Do Illinois Farmers Follow University-Based Nitrogen Recommendations?

Sarah C. Sellars
Graduate Research Assistant
Department of Agricultural and Consumer Economics
University of Illinois at Urbana-Champaign
ssellar2@illinois.edu

Gary D. Schnitkey
Professor of Farm Management
Soybean Industry Chair in Agricultural Strategy
Department of Agricultural and Consumer Economics
University of Illinois at Urbana-Champaign
schnitke@illinois.edu

Laura F. Gentry
Adjunct Assistant Professor
Department of Natural Resources and Environmental Sciences
University of Illinois at Urbana-Champaign
Director of Water Quality Science, IL Corn Growers
lauragen@illinois.edu

Abstract

In Illinois, university nitrogen recommendations shifted from a yield-based recommendation, called the proven-yield (PY) method to the Maximum Return to Nitrogen (MRTN) recommendation in 2005 after research showed yield-based recommendations, which had been the standard for almost 40 years, were too high for Illinois soils and little or no relationship exists between nitrogen rates and yield at those levels. We identify if farmers in the sample are following the MRTN and analyze the effect following the MRTN recommendation has on yield and operator and land return. The analysis uses data from Precision Conservation Management, a farmer service program led by the Illinois Corn Growers Association which collects data from over 300 farmers enrolled in its 16-county service area, representing over 200,000 acres of Illinois farmland. The data show 67% of the fields in the sample receive a nitrogen application above the MRTN recommended rate. A linear regression model is used to test the effect of the Soil Productivity Index (SPI) and nitrogen application rate on both yield and operator and land return. Results show that although yield increases as farmers apply nitrogen at rates above the MRTN recommended rate, operator and land return decreases. For nitrogen applications ranging from 1 to 60 or more pounds above the MRTN recommendation, farmers are losing between $20 to $32 per acre of operator and land return compared to applying at the MRTN recommended rate, with losses increasing as nitrogen rates increase.

Keywords: nitrogen, MRTN, corn, net returns, yield

Introduction

Corn yield response to nitrogen applications is well-studied by agricultural economists (Babcock, Boyer, et.al., Bullock and Bullock, Parris, Paulson and Babcock), both because of its importance to farm profitability and because of externalities resulting from nitrogen applications. Prior to 2005, a yield-goal-based nitrogen recommendation system called the proven-yield (PY) method was the standard in Illinois, with farmers advised to follow the rule "1.2 is the most [we] should do (Rodriguez et. al., 2019, Fernandez, et. al. 2009, p. 113)." This rule was based on agronomic research up to that point. However, subsequent research began to show these yield-based recommendations were often too high for Illinois soils, with little or no relationship between nitrogen rates and yields at those levels. Based on these findings, it was determined that a new nitrogen recommendation system was needed, resulting in the development of the maximum return to nitrogen (MRTN) approach to nitrogen recommendations (Fernández et. al. 2009).

The MRTN approach fits a curve through nitrogen trial data obtained from research sites across Illinois, calculating the "(net) return to N" (RTN) yield across a range of nitrogen rates ("Corn Nitrogen Rate Calculator", 2020). Individual curves are created for different regions and preceding crops, and the nitrogen rate associated with the high point on each curve is determined to be the "maximum return to N (MRTN)" rate for that system/region. A "Profitable N Rate Range" is also provided, calculated as the N rate values for $1/acre net return above and below the MRTN value. Overall, MRTN rates are lower than the old 1.2 yield goal. Conversations with farmers and industry professionals suggest that adoption of the MRTN recommendation system has been low. Evidence suggests that many farmers apply more than MRTN rates, coming much closer to the 1.2 rule (see Babcock, Rajsic et. al., Sheriff for other studies suggesting farmers overapply nitrogen). Our objective is to investigate whether PCM data supports the MRTN

recommendation in Illinois. The specific objectives are identifying if farmers in Central Illinois in our dataset follow the MRTN, analyzing yield response to different rates of nitrogen application, and determining profitable levels of nitrogen application.

