Policy Instruments to Promote the Adoption of Sustainable Nitrogen Management Practices

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Selected Paper prepared for presentation at the 2024 Agricultural & Applied Economics Association Annual Meeting, New Orleans, LA; July 28-30, 2024

Abstract

Nitrogen management practices on corn production in the United States may result in excessive nitrogen applications, leading to profit losses and environmental concerns. This study aims to investigate the influence of farmers' risk preferences on their nitrogen management decisions and identify policy instruments for promoting sustainable nitrogen management. We use a biophysical model simulated dataset comprising over four million observations encompassing 4,236 fields and representing 2,758 soil types in Illinois over 30 years. Additionally, we conducted predictions and simulations based on a total of 183 combinations of corn and nitrogen prices ranging from 2008 to 2023. We find that the incorporation of farmers' risk aversion yields adoption estimates for N management practices that are consistent with existing research findings. Our findings suggest that gradually increasing lump sum payments and taxes on N that exceeds the N balance threshold can enhance the adoption rate of MRTN until it reaches its maximum potential. Besides, our results indicate that establishing price premiums not exceeding 0.037 $/bushel and trigger levels for green insurance between 35% and 98% of yield goal yield can effectively promote widespread acceptance of MRTN. Furthermore, when the trigger levels for green insurance exceed 98%, substantial promotion of VRT adoption can be achieved.

1 Introduction

In 2023, farmers in the US produced approximately 32% of the world's corn (USDA FAS, 2024). Nitrogen (N) fertilizer plays a crucial role in corn production, with N expenses representing around 37% - 50% of variable costs between 1996 and 2016 (Bekkerman et al., 2020). Due to concerns over yield penalties under unpredictable weather, risk neutral and aversion farmers may follow N application rates that are based on a yield goal approach (Babcock, 1992; Babcock & Hennessy, 1996). However, "yield goal" based fertilizer recommendations were found too high to generate significant marginal yield improvements (Sellars et al., 2020). This adversely affects farmers' profits and poses environmental threats such as increased leaching of nitrogen into water bodies and heightened greenhouse gas emissions.

To address these challenges, Maximum Return to Nitrogen (MRTN) approach (Sawyer et al., 2006) was developed to offer economic optimum N rate (EONR) recommendations based on multi-year-field trials. However, this recommendation provides a uniform rate for a specific region under fixed corn and N fertilizer price ratios. In order to provide EONR at the soil level, variable rate technology (VRT) has been introduced to offer variable rate recommendations based on soil characteristics and yield records. Despite being recommended for several years, the adoption rates of these tools remain low. Sellars et al. (2020) reported that in Illinois, 67% of fields received N fertilizer rates exceeding the MRTN recommended rates. Furthermore, based on the 2016 USDA ARMS survey, the adoption rate of variable rate fertilizers and lime applications across corn-planted acres was reported to be 28.2% (McFadden et al., 2023). Consequently, it becomes imperative to implement policy instruments that can effectively promote the widespread adoption of sustainable nitrogen management practices, such as MRTN or VRT, considering farmers' risk preferences while simultaneously yielding economic and environmental benefits.

Numerous studies have investigated the potential overapplication of nitrogen fertilizer resulting from production uncertainty. Babcock (1992) theoretically demonstrated that risk-neutral farmers tend to apply excessive amounts of nitrogen fertilizer when faced with stochastic weather and soil conditions. This is because, under specific circumstances, a linear-plateau (LP) function shows profit gains in good years that outweigh the profit declines in bad years. However, this phenomenon has not been thoroughly examined under different conditions or using alternative yield response to N functions (Rajsic et al., 2009). Rajsic et al. (2009) employed a certainty-equivalent model to assess the impact of production risk or profit variance on nitrogen application levels. Their findings suggest that an increase in N application rate leads to a higher variance of expected profits, indicating that risk-averse farmers should apply less N than the recommended application rate. These results align with previous empirical analyses conducted using experimental data (Love & Buccola, 1991; Roosen & Hennessy, 2003). However, it is important to note that these studies were based on field trials conducted at limited specific sites and within a restricted time period.

To overcome this limitation, we will use a biophysical model simulated dataset covering more than 4000 fields in Illinois from 1989 to 2018 (Mandrini, Archontoulis, et al., 2022) for this research. This dataset has been previously used to compare the impacts of static and dynamic N recommendation tools on profits and N leaching (Mandrini, Pittelkow, et al., 2021), evaluate diverse N management strategies using environmental and economic indicators (Mandrini, Bullock, et al., 2021), as well as quantify the effects of policy scenarios aimed at reducing N usage (Mandrini, Pittelkow, et al., 2022). However, these analyses did not incorporate farmers' risk preferences or provide a comparison of performance and adoption estimation for three commonly used nitrogen management practices - VRT, MRTN, and yield goal approach.

To incorporate the risk preferences and estimate the adoption of N management practices, we will use a utility function used in Ma et al. (2023) to model farmer's decision making under production uncertainty. Ma et al. (2023) employed this utility function to analyze the adoption of cover cropping and compare the performance of conservation incentives considering yield uncertainty and farmer risk aversion. This research contributes to the existing literature by using a comprehensive multi-year-field soil-level dataset and incorporating a utility function that accounts for the impact of risk preferences and production uncertainty on decision making. These aspects enable us to estimate farmers' adoption with respect to yield goal approach, MRTN, or VRT by incorporating farmer's risk preferences and production uncertainties; as well as compare the effectiveness of different policy instruments in promoting the adoption of MRTN and VRT.

The data will be discussed in the following section, followed by a description of the methods employed, presentation of the results, and conclusions.

2 Data and Methods

2.1 Data

This study uses a simulated dataset (Mandrini, Archontoulis, et al., 2022) comprising over four million observations spanning a period of 30 years (1989-2018), encompassing 4236 fields of 40 hectares (98.9 acres) each and representing 2744 soil types across the northern, central, and southern regions of Illinois. The total agricultural land covered in this study accounts for approximately 3.8 percent of corn planting acreage in Illinois for the year 2023. This comprehensive dataset includes simulated corn yields, nitrogen application rates, N leaching rates, planting dates, weather data, and soil characteristics at the individual soil level. Corn yield is calculated with a moisture content of 15%. Nitrogen application rates range from 0 to 320 kg N/ha (0 to 285.5 lb N/acre) with increments of every 10 kg/ha (8.9 lb N/acre). The reported N leaching rates (N kg/ha) represent the cumulative two-year leaching during corn and soybean rotation from April 1st in year one to March 31st in year three. The weather data encompass the average air temperature, total precipitation, and average solar radiation across six periods spanning from January 1st to planting, four growing stages until harvesting, and harvesting to December 31st. Soil characteristics include water holding capacity, sand content from 0 to 20 cm depth, and clay content from 0 to 20 cm depth. Additionally, control variables consist of soil water content, soil organic carbon, and soil N (NO_3 and NH_4) within the topmost 60 cm at corn growth stage V5 (5 leaf collars present). Summary statistics for these variables can be found in Appendix Table A1.

Additionally, the analysis incorporates a dataset consisting of one hundred and eighty-three combinations of monthly corn prices (USDA-NASS, 2024) and nitrogen fertilizer prices (USDA-AMS, 2024), spanning from 2008 and 2023. Detailed summary statistics for these variables can be found in Appendix Table A2.

2.2 Methods

The objectives of this research are to examine the influence of farmers' risk preferences on their nitrogen management decisions and identify effective policy instruments for promoting sustainable nitrogen management. Our analyses are grounded in farmers' utility maximization behavior, assuming that they value higher expected profits but associate negative utility to the variance of profits and their risk aversion. The utility function is specified as follows, which bears resemblance to the study of Ma et al. (2023).

$$u^j = E(\pi^j) - kVar(\pi^j), \quad (1)$$

where $j \in \{y, m, v\}$, y denotes the yield goal approach; m represents MRTN calculator; and v signifies VRT. $E(\pi^j)$ and $Var(\pi^j)$correspond to the expected profits and profit variance achieved by adopting nitrogen management practice j, respectively. Here, we consider a parameter $k \geq 0$ to capture farmers' risk aversion, acknowledging that this parameter varies across farmers and follows a distribution denoted as $R(k)$.

2.2.1 Corn Yield, Nitrogen Leaching, Expected Profits, and Profit Variances

Each field is considered as an independent decision-making unit when farmers select nitrogen management practices. Hence, it becomes imperative to determine the adoption of nitrogen management practices by assessing the expected profits and their variance for each field and practice. Initially, we employ a general quadratic function (Griffin et al., 1987) as follows and utilize soil-level data to estimate the response functions of corn yields and N leaching rates in relation to nitrogen application rates while controlling for weather and soil characteristics, respectively.

$$Y = \alpha^y + \sum_i \beta_i^y x_i + \sum_i \sum_k \delta_{ik}^y x_i x_k, \quad (2)$$

$$Nleach = \alpha^n + \sum_i \beta_i^n x_i + \sum_i \sum_k \delta_{ik}^n x_i x_k, \quad (3)$$

where Y represents corn yield and $Nleach$ represents the rate of N leaching, encompasses variables such as nitrogen application rate, planting date, weather conditions, soil characteristics, and other aforementioned control variables. The subscripts i and k denote different variables, while the superscripts y and n indicate the yield equation and N leaching equation, respectively.

The expected profit, denoted as $E(\pi_{psf}^{j})$, resulting from the adoption of nitrogen management practice j in field s for a combination of corn and N prices p on soil type s, can be determined by

$$E(\pi_{psf}^{j}) = P_{pC}Y_{sf}^{j} - P_{pN}N_{sf}^{j}, \tag{4}$$

where P_{pC} and P_{pN} represent the prices of corn and nitrogen, respectively, for a given combination p of prices. Y_{sf}^{j} denotes the yield of corn in field f with soil type s, considering the application rate of nitrogen (denoted as N_{sf}^{j}) based on adopting specific nitrogen management practices (represented by practice j) for soil type s in field f.

To determine the optimal N application rate for maximizing profits in each soil type and field, nitrogen application rates ranging from 0 to 295 lb N/acre with increments of 1 lb N/acre were employed to identify the maximum profitability. Additionally, average water holding capacity, sand content, clay content, soil water content, soil organic carbon, and soil N levels specific to each soil type were considered as well as average planting date, precipitation, air temperature, and solar radiation across multiple years serving as control variables for yield prediction.

The soil-level profit-maximization N application rates predicted in this study correspond to the recommended N application rates for variable rate technology (VRT). Since the MRTN and Yield Goal recommendations provide uniform rates at the field level, it is necessary to compare them with the field-level VRT recommended N application rates. These field-level rates are calculated by considering the area share of each soil type within each field as weights, thereby obtaining a weighted mean of N application rates. The MRTN recommended N application rates for different combinations of corn and N price, as well as for north, central, and south regions of Illinois, were determined using the Corn Nitrogen Rate Calculator (CNRC, 2024). On the other hand, yield-goal-based N recommendations were calculated through multiplying 1.2 by the average yield from the last three years of corn planting after subtracting 40 lb "soybean N credit" for corn following soybean rotation (Nafziger, 2017).

The soil-level yield and profits for VRT, MRTN, and the yield goal approach are predicted by utilizing the response function of yield to nitrogen application rate along with various combinations of corn and N prices. Similarly, the field-level yield and profits for these three nitrogen management practices are calculated as weighted means. To obtain the weighted mean of profits by adopting practice j for price combination p and field f (denoted as $E(\pi^j_{pf})$), the following equation is employed.

$$E(\pi^j_{pf}) = \sum_{sf=1}^{SF} w_{sf} E(\pi^j_{psf}), \tag{5}$$

where w_{sf} represents the proportion of soil type s in field f, while SF denotes the total number of soil types present in field f.

The expected profits, taking into account uncertainties in prices and weather conditions over multiple years (denoted as $E(\pi^j_f)$), can be computed by

$$E(\pi^j_f) = \frac{1}{183} \sum_{p=1}^{183} E(\pi^j_{pf}), \tag{6}$$

where $E(\pi^j_{pf})$ represents expected profits obtained from implementing practice j for a specific price combination p and field f, which is computed as the weighted average of the profitability at soil level.

The profit variance resulting from the adoption of VRT, MRTN, and yield goal approaches across different years and combinations of prices for a specific field, denoted as ${\sigma_f^j}^2$, can be mathematically represented by

$$ {\sigma_f^j}^2 = \frac{1}{183 \times 15} \sum_{p=1}^{183} \sum_{n=1}^{15} (\pi_{pnf}^j - E(\pi_{pf}^j))^2, \tag{7} $$

where π_{pnf}^j represents the profits for the combination p of corn and nitrogen prices in year n and field f, based on a specific nitrogen application rate recommended by management practices. There are one hundred and eighty-three unique combinations of corn and nitrogen prices considered, spanning fifteen years of corn planting following soybeans rotation.

2.2.2 Adoption of Nitrogen Management Practices

A farmer adopts VRT in field f if $u_f^v \geq u_f^m$ and $u_f^v \geq u_f^y$; chooses MRTN in a field if $u_f^m \geq u_f^y$ and $u_f^m \geq u_f^v$; and implements yield goal approach in a field if $u_f^y \geq u_f^m$ and $u_f^y \geq u_f^v$. According to equation (1), (6), and (7), we can derive the critical values of risk aversion k that result in farmers being indifferent between two nitrogen management practices. The critical value of k for two nitrogen management practices in a field is as follows:

$$ k_f^{ij} = \frac{E(\pi_f^i) - E(\pi_f^j)}{{\sigma_f^i}^2 - {\sigma_f^j}^2} = \frac{\Delta E(\pi_f^{ij})}{\Delta V\left(\pi_f^{ij}\right)} $$

$$ = \frac{\frac{1}{183}\sum_{p=1}^{183}\sum_{sf=1}^{SF} w_{sf}(P_{cN}(Y_{sf}^i - Y_{sf}^j) - P_{pN}(N_{sf}^i - N_{sf}^j))}{\frac{1}{183 \times 15}\sum_{p=1}^{183}\sum_{n=1}^{15} {P_{pC}}^2((\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^i - Y_{sf}^i))^2 - \left(\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^j - Y_{sf}^j)\right)^2)}, \tag{8} $$

$$ k_f^{il} = \frac{E(\pi_f^i) - E(\pi_f^l)}{{\sigma_f^i}^2 - {\sigma_f^l}^2} = \frac{\Delta E(\pi_f^{il})}{\Delta V(\pi_f^{il})} \tag{9} $$

$$= \frac{\frac{1}{183}\sum_{p=1}^{183}\sum_{sf=1}^{SF} w_{sf}\left(P_{cN}\left(Y_{sf}^{i} - Y_{sf}^{l}\right) - P_{pN}\left(N_{sf}^{i} - N_{sf}^{l}\right)\right)}{\frac{1}{183\times 15}\sum_{p=1}^{183}\sum_{n=1}^{15} {P_{pC}}^{2}\left(\left(\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^{i} - Y_{sf}^{i})\right)^{2} - \left(\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^{l} - Y_{sf}^{l})\right)^{2}\right)},$$

where $i \ or \ j \ or \ l \in \{y, m, v\}$, y denotes yield goal approach; m represents MRTN calculator; and v signifies VRT. $\Delta E(\pi_f^{ij})$ or $\Delta E(\pi_f^{il})$ corresponds to the difference in profits from adopting two different nitrogen management practices. The term $\Delta V(\pi_f^{ij})$ or $\Delta V(\pi_f^{il})$ represents the difference in profit variance from the adoption of two distinct practices. The probability of a farmer with an unknown level of risk aversion k adopting nitrogen management practice i in field f, P_f^i, is given by:

