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Using On-farm Precision Experimentation Data to Analyse Maximum Return to Nitrogen (MRTN) Recommendations

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Abstract

Alternative derivatives of the original yield-goal based recommendations have been employed by researchers, outreach personnel, and private-sector crop management consultants to direct farmers. Current research indicates, however, that the original yield-goal-based method used scant data, questionable data omissions, and flawed statistical analysis. Maximum Return to Nitrogen (MRTN) recommendation is the first publicly available nitrogen recommendation tool to consider economic outcome when recommending nitrogen application rate. However, MRTN adoption is low; farmers may still be following retailer recommendations or prior experience, in part because the nitrogen application rate suggested by the MRTN system is relatively low. This study aims to determine the efficiency of the MRTN recommendations in directing nitrogen application rates in the corn belt. Between 2016 and 2021, forty-two on-farm precision experiments were conducted in Illinois and Ohio to determine the ex-post economically optimal nitrogen rate (EONR), which are used here to evaluate MRTN rates. MRTN rates are compared to the current rates of farmers to determine which achieves relatively high profit margins. Findings suggest that MRTN recommendations can be excessively high or inadequately low across fields in the same region and during the same year. Additionally, grower chosen rates performed better than MRTN on some fields in some regions. Thus, adopting the MRTN recommendation appears riskier than developers claimed.

Keywords

On-Farm Precision Experimentation, Nitrogen Recommendation Tool, Maximum Return to Nitrogen Recommendation

Presenter Profile

A devoted professional with more than 5 years of experience in Digital Agriculture incorporated with rigorous data analytics (R and GIS Software), helping farmers conduct field experiments aiming for superior input rate strategies and higher productivity in 5 countries (the U.S., South Africa, Argentina, Columbia, and Brazil). Has extensive experience leading team-oriented projects facilitating the digital transformation of agriculture in both developed and underdeveloped countries.

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Introduction

To ensure that enough food is produced to feed the world's population, nitrogen fertilizers are required in crops. Nitrogen fertilizers provide crops with minerals like potassium, phosphorus, and nitrogen, which helps plants grow bigger, faster, and produce more food. Nitrogen is present in almost all of the air we breathe, accounting for around 78 percent of it. However, plants require nitrogen compounds from the soil to thrive, which can be supplied either naturally or through nitrogen fertilizers.

The 'Green Revolution' of the 1960s encouraged growers to employ large nitrogen fertilizer inputs in order to get the highest yields possible. Both the introduction of high-yielding crop varieties, as well as lower fertilizer prices, have boosted the usage of nitrogen fertilizers in American agriculture significantly. If crop profitability increased with nitrogen application, increased nitrogen applications would be reasonable. However, nitrogen fertilizer may have been applied excessively due to its low cost. In this case, excessive fertilizer use not only contributes to the release of harmful greenhouse gases and the eutrophication of our waterways, but yield losses and, consequently, profit losses may also occur (Skeffington and Wilson, 1988; Byrnes, 1990; Albornoz, 2016; Kumar et al., 2019).

Due to the uncertainty in soil nitrogen availability and crop nitrogen requirements, farmers face challenges when choosing nitrogen fertilizer rates (Tisdale and Nelson, 1966; Brady et al., 2008). They may find it difficult to apply the appropriate amount of nitrogen because increased nitrogen application without a matching rise in yield leads to profit losses due to the wasted costs, whereas under-applying results in missed profit chances due to lower yield. Numerous nitrogen recommendation tools that advise farmers on how much nitrogen to apply to their fields have emerged as a result of developments in academia and industry.

Development of Nitrogen Recommendation tools

Temperature, rainfall timing, intensity, and amount, as well as temperature and rainfall interactions with nitrogen source, timing, placement, plant genetics, and soil characteristics, make recommending nitrogen rates for a single field or site difficult. As a result, numerous studies have been conducted to investigate better nitrogen management, and various nitrogen rate decision-making models have emerged that generate nitrogen recommendations in the presence of uncertainty in nitrogen supply and demand (Meynard et al., 2002; Lobell, 2007; Setiyono et al., 2011). The goal of these nitrogen recommendation tools is to predict the plant's nitrogen requirements in addition to soil nitrogen.

Prior to the late 1950s, nitrogen rate recommendations were based on soil parameters and crop management (Morris et al., 2018), as soil systems provide a portion of the total nitrogen accumulated by plants. As corn yields increased in the 1980s and 1990s, nearly all nitrogen recommendation systems for corn in the United States endorsed Stanford's proven-yield (PY) method (Stanford, 1966, 1973). Nitrogen prescriptions are based on yield goals in this approach. It quickly became the industry standard in Illinois and many other Midwestern states at the time, with farmers encouraged to follow the rule "1.2 is the maximum" (Fernández et al., 2009). The research conducted by Stanford demonstrated that the amount of nitrogen a plant requires is proportional to its production; specifically, the "optimal" yield level divided by the optimal nitrogen rate resulted in an average of approximately 1.2 pounds of nitrogen per bushel of yield. Most states, using the PY method, would recommend nitrogen rates based on a factor multiplied by yield goal.

The generation of nitrogen application range boils down to understanding the relationship between corn yield and nitrogen fertilization, and (Rodriguez et al., 2019) demonstrated that the yield-goal based recommendation was based on scant data, questionable data omissions, and insignificant and flawed statistical analysis, and thus the linear relationship between corn yield and optimal nitrogen fertilization cannot be trusted. In addition, the nitrogen-to-corn price ratio is not considered in the yield-goal based recommendation system, so this system may not be profitable when fertilizer costs and crop prices fluctuate significantly. For example, given the recent increase in fertilizer costs relative to crop prices, yield-based recommendations may be less profitable, as they were developed when fertilizer was relatively inexpensive.

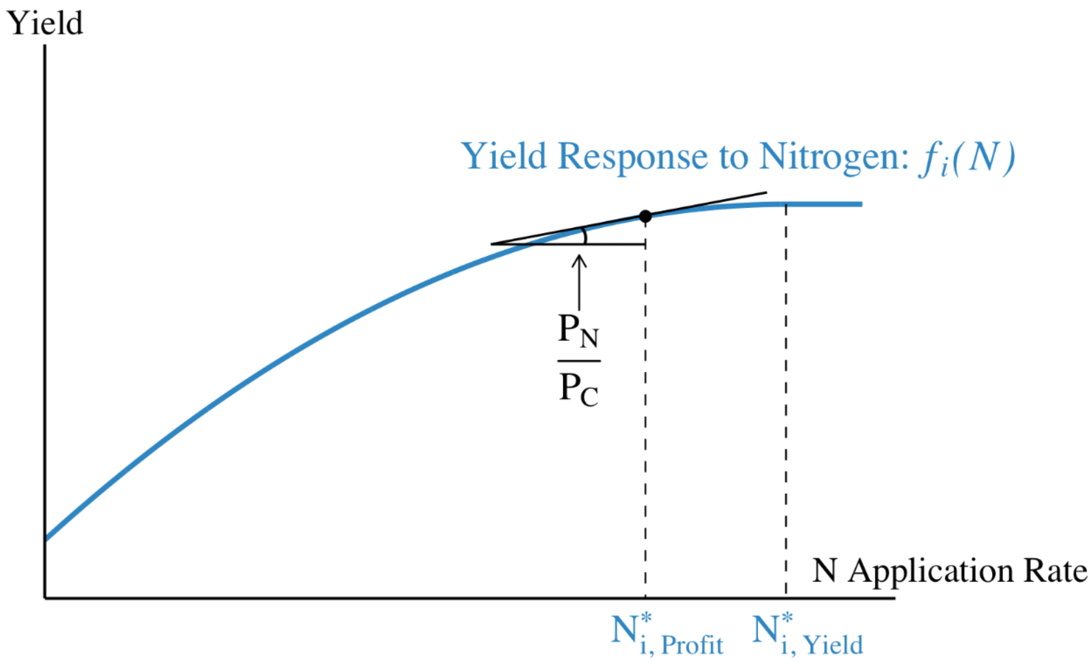

Figure 1: A Conceptual Yield Response to Nitrogen

Figure 1 depicts a currently widely accepted conceptual yield response to nitrogen curve from the standpoint of agronomy. When nitrogen application approaches $Ni, Yield^*$, yield increases until a yield plateau is reached. The subscript i denotes a yield response curve for a specific site i, and the nitrogen yield response curve varies depending on soil parameters and meteorological conditions in that particular year. Although the figure shows that excessive nitrogen application does not always have a negative impact on yield, as shown by the plateau, it can reduce profit. Because yield does not decrease with overapplication and nitrogen costs were not fully considered in its development, the PY method encouraged setting a high yield goal and applying high nitrogen rates, which can cause nitrogen losses in agroecosystems through volatilization, denitrification, leaching, and runoff. As a result, over the last decade, studies have criticized the PY method for resulting in excessively high external environmental costs (Ransom et al., 2020).