Literature

For many years, farmers and industry professionals have relied on the land-grant institutions as a main source of nitrogen rate recommendations. From approximately 1970 to 2005, recommendations were almost all "yield based," which involved estimating the field's yield under the most favorable growing conditions and then applying nitrogen at the rate of 1.2 multiplied by the field's yield estimate (Rodriguez et. al. 2019). This recommendation system was based on the idea farmers who have higher optimum yields have higher optimum fertilizer levels (Babcock and Blackmer 1994). Later analysis of the derivation of the "1.2 rule" suggests some data and statistical problems existed in the creation of this recommendation which contributed to its inaccuracy (Rodriguez et al., 2019).

In 2004, a group of researchers from various land-grant institutions met to discuss nitrogen rates corn production. The discussion led to the development of the MRTN recommendation system as a solution to concerns about nitrogen application rates (Sawyer et al., 2006). After the development of the MRTN system, extension personnel and researchers began to move away from the yield-based system and began making recommendations based on the MRTN system in Illinois.

The yield-based nitrogen recommendation rule was the dominant rule for nitrogen applications for almost 40 years before the MRTN was developed, so there may be difficulties transitioning away from it. The yield-based rule has some strengths, such as it is perceived as

"logical" by users and it is easy to implement (Morris et al., 2018). Research shows the yield-based rule is still prevalent, with many state Land Grant Universities and agricultural software decision tools still following a yield-based recommendation system (Rodriguez et al., 2019). Morris et al. (2018) state that 34 Land Grant Universities in the U.S. still use the yield-based nitrogen method to make recommendations to farmers.

For years, studies have been suggesting farmers over-apply nitrogen and investigating reasons for over-application. SriRamaratnam et. al. (1987) suggest farmers tend to over-estimate the yield response to nitrogen fertilizer on their farms, leading to over-application. Trachtenberg and Ogg (1994) estimate the magnitude of nitrogen over-application and suggest the excess nitrogen applied to conventional crops is between 2.5 to 3.3 billion pounds, leading farmers to spend an additional $470 to $624 million more per year on fertilizer than necessary. Sheriff (2005) suggests uncertainty about weather and soil characteristics can encourage risk-adverse and risk-neutral farmers to over-apply nutrients. Paulson and Babcock (2010) investigate the "fertilizer problem": the paradox of fertilizer being cited as both a risk-increasing input and over-applied. They find input uncertainty may cause farmers to over-apply nitrogen, with risk-averse farmers choosing to apply less than the risk-neutral producer. This reliance on the yield-based method could also contribute to the over-application of nitrogen. Mulvaney et al. (2006) find for the proven-yield method, 13% of sites were under-fertilized, 18% of sites were adequately fertilized, and 69% of sites were over-fertilized. However, results exist which suggest Illinois farmers follow the MRTN. In the Illinois Nutrient Loss Reduction Strategy, researchers find producers in central and northern Illinois are on average applying nitrogen at rates similar to the MRTN recommendation and in southern Illinois farmers are applying at rates above the MRTN (IEPA et. al, 2015).

Nitrogen recommendations have major implications for water quality in Illinois. A major concern with the over-application of nitrogen is nutrient loss and water pollution. Nutrient loss not only threatens water quality in Illinois, but also contributes to the hypoxic zone in the Gulf of Mexico (IEPA et. al, 2019). The Illinois Nutrient Loss Reduction Strategy was released in 2015 in and included a strategy to help Illinois reduce nitrate-nitrogen load by 15 percent by 2025, with an eventual target of a 45 percent reduction (IEPA et. al, 2015). One way to contribute to this goal is for farmers to reduce their nitrogen applications to the MRTN rate. The Illinois Nutrient Loss Reduction Strategy suggests in a scenario where 10 percent of Illinois farmers are applying above the MRTN rate, reducing the nitrogen rate to the MRTN results in a 10 percent reduction in nitrate-nitrogen losses per acre, reducing the overall nitrate-nitrogen load by 2.3 million pounds per year in Illinois (IEPA et. al., 2015).