$$P_f^i = \begin{cases} 1 & \text{if } \Delta E(\pi_f^{ij}) \geq 0, \Delta V(\pi_f^{ij}) \leq 0, \Delta E(\pi_f^{il}) \geq 0, \Delta V(\pi_f^{il}) \leq 0, \\ R(k_f^{il}) & \text{if } \Delta E(\pi_f^{ij}) \geq 0, \Delta V(\pi_f^{ij}) \leq 0, \Delta E(\pi_f^{il}) > 0, \Delta V(\pi_f^{il}) > 0, \\ 1 - R(k_f^{il}) & \text{if } \Delta E(\pi_f^{ij}) \geq 0, \Delta V(\pi_f^{ij}) \leq 0, \Delta E(\pi_f^{il}) < 0, \Delta V(\pi_f^{il}) < 0, \\ R(k_f^{*}) & \text{if } \Delta E(\pi_f^{ij}) > 0, \Delta V(\pi_f^{ij}) > 0, \Delta E(\pi_f^{il}) > 0, \Delta V(\pi_f^{il}) > 0, \\ & \quad k_f^{*} = \min(k_f^{ij}, k_f^{il}), \\ R(k_f^{ij}) & \text{if } \Delta E(\pi_f^{ij}) > 0, \Delta V(\pi_f^{ij}) > 0, \Delta E(\pi_f^{il}) \geq 0, \Delta V(\pi_f^{il}) \leq 0, \\ R(k_f^{ij}) - R(k_f^{il}) & \text{if } \Delta E(\pi_f^{ij}) > 0, \Delta V(\pi_f^{ij}) > 0, \Delta E(\pi_f^{il}) < 0, \Delta V(\pi_f^{il}) < 0, \\ & \quad k_f^{ij} > k_f^{il} \\ 0 & \text{if } \Delta E(\pi_f^{ij}) > 0, \Delta V(\pi_f^{ij}) > 0, \Delta E(\pi_f^{il}) < 0, \Delta V(\pi_f^{il}) < 0, \\ & \quad k_f^{ij} < k_f^{il} \\ 1 - R(k_f^{ij}) & \text{if } \Delta E(\pi_f^{ij}) < 0, \Delta V(\pi_f^{ij}) < 0, \Delta E(\pi_f^{il}) \geq 0, \Delta V(\pi_f^{il}) \leq 0, \\ R(k_f^{il}) - R(k_f^{ij}) & \text{if } \Delta E(\pi_f^{ij}) < 0, \Delta V(\pi_f^{ij}) < 0, \Delta E(\pi_f^{il}) > 0, \Delta V(\pi_f^{il}) > 0, \\ & \quad k_f^{il} > k_f^{ij} \\ 0 & \text{if } \Delta E(\pi_f^{ij}) < 0, \Delta V(\pi_f^{ij}) < 0, \Delta E(\pi_f^{il}) > 0, \Delta V(\pi_f^{il}) > 0, \\ & \quad k_f^{il} < k_f^{ij} \\ 1 - R(k_f^{*}) & \text{if } \Delta E(\pi_f^{ij}) < 0, \Delta V(\pi_f^{ij}) < 0, \Delta E(\pi_f^{il}) < 0, \Delta V(\pi_f^{il}) < 0, \\ & \quad k_f^{*} = \max(k_f^{ij}, k_f^{il}), \\ 0 & \text{if } \left(\Delta E(\pi_f^{ij}) \leq 0, \Delta V(\pi_f^{ij}) \geq 0\right) \text{ or } \left(\Delta E(\pi_f^{il}) \leq 0, \Delta V(\pi_f^{il}) \geq 0\right). \end{cases} \tag{10}$$

If the expected profits of adopting nitrogen management practice i in field f exceed those of the other two practices, while also exhibiting lower profit variance, a risk-averse farmer will consistently opt for nitrogen management practice i in field f. In cases where the expected profits and profit variance associated with adopting practice i in field f are higher and lower than one practice respectively, and either higher or lower than the other practice, the decision to adopt practice i in field f hinges upon the positive critical value. A farmer will choose to adopt practice i in field f if their level of risk aversion is below (above) this positive critical value when both expected profits and profit variance are higher (lower). If the expected profits and profit variance of adopting practice i in field f are both higher (lower) than the other two practices, a farmer will adopt practice i in field f if their risk aversion is lower (higher) than the smaller (larger) critical value among the two. If the expected profits and profit variance of adopting practice i in field f are both higher than one practice, while being lower than the other practice, the adoption of practice i in field f will depend on the magnitude of the critical values. If the critical value for former is larger than that for latter and a farmer's risk aversion lies between these two values, they will adopt practice i in field f.

2.2.3 Policy Instruments to Promote the Sustainable Nitrogen Management

We propose four policy instruments to facilitate the adoption of sustainable nitrogen management practices, namely MRTN and VRT. These include a price premium, lump-sum payment, tax on N exceeding the N balance threshold (Mandrini, Pittelkow, et al., 2022), and insurance against yield loss. It is assumed that the price premium, lump-sum payment, and insurance coverage for yield loss are consistent across both MRTN and VRT approaches; while the tax on N exceeding the N balance threshold remains uniform across all three nitrogen management practices.

2.2.3.1 Price Premium

Farmers considering the adoption of Variable Rate Technology (VRT) or Maximum Return to Nitrogen (MRTN) can benefit from a price premium, denoted as v (\$/bushel), which effectively increases the output's price by adopting sustainable nitrogen management practices to $P_{pC} + v$. The critical values of k required for determining the adoption of VRT or MRTN in field f under the incentive of a price premium are:

$$k_f^{iy,prem} = \frac{\frac{1}{183}\sum_{p=1}^{183}\sum_{sf=1}^{SF} w_{sf}\left((P_{pC}+v)Y_{sf}^{i} - P_{pC}Y_{sf}^{y} - P_{pN}(N_{sf}^{i} - N_{sf}^{y})\right)}{\frac{1}{183\times 15}\sum_{p=1}^{183}\sum_{n=1}^{15}\left(\left(\sum_{sf=1}^{SF} w_{sf}(P_{pC}+v)(Y_{nsf}^{i} - Y_{sf}^{i})\right)^2 - \left(\sum_{sf=1}^{SF} w_{sf}P_{pC}(Y_{nsf}^{y} - Y_{sf}^{y})\right)^2\right)} = \frac{\Delta E(\pi_f^{iy,prem})}{\Delta V(\pi_f^{iy,prem})}, \quad (11)$$

$$k_f^{ij,prem} = \frac{\frac{1}{183}\sum_{p=1}^{183}\sum_{sf=1}^{SF} w_{sf}\left((P_{pC}+v)\left(Y_{sf}^{i} - Y_{sf}^{j}\right) - P_{pN}(N_{sf}^{i} - N_{sf}^{j})\right)}{\frac{1}{183\times 15}\sum_{p=1}^{183}\sum_{n=1}^{15}(P_{pC}+v)^2\left(\left(\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^{i} - Y_{sf}^{i})\right)^2 - \left(\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^{j} - Y_{sf}^{j})\right)^2\right)} = \frac{\Delta E(\pi_f^{ij,prem})}{\Delta V(\pi_f^{ij,prem})}, \quad (12)$$

where i denotes VRT or MRTN, y represents yield goal approach in equation (11). Where i in equation (12) represents the same practice as that in equation (11), while j in equation (12) represents an alternative sustainable nitrogen management practice.

When comparing the critical value equations (11) and (12) for price premium with those of no incentive equations (8) and (9), it becomes evident that price premium amplifies both the disparity in expected profits and profit variance. Consequently, it remains uncertain whether paying a price premium to farmers adopting sustainable nitrogen management practices will result in an increase or decrease in the critical values of k.

2.2.3.2 Lump-sum Payment

Now, let us consider a lump-sum payment, denoted as ω (\$/acre), to be provided to farmers in order to incentivize the adoption of VRT or MRTN. The critical values of k that determine the adoption of VRT or MRTN in field f under lump sum subsidies are as follows:

$$k_f^{iy,lump\_sum} =$$

$$\frac{\frac{1}{183}\sum_{p=1}^{183}\sum_{sf=1}^{SF} w_{sf}\left(P_{pC}(Y_{sf}^{i} - Y_{sf}^{y}) - P_{pN}(N_{sf}^{i} - N_{sf}^{y})\right) + \ \omega}{\frac{1}{183 \times 15}\sum_{p=1}^{183}\sum_{n=1}^{15} {P_{pC}}^2\left(\left(\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^{i} - Y_{sf}^{i})\right)^2 - \left(\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^{y} - Y_{sf}^{y})\right)^2\right)}$$

$$= \frac{\Delta E(\pi_f^{iy,lump\_sum})}{\Delta V(\pi_f^{iy,lump\_sum})}, \quad (13)$$

$$k_f^{ij,lump\_sum} =$$

$$\frac{\frac{1}{183}\sum_{p=1}^{183}\sum_{sf=1}^{SF} w_{sf}\left(P_{pC}(Y_{sf}^{i} - Y_{sf}^{j}) - P_{pN}(N_{sf}^{i} - N_{sf}^{j})\right)}{\frac{1}{183 \times 15}\sum_{p=1}^{183}\sum_{n=1}^{15} {P_{pC}}^2\left((\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^{i} - Y_{sf}^{i}))^2 - (\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^{j} - Y_{sf}^{j}))^2\right)}$$

$$= \frac{\Delta E(\pi_f^{ij,lump\_sum})}{\Delta V(\pi_f^{ij,lump\_sum})}, \quad (14)$$

The comparison between critical value of k equations for lump sum payment and those without any incentives suggests that lump sum payment can increase the disparity in expected profits between VRT or MRTN and yield goal approach, while keeping the variance of the profits unchanged. However, it is worth noting that lump sum payment does not alter the critical value of k between VRT and MRTN.

2.2.3.3 Tax on N That Exceeds N Balance Threshold

The N balance for this policy instrument is determined following the methodology described in Eagle et al. (2020):

$$N_{balance} = N_{fertilizer}\ (lb\ N/acre) - N_{removed}(lb\ N/acre), \quad (15)$$

where $N_{fertilizer}$ represents the N fertilizer applied, and $N_{removed}$ is the N harvested in corn grain estimated assuming a grain N concentration of 0.644 lb N/bushel corn (Tenorio et al., 2019). The N balance threshold, set at 53.53 lb/acre across Illinois following the analysis in Mandrini, Pittelkow, et al. (2022), determines the tax levied on nitrogen (N) above this threshold. Tax, τ (\$/lb N), is levied for N above the N balance threshold. Taxes for nitrogen management practice j in field f, denoted as t_f^j, can be calculated by

$$t_f^j = \begin{cases} 0 & \text{if } N_f^j - 0.664 \times Y_f^j \leq 53.53 \\ \tau * \left(N_f^j - 0.664 \times Y_f^j - 53.53\right) & \text{if } N_f^j - 0.664 \times Y_f^j > 53.53 \end{cases}, \quad (16)$$

where τ (\$/lb N) denotes the levy imposed on each unit of N exceeding the N balance threshold.

The critical values of k for determining the adoption of VRT or MRTN in field f, subject to taxation on N exceeding the N balance threshold, are as follows:

$$k_f^{iy,tax} = \frac{\frac{1}{183}\sum_{p=1}^{183}\sum_{sf=1}^{SF} w_{sf}\left(P_{pC}(Y_{sf}^i - Y_{sf}^y) - P_{pN}(N_{sf}^i - N_{sf}^y)\right) - (t_f^i - t_f^y)}{\frac{\sum_{p=1}^{183}\sum_{n=1}^{15}\left(\left(\sum_{sf=1}^{SF} w_{sf}P_{pC}(Y_{nsf}^i - Y_{sf}^i) - (t_{nf}^i - t_f^i)\right)^2 - \left(\sum_{sf=1}^{SF} w_{sf}P_{pC}(Y_{nsf}^y - Y_{sf}^y) - (t_{nf}^i - t_f^i)\right)^2\right)}{183 \times 15}}$$

$$= \frac{\Delta E(\pi_f^{iy,tax})}{\Delta V(\pi_f^{iy,tax})}, \quad (17)$$

$$k_f^{ij,tax} = \frac{\frac{1}{183}\sum_{p=1}^{183}\sum_{sf=1}^{SF} w_{sf}\left(P_{pC}\left(Y_{sf}^{i} - Y_{sf}^{j}\right) - P_{pN}\left(N_{sf}^{i} - N_{sf}^{j}\right)\right) - \left(t_f^{i} - t_f^{j}\right)}{\frac{\sum_{p=1}^{183}\sum_{n=1}^{15}\left(\left(\sum_{sf=1}^{SF} w_{sf}P_{pC}\left(Y_{nsf}^{i} - Y_{sf}^{i}\right) - \left(t_{nf}^{i} - t_f^{i}\right)\right)^2 - \left(\sum_{sf=1}^{SF} w_{sf}P_{pC}\left(Y_{nsf}^{j} - Y_{sf}^{j}\right) - \left(t_{nf}^{j} - t_f^{j}\right)\right)^2\right)}{183 \times 15}}$$

$$= \frac{\Delta E(\pi_f^{ij,tax})}{\Delta V(\pi_f^{ij,tax})}, \quad (18)$$

The changes in critical values of k for N balance tax, compared to those without imposing tax, will depend on the N balance above the N balance threshold after adopting different nitrogen management practices. Taxation on N balance alters both the difference in expected profits and their variance.

2.2.3.4 Insurance for Yield Loss

We finally consider an insurance type that provides coverage for yield losses below a specified threshold, δY_f^y, Y_f^y represents the expected yield under the yield goal approach in field f and δ is the percentage of this yield. The compensation received because of this insurance at price combination p for adopting sustainable nitrogen management practice i (VRT or MRTN) in field f, denoted as I_{pf}^i, is

$$I_{pf}^{i} = \begin{cases} 0 & \text{if } Y_f^i \geq \delta Y_f^y \\ P_{pC} * (\delta Y_f^y - Y_f^i) & \text{if } Y_f^i < \delta Y_f^y \end{cases}, \quad (19)$$

The critical values of k for determining the adoption VRT or MRTN are as follows:

$$k_f^{iy,insur} = \frac{\frac{1}{183}\sum_{p=1}^{183}\sum_{sf=1}^{SF} w_{sf}\left(P_{pC}\left(Y_{sf}^{i} - Y_{sf}^{y}\right) - P_{pN}\left(N_{sf}^{i} - N_{sf}^{y}\right)\right) + I_{pf}^{i}}{\frac{1}{183 \times 15}\sum_{p=1}^{183}\sum_{n=1}^{15}\left(\left(\sum_{sf=1}^{SF} w_{sf}P_{pC}\left(Y_{nsf}^{i} - Y_{sf}^{i}\right) + I_{pnf}^{i} - I_{pf}^{i}\right)^2 - \left(\sum_{sf=1}^{SF} w_{sf}\left(Y_{nsf}^{y} - Y_{sf}^{y}\right)\right)^2\right)}$$

$$= \frac{\Delta E(\pi_f^{iy,insur})}{\Delta V(\pi_f^{iy,insur})}, \quad (20)$$

$$k_f^{ij,insur} =$$

$$\frac{\frac{1}{183}\sum_{p=1}^{183}\sum_{sf=1}^{SF} w_{sf}\left(P_{pC}\left(Y_{sf}^i - Y_{sf}^j\right) - P_{pN}\left(N_{sf}^i - N_{sf}^j\right)\right) + I_{pf}^i - I_{pf}^j}{\frac{\sum_{p=1}^{183}\sum_{n=1}^{15} P_{pC}{}^2\left(\left(\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^i - Y_{sf}^i) + I_{pnf}^i - I_{pf}^i\right)^2 - \left(\sum_{sf=1}^{SF} w_{sf}(Y_{nsf}^j - Y_{sf}^j) + I_{pnf}^j - I_{pf}^j\right)^2\right)}{183 \times 15}}$$

$$= \frac{\Delta E(\pi_f^{ij,insur})}{\Delta V(\pi_f^{ij,insur})}, \quad (21)$$

The insurance on yield loss may alter the disparity in expected profits and their variance, contingent upon whether the yield achieved through VRT or MRTN is inferior to the green insurance trigger level.

3 Results

3.1 Yield Response to N and N Leaching Response to N Application Rate

The estimated corn yield response to nitrogen (N) and the leaching response to N functions are presented in Appendix Table A3. Due to the extensive number of control variables, including 375 variables, the levels and quadratic effects of planting date, soil characteristics, weather variables, and their interactions were not included in the results table.