Researchers then shifted away from yield-goal based recommendation algorithms due to advancements in hybrids that resulted in higher yields and stronger root systems, as well as changes in the crop-fertilizer price ratio over the past twenty years. Some researchers began to recognize that economics must be factored into a nitrogen recommendation system, and the optimization problem was shifted from finding the $N^*_{i,Yield}$ that maximizes yield to solving for the $N^*_{i,Profit}$ that maximizes profit (Mamo et al., 2003; Hong et al., 2007). In 2005, seven states implemented the Maximum Return to Nitrogen (MRTN) recommendation system, a relatively new method for estimating the amount of nitrogen required by plants that is not delivered by the soil (Sawyer et al., 2006; Sawyer, 2013; Laboski et al., 2015; Nafziger et al., 2022). They claim to be able to predict the nitrogen rate that will yield the highest return on nitrogen investment based on the corn and nitrogen prices entered into their calculator.

Several changes have occurred in the optimization setting during the development of nitrogen recommendation tools, including a shift in the objective from $Ni, Yield^*$ to $Ni, Profit^*$; a dramatic shift in corn and nitrogen fertilizer prices in recent years, which has an impact on $Ni, Profit^*$ and the evolution of the yield response to nitrogen curve due to advances in seed, soil changes, and other factors. As a result of these changes, the optimal nitrogen rate recommendation has shifted over the last century. The purpose of this research is to examine at the effectiveness of MRTN, which provides nitrogen recommendations based on both nitrogen fertilizer and corn prices, with the objective of maximizing profit.

What is MRTN?

The maximum return to nitrogen, or MRTN, is a data-driven regional approach to nitrogen guidelines used in Iowa, Wisconsin, Illinois, Indiana, Michigan, Minnesota, and Ohio to establish nitrogen recommendation rates. The MRTN system was created by Midwest Land Grant University researchers and has been funded by the Illinois Nutrient Research & Education Council since 2012. The MRTN recommendation is essentially an estimate of EONR that takes nitrogen's return on investment into account (University of Minnesota Extension, 2022), and the MRTN developers claim that this is the first nitrogen recommendation system that takes economics into account in practice. The MRTN tool is open-source and can be found online at Nitrogen Rate Calculator. This online tool hosted by Iowa State University generates nitrogen guidelines based on location, previous crop, corn price, and nitrogen price.

MRTN's Data

The database used in the MRTN method dates back to 1990 and includes data from hundreds of trials. Small-plot trials performed manually, or strip trials may be employed. Six different nitrogen treatment rates are typically planned for strip trials, and each nitrogen rate was applied to three (or more) strips to ensure that the yield variations later detected were due to the variable nitrogen rate.

MRTN attempts to incorporate changes over time as hybrids, new weather conditions, and new management practices emerge by continually adding data to the database. Thus, the database is evolving and reflecting some changes in environmental conditions, hybridization, and other factors. The states of Illinois, Indiana, Iowa, and Wisconsin have been divided into geographic or soil regions, and MRTN recommendations are generated separately for the fields in each region. Thereby, the data used by the MRTN system differ by region, and each region is responsible for gathering its data. As a result, utilizing different databases, distinct yield responses to nitrogen are estimated for different regions.

MRTN’s Method

The return to nitrogen (RTN) generated per acre in a trial at a given nitrogen rate is calculated by multiplying the yield increase from nitrogen at that rate (minus the yield without nitrogen fertilizer) by the corn price, then subtracting the cost of nitrogen (the nitrogen rate times the price of nitrogen). The MRTN approach calculates the return to nitrogen (RTN) across a variety of nitrogen rates by fitting a curve using nitrogen trial data acquired from different research locations, and RTN for a state or region will then be estimated by averaging the fitted curves from all trials within that state or region.

Individual curves comparing nitrogen application rates (lb/ac) versus RTN ($/ac) are constructed for different regions and preceding crops, and the nitrogen rate corresponding to the maximum RTN across trials in a region/state is the “Maximum Return to Nitrogen” for that region/state. The MRTN system also provides a profitable nitrogen rate range, which is defined as the nitrogen rates above and below the MRTN rate resulting a -$1/ac difference in RTN when compared to the RTN associated with the MRTN rate (Dr. Emerson Nafziger, 2018; University of Minnesota Extension, 2022).

Developers of the MRTN approach claim that they incorporate all variables affecting nitrogen response into the MRTN recommendation through including in yield response estimation model: weather conditions, soil types, and a variety of other characteristics. The R^2 reported for the yield response estimation model is approximately 0.57 (University of Minnesota Extension, 2022).

Discussions over MRTN

The three most important advantages of the MRTN system were emphasized by the system’s developers. First, because the database is regularly updated, it is a dynamic model that captures changes in weather and soil. Second, because the profitable range of MRTN allows farmers to select alternative rates on their own fields, it is flexible and adaptive and allows for the customization of nitrogen rates applied to a specific field. Furthermore, the calculation can consider different pricing scenarios, and this is meaningful given the recent changes in corn and nitrogen prices, as well as the fact that different farmers buy fertilizer and sell corn at different prices.

Despite the negative effects on water quality and the ecosystem, as well as the potential benefits of following the MRTN recommendations, (Sellars et al., 2021) discovered that 70 percent of corn fields receive nitrogen applications above the MRTN profitable range using field-level data from Precision Conservation Management (PCM), a farmer service program led by the Illinois Corn Growers Association and Illinois Soybean Association.

Given that the profit maximizing nitrogen rate, varies across fields and over time due to interactions between soil and weather conditions [Bundy and Andraski (1995); Mamo et al. (2003); schmitt1994developing; lory2003yield; dhital2016variability], the MRTN system’s failure to differentiate its recommendations on different fields within the designated region may have weakened farmers’ confidence in the MRTN recommendations. Additionally, the MRTN system also lacks some transparency by not sharing the EONR calculated for the individual sites used for their regional recommendation; thus, the farmers cannot see how varied the EONRs may be in their region. Furthermore, if the true optimal nitrogen rate is not included in the experimental nitrogen range, the MRTN recommendations will be either too high or too low. Finally, farmers may find following the MRTN recommendations to be risky, because they are sometimes lower than the nitrogen rates farmers have been using in the past.

The developers of MRTN propose as a solution to the first problem that farmers can experiment on their farm within the MRTN profitable range and estimate the optimal rate on their own (University of Minnesota Extension, 2022). However, farmers may find it challenging to design and analyze meaningful experiments. To determine why farmers are hesitant to use the MRTN recommendations and whether farmers should follow the MRTN recommendations, however, real trial experiments must be employed to investigate the effectiveness of the MRTN approach in guiding nitrogen application.

Given that MRTN is still a relatively new method, the majority of studies examining the MRTN approach are conducted by the developers of the MRTN system. The major flaws of MRTN approach summarized from these studies include the fact that year-to-year temperature and precipitation variations are not addressed in the recommendations and within-field spatial heterogeneity due to soil and water quality is not considered, both of which are already evident from the method's description. Using EONR derived from small-plot trials and reviewing eight nitrogen recommendation tools, including the MRTN approach, (Ransom et al., 2020) determined that the MRTN recommendations overestimated EONR by 14 to 17 lb per acre on average. Together, the findings of (Ransom et al., 2020) and (Sellars et al., 2021) are concerning, as they indicate that 70 percent of the fields in Illinois received nitrogen applications that exceeded the MRTN recommendations, which were already higher than EONR. This is both economically and environmentally harmful.