Another aspect to the nitrogen recommendation literature is investigating which functional form best represents the yield response to nitrogen. Bullock and Bullock (1992) find the quadratic-plus-plateau is better than the quadratic model for predicting nitrogen fertilizer requirements for corn. Boyer et al. (2013) find linear response stochastic plateau functions describe the yield response to nitrogen the best for their data. Cerrato and Blackmer (1990) find the quadratic-plus-plateau model best describes the yield response to nitrogen in their study. Tembo et al. (2008) develop a linear response stochastic plateau model with random effects which shift the intercept and plateau to capture the variability in the plateau across fields and years.

Data

The data for this study comes from Precision Conservation Management (PCM). PCM is a farmer service program led by the Illinois Corn Growers Association in partnership with over 30

entities including other commodity associations, conservation groups, private foundations, supply chain providers, the Soil and Water Conservation Districts, and the Natural Resource Conservation Service (NRCS). In an effort to address the goals of the Illinois Nutrient Loss Reduction Strategy, the mission of PCM is to help farmers make decisions about adopting on-farm conservation practices in a financially responsible way. Through PCM's regional specialists, PCM works one-on-one with over 300 farmers enrolled in its 16-county service area, representing over 200,000 acres of Illinois farmland. The PCM data used in this research consists of all the fields from 2015-2019 planted with corn, representing a total of 2,029 unique fields and over 165,000 acres. Of the total unique corn fields, 1,384 (68%) of the fields are classified as high productivity soil, with a Soil Productivity Index above 130.

PCM collects data about all inputs used, agricultural practices performed, and yields for each field, but crop price and input cost data are not collected from the farmers. Instead, standard prices and costs are used to construct costs and revenue for each field. This includes:

- **Revenue from crop sales**: The field's yield is multiplied by a standard yearly price, which is the same across all farms.

- **Direct costs**: Direct costs included seed, fertilizer, pesticides, drying, storage, and crop insurance. Actual input amounts recorded by each farmer are multiplied by a standard input price, which is the same across all farmers.

- **Power costs**: Each field pass is assigned a cost based on Machinery Cost Estimates from the University of Illinois which is based on the farmer's actual implement and a general tractor cost. The sum of all these field pass costs represent machinery-related power costs.

- **Overhead costs**: Overhead costs are based on Illinois Farm Business Farm Management Association (FBFM) data and are the same for all farms.

These economic reports result in operator and land return, a measure of return for farmland. Operator and land return is revenue from crop sales minus the costs listed above, and they do not include a cost for land. Subtracting off a land cost, such as cash rent, would give a farmer net return. The operator and land return constructed from these economic reports is used as a dependent variable in the analysis.

Identifying Farmers who Follow the MRTN

With the movement of university recommendations away from yield-based recommendations toward the MRTN recommendation in Illinois, the expectation is many farmers are following the MRTN recommendation. However, conversations with farmers and industry professionals suggest that adoption of MRTN recommendations is low, with the majority of previous literature supporting the idea farmers over-apply nitrogen.

The first objective is to identify the number of farmers in the sample following the MRTN recommendation. The MRTN rates were obtained for Central Illinois corn fields for each year in our sample, and the rates are shown in Table 1. To identify the number of farmers following the MRTN recommendation for each year, first all the nitrogen observations for each field were divided into 6 bins. The MRTN bin contains all observations where the nitrogen application rate is 20 pounds above or below the MRTN rate for that year. For example, the MRTN recommendation for 2015 is 167 pounds per acre. The MRTN bin includes all observations between 147 and 187 pounds per acre for 2015.

The below MRTN bin contains all the observations below the lower bound of the MRTN bin. There are a total of 4 above MRTN bins, with the first bin containing the observations 1 to 20 pounds above the MRTN, the second bin containing the observations 21 to 40 pounds above the MRTN bin, the third bin containing the observations 41 to 60 pounds above the MRTN bin, and the fourth bin capturing all observations greater than 60 pounds above the MRTN bin. Table 2 shows the average nitrogen application rate for each nitrogen bin.