The coefficients for nitrogen application rate and squared nitrogen application rate in the yield response to N function are 1.28 and -0.0017, respectively; both coefficients are statistically significant. These findings suggest that increasing the rate of nitrogen application can enhance crop yield, but at a diminishing rate, indicating a threshold beyond which further increases in nitrogen application do not lead to additional yield gains.

The coefficients for the N leaching yield response to N function, representing the effects of both N application rate and squared N application rate, are determined as 0.34 and 0.0008 respectively, with a statistically significant level of 99%. These findings suggest that an increase in N application rate leads to a corresponding increase in N leaching at an accelerating pace.

3.2 Recommended N Application Rates, Yield, Profits, N Leaching and Their Variances

The mean and standard deviations of N application rates recommended by the yield goal approach, MRTN, and VRT across 4,236 fields at 183 combinations of corn and N prices are respectively presented in Appendix Figure A1 and Figure A2, Panel A. The mean and standard deviations of N application rate recommended by the yield goal approach remain constant across different ratios of corn and N prices (approximately 205 lb N/acre and 20 lb N/acre, respectively), as it is solely determined by yield considerations. This mean rate along with its standard deviation surpass all other means and standard deviations of N application rates suggested by MRTN and VRT for various corn to N price ratios. Specifically, the mean values for MRTN range from around 160 to 201 lb N/acre, while for VRT they range from 172 to 202 lb N/acre. The standard deviations for MRTN range from approximately 6.5 to 8.5 lb N/acre; however, they are larger but within a narrower range from approximately 16.398 to 16.410 lb N/acre for VRT.

Both MRTN and VRT exhibit an increasing trend in recommended rates with higher corn and N price ratios; however, this increase occurs at a diminishing rate. It is worth noting that the relationship between N rates and price ratios is nearly linear for MRTN recommendations. The disparities in recommended N application rates can be attributed to regional specificity in MRTN recommendations compared to soil-specificity in VRT recommendations, which stem from underlying differences in production functions.

The Appendix Figure A1 and Figure A2, Panel B, illustrate the expected rates of N leaching and their corresponding standard deviations, respectively. The N leaching rates for yield goal, MRTN, and VRT are approximately 52.5 lb N/acre, ranging from 39 to 51 lb N/acre, and varying between 42.5 and 51.5 lb N/acre, respectively. The standard deviations of expected N leaching remain constant at 21.3 lb N/acre across corn to N ratios. In contrast to the absence of any discernible patterns in the standard deviations of N application rates for MRTN and VRT approaches, the standard deviations of expected N leaching exhibit a diminishing increase as the corn-to-N price ratio increases. These values range from 15.5 to 17.5 lb N/acre and from 14.4 to 15.6 lb N/acre for MRTN and VRT approaches, respectively; they are smaller than those obtained using the yield goal approach.

The average expected corn yields and their standard deviations across fields at different price ratios are depicted in Appendix Figure A1 and Figure A2, Panel C. The average expected yield obtained using the yield goal approach remains relatively stable at around 201 bushels per acre and is not influenced by changes in prices. However, it should be noted that this yield does not represent the highest among the expected yields implied by three N management practices, despite these fields receiving the highest N application rates. Specifically, for MRTN and VRT approaches, the range of average expected yields is approximately from 198 to 203 bushels per acre and from 200.5 to 204 bushels per acre, respectively. Furthermore, it can be observed that as both corn and N price ratios increase, there is a gradual but diminishing rate of increase in expected yield; notably, this decreasing rate is more pronounced for VRT compared to MRTN. The average expected yield achieved through the adoption of VRT surpasses that of MRTN at any given corn and price ratio, potentially due to the relatively higher recommended average N application rates associated with VRT.

Similar to the observed patterns for the standard deviations of N application rates and N leaching rates, the standard deviations of yield mean for the yield goal approach exhibit the highest variability (16.2 bushel/acre) among the three N management practices. The ranges of standard deviations of yield mean for MRTN and VRT are closely comparable, with VRT displaying a narrower range ranging from 14.7 to 14.95 bushel/acre and from 14.673 to 14.675 bushel/acre, respectively.

The average expected profits and their corresponding standard deviations obtained from employing these three nitrogen management practices are illustrated in Appendix Figure A1 and A2, Panel D, respectively. The expected profits vary from around 590 to 1420 $/acre across different corn and N price ratios, while their standard deviations range from 46 to 115 $/acre. No discernible patterns can be observed among all the employed practices.

In addition, we calculated the average recommended application rates of N, corresponding expected yield and profits, as well as the expected N leaching rates over corn and price ratios for each field. Furthermore, we computed the variances and standard deviations across price ratios for N rates, as well as across years and prices for the other variables.

The recommended N application rates vary heterogeneously across fields, primarily across regions. In the northern region, fields receive the highest N applications when farmers adopt the yield goal approach. Conversely, in the southern region, fields receive the lowest N applications under this approach. However, for farmers adopting VRT, the situation is reversed; recommended N rates are lowest in the north and highest in the south. The regional heterogeneity induced by VRT adoption aligns with that observed for N application rates recommended by MRTN. Nevertheless, there is a smaller variance across price ratios of N recommendations from VRT compared to those from MRTN. Amongst these approaches, yield goal exhibits the largest range of heterogeneities in N rates across fields, ranging approximately from 125 to 240 lb/acre.

This is followed by VRT with a range of 135 to 240 lb/acre while MRTN suggests values of 180.5, 183.4 and 203.9 lb/acre.

The expected yields, following the N application rates recommended by three N management practices, exhibit similar patterns with the highest yields concentrated in the northern region and the lowest yields clustered in the southern region. The expected yield ranges and standard deviations across fields are comparable for VRT and MRTN, ranging approximately from 140 to 240 bushels per acre and from 15 to 50 bushels per acre, respectively. Conversely, yield goal demonstrates smaller ranges for both expected yields and their variances.

Similar trends can be observed in terms of expected profits and their standard, where the highest profits are found in the northern region while the lowest profits reside in the southern region. The range of projected profits is approximately between $600 to $1000 per acre with a standard deviation range of $100 to $250 per acre.

In terms of three N management practices, most expected N leaching rates fall within the range of 30 to 80 lb N/acre. Additionally, the expected N leaching rates demonstrate a standard deviation range from 5 to 25 lb N/acre.

3.3 The Differences in Recommended N Application Rates, Yield, Profits, N leaching and Their Variances between Two Nitrogen Management Practices

The comparison of recommended N application rates, yield, profits, N leaching, and their standard deviations between two nitrogen management practices can be observed in Appendix Figure A3 to A6. There are three panels in each figure: panel A represents the comparison between VRT and the yield goal approach; panel B illustrates the differences between MRTN and the yield goal; while panel C compares VRT with MRTN.

The comparison of N rates between VRT and the yield goal approach suggests that VRT recommends lower N rates for almost all fields in the north region, as well as most fields in the central region. However, VRT suggests higher N rates should be applied to most fields in the south region. The differences in N rates between VRT and yield goal typically range from -50 to 50 lb N/acre, with a few exceptions being as low as -100 lb N/acre in the north region and as high as 75 lb N/acre in the south region. The standard deviations of recommended N rates by these two nitrogen management practices show a small range of differences, approximately ranging from 5.85 to 5.92 lb N/acre.

The comparison of N rates between the MRTN approach and yield goal indicates that most fields in the northern and central regions receive lower N rates when following MRTN recommendations. However, MRTN suggests higher N rates for fields in the southern region. Similar to the comparison between VRT and yield goal, larger differences are observed in the northern region compared to the central region. The range of disparities in N rates between MRTN and yield goal is narrower than that of the previous pair, ranging from -60 to 70 lb N/acre, while there are greater variations in standard deviation.

The indications of disparities in N rates between VRT and MRTN are inconclusive across all regions. In the northern region, the majority of fields receive lower N rates recommended by VRT, followed by the central region, while the southern region exhibits the smallest proportion. Most variations in N rates between these two approaches range from -25 to 25 lb N/acre, with a few exceptions reaching as low as -50 lb N/acre in the north and as high as 40 lb N/acre in the south. The standard deviations of VRT's N recommendations are smaller than those of MRTN.

The differences in the expected yield between VRT and the yield goal approach, as well as between MRTN and the yield goal approach, are relatively smaller despite significant variations in N levels. In most fields located in the north and central regions, corn yields obtained through VRT adoption are only 1 or 2 bushels/acre lower than the yield goal. However, a few fields in the northeastern region and southern part of the central region achieve approximately 5 bushels/acre higher yields with VRT adoption. In the southern region, adopting VRT results in yields that are about 10 to 15 bushels/acre higher compared to the yield goal for most fields. This discrepancy may be attributed to higher recommended N application rates by VRT specifically tailored for this region. The standard deviations between these two N practices range from -3 to 3 bushels/acre, with lower values observed for VRT implementation in north and central regions but higher values noted in the south when compared to using a yield goal approach. The northeastern region exhibits the most pronounced negative deviations in standard deviation.

The overall comparison results between the yield obtained from the MRTN approach and the yield goal approach exhibit a high degree of similarity to those observed between VRT and the yield goal approach. However, there are a few exceptions scattered in western regions and the southern region where the MRTN approach yields more than 5 bushels/acre lower than the yield goal approach. In contrast, when comparing VRT with MRTN, we observe a wider range of discrepancies in yield. Most of these differences fall within -25 to 25 bushels/acre, although there are a few exceptional cases reaching approximately -50 or 50 bushels/acre. Notably, most negative differences occur in the northeastern region, potentially attributed to the lower recommended rates of N application by VRT. Furthermore, it is worth mentioning that compared to previous comparisons, the range of differences in standard deviations is narrower at around -1.5 to 1.5 bushels/acre.

The comparison of profits among different N management practices indicates that the adoption of VRT yields the highest profits. This underscores the significance of incorporating farmers' risk aversion into the consideration of their adoption of N management practices, as neglecting this aspect would invariably lead to a preference for VRT over other practices.

Nevertheless, in practice, the uptake of VRT remains limited. VRT implementation can generate an additional profit ranging from $10 to $80 per acre compared to the yield goal approach, and slightly more than $0 to $20 per acre compared to the MRTN approach. In most fields in the northern region, VRT can generate over $20 per acre more profits than the yield goal approach, while in central and southern regions, the benefits of adopting VRT are approximately $20 per acre or lower compared to using the yield goal approach. The differences between VRT and MRTN are generally around $5 per acre or lower across most fields in Illinois.

Although adopting MRTN leads to higher profits than using the yield goal approach in most fields, there are sporadic negative differences observed in central and southwestern parts of the northern region. Notably, clusters of significantly positive profit differences between MRTN and VRT are found in eastern areas of the northern region. The majority of VRT profit standard deviations in the north and central regions of Illinois are smaller compared to the yield goal approach. A similar trend can be observed between MRTN and yield goal approaches when considering the standard deviation of profits. Notably, negative differences in standard deviations between VRT and MRTN primarily occur in the eastern part of the north and central regions of Illinois.

The comparison results of N leaching exhibit a strong correlation with N rates, thereby demonstrating their similarity. In the northern and central regions, most fields show lower N leaching rates for VRT compared to the yield goal approach, while higher N leaching rates are observed in the southern region. This pattern can be attributed to the consistent differences in N rates between these two practices. Most of variations in N leaching between VRT and the yield goal approach fall within the range of -20 to 20 lb N/acre. Similar trends are evident when comparing MRTN with the yield goal approach.

Negative differences in N leaching between VRT or MRTN and the yield goal approach primarily occur in the north region and eastern part of the central region, ranging from -10 to 0 lb N/acre. Notably, negative deviations in standard deviation of N leaching between VRT or MRTN and the yield goal approach predominantly manifest in fields located within north and central regions, with most differences falling within -2 to 0 lb N/acre. The majority of the differences in standard deviation for N leaching between VRT and MRTN fall within the range of -1 to 1 lb N/acre.

3.4 Adoption of Nitrogen Management Practices Without Incentives

We assume that farmers adopt only one nitrogen management practice at a time, implying the mutual exclusivity of the three different practices. Due to our lack of knowledge regarding each farmer's risk aversion, we consider the adoption of a practice only when the probability of adopting it is 1, as determined by equation (10). This implies that a farmer will definitely adopt a nitrogen management practice if its expected profits are the highest and the variance of expected profits is the lowest. Following this rule, we initially calculated the adoption of VRT and assumed non-VRT adopters would either choose MRTN or yield goal approach. Subsequently, the decision to adopt MRTN was determined by comparing expected profits and their variances between MRTN and yield goal approach. The adoption rate for the yield goal approach was obtained by subtracting the adoption rates of VRT and MRTN from 1.

The adoption rates were determined based on the average expected profits derived from adopting VRT, MRTN, and yield goal across 183 combinations of corn and price, as well as the variances in expected profits calculated under different weather conditions and price scenarios. Table 1 presents both overall adoption rates and regional adoption rates for VRT, MRTN, and yield goal. In the absence of any incentives, the overall VRT adoption rate stands at 21.3% for a total of 4,236 fields in Illinois; meanwhile, the MRTN adoption rate reaches 32.5%, with yield goal representing the largest share at 42.6%. Notably, our estimated VRT adoption rate is approximately 7% lower than that obtained from USDA ARMS survey data in 2016 regarding variable rate fertilizers and lime applications across corn-planted acres (McFadden et al., 2023). This discrepancy can be attributed to historically lower levels of VRT adoption prior to 2016; moreover, our estimate incorporates price conditions dating back to 2008 and weather conditions dating back to 1989. Furthermore, it is reasonable that our estimated adoption rate of VRT for N application is lower than the reported rate by McFadden et al. (2023), as their rate encompasses the adoption for N and other fertilizers as well as lime application. The estimated adoption rate of MRTN closely aligns with the reported adoption rate of online calculators by Houser et al. (2019) and the implied adoption rate of MRTN according to Sellars et al. (2020).

The adoption rate of VRT in the northern region is the highest, reaching 61.8%. The adoption rate of MRTN in the north region closely aligns with the overall state adoption rate. However, approximately forty percent of farmers in the central region express willingness to adopt MRTN, which is the highest among all three regions. Conversely, VRT adoption decreases significantly to 11% in the central region. In contrast, yield goal management dominates nitrogen practices in the southern region with an adoption rate of approximately 99%. Figure 5 illustrates a visual representation of discrepancies and distribution patterns regarding nitrogen management practice adoptions. Specifically, VRT adoption clusters predominantly within the northeastern region while MRTN adoptions are randomly distributed across both central and western parts of the north region.

3.5 Policy Instruments to Incentivize the Adoption of Sustainable N Management Practices

Four policy instruments were employed for comparison, namely price premium, lump-sum payment, tax on N above the N balance threshold (Mandrini, Pittelkow, et al., 2022), and green insurance to compensate for profits loss due to yield reduction. One hundred scenarios were simulated for each policy instrument. These instruments change the adoption rates of various nitrogen management practices by altering expected profits and their variances. The simulated adoption rates of three nitrogen management practices under different scenarios are depicted in Figure 2.

In the simulation, the average corn price over the years was \$4.65 per bushel. We varied the price premium from 0.2% to 20% of the average corn price with a 0.2% increment. The introduction of a price premium can enhance expected profits associated with adopting VRT or MRTN, but it may also affect the variance of these expected profits. Figure 2, Panel A illustrates that adding a \$0.037 per bushel price premium increases MRTN adoption from 32.3% to 56.8%. However, it has a slight negative impact on VRT adoption, reducing it from 21.2% to 20.8%, and significantly decreasing yield goal adoption from 46.7% to 22.6%. Notably, as the price premium continues to increase, both MRTN and VRT adoption rates gradually decline until they reach zero at a price premium of \$0.688 per bushel; meanwhile, yield goal adoption reaches its maximum level at this point.

The average expected profits obtained by yield goal across fields amount to \$848.0 per acre. The lump-sum payment used for simulation ranges from 0.02% to 2% of this average yield goal profit, with a 0.02% incremental increase. It is important to note that the lump-sum payment solely affects the expected profits of sustainable N management practices and does not alter their variances. Given that VRT yields higher expected profits compared to MRTN and yield goal without any policy instruments, the adoption rate of VRT remains unaffected by the lump-sum payment incentive.

