply sufficient nitrogen to the 0/OS treatments. The results suggest that additional research may be warranted to either improve the algorithm used to determine the site-specific application rates or to improve the applicator (Raun et al., 2003).

Estimated annual ownership and operating costs, including the cost of implementing the NRS for the site-specific system are reported in Table 2. Results indicate, as expected, that an inverse relationship exists between the annual cost per acre and the number of days per year the machine is used. Since the window for machine use in the spring for applying nitrogen to wheat is expected to be about 15 days per year, the cost of $5.01 per acre was used to estimate net returns above the cost of fertilizer application for the 0/OS treatment, and $4.77 per acre for the 40/OS treatment. These costs are based on (1) the cost of non site-specific nitrogen fertilizer application ($2.90/acre), (2) an estimated cost of $60,000 to equip the fertilizer applicator with the site-specific technology, and (3) the cost of treating the NRS in the fall prior to planting wheat. Application costs for anhydrous ammonia, ammonium nitrate, and non-site specific UAN were based upon average custom charges for the area of $6.12, $2.50, and $2.90 per acre (Kletke and Doye).

Net returns above the cost of nitrogen fertilizer and application for each year and treatment, assuming ammonium nitrate was used as the source of preplant nitrogen, are reported in Table 3. The eight treatments performed about the same for each of the three years; no statistically significant differences were found across the eight treatments. Four treatments (0/40, 40/40, 80/0, and 0/OS) had an average net return above the cost of nitrogen fertilizer and application of $99 per acre. The average net return for the 40/OS treatment was $96 per acre. Net returns for 2001 were low for all treatments, especially for the 0/80 and 40/OS. This was due to worse than average growing conditions that resulted in below average yields. The average net returns for 2003 were high due to better than average growing conditions. Over the three years both above and below average yields were included, which is representative of the variability of growing conditions in the southern Great Plains.

Net returns for each year and treatment, assuming that anhydrous ammonia was used as the source of preplant nitrogen fertilizer, are reported in Table 4. When the price of anhydrous ammonia was set equal to $0.15 per pound, the top performing treatment was the 80/0, which realized an average net return of $104 per acre. The next best treatments for this scenario included the 0/40, 40/40, and the 0/OS, each with an average net return of $99 per acre.

When the price of anhydrous ammonia was set equal to $0.22 per pound, the top performing treatments were the 0/40 and the 0/OS, both realizing an average net return of $99 per acre. The 80/0 treatment averaged $98 per acre. The average net return for the 40/OS was $93 per acre.

Conclusions

Several things can be learned from this study. First, the average ownership and operating costs of using the optical sensing technology is sensitive to the number of acres on which the machine is used per year. However, if it can be used for 15 or more days per year, it is relatively inexpensive. With a zero level of preplant nitrogen application, and an expected 15 days of use per year, these costs, including the cost of the NRS, are approximately $5.01 per acre. This is approximately 73% greater than the $2.90 per acre charged for applying UAN as a topdress with conventional non-site specific technology. However, potential benefits from reductions in the cost of the technology (approximately $2 per acre) such as reducing the number of sensors and increasing the grid size are not great.

A second finding is that the economics of the technology depends critically upon the price of UAN relative to the price of NH_3. For the historic price ratio of 1.67 ($0.25 per pound of nitrogen as UAN to $0.15 per pound of nitrogen as NH_3) and application costs, 61 pounds of nitrogen applied as UAN has the same cost as 80 pounds applied as NH_3. Given that the technology requires UAN, the cost difference reduces the value of precision.

A third finding is that the results from use of the technology on farm fields were disappointing. For example, during the 2002 season, the average yield from the 0/0 treatment was the same as that obtained from both site-specific treatments. However, the technology applied nitrogen that, in hindsight, should not have been applied. In 2003, the technology did not apply enough nitrogen. These results suggest that additional research will be required to either improve the algorithm used to determine the site-specific application rates or to improve the applicator.

The expected net benefits from the treatments that use the site-specific system are not substantially greater than those produced by the 80/0 treatment. If the results obtained on these farms are representative, widespread adoption is unlikely unless either (a) the technology is improved, or (b) the price of UAN declines relative to NH_3, or (c) restrictions are placed upon the quantity of nitrogen that may be applied per acre.

The technology is in the early development. The algorithm used to estimate nitrogen requirements did not consider economics. Fine-tuning the nitrogen fertilizer optimization algorithm in a way that incorporates prices of nitrogen and wheat may improve nitrogen recommendations, which could translate into additional net benefits to the farm operation. That is, in good years, more would be applied than that of current recommendations, and in poor years less would be applied. Additionally, in some years and fields where a zero level should be applied, it might be economical to pay an operator the per acre custom charge for that information. This would provide additional savings on unnecessary application expenses. Another potential benefit from this technology stems from the idea that not all fields would necessarily require a nitrogen rich strip. Producers throughout the region could take advantage of region-wide samples of sensor readings taken from nitrogen rich strips that are selectively placed on fields throughout the region.

As the development of the site-specific sensing and application system progresses, and better data become available, further research oriented at econometric estimation of yield response functions conditional on the optical reflectance information could be conducted in an effort to improve the nitrogen fertilizer optimization algorithm. Further development and refinement of the technology including improvements to the application algorithm, combined with an increase in the price of anhydrous ammonia relative to the price of UAN could alter the economics to favor the technology. The potential benefits to the environment from reducing nitrogen application clearly favor the technology.