Table 3 displays the number of observations in the dataset and in each nitrogen bin and the total number of fields. Next, calculations were completed for the percentage of fields where nitrogen was applied at, below, and above the MRTN rate. In all years, only 28% of the fields received a MRTN rate nitrogen application. There are 5% of the fields below the MRTN and the other 67% of fields received an application above the MRTN rate, which indicates most farmers are not following the MRTN recommendation. Looking at the fields with MRTN application by year, the number of fields with MRTN application increases over time, so more farmers appear to follow the MRTN as time passes. In 2015, 19% of fields received a MRTN application while in 2019, 38% of fields received a nitrogen application at the MRTN recommended level.

Methodology

The next objective is to analyze yield and operator and land return response to different rates of nitrogen applications. An Ordinary Least Squares (OLS) linear regression model is used to determine this relationship.

The first equation is the regression of soil productivity index (SPI), nitrogen bin, and year on yield:

$$Y = \beta_0 + \beta_1 SPI + \beta_2 Below + \beta_3 Above1 + \beta_4 Above2 + \beta_5 Above3 + \qquad (1)$$

$$\beta_6 Above4 + \beta_7 2015 + \beta_8 2016 + \beta_9 2017 + \beta_{10} 2019$$

where Y is corn yield (bu/acre), SPI is the soil productivity index, Below is the bin of observations below the MRTN (lbs/acre), Above1 is the observations 1 to 20 lbs. above the MRTN recommendation , Above2 is the observations 21 to 40 lbs. above the MRTN recommendation, Above3 is the observations 41 to 60 lbs. above the MRTN recommendation, and Above4 is the observations greater than 60 lbs. above the MRTN recommendation, and 2015, 2016, 2017, and 2019 are the crop years. The SPI is included because it is expected yield will increase as soil productivity increases. The categorical variables on nitrogen use are included in order to deal with any specification problems. Year variables are included to control for the variation between years.

Then, Equation (2) is calculated separately for each year:

$$Y = \beta_0 + \beta_1 SPI + \beta_2 Below + \beta_3 Above1 + \beta_4 Above2 + \beta_5 Above3 + \beta_6 Above4 \qquad (2)$$

Separate equations for each year are included as a specification test to see if results are robust across years.

For farmers, an increase in yield does not necessarily result in an increase in profits. The first set of equations tested whether yield increases with nitrogen rates, and the second set of equations tests whether profitability increases with nitrogen rate. The second regression is SPI, nitrogen bin, and year on operator and land return:

$$Opr = \beta_0 + \beta_1 SPI + \beta_2 Below + \beta_3 Above1 + \beta_4 Above2 + \beta_5 Above3 + \qquad (3)$$

$$\beta_6 Above4 + \beta_7 2015 + \beta_8 2016 + \beta_9 2017 + \beta_{10} 2019$$

where Opr is operator and land return and the independent variables are the same as equation (1).

The regression from equation (3) is also performed for each year:

$$Opr = \beta_0 + \beta_1 SPI + \beta_2 Below + \beta_3 Above1 + \beta_4 Above2 + \beta_5 Above3 + \beta_6 Above4 \qquad (4)$$

Results of Yield and Returns Response to Nitrogen Applications

The estimates for the yield analysis are presented in Table 4. For the overall regression, the signs of the coefficients are as expected. The expectation is SPI has a positive effect on yield, and results show as SPI increases by 1, yield increases by 0.77 bushels per acre. All the MRTN dummies are significant except for the Above1 variable, which consists of the observations 1 to 20 lbs. above the MRTN recommendation. Applying nitrogen at rates below the MRTN has a negative significant effect on yield, while applying nitrogen at rates above the MRTN has a positive significant effect on yield. The yearly dummies are also significant, with the year 2018 as the dropped dummy variable, as it is the year with highest yield.