However, the introduction of a lump-sum payment increases the expected profits associated with MRTN, consequently amplifying the differences between MRTN and yield goal in terms of profitability. This adjustment has potential implications as it can transform negative differences into positive ones, thereby increasing the adoption rate of MRTN for fields characterized by lower variance in expected profits. The results presented in Figure 2, Panel B demonstrate that the adoption rate of MRTN increases to 58.6% when the lump-sum payment reaches $4.92 per acre, leading to a corresponding decrease in the adoption rate of the yield goal approach. Notably, the highest adoption rate for MRTN is achieved at 61.2% when the payment value reaches $11.5 per acre. Furthermore, it is observed that there is no change in the adoption rate of MRTN even if the payment exceeds this threshold.

The average price of N is $0.446 per pound of N. A tax scheme on N above the N balance threshold was implemented, ranging from 2.5% to 250% of this price with a 2.5% incremental increase. This tax reduces farmers' expected profits and alters the variance in expected profits. Figure 2, Panel C demonstrates that it has minimal impact on the adoption of VRT technology. However, it significantly increases the adoption rate of MRTN to 49.4% and 60.1%, respectively, when the N tax is set at $0.2 per pound of N and $0.6 per pound of N.

The green insurance trigger level, representing the percentage of the yield goal yield, ranges from 1 to 100 as depicted in Figure 2, Panel D. It is evident that the adoption rate of three management practices remains relatively stable until the trigger level reaches 35% of the yield goal yield. Subsequently, there is a gradual increase in the adoption rate of MRTN, reaching 52.6% at a level of 98% of the yield goal yield. Simultaneously, there is a decline in the adoption rate of yield goal to 25.3%. Notably, once the trigger level exceeds 98% of the yield goal yield, there is a significant shift in N management practice adoption patterns: VRT experiences an increase with an adoption rate of 82.5%, while both MRTN and yield goal witness decreases with adoption rates dropping to 17.5% and 0%, respectively.

The cost-effectiveness of three policy instruments, namely price premium, lump-sum payment, and green insurance, in promoting the adoption rate of MRTN is depicted in Figure 3. The price premiums range from 0% to 2.4% of $4.65 per bushel, while lump-sum payments vary from 0% to 2% of $848.0 per acre. Additionally, the trigger levels for green insurance span from 0% to 100% of the average yield goal yield. Among these instruments, lump-sum payment emerges as the most economically efficient means to incentivize farmers towards adopting MRTN, followed by price premium and green insurance.

The changes in fields adopting adopting maximum potential rates of MRTN under different policy instruments are illustrated in Figure 4. These changes exhibit remarkable similarity across three policy instruments including price premium, lump sum payment, and tax on N that exceeds N balance threshold. The adoption of MRTN incentivized by these instruments is primarily concentrated in central Illinois. However, a few farmers discontinue using MRTN after the implementation of price premium and tax on N that exceeds N balance threshold due to alterations not only in expected profits but also in the variance of the expected profits. In contrast to the other three policy instruments, green insurance stimulates farmers in southern Illinois to embrace MRTN. This suggests that diverse policy instruments can be employed to encourage MRTN adoption among farmers residing in different regions.

The spatial distribution of maximum potential VRT adoption under green insurance is presented in Figure 5. Predominantly, VRT adoption due to green insurance is observed in the western and central regions of Illinois, with a limited number of fields adopting VRT in southern Illinois. Similar to the impact on expected profits resulting from the implementation of price premium and tax on N, both the mean and variance of expected profits are influenced by green insurance, leading to a transition from VRT practices to alternative nitrogen management approaches for a few fields.

3.6 Adoption of VRT Considering Additional Costs

The cost of VRT adoption was not considered in the previous analyses. Subsequently, we investigated the influence of varying VRT adoption costs (ranging from 0.1 to 5 $/acre with an incremental increase of 0.1 $/acre) on farmers' decision-making regarding N management. The findings are presented in Figure 6. The implementation of yield goal remains unaffected by variations in VRT costs; however, escalating VRT expenses gradually drive up the adoption rate of MRTN while decreasing the adoption rate of VRT. When the cost of VRT reaches 5 $/acre, there is a seventeen percent increase in MRTN adoption compared to scenarios where no VRT costs were considered.

Changing the cost of variable rate technology (VRT) solely impacts the disparities in expected profits between VRT and MRTN. The decrease in VRT adoption suggests minimal discrepancies in expected profits between VRT and MRTN. According to McFadden et al. (2023), recent surveys conducted in the Great Plains indicate negligible application costs for using VRT, ranging from approximately $1.2 to $1.9 per acre. Assuming an additional cost of around $1.5 per acre in Illinois, the adoption rate of VRT decreases to 12.6%, which is approximately 8.5% lower than the scenario without any additional costs associated with utilizing VRT. This suggests that some farmers with relatively high levels of risk aversion may choose to adopt VRT even when both expected profits and variances are lower compared to

MRTN, thereby maintaining an adoption rate above 12.6% if considering a cost of $1.5 per acre for VRT adoption.

4 Conclusions

Nitrogen fertilizer plays a crucial role in corn production in the United States. However, excessive application of nitrogen fertilizer can result in profit losses and degradation of water quality. This study aims to investigate the influence of farmers' risk preferences on their decisions regarding nitrogen management and identify effective policy instruments for promoting sustainable nitrogen management practices. We utilized a simulated dataset comprising over four million observations, encompassing 4236 fields spanning an area of 40 hectares each, and representing 2758 soil types in Illinois from 1989 to 2018. Furthermore, we conducted predictions and simulations based on a total of 183 combinations of corn and nitrogen prices ranging from 2008 to 2023. This study demonstrates that incorporating farmers' risk aversion can lead to a more reasonable adoption of N management practices, aligning closely with reported rates from other studies. However, considering only the profit-maximizing behavior of farmers would significantly increase the adoption rate of VRT. On average, both MRTN and VRT recommend lower N application rates and anticipate reduced N leaching compared to the yield goal approach. Furthermore, despite the highest recommended N application rates among the three N management practices, the yield goal approach does not consistently result in achieving the highest yields.

Our study reveals that the implementation of lump sum payments and a tax on N exceeding the N balance threshold can effectively incentivize the adoption of MRTN. For instance, with a lump sum payment amounting to either $1 or $4.9 per acre, the adoption rate for MRTN could be promoted to reach approximately 42% or even up to around 58.6%. Similarly, imposing a tax equivalent to \$0.2 and \$0.4 per pound N, respectively, could significantly drive MRTN adoption rates as high as 49.4% and 57.2%. Our findings also highlight the importance of establishing appropriate price premiums and trigger levels for green insurance to effectively encourage the widespread uptake of MRTN and VRT. The price premium can only drive the adoption of MRTN up when it is below \$0.037 per bushel. The adoption of MRTN can only be promoted substantially when the trigger level is set in a range between 40 and 85 percent of yield goal yield. To encourage VRT adoption, the trigger level needs to exceed 98%. The maximum adoption rates for MRTN driven by price premium and green insurance are 56.8% and 52.6%, respectively. By setting the trigger level for green insurance as 100% of yield goal approach yield, VRT adoption can be incentivized up to 82.5%.

Additionally, we found that the lump sum payment is the most cost-effective instrument for incentivizing the adoption of MRTN when compared to price premium and green insurance. Moreover, it is noteworthy that different regions exhibit varying preferences in adopting MRTN under green insurance versus the other three policy instruments. Specifically, there is a significant increase in MRTN adoption observed in the southern region of Illinois under green insurance, while central Illinois demonstrates an increase in MRTN adoption under the remaining three policy instruments. These findings imply that selecting appropriate policy instruments should be contingent upon specific target regions.

This study has certain limitations. To enhance the accuracy of predicting soil-level profit maximizing N rates and corresponding yield, profits, and variances, it would be beneficial to utilize a forecasted weather condition dataset along with the variances associated with these conditions. Additionally, the estimation of N practice adoption is hindered by the unknown risk aversion parameter for each farmer, thereby reducing its accuracy.

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Table 1. Adoption rates of three N management practices in Illinois

Adoption Rate (%)	Yield Goal	MRTN	VRT	Observations
Overall	46.2	32.5	21.3	4236
North	6.0	32.2	61.8	971
Central	49.5	39.5	11.0	2693
South	99.1	0	0.9	572

Notes: In the first column, "Overall" represents the adoption rate for the whole Illinois state; "North", "Central", and "South" denote the northern, central, and southern regions of Illinois.

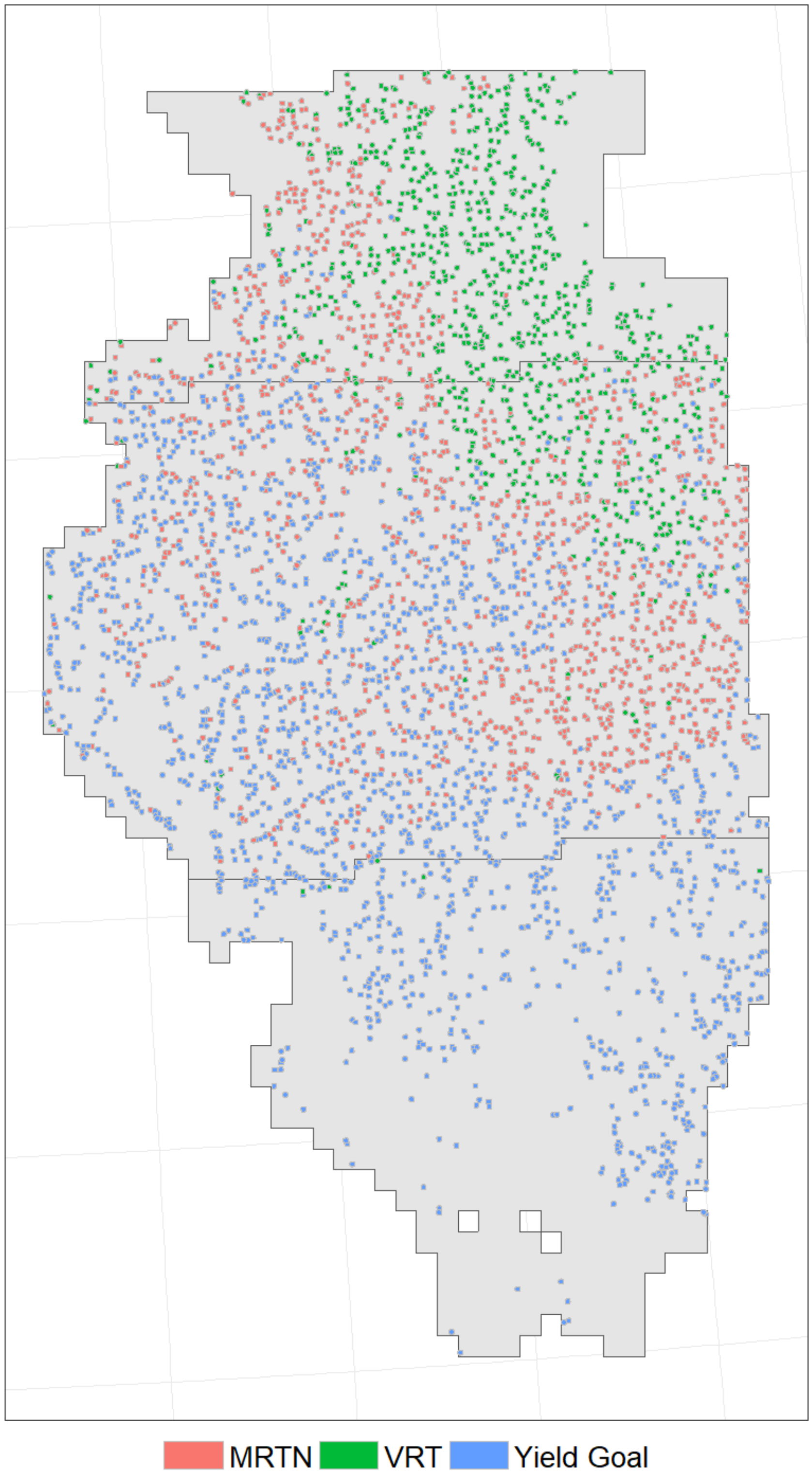


Figure 1. Adoption of three different nitrogen management practices across Illinois

Notes: The presented data illustrates the estimated adoption rates of three distinct nitrogen management practices (MRTN, VRT, and yield goal approach) based on farmers' utility maximization behavior. However, it does not account for additional costs associated with VRT or any policy incentives.

Panel A.

Panel B.

Panel C.

Panel D.