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Table 1. Wheat Grain Yields for Each System, Year, and Location

Year	System	Preplant Level (lb/ac)	Topdress Level (lb/ac)	Yield L1	Yield L2	Yield L3	Yield L4	Yield L5	Yield L6 (bu/ac)	Yield L7	Yield L8	Yield L9	Yield L10	Yield Average
2001	0/0	0	0	14	15				23	19				18
2001	0/40	0	40	20	21				30	20				22
2001	0/80	0	80	23	21				37	20				25
2001	40/40	40	40	28	25				41	24				29
2001	40/0	40	0	NA	NA				NA	NA				NA
2001	80/0	80	0	31	26				35	24				29
2001	0/OS	0	OS	23 (45)	21 (18)				38 (52)	19 (52)				25 (42)
2001	40/OS	40	OS	25 (22)	18 (9)				29 (30)	21 (30)				23 (23)
2002	0/0	0	0	30	45	62	19				52			42
2002	0/40	0	40	36	46	63	20				49			43
2002	0/80	0	80	36	29	61	17				57			40
2002	40/40	40	40	43	32	58	20				54			41
2002	40/0	40	0	37	42	63	18				59			44
2002	80/0	80	0	41	33	63	17				52			41
2002	0/OS	0	OS	33 (7)	39 (11)	64 (7)	19 (3)				55 (14)			42 (8)
2002	40/OS	40	OS	37 (9)	35 (11)	65 (9)	21 (3)				50 (15)			42 (10)
2003	0/0	0	0	29				41	51		41	13	50	38
2003	0/40	0	40	50				41	63		44	19	62	46
2003	0/80	0	80	62				37	68		46	24	71	51
2003	40/40	40	40	67				43	73		50	21	66	53
2003	40/0	40	0	53				41	67		49	15	62	48
2003	80/0	80	0	67				42	70		48	22	66	52
2003	0/OS	0	OS	40 (35)				42 (15)	57 (17)		47 (35)	16 (22)	56 (15)	43 (23)
2003	40/OS	40	OS	71 (55)				43 (16)	68 (19)		47 (9)	23 (29)	69 (20)	53 (25)

Note: Numbers in parentheses are levels of nitrogen applied as 28% urea-ammonium nitrate applied using the site-specific applicator equipped with optical sensing technology (pounds per acre). L1 is Lahoma, L2 is Chickasha, L3 is Blackwell, L4 is Haskell, L5 is Altus, L6 is Covington, L7 is Perkins, L8 is Hennessey, L9 is Tipton, and L10 is Perry.

Table 2. Ownership and operating cost for the self-propelled applicator equipped with optical sensing technology

Acres Covered Per Hour (ac)	Hours Used Per Day (hr)	Days Used Per Year (d)	Acres Covered Per Year (ac)	Current Cost of Nitrogen Application	Cost of Optical Sensing Technology	Cost of N-Rich Strip for 0/OS	Ownership & Operating Cost for 0/OS	Cost of N-Rich Strip for 40/OS	Ownership & Operating Cost for 40/OS
				($/ac)					
83	10	5	4,150	2.90	3.14	0.84	6.88	0.60	6.64
83	10	15	12,450	2.90	1.27	0.84	5.01	0.60	4.77
83	10	25	20,750	2.90	0.93	0.84	4.67	0.60	4.43
83	10	35	29,050	2.90	0.80	0.84	4.54	0.60	4.30
83	10	45	37,350	2.90	0.73	0.84	4.47	0.60	3.23
83	10	55	45,650	2.90	0.70	0.84	4.44	0.60	3.20

Note: Cost of optical sensing technology assumes the cost of modifying a boom sprayer with computers, sensors, and GPS is $60,000. Cost of the N-Rich strip includes the cost of fertilizer and application in the fall prior to planting. The self-propelled applicator has a 65-foot operating width, a field speed of 15 miles per hour, and a field efficiency level of 70%.

Table 3. Net returns for each Year and System Assuming Ammonium Nitrate as the Preplant Nitrogen Source

Year	0/0	0/40	0/80	40/40	40/0	80/0	0/OS	40/OS
					($/ac)			
2001	54	55	53	63	NA	64	60	47
2002	125	116	97	98	119	100	119	105
2003	113	127	131	134	130	134	118	136
Mean	97	99	94	99	NA	99	99	96

[a] 40/0 was not included in the experiment for 2001.

Table 4. Net returns for each Year and System and Assuming Anhydrous Ammonia as the Preplant Nitrogen Source

Year	0/0	0/40	0/80	40/40	40/0	80/0	0/OS	40/OS
					($/ac)			
Anhydrous Ammonia price of $0.15 per pound								
2001	54	55	53	63	NA[a]	68	60	47
2002	125	116	97	99	119	105	119	105
2003	113	127	131	135	131	139	118	136
Mean	97	99	94	99	NA	104	99	96
Anhydrous Ammonia price of $0.22 per pound								
2001	54	55	53	60	NA	63	60	44
2002	125	116	97	96	117	99	119	102
2003	113	127	131	132	128	133	118	133
Mean	97	99	94	96	NA	98	99	93

[a] 40/0 was not included in the experiment for 2001. Price for 28% urea-ammonium nitrate held constant at $0.25 per pound.