For the yearly regressions, note the SPI remains positive and significant between years, as expected. However, nitrogen does not always have the same impact from year to year. For example, the effect of applying nitrogen is very positive in 2015, less positive in 2016, and varied from 2017 to 2019. This is expected, as growing conditions vary from year to year, nitrogen uptake, the amount of nitrogen in the soil available to the plant, and nitrogen losses vary from year-to-year as well. Overall, the results show as nitrogen rates increase, yields increase, but this does not necessarily result in higher profitability for the farmer.

The estimates for the profitability analysis are presented in Table 5. The overall regression results are as expected, with SPI having a positive significant effect on operator and land return and applying above and below the MRTN having a negative effect on operator and land return. The yearly dummy variables are also negative significant. Overall, applying below

the MRTN reduces operator and land return by $16/acre compared to applying at the MRTN rate. For applying nitrogen at a rate between 1 and 20 pounds above the MRTN rate, farmers are losing approximately $20 per acre of operator and land return compared to applying the MRTN recommended rate, with overall losses from applying above the MRTN recommendation ranging from $20 to $32 per acre compared to applying at the MRTN recommended rate. As nitrogen application increases, farm profitability goes down, which supports the MRTN recommendation

For the yearly profitability results, applying below the MRTN has a negative significant effect in 2015 and 2019. In most years, applying nitrogen rates above the MRTN has a negative significant effect on operator and land return. The yearly results support the findings of the overall regression. The effect differs from year to year, but there is never a case where an above the MRTN application results in statistically positive results.

Conclusion

Although many universities switched their nitrogen recommendation system from the proven yield method (also known as the "1.2 rule"), most corn fields in this dataset receive a nitrogen application above the MRTN recommendation. The results in this paper support the previous literature which suggests farmers over-apply nitrogen. The analysis shows although yields increase when nitrogen application increases, operator and land return decreases in most years. The magnitude of the decrease in operator and land return varies from year to year and by level of over-application, ranging from $23 to $32 per acre for the significant variables. The implication of this study is farmers in Illinois are contributing to nutrient loss by applying nitrogen at rates above the MRTN, and by reducing their application to the MRTN rate Illinois farmers could save money while benefitting water quality in Illinois.

Table 1. MRTN by Year for Central Illinois, Corn following Soybeans[*]

Year	MRTN Rate
2015	167
2016	175
2017	172
2018	175
2019	180

*Assuming a 0.1 price ratio
Source: Nafziger, 2020

Table 2. Average Nitrogen Applied by Bin (Lbs./Acre)

	Below MRTN	MRTN	1-20 Lbs. Above MRTN	21-40 Lbs. Above MRTN	41-60 Lbs. Above MRTN	> 60 Lbs. Above MRTN
All Years	118	181	206	224	241	275
2015	129	166	199	217	240	251
2016	138	182	204	224	240	278
2017	131	179	203	222	239	273
2018	127	180	205	223	241	274
2019	104	182	210	229	246	278

Table 3. Percentage of Observations and Number of Fields in Each MRTN Category

	MRTN	Below MRTN	1-20 Lbs. Above MRTN	21-40 Lbs. Above MRTN	41-60 Lbs. Above MRTN	> 60 Lbs. Above MRTN	Total Fields
All Years	28%	5%	34%	22%	8%	3%	3100
2015	19	3	38	25	14	1	150
2016	25	5	33	25	8	4	362
2017	21	4	36	25	10	4	696
2018	26	3	35	22	11	3	914
2019	38	7	31	17	5	2	978