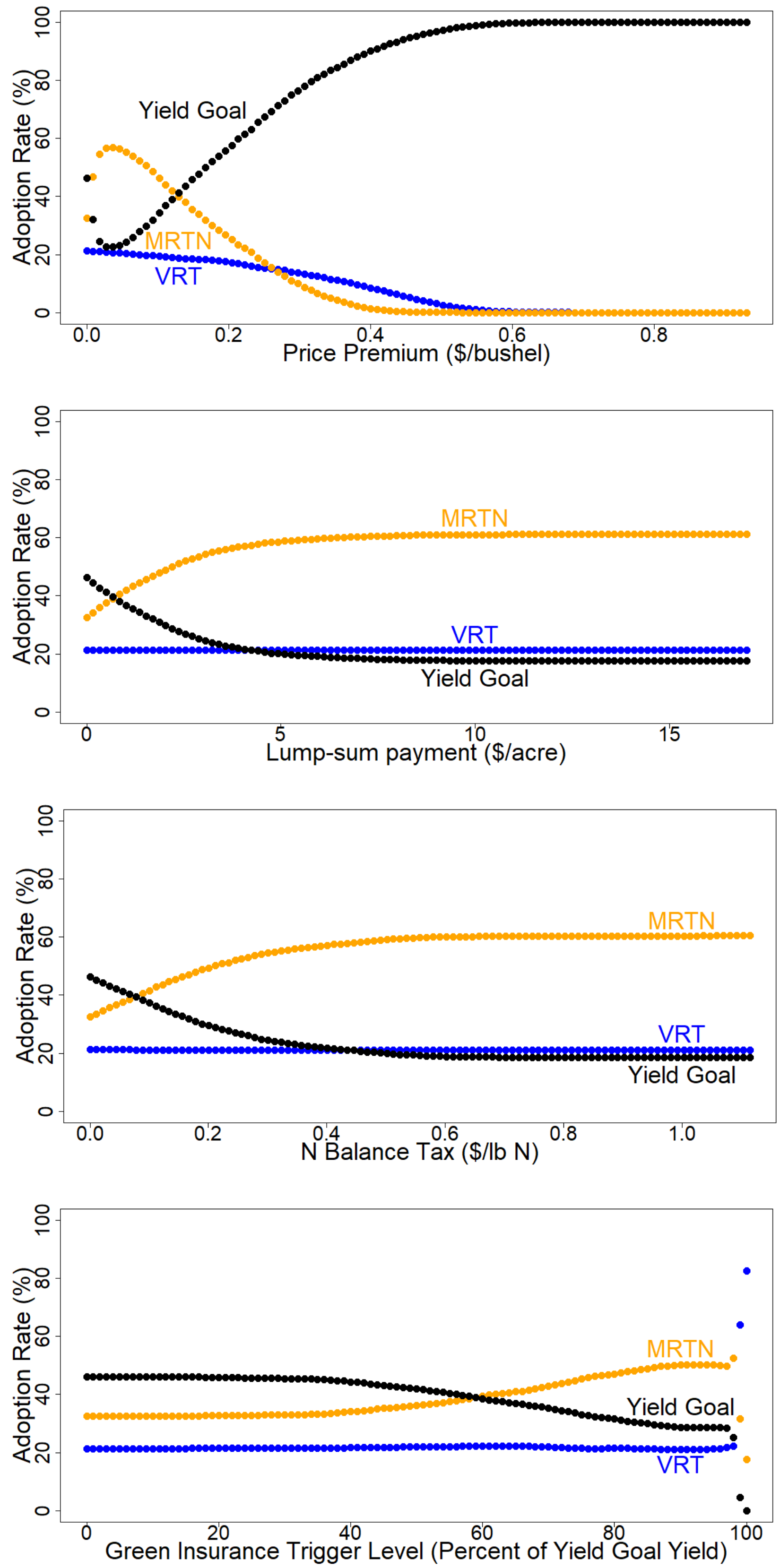
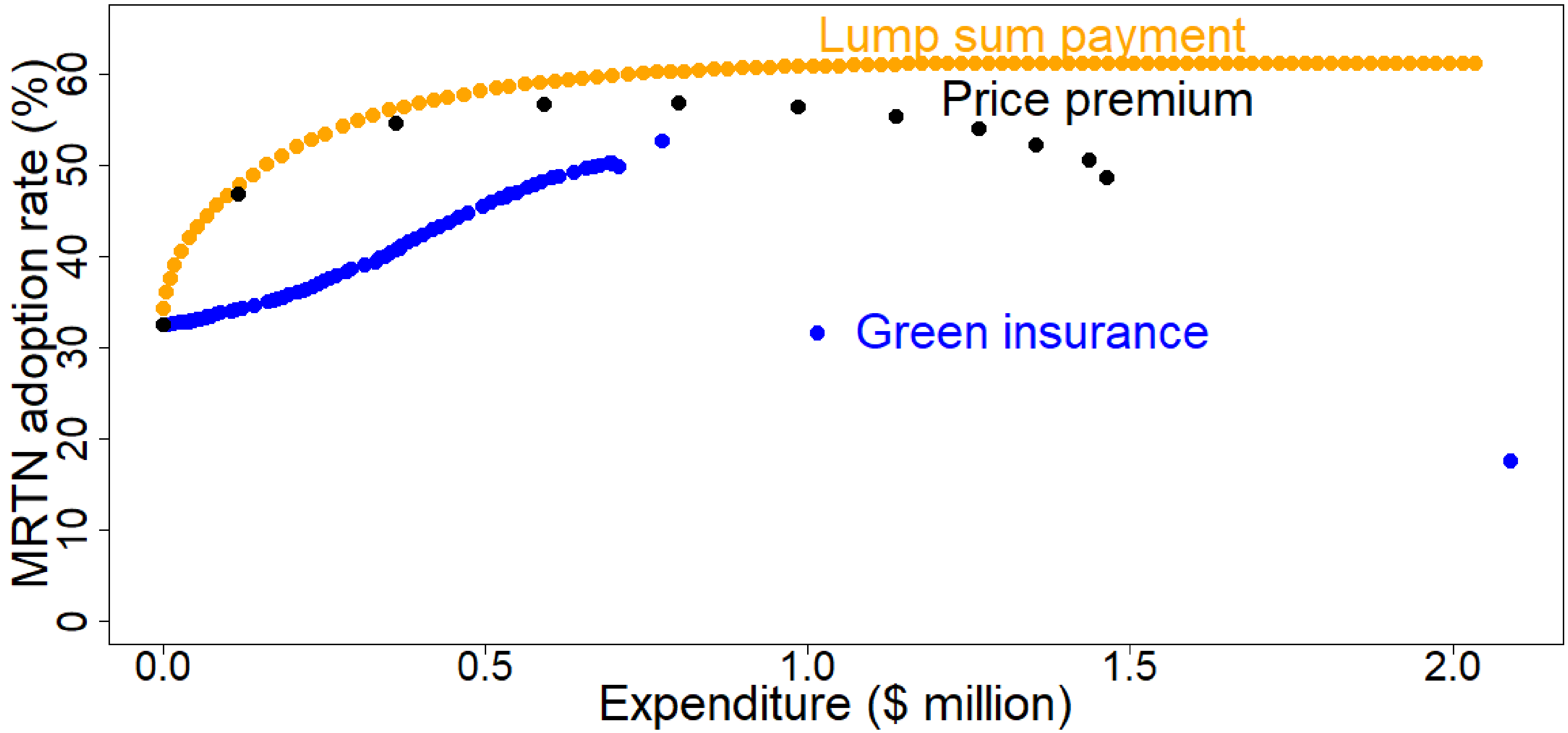
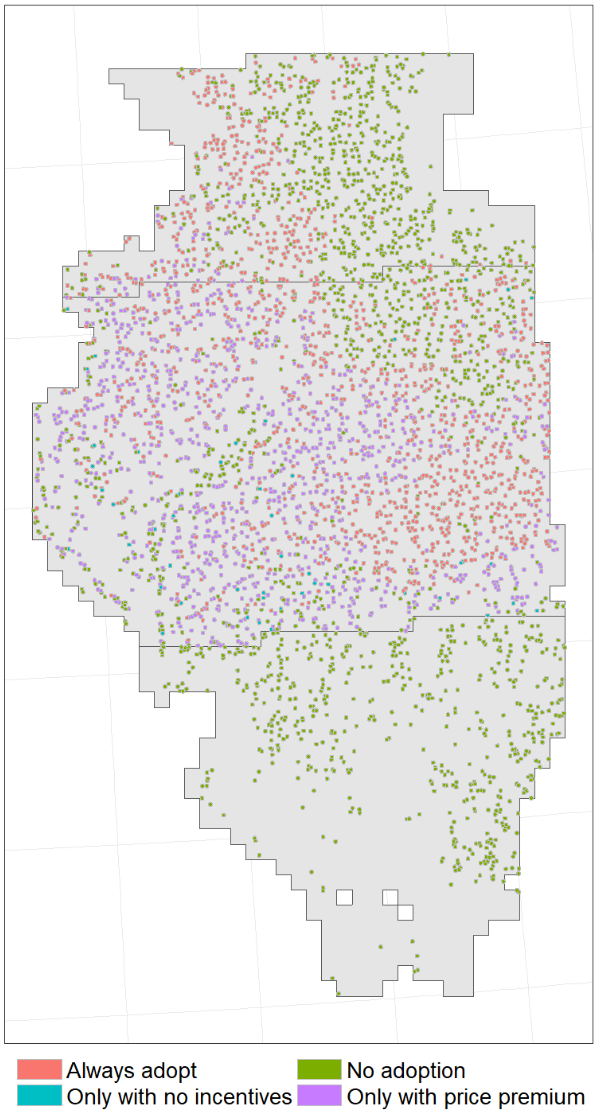


Figure 2. Adoption rates under different policy instruments

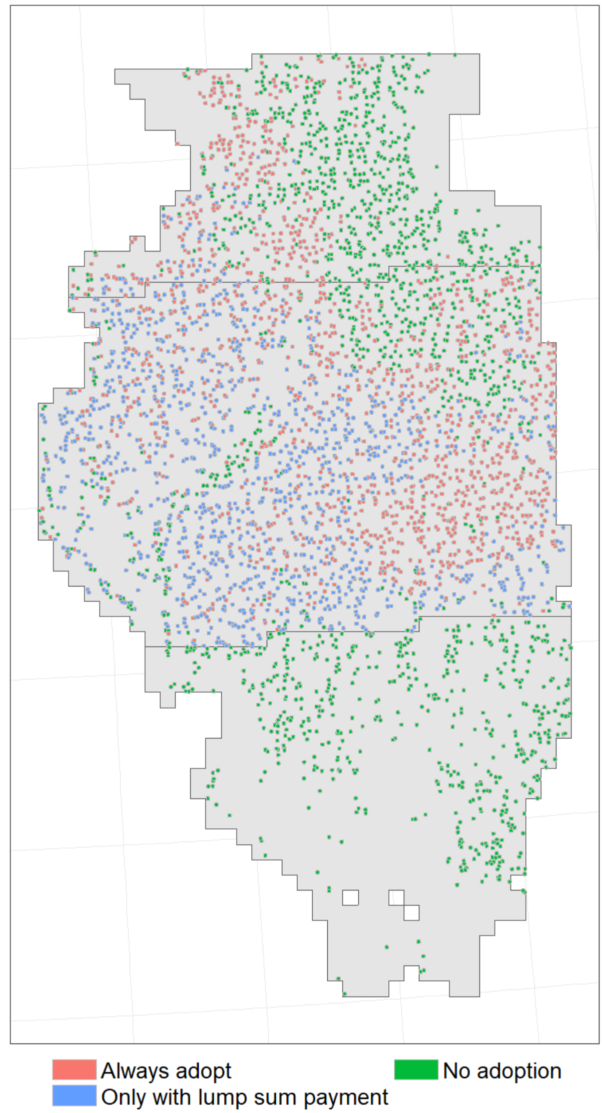


Notes: This figure illustrates the adoption rate of MRTN across 4,236 fields under different expenditure levels of each instrument

Panel A



Panel B



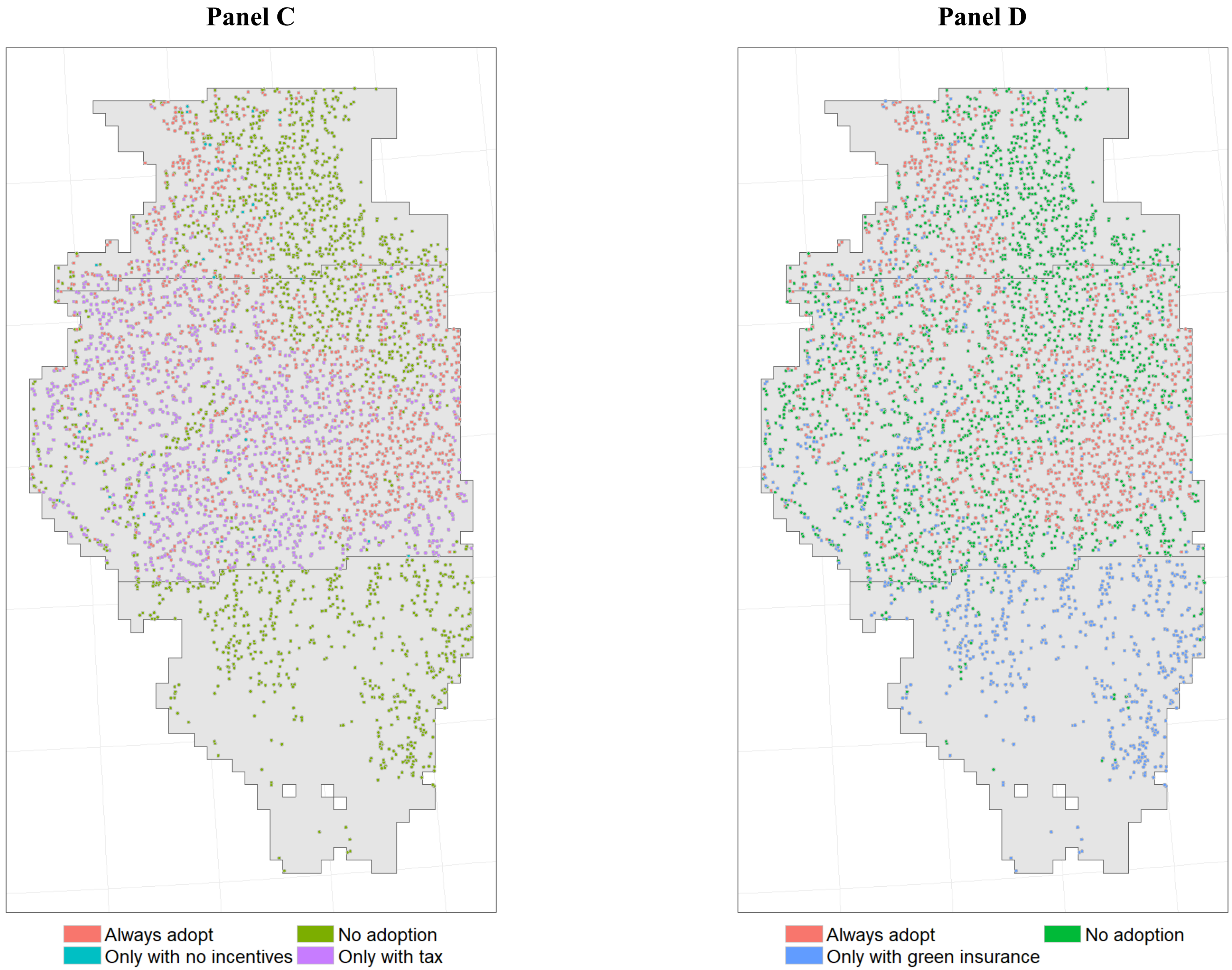


Figure 4. MRTN adoption status across fields under given policy instrument

Notes: Panel A, B, C, and D represent MRTN adoption status across fields with implementing price premium, lump sum payment, tax on N that exceeds N balance threshold, and insurance on yield loss, respectively, to drive the MRTN adoption rate to the maximum potential for the given policy instrument. “Always adopt” and “No adoption” denote the fields always adopt and never adopt MRTN no matter the given policy instrument is in place or not, respectively. “Only with no incentives” signifies that the fields only adopt MRTN when the given instrument is not in place. “Only with [incentive]” represents the fields only adopt MRTN when the given instrument is in place.

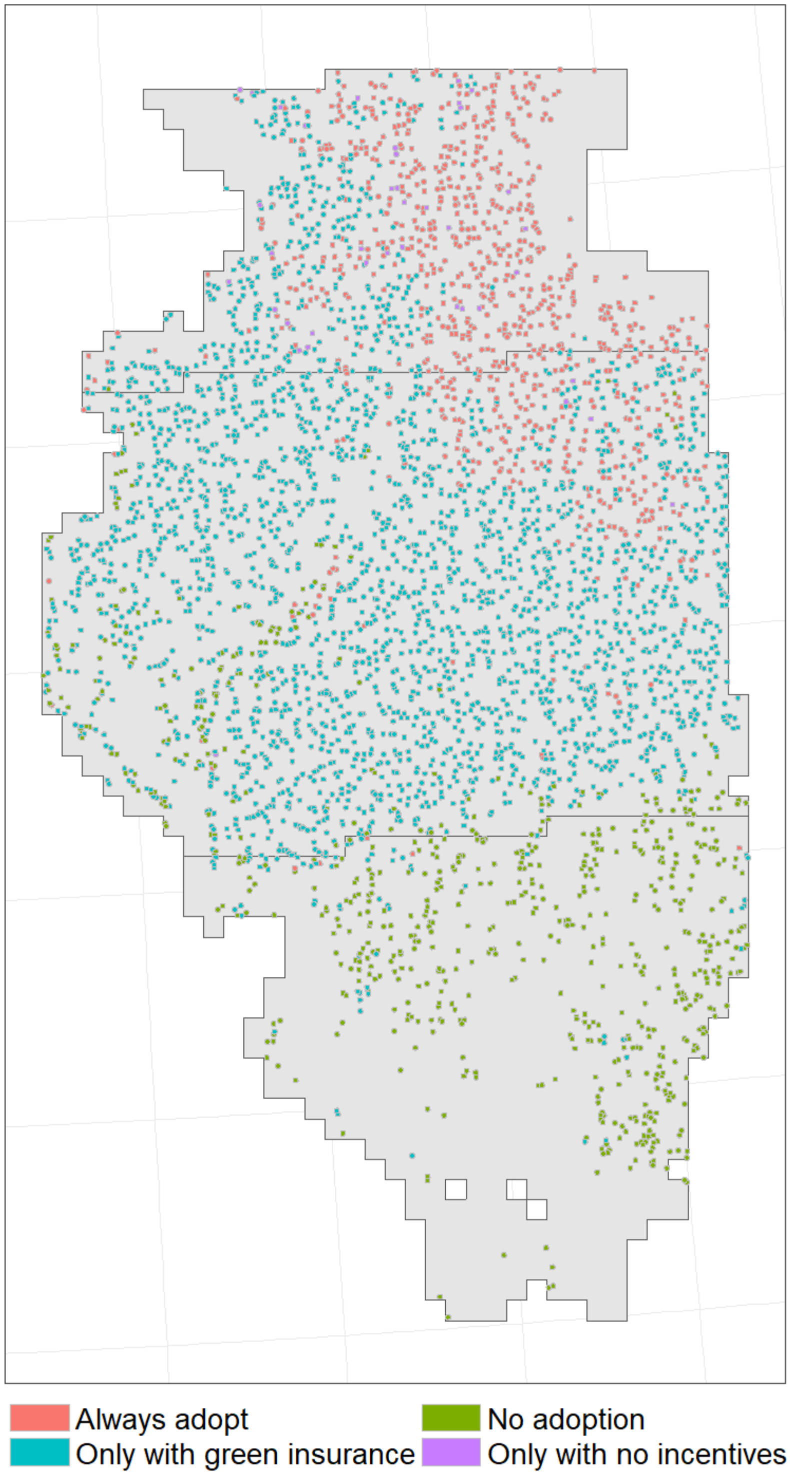


Figure 5. VRT adoption status across fields under green insurance

Notes: "Always adopt" and "No adoption" denote the fields always adopt and never adopt VRT no matter green insurance is in place or not, respectively. "Only with no incentives" signifies that the fields only adopt VRT when green insurance is not in place. "Only with green insurance" represents the fields only adopt VRT when green insurance is in place.