(Ransom et al., 2020) also pointed out one weakness of the MRTN system being it cannot provide recommendation for a particular weather year. However, this critique can be too strict, as no one can predict weather, and MRTN system has made good effort in including data from multiple years to embed different weather conditions in its estimation. Nonetheless, another concern that has not been addressed in the existing literature is that MTRN combining trials dated back to 1990s in the same region can be risky. First, MRTN system lacks transparency in how trials are designed, and if trials within a region do not receive identical experimental nitrogen rates, they are not comparable to each other, and thus, should not be merged together for analysis. Second, data from 1990s should not be used to estimate the current nitrogen recommendation rate because we no longer use the hybrid from 30 years ago. Therefore, the 1990s data does not accurately reflect the current relationship between yield and nitrogen.

Objectives

The quality of nitrogen recommendations made to farmers is restricted by the estimation of the yield response to nitrogen. In order to properly evaluate the MRTN recommendations, it is necessary to use real trial data from the same site and different years that have been properly processed. While Ransom et al. discovered that MRTN rates are, on average, higher than EONR rates (2020). First, the EONR was derived using data from small-plot trials that do not accurately represent entire fields. Second, neither the profitability of MRTN rates nor its profitable range were evaluated. Thirdly, only one model was used to estimate the EONR, despite the fact that the EONR is sensitive to the production model used for estimation.

In recent years, agricultural scientists have increasingly designed and implemented a modern type of agronomic field experiment known as on-farm precision experimentation (OFPE). OFPE brings together researchers and farmers to undertake agronomic studies, using variable-rate input technology and GPS to automate the application of designed nitrogen rates across multi-hectare agricultural fields and yield monitors to collect yield data at harvest.

The overarching objective of this study is to evaluate the MRTN recommendations, including the MRTN rates and their profitable range, using data from forty-two OFPE trials. Specifically, we estimate the ex-post EONR for each of the forty-two OFPE trials and use the estimated yield response to nitrogen to assess the profitability of the MRTN recommendations. In addition, the profit performance of the farmers' chosen rates is compared to MRTN rates. To test for robustness, yield response to nitrogen was estimated using various models.

Methods

Data Description

The datasets used for this research come from twelve different farms, including forty-two separate field-year corn trials, as shown in Figure 2. Among the twelve farms, three are in northern Illinois, four are in central Illinois, three are in southern Illinois, and two are in Ohio. Specifically, nine field-year experiments were conducted in northern Illinois, twelve field-year trials were conducted in Central Illinois, fourteen field-year trials were conducted in southern Illinois, and seven field-year trials were conducted in Ohio. All trials are in locations with MTRN guidelines.

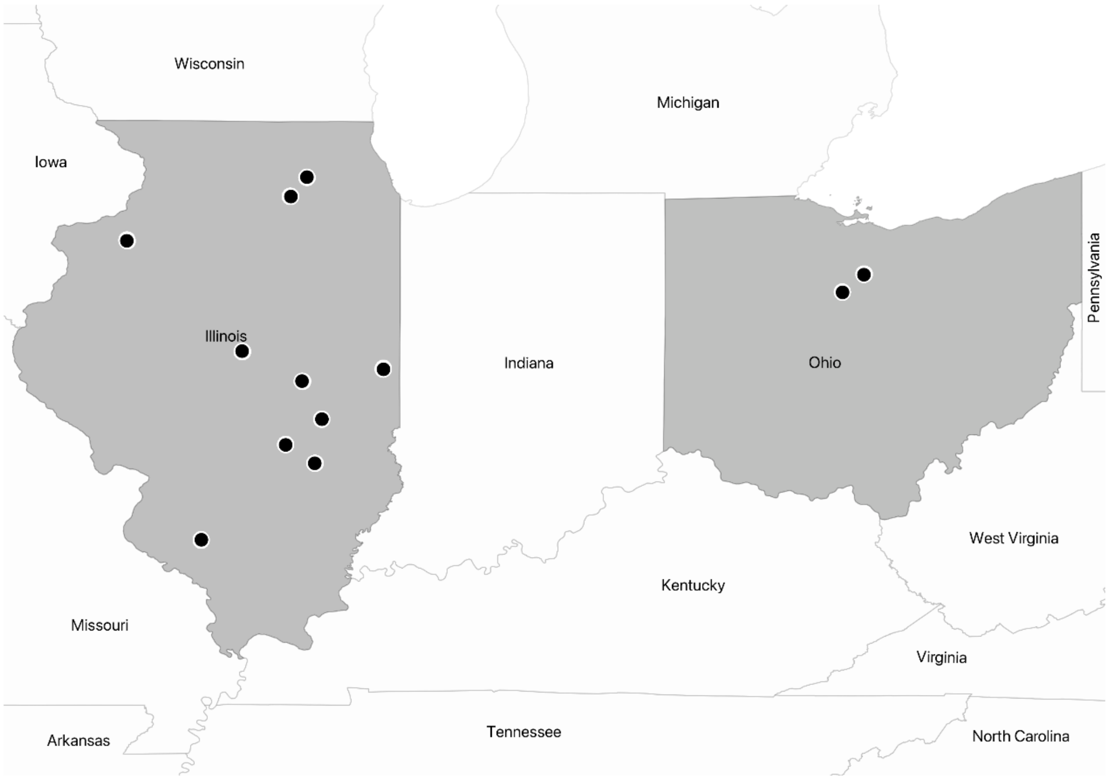

Figure 2: Distribution of the Forty-two Trials

Data Processing

Raw as-applied and harvest data were retrieved from the variable-rate applicators and yield monitors. The raw data were cleaned to remove observations with extreme yield or as-applied rates ("outliers"). Points were also removed from the headlands, where the data is less reliable due to differences in sun exposure, driving speeds, potential application overlaps, and other factors. The distance between points, swath width, and headings recorded in the raw yield data was used to make yield polygons, and subplots were made by combining contiguous yield polygons with similar nitrogen rates into groups, where the number of yield polygons combined should make a subplot of around twelve meters in length. (In later analysis, the subplots were used as the unit of observation.)

When the standard deviation of the treatment values at points within a yield polygon was below 40 lbs/ac of nitrogen and 10K seed, the polygon was considered as not having mixed treatments. This means that the yield observation came from mostly one of the treatments. Yield polygons from mixed treatments are not included in the future processing steps or analysis. The yield polygons are grouped where adjacent as-planted polygons are in the same group if the difference in their treatment rates is below a given threshold. This method also helps to eliminate "transition zones," which are areas where the harvester and planter are adjusting to a new target rate or yield level when moving from one treatment plot to another. The mean as-planted rate and yield for each subplot are recorded. Finally, the means of electrical conductivity, SSURGO soil data, and USGS digital elevation data are recorded for each subplot. In addition, digital elevation maps are used to calculate the values of topographical aspect, slope, curvature, topographical position index, and topographical wetness index, and the means of these values are included in the data for analysis.

Historical corn and nitrogen prices from 2015 to 2021 are used to obtain the MRTN recommendation for all the trials, specifically, the historical corn prices come from the website Macrotrend, and the historical nitrogen prices are from DTN. Table 1 summarizes the historical corn and nitrogen prices used for each year.

Table 1: Historical Corn and Nitrogen Prices used in this Research

Year	Corn Price ($/bu)	Nitrogen Price ($/lb)	Nitrogen/Corn Price Ratio
2015	3.81	0.42	0.11
2016	3.53	0.35	0.10
2017	3.48	0.24	0.07
2018	3.66	0.32	0.09
2019	3.92	0.36	0.09
2020	4.17	0.33	0.08
2021	6.29	0.80	0.13

The MRTN for the forty-two trials in different regions and years are summarized in Table 2. Trials in the same region and year have identical MRTN recommendation rates, as well as profitable range. Table 3 presents the descriptive statistics for the trial data. To evaluate the MRTN recommendations, we only use the EONR derived from trials that received experimental nitrogen ranges that cover the MRTN rate.