Table 4. Estimated Effect of SPI, Nitrogen Application, and Year on Yield

	Overall	2015	2016	2017	2018	2019
Intercept	123.010***	93.386***	92.699***	110.340***	162.150***	51.255***
	(5.498)	(25.819)	(17.571)	(12.469)	(8.450)	(10.322)
SPI	0.767***	0.638***	0.920***	0.777***	0.456***	1.082***
	(0.040)	(0.187)	(0.129)	(0.091)	(0.062)	(0.076)
Below	−16.308***	−39.288**	3.454	−3.377	−14.132***	−24.148***
	(2.435)	(15.521)	(5.377)	(5.705)	(5.209)	(3.792)
Above 1	−1.407	12.580*	0.863	−6.860**	−1.472	1.431
	(1.211)	(7.406)	(2.845)	(2.834)	(2.154)	(2.199)
Above 2	6.170***	16.185**	4.507	−1.136	12.542***	7.608***
	(1.371)	(8.027)	(3.045)	(3.045)	(2.403)	(2.680)
Above 3	6.942***	23.770**	−3.049	4.914	9.501***	9.093**
	(2.338)	(9.242)	(4.358)	(3.976)	(3.048)	(4.505)
Above 4	18.367***	44.734*	22.468***	25.086***	14.336***	11.899*
	(2.960)	(23.429)	(5.516)	(5.888)	(5.043)	(6.426)
2015	−37.137***					
	(2.407)					
2016	−9.060***					
	(1.694)					
2017	−14.625***					
	(1.386)					
2019	−29.149***					
	(1.253)					
Obs.	3100	150	362	696	914	978
df	3089	143	355	689	907	971
Adjusted R-Squared	0.281	0.161	0.158	0.133	0.122	0.219

*** significant at $p = 0.01$; ** significant at $p = 0.05$; * significant at $p = 0.10$

Note: Standard errors are in parentheses.

Table 5. Estimated Effect of SPI, Nitrogen Application, and Year on Operator and Land Return

	Overall	2015	2016	2017	2018	2019
Intercept	44.204**	−91.478	−28.243	−8.120	186.860***	−222.150***
	(19.919)	(97.541)	(62.583)	(40.461)	(32.495)	(38.137)
SPI	2.025***	1.932***	2.161***	1.644***	0.983***	3.500***
	(0.146)	(0.705)	(0.460)	(0.296)	(0.240)	(0.282)
Below	−16.121*	−100.730*	−4.766	12.175	−4.190	−32.667**
	(8.821)	(58.634)	(19.151)	(18.511)	(20.032)	(14.010)
Above 1	−20.373***	26.111	−15.734	−32.508***	−28.946***	−23.661***
	(4.387)	(27.978)	(10.132)	(9.197)	(8.283)	(8.126)
Above 2	−21.128***	17.319	−27.913***	−39.161***	−7.069	−33.204***
	(4.966)	(30.325)	(10.846)	(9.882)	(9.242)	(9.901)
Above 3	−31.679***	19.537	−62.348***	−35.979***	−32.043***	−31.032*
	(8.470)	(34.913)	(15.521)	(12.903)	(11.722)	(16.646)
Above 4	−30.928***	78.635	−58.490***	−0.872	−54.478***	−38.104
	(10.724)	(88.510)	(19.647)	(19.107)	(19.392)	(23.743)
2015	−115.130***					
	(8.721)					
2016	−57.358***					
	(6.136)					
2017	−110.940***					
	(5.021)					
2019	−73.559***					
	(4.540)					
Obs.	3100	150	362	696	914	978
df	3089	143	355	689	907	971
Adjusted R-Squared	0.213	0.047	0.091	0.067	0.036	0.147

*** significant at $p = 0.01$; ** significant at $p = 0.05$; * significant at $p = 0.10$

Note: Standard errors are in parentheses.

References

Babcock, B.A. "The Effects of Uncertainty on Optimal Nitrogen Applications." 1992. *Review of Agricultural Economics* 14(2):271-280.

Babcock, B.A. and A.M. Blackmer. 1994. "The *Ex Post* Relationship between Growing Conditions and Optimal Fertilizer Levels." *Review of Agricultural Economics* 16(3):353-362.

Boyer, C.N., J.A. Larson, R.K. Roberts, A.T. McClure, D.D. Tyler, and V. Zhou. 2013. "Stochastic Corn Yield Response Functions to Nitrogen for Corn after Corn, Corn after Cotton, and Corn after Soybeans." *Journal of Agricultural and Applied Economics* 45(4):669-681.