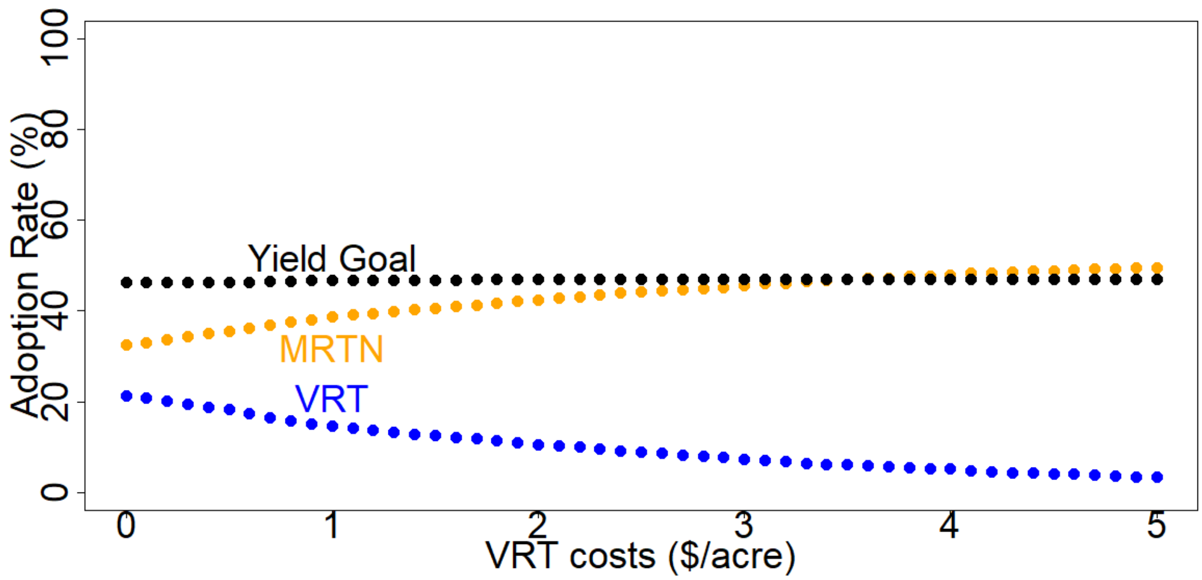


Figure 6. Adoption rates under different VRT cost scenarios

Appendix Tables and Figures

Table A1. Summary Statistics of variables in the regressions

Variable	Mean	Std. Dev.	Min	Pctl. 25	Pctl. 75	Max
Corn Yield (bu/acre)	168.6	41.19	0.0	140.0	202.2	241.6
N leaching rate (N lb/acre)	36.44	30.40	0.00	14.81	50.50	320.20
N application rate (N lb/acre)	142.75	84.95	0.00	71.37	214.12	285.50
Planting date (Julian date)	103.7	4.1	89.0	101.0	106.0	113.0
Water holding capacity (mm)	256.4	43.4	81.0	232.0	283.0	568.0
Sand content (0 – 20 cm) (%)	10.73	14.56	1.00	4.00	8.06	96.00
Clay content (0 – 20 cm) (%)	25.12	6.45	1.50	21.61	30.74	57.00
Total precipitation in period 1	218.3	73.7	50.0	164.0	263.0	903.0
Total precipitation in period 2	157.8	74.5	12.0	102.0	202.0	621.0
Total precipitation in period 3	117.0	61.9	6.0	67.0	157.0	431.0
Total precipitation in period 4	85.2	57.4	0.00	40.0	117.0	390.0
Total precipitation in period 5	61.2	38.9	0.00	33.0	81.0	411.0
Total precipitation in period 6	403.1	112.3	140.0	316.0	477.0	1010.0
Average air temperature in period 1	1.01	2.28	-6.50	-0.56	2.58	8.96
Average air temperature in period 2	14.61	1.08	11.35	13.96	15.36	18.55
Average air temperature in period 3	21.01	1.31	17.34	20.16	21.77	24.66
Average air temperature in period 4	23.54	1.41	18.73	22.68	24.52	27.71
Average air temperature in period 5	23.90	2.07	17.24	22.34	25.43	30.17
Average air temperature in period 6	11.60	2.11	4.48	10.23	13.11	17.97
Average solar radiation in period 1	12.05	0.54	10.30	11.69	12.38	14.24
Average solar radiation in period 2	19.75	1.03	16.72	19.04	20.41	23.63
Average solar radiation in period 3	20.81	1.15	16.69	19.98	21.67	24.42
Average solar radiation in period 4	20.65	1.46	16.07	19.70	21.60	25.32
Average solar radiation in period 5	19.80	1.34	15.17	18.88	20.81	23.56
Average solar radiation in period 6	11.52	0.77	8.39	11.05	12.08	14.17
Soil water content at V5	623.0	93.1	152.7	606.3	674.3	1004.1
Soil Organic Carbon at V5 (0 – 20 cm)	2.05	0.69	0.29	1.45	2.62	5.81
Soil N (NO_3 and NH_4) at V5 (0 – 60 cm)	49.28	29.01	1.50	28.10	65.10	270.60

Notes: The summary statistics are presented for a total of 478,6650 observations. Period 1 to 6 are the periods from January 1 to planting, from planting to corn vegetable state V5, from V5 to reproductive stage R1, from R1 to R3, from R3 to R6, and from harvest to December 31. V5 represents 5 leaf collars present, R1 denotes one or more silks extends outside of husk leaves, R3 signifies kernels filled with “milky” fluid, and R6 indicates kernels at maximum dry matter accumulation. (Iowa State University Extension and Outreach, n.d.)

Table A2. The summary statistics of price variables

Variable	Mean	Std. Dev.	Min	Pctl. 25	Pctl. 75	Max
Corn Price ($/bushel)	4.652	1.332	3.120	3.585	6.055	7.580
Nitrogen Price ($/lb N)	0.4457	0.1644	0.2450	0.3180	0.5062	0.9884
Corn/N price ratio	10.826	1.990	6.025	9.501	12.401	15.687

Notes: The summary statistics are presented for a total of 183 observations.

Table A3. Regression results

	(1) Corn Yield		(2) N leaching	
	Estimate	Std. Error	Estimate	Std. Error
N application rate	1.28***	0.008	0.34***	0.008
N application rate ^2	-0.0017***	0.000001	0.0008***	0.000001
Number of Controls	375		375	
Observations	4,786,650		4,786,650	
Adjusted R-squred	0.8903		0.8169	
Residual standard error	13.65		14.58	

Notes: The number of controls presented here reflects those excluded from the table but included in the regression analysis. The omitted factors in this table encompass planting date, soil characteristics, weather conditions, as well as the squares and interaction terms of these variables.

Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

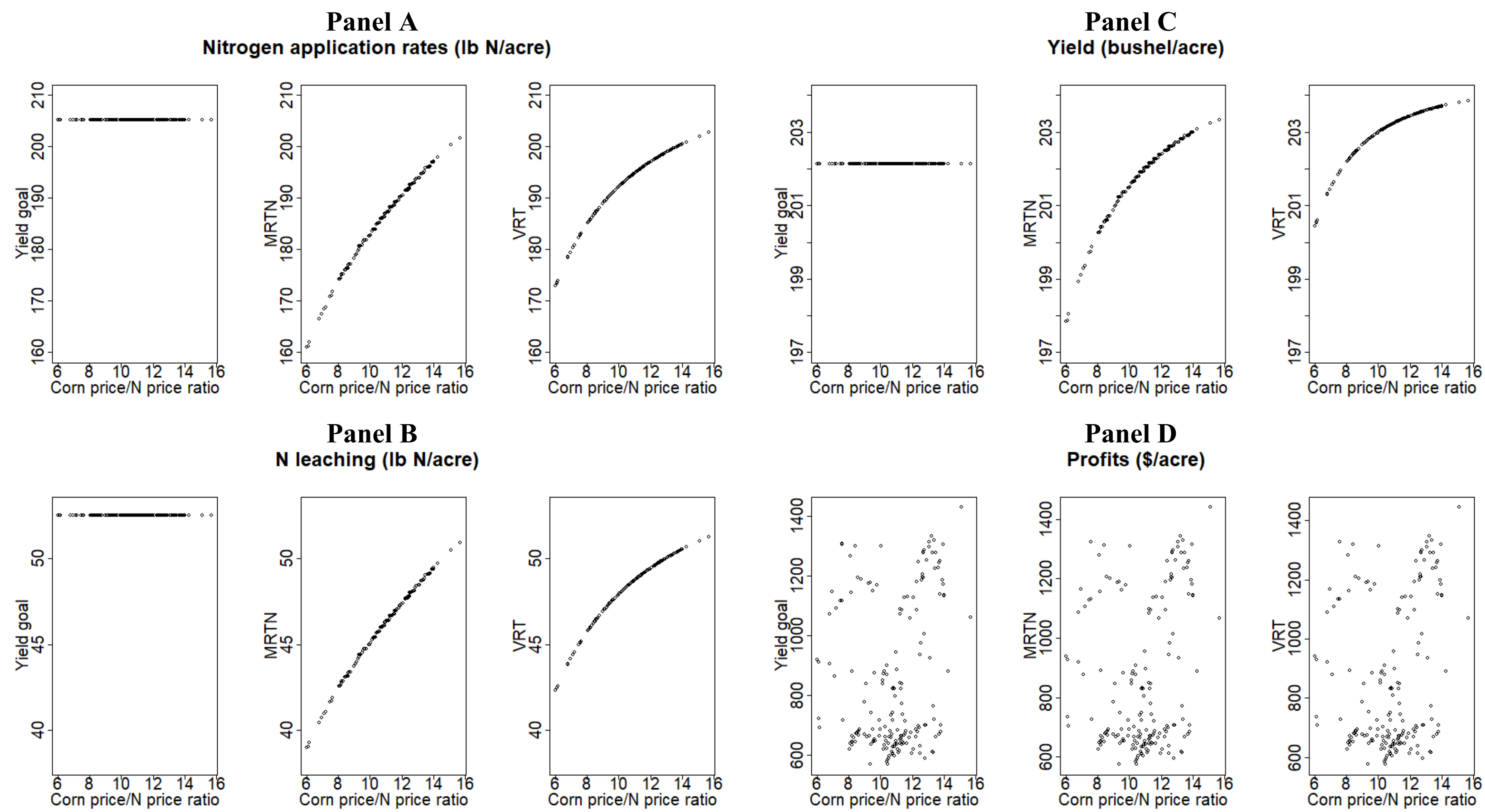


Figure A1. N application rate, N leaching, yield, and profits across corn/N price ratios

Notes: Each dot in panel A represents the mean over 4236 fields across Illinois of N application rates recommended by yield goal approach, MRTN, and VRT at the given corn price and N price ratio. Similarly, each dot in panel B, panel C, and panel D represents the mean of corresponding N leaching, yield, and profits, respectively.

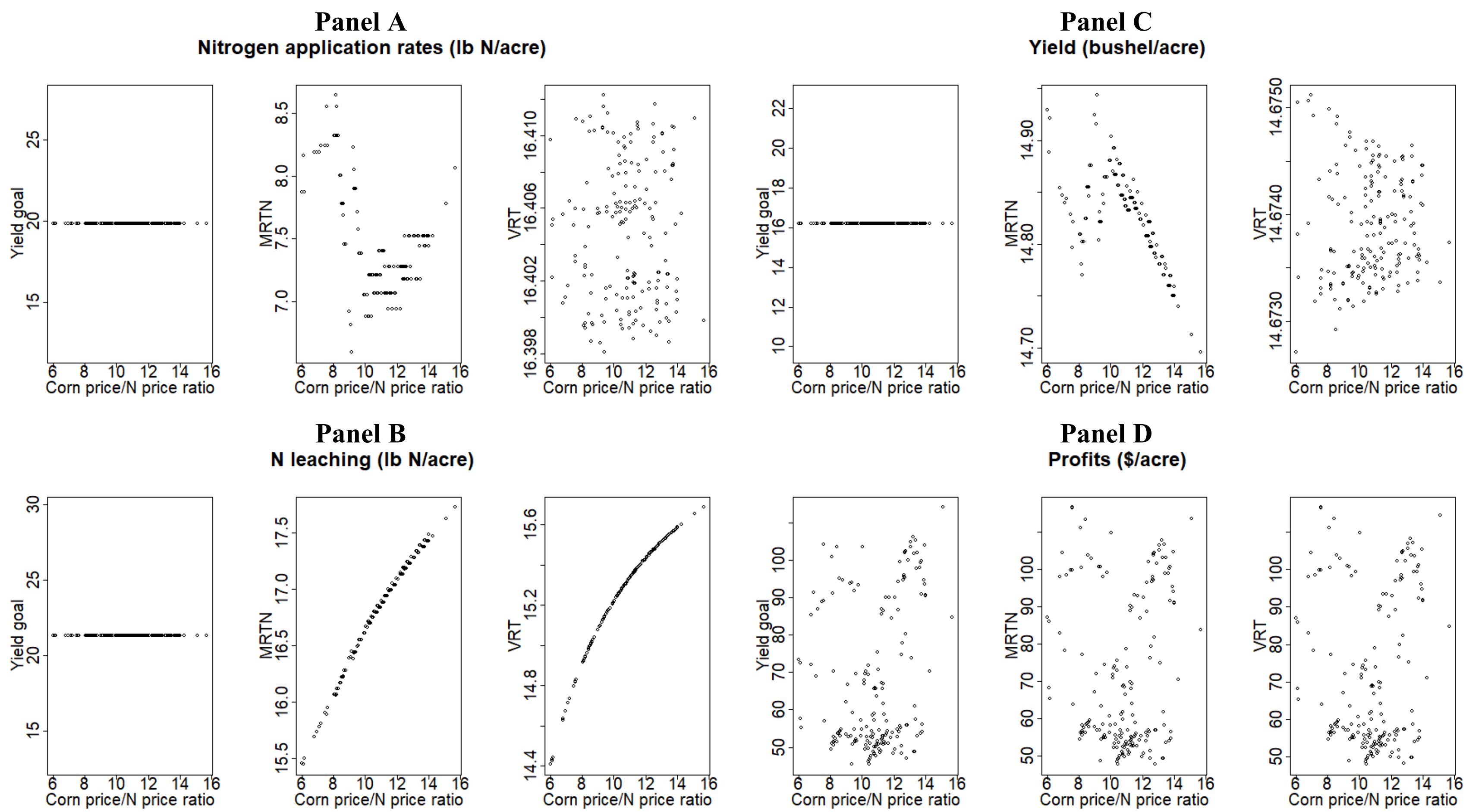
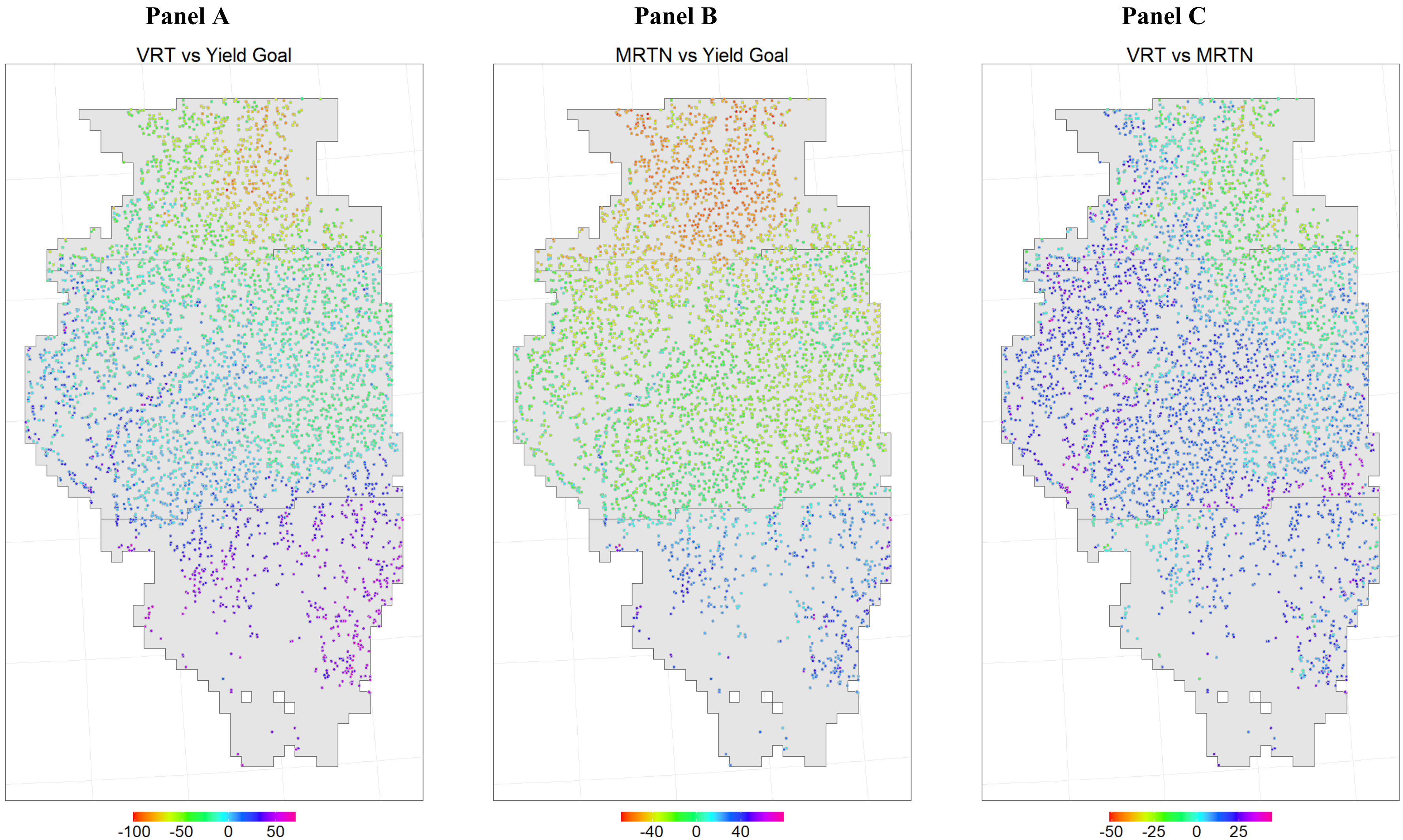