Table 2: MRTN recommendation for the forty-two trials in different regions and years

Farm	Field	Year	MRTN (lb/ac)	MRTN Low (lb/ac)	MRTN High (lb/ac)
Region: Central Illinois					
GI	Field1	2018	196	178	213
	Field2	2017	182	167	197
		2019	186	171	202
OV	Field3	2017	182	167	197
RO	Field4	2018	196	178	213
	Field5	2020	184	170	200
	Field6	2016	177	164	191
SA	Field7	2016	177	164	191
		2018	196	178	213
		2020	184	170	200
	Field8	2017	182	167	197
		2021	190	175	206
Region: Northern Illinois					
GO	Field9	2019	178	160	195
	Field10	2020	175	159	192
LA	Field11	2020	175	159	192
	Field12	2017	181	155	188
	Field13	2018	188	169	207
	Field14	2021	182	165	199
NE	Field15	2017	181	155	188
		2021	182	165	199
	Field16	2020	175	159	192
Region: Southern Illinois					
BO	Field17	2016	195	183	210
		2018	217	198	239
		2020	204	189	220
	Field18	2016	195	183	210
		2018	217	198	239
		2020	204	189	220
CA	Field19	2017	200	186	217
		2019	206	191	224
	Field20	2019	206	191	224
		2021	210	194	228
WE	Field21	2017	200	186	217
		2019	206	191	224
		2021	210	194	228
	Field22	2018	217	198	239
Region: Ohio					
HO	Field23	2021	192	175	210
	Field24	2018	200	179	219
		2020	185	168	202
	Field25	2017	180	163	198
		2019	186	169	205
		2021	192	175	210
NI	Field26	2018	200	179	219

Note: In addition to the MRTN rate, the MRTN website provides nitrogen rate ranges that could be considered profitable nitrogen ranges because nitrogen rates within this range would produce a net return of less than -$1/acre when compared to the MRTN rate. The low and high ends of the MRTN profitable range are termed as MRTN low and MRTN high in this table.

Table 3: Descriptive Statistics for the forty-two trials

Farm	Field	Year	Dry Yield (bu/ac)[5] Mean	First Decile	Ninth Decile	SD	Applied Nitrogen (lb/ac)[6] Mean	First Decile	Ninth Decile	SD
Region: Central Illinois										
GI	Field1	2018	249.6	237.9	260.8	9.2	187.8	150.2	223.8	23.4
	Field2	2017	234.9	218.5	252.3	13.4	199.2	169.7	229.2	21.1
		2019	206.8	192.4	220.9	11.1	193.0	141.1	236.8	41.2
OV	Field3	2017	229.2	213.4	243.4	11.9	177.0	155.8	197.5	14.6
RO	Field4	2018	217.3	180.0	248.8	30.2	205.9	187.3	226.6	14.6
	Field5	2020	247.7	224.1	267.4	18.2	173.4	131.8	214.2	28.9
	Field6	2016	228.9	212.8	244.9	12.7	190.4	160.3	217.5	17.7
SA	Field7	2016	220.5	210.6	231.3	16.7	190.1	160.0	220.0	20.7
		2018	254.4	230.7	279.4	19.5	204.8	192.0	217.1	8.3
		2020	245.0	230.4	257.9	11.3	211.9	162.5	255.2	31.4
	Field8	2017	224.7	211.2	241.4	13.7	254.8	225.4	282.3	22.5
		2021	237.5	197.4	264.3	25.7	181.4	141.5	226.6	33.1
Region: Northern Illinois										
GO	Field9	2019	185.9	157.1	210.8	21.1	183.6	139.4	240.4	37.4
	Field10	2020	175.3	124.0	225.8	43.2	184.4	150.8	220.4	27.5
LA	Field11	2020	185.6	169.7	200.7	12.9	193.0	181.3	201.9	8.1
	Field12	2017	345.4	311.5	375.7	25.3	180.4	147.0	212.0	22.0
	Field13	2018	240.0	198.2	273.4	29.6	202.8	179.6	229.8	17.4
NE	Field14	2021	200.2	128.4	260.8	51.8	178.9	119.4	238.4	40.2
	Field15	2017	262.0	238.1	288.2	20.9	181.5	147.3	210.3	22.6
		2021	223.7	192.9	252.8	23.2	167.2	119.3	224.7	38.5
	Field16	2020	224.2	198.2	245.2	19.4	180.0	134.7	222.6	28.5
Region: Southern Illinois										
BO	Field17	2016	138.1	92.6	180.4	36.5	170.1	140.0	200.0	19.0
		2018	174.0	123.4	219.6	36.3	175.4	151.8	193.4	14.4
		2020	143.6	84.2	189.3	40.4	220.7	176.8	267.3	34.3
	Field18	2016	129.0	84.6	172.1	34.1	169.1	139.1	198.5	18.9
		2018	205.3	170.5	235.9	25.1	178.5	157.2	195.4	13.5
		2020	143.8	89.2	190.8	39.2	203.0	162.9	247.4	31.9
CA	Field19	2017	172.6	131.4	206.8	29.5	202.5	176.2	227.7	19.2
		2019	134.6	98.8	172.9	28.0	183.5	132.8	223.9	35.7
	Field20	2019	159.5	132.6	189.3	21.7	188.5	141.0	235.7	34.4
		2021	189.2	164.9	213.4	18.8	150.2	100.9	183.8	35.3
WE	Field21	2017	230.3	210.4	249.6	15.1	196.9	160.2	223.3	21.1
		2019	205.3	167.2	240.8	28.9	213.4	162.6	257.1	35.6
		2021	247.6	215.1	280.9	25.4	242.6	190.4	308.8	45.9
	Field22	2018	235.8	206.0	262.3	22.0	175.0	160.0	197.1	14.7
Region: Ohio										
HO	Field23	2021	199.0	181.3	214.6	13.5	219.9	158.7	269.8	40.2
	Field24	2018	237.2	218.3	253.1	14.8	166.1	146.8	183.3	13.9
		2020	241.9	219.4	260.4	16.3	217.7	184.5	250.9	26.8
	Field25	2017	233.4	217.1	250.5	14.2	191.5	172.2	208.5	13.2
		2019	185.5	163.1	205.1	16.7	204.6	179.6	235.4	23.1
		2021	213.8	183.9	242.0	22.6	221.3	158.4	272.0	39.4
NI	Field26	2018	240.8	215.6	265.9	19.7	215.3	190.6	240.7	18.0

[5] This column provides an overview of the cleaned dry yield volume data, including the mean, first decile, ninth decile, and standard deviation.

[6] This column provides an overview of the cleaned applied nitrogen data, including the mean, first decile, ninth decile, and standard deviation.

EONR Calculation

The optimal nitrogen rate denotes the rates of nitrogen application expected to maximize net revenues from nitrogen applied per unit of land area. Specifically, the optimal nitrogen rate is obtained by solving the following objective function:

$$\text{Max}\{P_C f(N) - P_N N\} \quad (1)$$

In equation (1), P_C denotes the price of corn ($/bu), and P_N denotes the price of nitrogen ($/lb).

This study estimates the production function $f(N)$ for each of the thirty-eight trials and determines the optimal nitrogen rate for each trial. Then, we compare the online MRTN recommendation to the optimal nitrogen rate estimations to determine how far off the MRTN recommendation is in these trials. In addition, we analyze the profitability of the MRTN recommendation by substituting the MRTN recommendations into the estimated production function $f(N)$ and comparing the resulting profit to the maximum profit derived from this production function.

Generalized Additive Model (GAM)

Because researchers do not know the true functional form of the yield response to nitrogen, the generalized additive model (GAM) is used in the estimation of yield response to nitrogen to better capture the curvature of the function.

The generalized additive model (GAM) contains a parametric form for some components of the data with weak nonparametric restrictions on the remainder of the model. Letting ϕ_k denote the k^{th} cubic spline, then the parametric form of the non-linear function is $\sum_{k=1}^{K} \beta_k \, \phi_k(N_i)$, where$\beta_k$ are parameters to be estimated. Let ε denote the remainder of the model, following the conditional mean restriction on ε: $E(\varepsilon|N) = 0$. Thus, the estimating equation is:

$$y_i = \sum_{k=1}^{K} \beta_k \, \phi_k(N_i) + \varepsilon_i \quad (2)$$

Results

Profitability of MRTN Recommendations

Table 4 summarizes the profit difference between applying optimal nitrogen rates estimated by GAM and applying MRTN recommendations, as well as the profit difference between using grower-chosen rates and MRTN nitrogen rates. In general, the larger the number on the number, the less profitable the MRTN recommendations are in comparison to the estimated optimal nitrogen rates and grower-chosen rates. According to the MRTN definition and its profitable range, the difference in value between any two of these three columns should be less than $1/ac. However, we find that the difference between these three columns is almost always much greater than $1/ac. In terms of profitability, this indicates that following the MRTN recommendations is significantly riskier than what the developers claim.