Bullock, D.G., and D.S. Bullock. 1994. ''Quadratic and Quadratic-plus-Plateau Models for Predicting Optimal Nitrogen Rate of Corn: A Comparison.'' *Agronomy Journal* 86(1): 191–95.

Cerrato, M.E. and A.M. Blackmer. 1990. "Comparison of Models for Describing Corn Yield Response to Nitrogen Fertilizer." *Agronomy Journal* 82:38-143.

"Corn Nitrogen Rate Calculator." Iowa State University, accessed May 1, 2020, http://cnrc.agron.iastate.edu/

Fernández, F.G, E.D. Nafziger, S.A. Ebelhar, and R.G. Hoeft. 2009. "Managing Nitrogen." *Illinois Agronomy Handbook* (9).

IEPA, IDOA, and University of Illinois Extension. 2015. "Illinois Nutrient Loss Reduction Strategy." Illinois Environmental Protection Agency and Illinois Department of

Agriculture; Springfield, Illinois. University of Illinois Extension; Urbana, Illinois.

https://www2.illinois.gov/epa/Documents/iepa/water-quality/watershed-management/nlrs/nlrs-final-revised-093115.pdf.

IEPA, IDOA, and University of Illinois Extension. 2019. "Illinois Nutrient Loss Reduction Strategy Biennial Report 2017-2018." Illinois Environmental Protection Agency and Illinois Department of Agriculture; Springfield, Illinois. University of Illinois Extension; Urbana, Illinois. https://www2.illinois.gov/epa/topics/water-quality/watershed-management/excess-nutrients/Documents/NLRS-Biennial-Report-2019-Final.pdf.

Morris, T.F., et. al. 2018. "Strengths and Limitations of Nitrogen Rate Recommendations for Corn and Opportunities for Improvement." *Agronomy Journal* 110:1-37.

Mulvaney, R.L., S.A. Khan, and T.R. Ellsworth. 2006. "Need for a Soil-Based Approach in Managing Nitrogen Fertilizers for Profitable Corn Production." *Soil Science Society of America Journal* 70:172-182.

Nafziger, E.D., email message to authors, April 30, 2020.

Paris, Q. 1992. ''The Von Liebig Hypothesis.'' American Journal of Agricultural Economics 74(4): 1019–28.

Paulson, N.D., and B.A. Babcock. 2010. ''Readdressing the Fertilizer Problem.'' Journal of Agricultural and Resource Economics 35(3):368–84.

Rajsic, P., A. Weersink, and M. Gandorfer. 2009. "Risk and Nitrogen Application Levels." *Canadian Journal of Agricultural Economics* 57(2):223-239

Rodriguez, D.G., D.S. Bullock, and M.A. Boerngen. 2019. "The Origins, Implications, and Consequences of Yield-Based Nitrogen Fertilizer Management." *Agronomy Journal* 111:725-735.

Sawyer, J., E. Nafziger, G. Randall, L. Bundy, G. Rehm, and B. Joern. 2006. "Concepts and Rationale for Regional Nitrogen Rate Guidelines for Corn." *Iowa State University Extension*

Sheriff, G. 2005. "Efficient Waste? Why Farmers Over-Apply Nutrients and the Implications for Policy Design," *Review of Agricultural Economics* 26(4):542-557.

SriRamaratnam, S., D. Bessler, M. Rister, J. Matocha, and J. Novak. 1987. "Fertilization under Uncertainty: An Analysis Based on Producer Yield Expectations." *American Journal of Agricultural Economics* 69(2):349-357.

Tembo, G., B. Brorsen, F. Epplin, and E. Tostão. 2008. "Crop Input Response Functions with Stochastic Plateaus." *American Journal of Agricultural Economics* 90(2):424-434.

Trachtenberg, E. and C. Ogg. 1994. "Potential for Reducing Nitrogen Pollution through Improved Agronomic Practices." *Water Resources Bulletin* Paper No. 94049.