Figure A2. Standard deviations of N application rate, N leaching, yield, and profits across corn/N price ratios

Notes: Each dot in panel A represents the standard deviation over 4236 fields across Illinois of N application rates recommended by yield goal approach, MRTN, and VRT at the given corn price and N price ratio. Similarly, each dot in panel B, panel C, and panel D represents the standard deviation of corresponding N leaching, yield, and profits, respectively.

Differences in N application rates (lb N/acre)



Differences in standard deviations of N application rates (lb N/acre)

Panel A **Panel B** **Panel C**

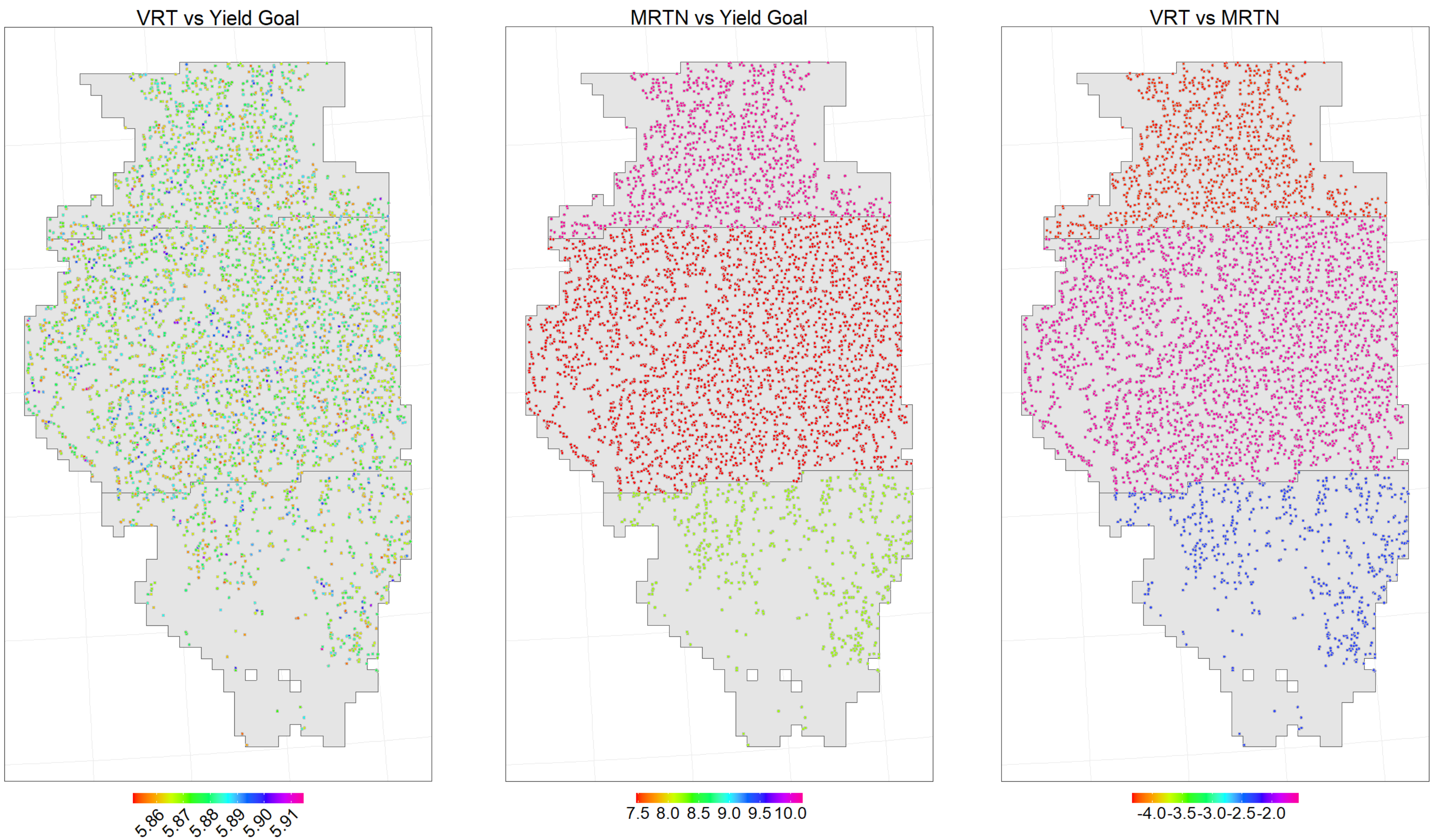
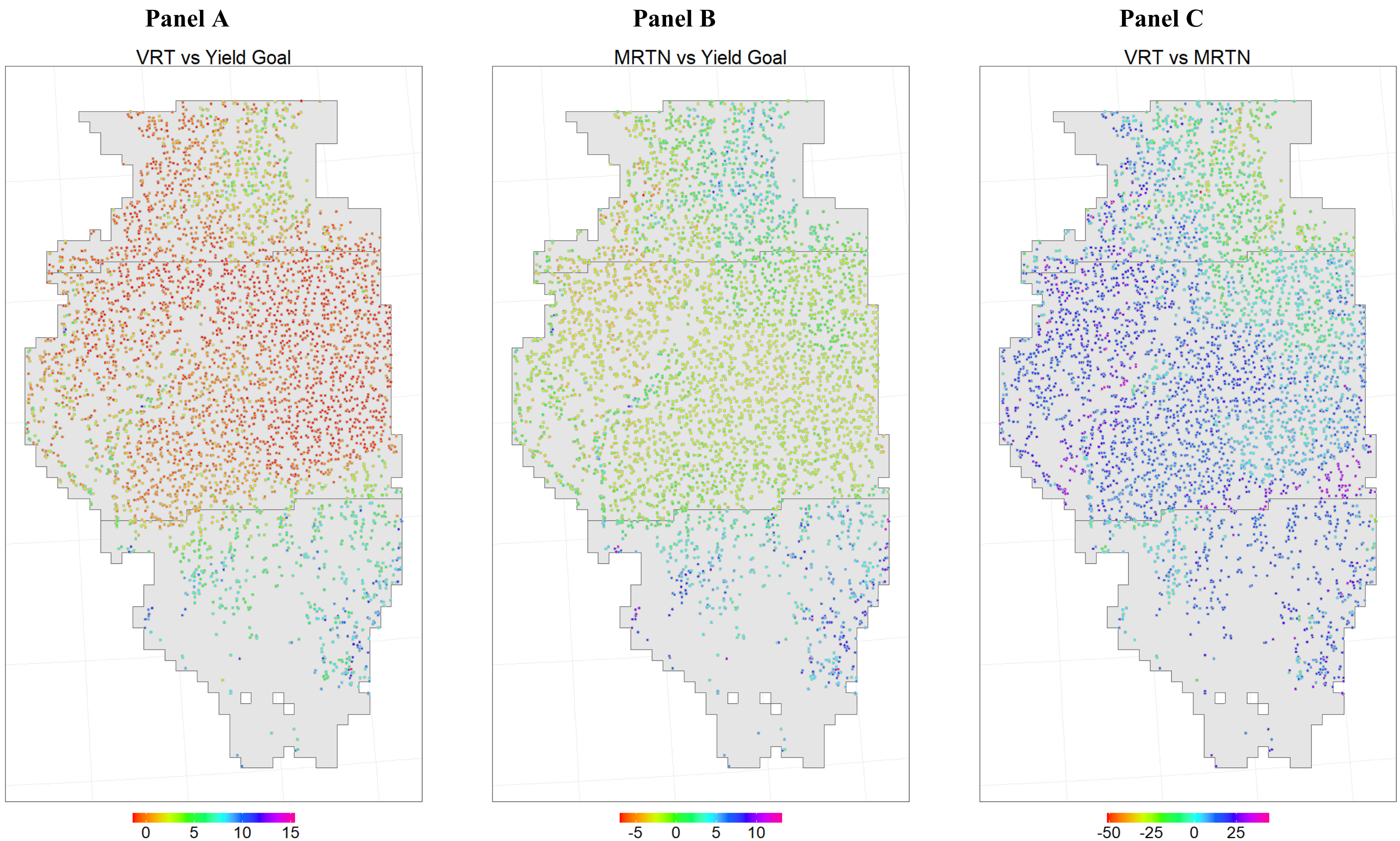


Figure A3. Differences in N rates and their standard deviations

Notes: The dots in panel A, panel B, and panel C represent the differences in mean and standard deviation of N application rates between VRT and the yield goal approach, MRTN and yield goal approach, and VRT and MRTN over 183 combinations of corn and N prices, respectively, at 4236 fields across Illinois.

Differences in yields (bushel/acre)



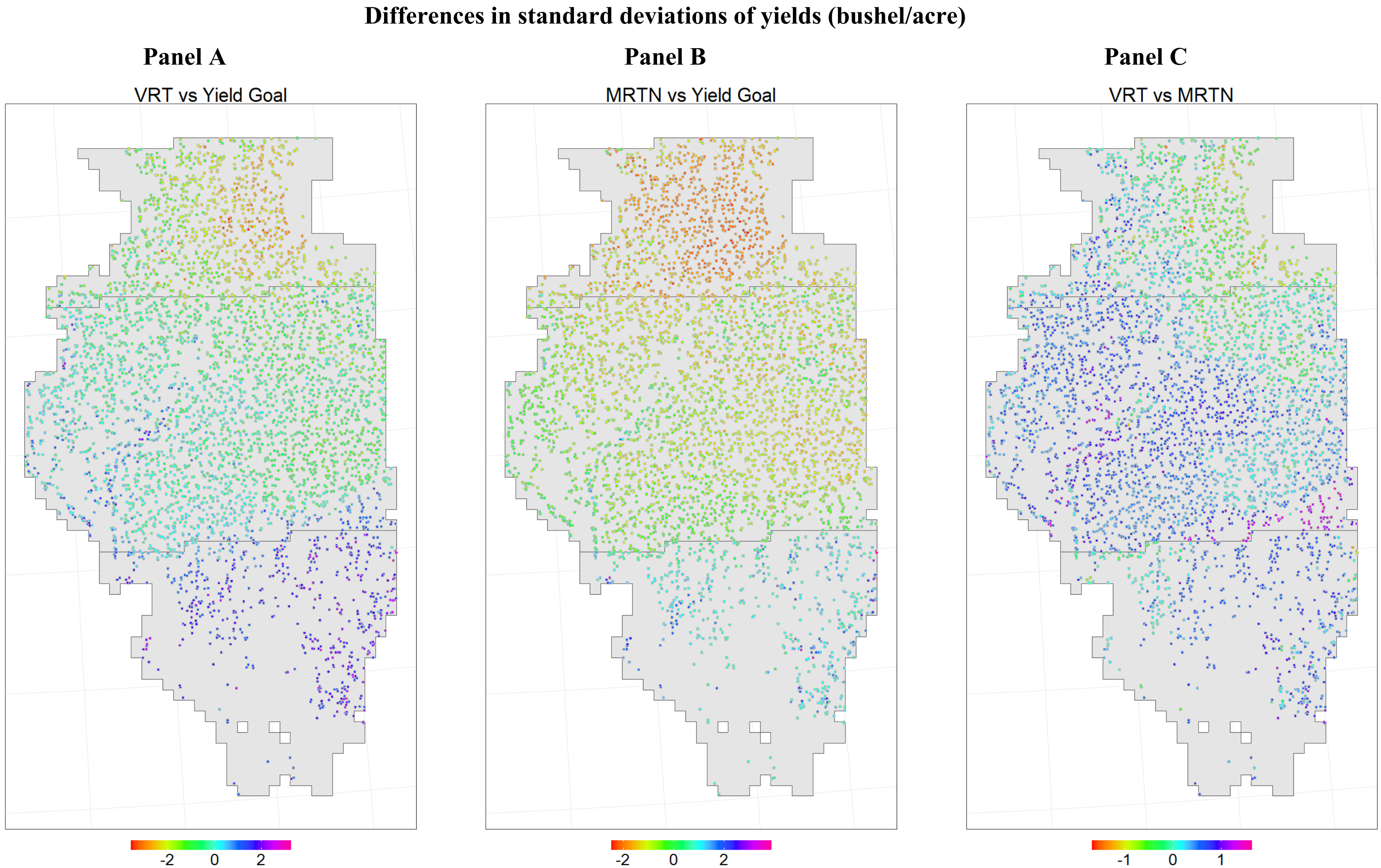
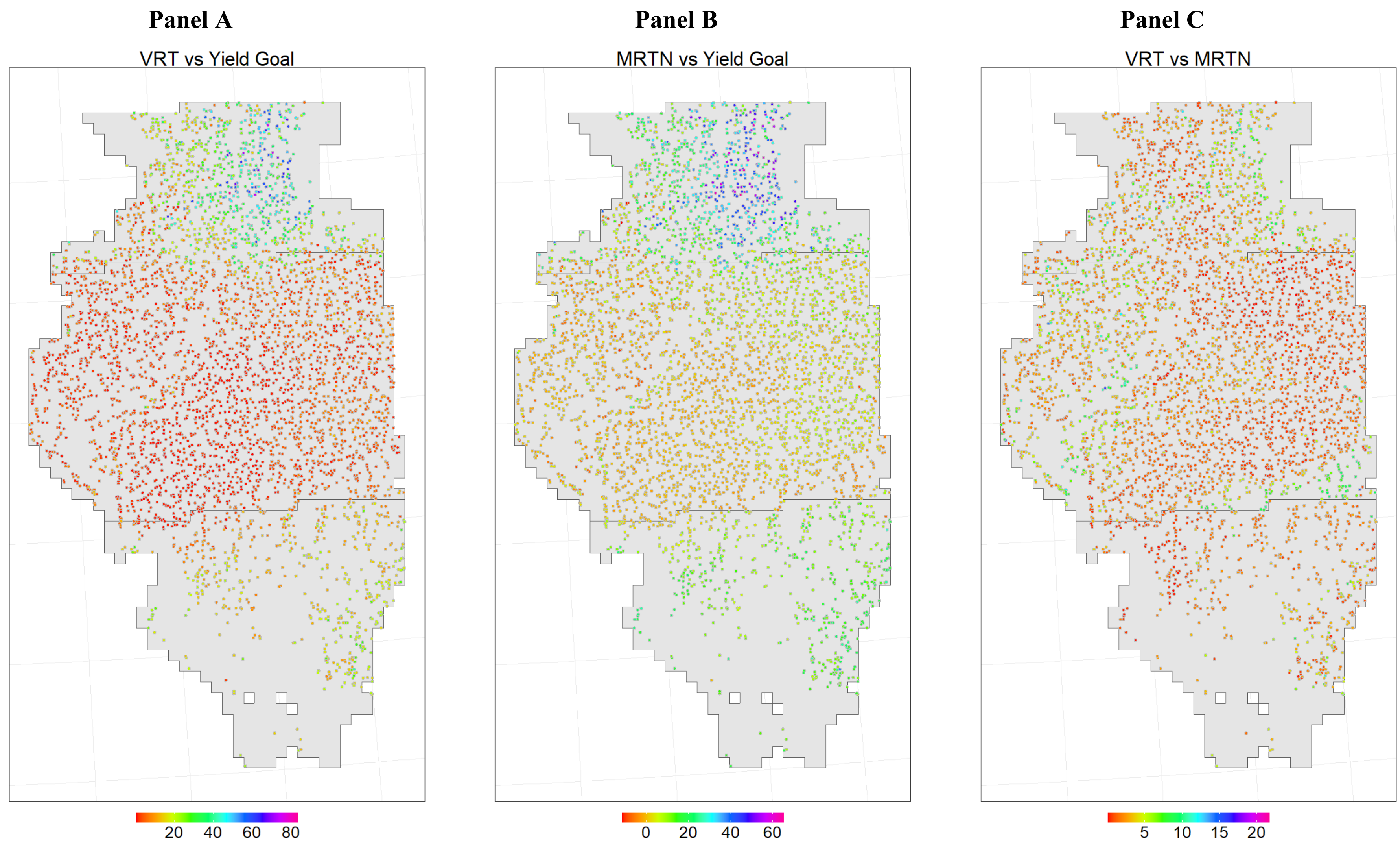