Table 4: Profit difference estimated by GAM

Farm	Field	Year	MRTN ($/ac)[a]	MRTN Low ($/ac)[b]	MRTN High ($/ac)[c]	Grower Chosen Rate ($/ac)[d]
Region: Central Illinois						
GI	Field1	2018	2.3	0	7.7	2.2
	Field2	2017	0	0.4	0.4	-1.6
		2019	0	1.5	0.9	-10.4
OV	Field3	2017	6.1	13.3	1.2	-0.8
RO	Field4	2018	21.7	37.4	9.4	10.4
	Field5	2020	12.6	16.4	8	-1.2
	Field6	2016	13	17.2	8.5	6.9
SA	Field7	2016	10.5	2.6	16	-6.7
		2018	17.2	30.4	4.5	10.4
		2020	7.8	14.4	2.3	7.3
	Field8	2017	NA	NA	NA	NA
		2021	7.6	25.2	0.1	6
Region: Northern Illinois						
GO	Field9	2019	3.4	9.6	0.4	0.5
	Field10	2020	4.5	3	6.2	-1.1
LA	Field11	2020	6.5	NA	9.3	-2.9
	Field12	2017	23.5	66	15.9	11.2
	Field13	2018	14.8	9.2	13.3	-0.4
NE	Field14	2021	44.1	36.2	48.2	0.4
	Field15	2017	5.8	2.1	5.6	0.1
		2021	14	10.2	17.7	0.2
	Field16	2020	7.4	17.1	1.5	2.5
Region: Southern Illinois						
BO	Field17	2016	4.6	0.6	11	4.5
		2018	NA	NA	NA	NA
		2020	11.9	20.4	5.3	4.9
	Field18	2016	0.8	3.8	NA	-3.8
		2018	NA	NA	NA	NA
		2020	7.2	8.9	5.4	1.2
	Field19	2017	77.5	107	41.8	-84
		2019	41.8	57.9	22.2	4.3
CA	Field20	2019	10.2	19.1	4	-8.3
		2021	NA	NA	NA	NA
WE	Field21	2017	12.7	18.7	5.3	248.2
		2019	53.3	80	28.9	118
		2021	89.6	120	58.8	60.7
	Field22	2018	53.9	15.7	108.4	53.8
Region: Ohio						
HO	Field23	2021	11.8	6.9	16.9	1.4
	Field24	2018	8.4	1.5	15.1	-32
		2020	13.4	23	5.6	1.1
	Field25	2017	1.2	NA	4.5	-1.5
		2019	11.2	22.1	2.8	-14.8
		2021	4	14.1	0	-19.4
NI	Field26	2018	23	42.4	9.1	-18.5

Note: When the MRTN rate is outside the trial's applied nitrogen rate range, the estimated profit difference will be NA in all four columns because the MRTN rate cannot be evaluated using the trial's data. While the MRTN rate is within the trial's applied nitrogen rate range and is being evaluated, the value in columns MRTN Low and MRTN High may be NA in some cases as MRTN Low and MRTN High may fall outside the nitrogen application of that trial.

[a]The profit difference between applying the MRTN rates obtained from the MRTN website and applying the optimal nitrogen rate determined by the GAM model is shown in this column.

[b]The profit difference between using the recommended nitrogen rate determined by the GAM model and the lower end of the MRTN profitable range is shown in this column.

[c]The profit difference between using the recommended nitrogen rate determined by the GAM model and the higher end of the MRTN profitable range is shown in this column.

[d]This column displays the profit difference between applying the grower chosen rates and applying the MRTN rates from the MRTN website. Grower chosen rates outperforms the MRTN rates when that value is positive.

Figure 3 demonstrates, for instance, that in field 19, there is a significant yield response to nitrogen, and the optimal nitrogen rates shown in Table 95 suggested applying a similarly high nitrogen rate to that field in 2017 and 2019. However, the MRTN recommendation must have underestimated the slope of the yield response to nitrogen increment on the field because it recommended a profitable nitrogen range with nitrogen rates 50 to 20lb/ac below the estimated optimal nitrogen rates, resulting in a profit loss of $107/ac to $22/ac. Furthermore, in twenty-three of the forty-two trials, grower-chosen rates outperformed MRTN rates. In other words, more than fifty percent of the time, MRTN rates do not provide a profitable advantage over grower-chosen rates, despite their claim to be the lowest possible nitrogen rate that provides the highest returns.

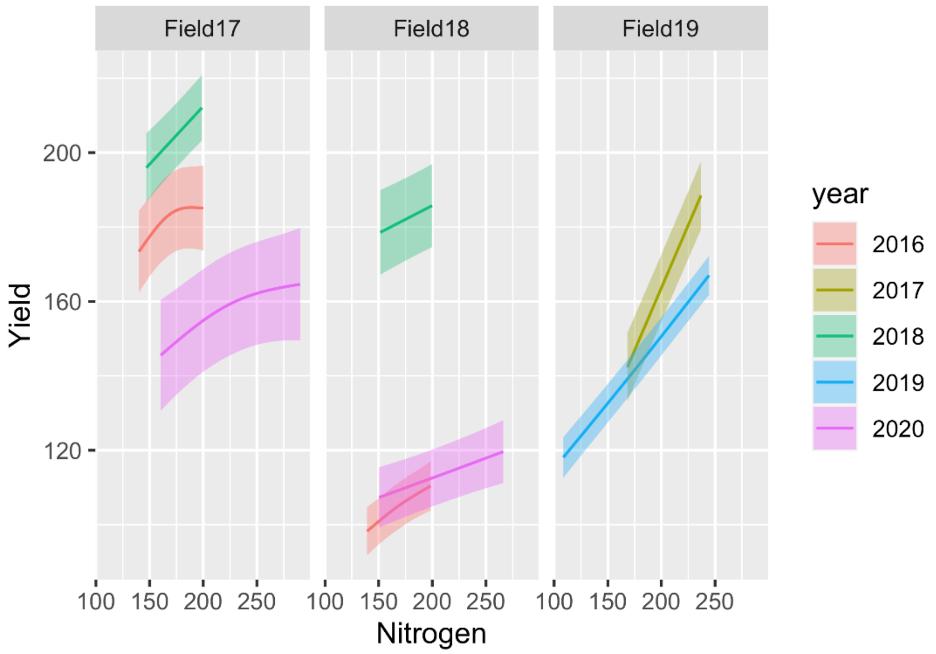

Figure 3: Estimated Yield Response to Nitrogen on Farm BO (GAM Model)

We also compare the optimal nitrogen rates estimated by GAM to the MRTN recommendations in Table 5 for thirty-eight trials to determine whether the MRTN recommendation is consistently higher or lower than the optimal nitrogen rate estimates. In thirty-one of thirty-eight trials, the estimated optimal nitrogen rates differ from the MRTN rates by tens of pounds per acre and are also outside the MRTN profitable range. Twenty-three of the thirty-one trials have estimated optimal nitrogen rates that are higher than the profitable range provided by the MRTN website, while eight have estimates that are lower. The MRTN recommendation is neither consistently higher nor lower than estimates of the optimal nitrogen rate. Depending on the soil and climate, the MRTN recommendation may be excessively high or insufficient.

Table 5: Optimal nitrogen rates estimated by GAM

Farm	Field	Year	MRTN (lb/ac)[a]	GAM (lb/ac)[b]	Grower Chosen Rate (lb/ac)[d]
GI	Field1	2018	196 (178, 213)	176.8	180
	Field2	2017	182 (167, 197)	184.7	210
		2019	186 (171, 202)	188.9	235
OV	Field3	2017	182 (167, 197)	201.4	180
RO	Field4	2018	196 (178, 213)	231.1	210
	Field5	2020	184 (170, 200)	226.8	179.6
SA	Field6	2016	177 (164, 191)	217.7	198.5
	Field7	2016	177 (164, 191)	160	200.3
		2018	196 (178, 213)	219	210
		2020	184 (170, 200)	219.5	210
	Field8	2017	182 (167, 197)	NA	198.3
		2021	190 (175, 206)	208.8	200
GO	Field9	2019	178 (160, 195)	204.7	180
	Field10	2020	175 (159, 192)	128.5	186
LA	Field11	2020	175 (159, 192)	203	180
	Field12	2017	181 (155, 188)	212	192
	Field13	2018	188 (169, 207)	231.6	192
NE	Field14	2021	182 (165, 199)	118.2	181
	Field15	2017	181 (155, 188)	146.4	187.2
		2021	182 (165, 199)	118.6	181
	Field16	2020	175 (159, 192)	208.1	180.7
BO	Field17	2016	195 (183, 210)	177.6	180
		2018	217 (198, 239)	NA	180
		2020	204 (189, 220)	253.6	215
	Field18	2016	195 (183, 210)	198.5	180
		2018	217 (198, 239)	NA	198

Farm	Field	Year	MRTN (lb/ac)[a]	GAM (lb/ac)[b]	Grower Chosen Rate (lb/ac)[d]
CA	Field19	2020	204 (189, 220)	266.1	215
		2017	200 (186, 217)	236.9	160
		2019	206 (191, 224)	244.3	210
	Field20	2019	206 (191, 224)	250	191.9
		2021	210 (194, 228)	NA	180
WE	Field21	2017	200 (186, 217)	228.9	757.5
		2019	206 (191, 224)	268.4	863.4
		2021	210 (194, 228)	306	250
	Field22	2018	217 (198, 239)	178.7	180
HO	Field23	2021	192 (175, 210)	150.9	(172.2,196.8)
	Field24	2018	200 (179, 219)	168.5	(75.7,95.6)
		2020	185 (168, 202)	230.9	(180.4,196.8)
	Field25	2017	180 (163, 198)	166.6	189.9
		2019	186 (169, 205)	224.7	(155.8,180.4)
		2021	192 (175, 210)	210.4	(155.8,180.4)
NI	Field26	2018	200 (179, 219)	242	180

Note: All four models' estimates of the optimal nitrogen rate will be NA when the MRTN rate is outside the trial's applied nitrogen rate range because the MRTN rate cannot be compared to the estimations in that situation.

[a]This column provides the MRTN rates obtained from the MRTN website, and the profitable range is presented below the MRTN rates.

[b]This column provides the optimal nitrogen rate estimated by the gam model.

[d]The grower chosen rates are shown in this column. When a commercial prescription map is available, a range is given, and when a farmer is adhering to a previous rate, a single rate is given. When the grower selected rates are significantly lower than in other fields and years, a base rate farmer would have been applied in advance, but we are unsure of what the base rate would have been.

The findings from the current analysis can be summarized as: (1) the MRTN does not follow the same trends as the GAM estimations. For example, in 2020 Field 25 had higher EONRs than in 2018, but the MRTN recommendation was lower in 2020 than in 2018 (2) MRTN recommendation is not consistently higher or lower than the EONR estimates. The MRTN recommendation can be both too high or too low, depending on the soil and weather year. (3) the EONR estimates for Field 23 and Field 25 are very different in the 2021 trials despite these being adjacent fields. The EONR estimation suggests a lower nitrogen rate on Field 23 in 2021 and a higher nitrogen rate on Field 25; (4) while the MRTN recommendation fluctuated within 20lb/acre across the three fields over the years in this farm, the estimated EONR using both yield estimation models varied by more than 60lb/acre on Field 24 during the two trial years, as shown in Table 4.

Trials with the identical MRTN Recommendations

The differences in MRTN recommendations for different fields over time within the same designated region are due entirely to the difference in corn and nitrogen prices entered into the MRTN calculator, without considering the variation in soil and weather conditions between fields and years. As part of our evaluation of the MRTN recommendations, we assess the soil and climate variation between fields in the same region over time, in addition to comparing the estimated optimal nitrogen rates on fields in the same region and year to the MRTN recommendation they receive.

Table 2 shows that the mean yield in different fields within the same MRTN designated region and during the same year can vary significantly despite receiving a comparable range of nitrogen application. Field 10 and field 16 are both located in Northern Illinois; however, the average yield on field 10 in 2020 is only 175bu/ac, while the average yield on field 16 in 2020 is as high as 224bu/ac. The weather conditions on these two fields in 2020 from Table 6 indicate that field 10 experienced significantly less precipitation during the pollination cycle and significantly more precipitation during the grain filling cycle than field 16. During these two periods, the temperature in field 16 was higher than in field 10. Field 10's yield may have been reduced as a result of hotter weather and less precipitation during pollination. In the absence of additional information, the soil conditions and weather conditions in these two fields are likely to be significantly different; thus, the optimal nitrogen rates for these fields in 2020 are also likely to vary as well. In this case, adhering to the MRTN recommendation and applying similar nitrogen rates to these two fields in 2020 could result in a catastrophic loss of profits. In fact, Figures 10.8 and 10.10 demonstrate low yield response to nitrogen on field 10 in 2020, and significant yield response to nitrogen increasing from 125lb/ac to 225lb/ac on field 16 in 2020, followed by a yield plateau. Estimated optimal nitrogen rates by GAM for field 10 were 128lb/ac, and 208lb/ac for field 16, nearly double that of field 10.

In addition, an example from HO farm shows that the optimal nitrogen rates vary on adjacent fields within the same farm and the same year. Field 23 and Field 25 are neighboring fields on the farm HO. Despite being only one mile apart, according to Table 6, field 25 received more precipitation than field 23 in 2021. Table 3 also indicates that the average yield on field 25 was higher in 2021. Figure 4 illustrates a linear yield response to nitrogen on field 23, resulting in a corner solution of 151lb/ac for the optimal nitrogen rate on this field; a higher yield response to the nitrogen with a quadratic shape was observed on field 25, and the optimal nitrogen rate is 210lb/ac, as shown in Table 5. The MRTN recommendations for this farm do not reflect the estimated changes in optimal nitrogen rates. Specifically, the MRTN recommendations did not vary by more than 20lb/ac across the three fields in this farm over the years, whereas the estimated optimal nitrogen rates using both yield estimation models varied by more than 60lb/ac on field 24 over the two trial years.

Table 6: Weather for the forty-two trials

Farm	Field	Year	Precipitation (in)[a] Pollination Cycle	Precipitation (in)[a] Grain Filling Cycle	Precipitation (in)[a] Growing Season	Temperature (°F)[b] Pollination Cycle	Temperature (°F)[b] Grain Filling Cycle	Temperature (°F)[b] Growing Season
Region: Central Illinois								
GI	Field1	2018	1.4	6.8	14.1	77.1	74.5	73.3
	Field2	2017	2.9	4.5	19.0	77.0	71.2	69.9
		2019	0.3	6.7	19.4	78.4	73.6	73.3
OV	Field3	2017	1.4	5.4	22.4	75.2	73.5	70.0
RO	Field4	2018	1.7	7.5	19.0	76.6	74.0	73.0
	Field5	2020	3.4	3.4	14.8	73.6	67.2	70.5
	Field6	2016	5.1	10.0	22.1	74.7	75.4	71.4
SA	Field7	2016	4.5	10.7	21.4	76.8	76.2	72.1
		2018	1.6	5.2	15.1	76.6	74.4	73.2
		2020	2.3	3.6	9.2	74.8	70.4	72.8
	Field8	2017	2.2	4.0	11.5	76.8	70.5	70.0
		2021	3.3	5.7	18.7	72.7	74.4	71.4
Region: Northern Illinois								
GO	Field9	2019	0.5	14.9	21.1	72.0	67.2	69.4
	Field10	2020	0.6	7.6	24.3	74.3	65.9	67.6
LA	Field11	2020	2.0	8.0	19.1	73.2	66.8	67.9
	Field12	2017	6.2	8.6	21.3	71.5	66.9	65.3
	Field13	2018	1.1	8.0	23.7	73.0	71.1	69.8
NE	Field14	2021	4.0	7.9	23.5	70.9	73.5	69.6
	Field15	2017	3.5	3.0	12.6	74.3	68.0	69.9
		2021	3.7	5.9	22.5	71.6	73.7	70.2
	Field16	2020	1.1	4.6	23.4	78.5	74.3	53.2
Region: Southern Illinois								
BO	Field17	2016	4.9	12.3	22.1	74.9	77.9	73.3
		2018	3.5	8.9	19.1	77.6	76.6	75.6
		2020	0.4	11.5	19.4	78.8	75.4	72.1
	Field18	2016	4.9	12.3	22.1	74.9	77.9	73.3
		2018	3.5	8.9	19.1	77.6	76.6	75.5
		2020	0.4	11.5	19.4	78.8	75.4	72.1
CA	Field19	2017	0.7	4.9	16.2	78.3	74.5	72.0
		2019	1.1	7.2	22.5	79.9	76.3	72.9
	Field20	2019	0.6	5.7	16.4	80.6	77.2	73.6
		2021	2.3	10.4	19.6	77.2	76.5	71.9
WE	Field21	2017	1.7	4.5	22.0	77.7	73.0	70.1
		2019	0.9	9.8	24.2	79.3	74.4	74.0
		2021	5.4	9.3	21.8	74.9	75.0	71.8
	Field22	2018	2.1	11.1	21.6	77.5	76.0	74.5
Region: Ohio								
HO	Field23	2021	3.3	6.8	17.2	73.0	72.4	71.9
	Field24	2018	1.8	5.7	15.2	75.2	72.9	71.5
		2020	5.2	9.2	15.4	73.6	66.3	69.8
	Field25	2017	4.5	5.3	22.9	74.6	68.9	67.0
		2019	2.2	5.0	17.4	75.6	70.9	71.5
		2021	5.6	9.6	22.6	74.0	73.1	69.1
NI	Field26	2018	0.7	5.3	14.5	74.5	73.1	71.5