Figure A4. Differences in yields and their standard deviations

Notes: The dots in panel A, panel B, and panel C represent the differences in mean and standard deviation of expected corn yields obtained using the recommended N rates between VRT and yield goal approach, MRTN and yield goal approach, and VRT and MRTN, respectively, over 183 combinations of corn and N prices and 15 years of weather conditions, at 4236 fields across Illinois.

Differences in profits ($/acre)



Differences in standard deviations of profits ($/acre)

Panel A **Panel B** **Panel C**

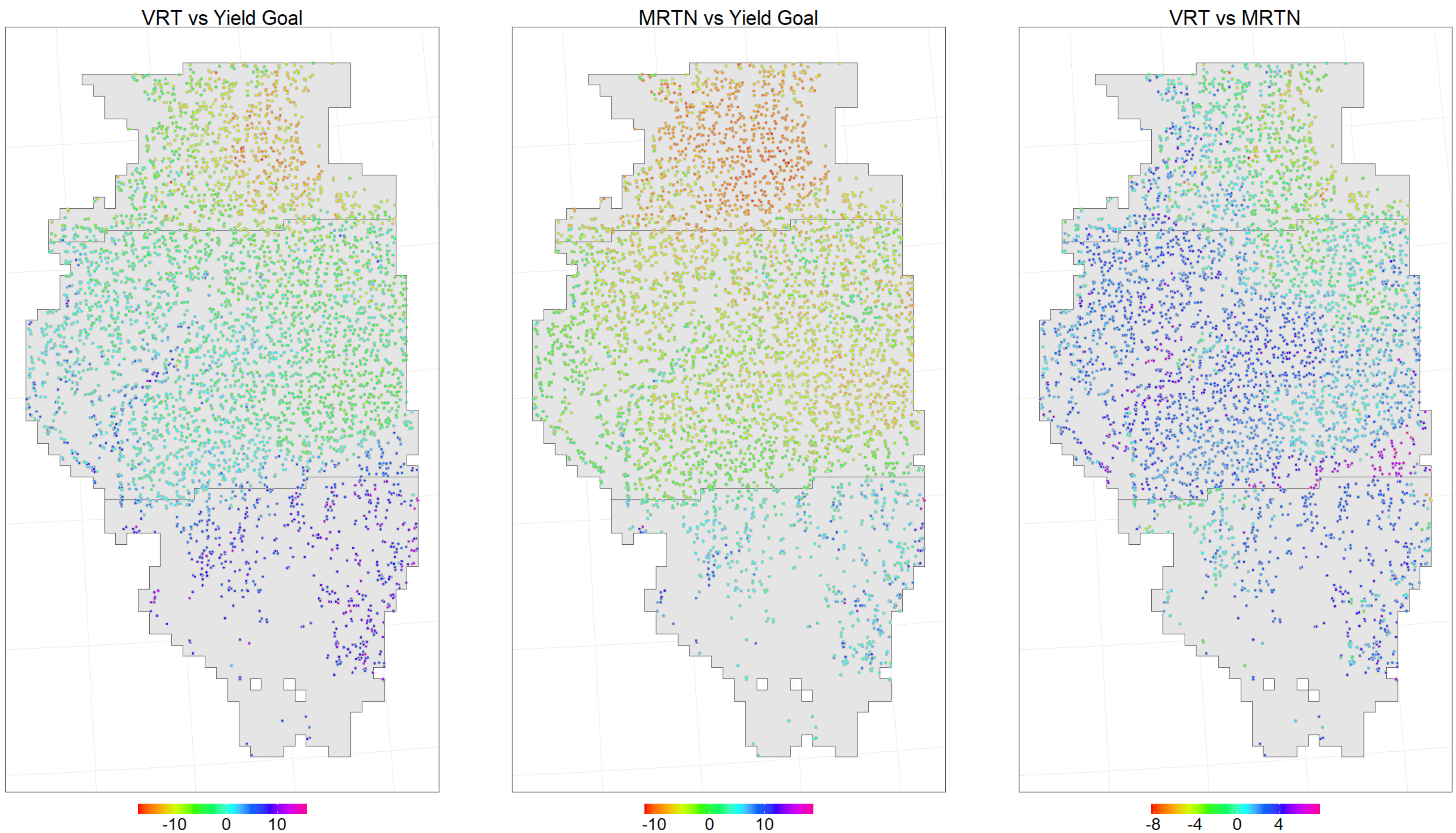
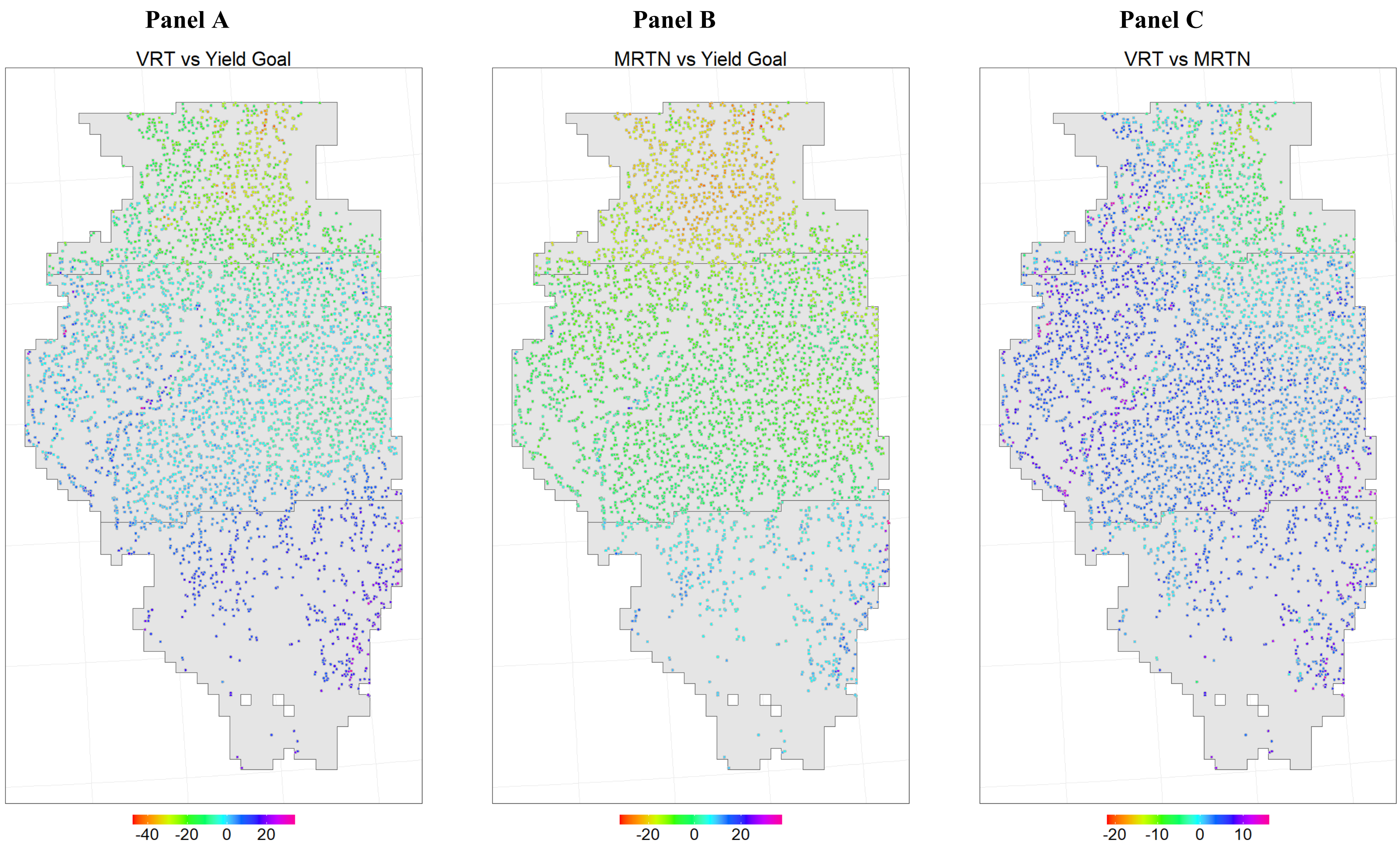


Figure A5. Differences in profits and their standard deviations

Notes: The dots in panel A, panel B, and panel C represent the differences in mean and standard deviation of expected profits obtained using the recommended N rates between VRT and yield goal approach, MRTN and yield goal approach, and VRT and MRTN, respectively, over 183 combinations of corn and N prices and 15 years of weather conditions, at 4236 fields across Illinois.

Differences in N leaching rates (lb N/acre)



Differences in standard deviations of N leaching rates (lb N/acre)

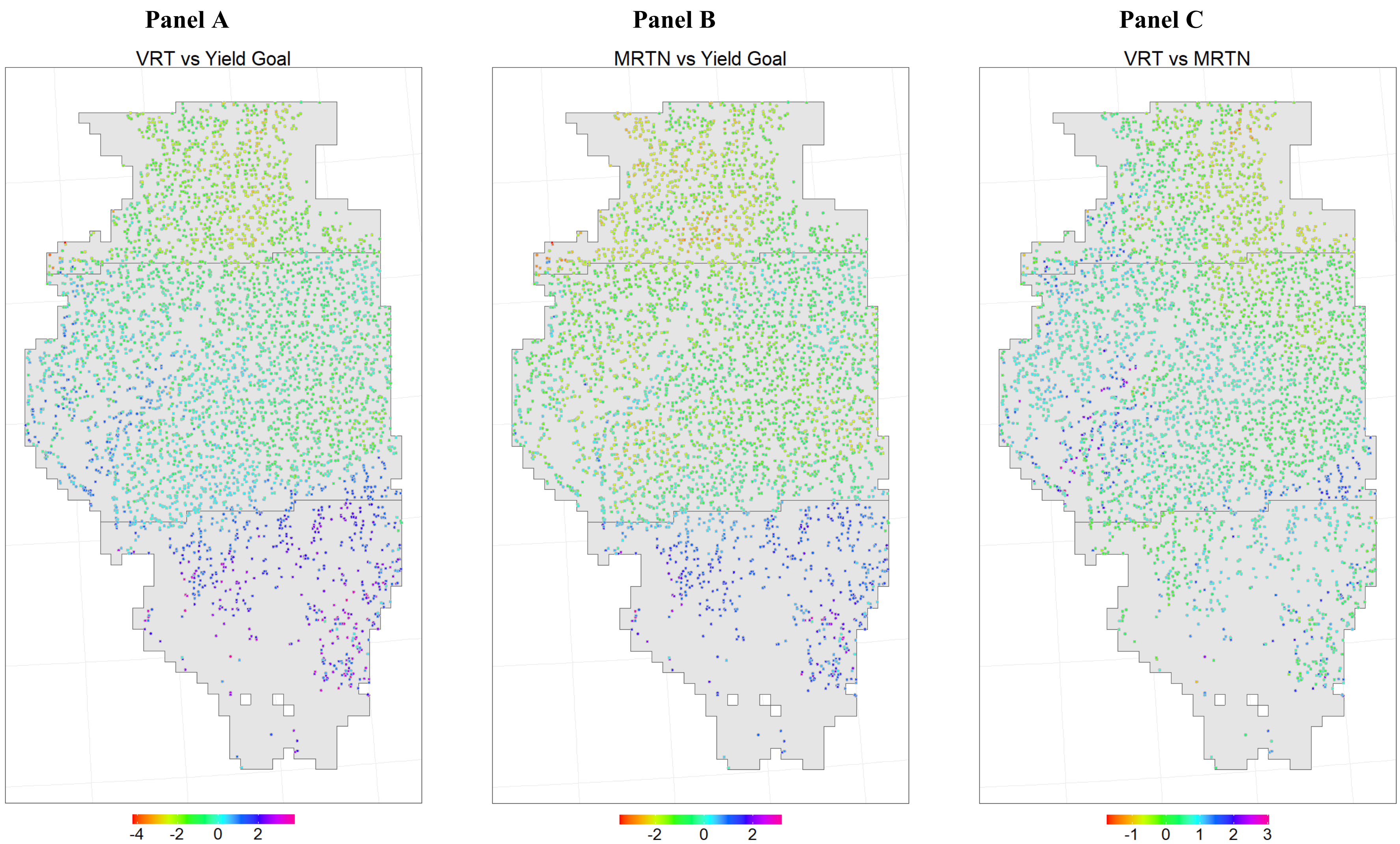


Figure A6. Differences in N leaching rates and their standard deviations

Notes: The dots in panel A, panel B, and panel C represent the differences in mean and standard deviation of expected N leaching obtained using the recommended N rates between VRT and yield goal approach, MRTN and yield goal approach, and VRT and MRTN, respectively, over 183 combinations of corn and N prices and 15 years of weather conditions, at 4236 fields across Illinois.