Note: The hybrid that was planted for each trial is recorded, and the breeders' websites commonly offer an estimation of the growing degree days until pollination and maturity. Using this information, the planting date, and the daily weather data from DaymetR, we determine the pollination and maturity dates for each trial. The weather is then calculated around the critical growth stages, and its impacts on the estimation of the optimal nitrogen rates can be examined.

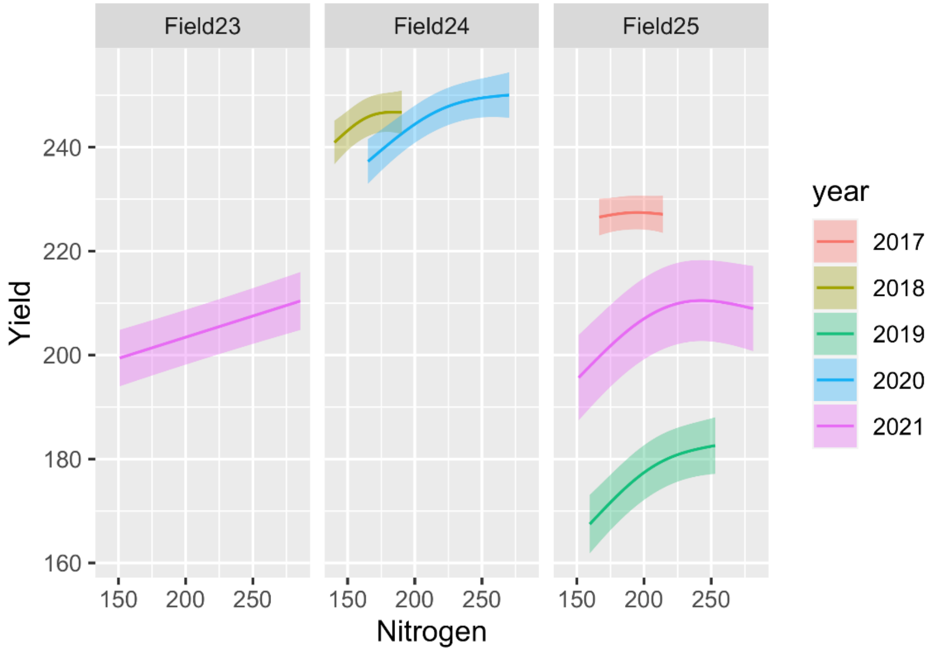

Figure 4: Estimated Yield Response to Nitrogen on Farm HO (GAM Model)

Conclusion

Including the economic perspective in their research on optimizing nitrogen application and the MRTN recommendation tool is a significant contribution for both academia and industry. However, the results of this study reveal that the MRTN recommendations are significantly riskier than advertised.

Tables 9.2 and 9.4 exemplify that yield level and weather conditions can vary significantly within the same MRTN designated region; consequently, the preferred nitrogen application rate on different fields within the same region is likely to vary by nature. The MRTN recommendation tool may not be applicable in the real world for the reason that it does not differentiate between fields that are hundreds of miles apart, with different soil compositions, and experiencing vastly different weather conditions.

In conclusion, adapting to the MRTN recommendations without conducting additional research on the soil conditions and yield performance from previous years on a field poses substantial economic risks due to both yield loss from insufficient nitrogen application and high application costs without a matching rise in yield.

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References

ALBORNOZ, F., 2016. Crop responses to Nitrogen Overfertilization: A Review. *Scientia Horticulturae*, 205, pp.79–83.

BYRNES, B.H., 1990. Environmental effects of N fertilizer use—an overview. *Fertilizer Research*, 26(1-3), pp.209–

215.

FERNÁNDEZ, F.G., NAFZIGER, E.D., EBELHAR, S.A. & HOEFT, R.G., 2009. Managing nitrogen. Illinois agronomy handbook, 24th ed. Univ. of Illinois, Urbana-Champaign, IL, pp.113-132.

HONG, N. et al., 2007. Economically optimal nitrogen rate reduces soil residual nitrate. *Journal of Environmental Quality*, 36(2), pp.354–362.

KUMAR, R., KUMAR, R. & PRAKASH, O., 2019. Chapter-5 the Impact of Chemical Fertilizers on Our Environment and Ecosystem. *Chief Ed*, *35*, p.69.

LOBELL, D.B., 2007. The cost of uncertainty for Nitrogen Fertilizer Management: A sensitivity analysis. *Field Crops Research*, 100(2-3), pp.210–217.

MAMO, M. et al., 2003. Spatial and temporal variation in economically optimum nitrogen rate for corn. *Agronomy Journal*, 95(4), p.958.

MEYNARD, J.-M. et al., 2002. Which decision support tools for the environmental management of Nitrogen? *Agronomie*, 22(7-8), pp.817–829.

MORRIS, T.F. et al., 2018. Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. *Agronomy Journal*, 110(1), pp.1–37.

NAFZIGER, E., 2018. Using the maximum return to nitrogen (MRTN) recommendation system in ... Available at: https://www.ifca.com/media/web/1537906005_NREC%20MRTN%20GUIDE%20Sept%202018.pdf.

NKOA, R., 2013. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: A Review. *Agronomy for Sustainable Development*, 34(2), pp.473–492.

RANSOM, C.J. et al., 2020. Corn nitrogen rate recommendation tools' performance across eight US midwest corn belt states. *Agronomy Journal*, 112(1), pp.470–492.

RODRIGUEZ, D.G., BULLOCK, D.S. & BOERNGEN, M.A., 2019. The origins, implications, and consequences of yield-based Nitrogen Fertilizer Management. *Agronomy Journal*, 111(2), pp.725–735.

SAWYER, J.E., 2014. Corn nitrogen rate management: Facts, concepts, and mother nature. *Proceedings of the Integrated Crop Management Conference*.

SELLARS, S.C., SCHNITKEY, G.D., GENTRY, L.F. & PAULSON, N., 2021. Illinois Farmers' Beliefs about the Maximum Return to Nitrogen (MRTN) Recommendation.

SETIYONO, T.D. et al., 2011. Maize-N: A decision tool for nitrogen management in Maize. *Agronomy Journal*, 103(4), pp.1276–1283.

SKEFFINGTON, R.A. & WILSON, E.J., 1988. Excess nitrogen deposition: Issues for consideration. *Environmental Pollution*, 54(3-4), pp.159–184.

STANFORD, G., 1973. Rationale for optimum nitrogen fertilization in corn production. *Journal of Environmental Quality*, 2(2), pp.159–166.

STANFORD, G., 2015. Assessment of soil nitrogen availability. *Nitrogen in Agricultural Soils*, pp.651–688.

SUTTON, M.A., OENEMA, O., ERISMAN, J.W., LEIP, A., VAN GRINSVEN, H. & WINIWARTER, W., 2011. Too much of a good thing. *Nature*, *472*(7342), pp.159-161.

TISDALE, S.L. & NELSON, W.L., 1966. Soil Fertility and Fertilizers. *Soil Science*, 101(4), p.346.

TRACY, B.F. & ZHANG, Y., 2008. Soil compaction, corn yield response, and soil nutrient pool dynamics within an integrated crop-livestock system in Illinois. *Crop Science*, 48(3), p.1211.

University of Minnesota Extension, 2022. Maximum Return to Nitrogen (MRTN) Approach to n Rate Guidelines. *United States: University of Minnesota Extension*. https://docs.google.com/document/d/e/2PACX-1vSSzY-BOZg-uH3Tj4ZCTCZmflK26RYObrqemxsFJnZYpsTkaLl2zhAF-yhHHC6s1NWY9TTM0oTHF9VC/pub.

WEIL, R.R. & BRADY, N.C., 2017. *The nature and properties of soils*, Harlow, England: Pearson.

Appendix

The fact that only one model was used to estimate the production function $f(N)$ is a significant deficiency in the existing literature that reviews the MRTN recommendation tool, as the estimated optimal nitrogen rates can vary substantially depending on the model chosen. This study assesses the robustness of the GAM results by comparing the findings of three additional models. Specifically, the shape constrained additive model, the spatial error model with quadratic form, and the quadratic plateau model are employed for robustness testing.

Shape Constrained Additive Model (SCAM)

A shape constrained additive model (Pya and Wood, 2015) provides functions for generalized additive modelling under shape constraints on the component functions of the linear predictor of the GAM. Models can contain multiple shape constrained and unconstrained terms as well as bivariate smooths with double or single monotonicity. Univariate smooths under eight possible shape constraints such as monotonically increasing/decreasing, convex/concave, increasing/decreasing and convex, increasing/decreasing and concave, are available as model terms.

Spatial Error Model (SEM)

A quadratic yield response function form with a spatial error term (Bongiovanni et al., 2000; Bullock et al., 2002; Anselin et al., 2004) is:

$$Y = aN + bN^2 + c + u \qquad (1)$$

Where the slope a and b describes the curvature of the yield response function, while c estimates the average yield without application of nitrogen.

Note that there are many other variables affecting yield that were left out of the yield response function above, which may result in a spatial correlation of the error term. Thus, a spatial error term is included in the residuals of the estimated yield response function to capture spatial correlation. The spatial simultaneous autoregressive error model is used to estimate the spatial error:

$$u = \lambda W u + e \qquad (2)$$

where W is the spatial weighted matrix, λ is a spatial autoregressive coefficient, which is assumed to be 0.75, and e is a vector of the error term. A nearest neighborhood structure was used as the weighting matrix W.

Quadratic Plateau Model (QPM)

A quadratic plateau model (Neeteson and Wadman, 1987; Cerrato and Blackmer, 1990; Mallarino and Blackmer, 1992; Bullock and Bullock, 1994) is similar to a linear plateau model, except that the linear segment is replaced with a quadratic function.

The fitted parameters a, b, and clx designate the best fit intercept, linear coefficient, and critical x value. The quadratic coefficient is calculated as

$$-0.5^{*} b/clx \qquad (3)$$

and the plateau value is denoted as

$$a + b^{*} clx - 0.5^{*} b^{*} clx \qquad (4)$$

The results obtained from different models are summarized in Table 1, as shown below.

Table 1: Optimal nitrogen rates estimated by four different models

Farm	Field	Year	MRTN (lb/ac)[a]	GAM (lb/ac)[b]	SCAM (lb/ac)[c]	SEM (lb/ac)[d]	QPM (lb/ac)[e]	Grower Chosen Rate (lb/ac)[f]
Region: Central Illinois								
GI	Field1	2018	196 (178, 213)	176.8	172.2	176.8	175.3	180
	Field2	2017	182 (167, 197)	184.7	182.8	168.4	187.2	210
		2019	186 (171, 202)	188.9	191.9	190.4	184.4	235
OV	Field3	2017	182 (167, 197)	201.4	201.4	201.4	201.4	180
RO	Field4	2018	196 (178, 213)	231.1	231.1	231.1	NA	210
	Field5	2020	184 (170, 200)	226.8	226.8	226.8	NA	179.6
	Field6	2016	177 (164, 191)	217.7	217.7	217.7	217.7	198.5
SA	Field7	2016	177 (164, 191)	160	160	160	NA	200.3
		2018	196 (178, 213)	219	219	219	212.4	210
		2020	184 (170, 200)	219.5	221.5	225.6	222.5	210
	Field8	2017	182 (167, 197)	NA	NA	NA	NA	198.3
		2021	190 (175, 206)	208.8	204.3	220.2	240.6	200
Region: Northern Illinois								
GO	Field9	2019	178 (160, 195)	204.7	212.3	194.7	193.5	180
	Field10	2020	175 (159, 192)	128.5	128.5	236.8	218.2	186
LA	Field11	2020	175 (159, 192)	203	203	203	174	180
	Field12	2017	181 (155, 188)	212	212	212	212	192
	Field13	2018	188 (169, 207)	231.6	231.6	180.5	166.7	192
NE	Field14	2021	182 (165, 199)	118.2	NA	118.2	NA	181
	Field15	2017	181 (155, 188)	146.4	146.4	184.2	201	187.2
		2021	182 (165, 199)	118.6	121	173.5	136.9	181
	Field16	2020	175 (159, 192)	208.1	215.6	200.7	204.9	180.7
Region: Southern Illinois								
BO	Field17	2016	195 (183, 210)	177.6	187.3	169.1	NA	180
		2018	217 (198, 239)	NA	NA	NA	NA	180
		2020	204 (189, 220)	253.6	265.4	261.4	281.1	215

Farm	Field	Year	MRTN (lb/ac)[a]	GAM (lb/ac)[b]	SCAM (lb/ac)[c]	SEM (lb/ac)[d]	QPM (lb/ac)[e]	Grower Chosen Rate (lb/ac)[f]
	Field18	2016	195 (183, 210)	198.5	186.5	198.5	154.1	180
		2018	217 (198, 239)	NA	NA	NA	NA	198
		2020	204 (189, 220)	266.1	247.4	150.3	150.3	215
	Field19	2017	200 (186, 217)	236.9	236.9	236.9	236.9	160
		2019	206 (191, 224)	244.3	244.3	NA	244.3	210
CA	Field20	2019	206 (191, 224)	250	241.6	250	226.1	191.9
		2021	210 (194, 228)	NA	NA	NA	NA	180
WE	Field21	2017	200 (186, 217)	228.9	228.9	228.9	228.9	757.5
		2019	206 (191, 224)	268.4	261.7	268.4	268.4	863.4
		2021	210 (194, 228)	306	288.5	320.6	301.6	250
	Field22	2018	217 (198, 239)	178.7	172.9	169.8	175.2	180
Region: Ohio								
HO	Field23	2021	192 (175, 210)	150.9	150.9	150.9	150.9	(172.2,196.8)
	Field24	2018	200 (179, 219)	168.5	177.1	190.3	165.5	(75.7,95.6)
		2020	185 (168, 202)	230.9	230.9	270.2	244.7	(180.4,196.8)
	Field25	2017	180 (163, 198)	166.6	166.6	182.9	166.6	189.9
		2019	186 (169, 205)	224.7	236	253	246.4	(155.8,180.4)
		2021	192 (175, 210)	210.4	193.3	211.7	205.1	(155.8,180.4)
NI	Field26	2018	200 (179, 219)	242	242	242	242	180

Note: All four models' estimates of the optimal nitrogen rate will be NA when the MRTN rate is outside the trial's applied nitrogen rate range because the MRTN rate cannot be compared to the estimations in that situation.

[a]This column provides the MRTN rates obtained from the MRTN website, and the profitable range is presented below the MRTN rates.

[b]This column provides the optimal nitrogen rate estimated by the gam model.

[c]This column provides the optimal nitrogen rate estimated by the scam model. It indicates that the scam model dose not converge when it is NA.

[d]This column provides the optimal nitrogen rate estimated by the spatial error model.

[e]This column provides the optimal nitrogen rate estimated by the quadratic plateau model. It indicates that the there exists a singularity issue in the regression when it is NA.

[f]The grower chosen rates are shown in this column. When a commercial prescription map is available, a range is given, and when a farmer is adhering to a previous rate, a single rate is given. When the grower selected rates are significantly lower than in other fields and years, a base rate farmer would have been applied in advance, but we are unsure of what the base rate would have been.