Explaining Farmer Decision about N Application Rates: Technological and Behavioral Drivers

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Abstract

Many U.S. farmers apply nitrogen fertilizer at rates higher than the recommended profit-maximizing level, causing potential profit losses and environmental concerns. This study investigates the technological and behavioral drivers behind overapplication, evaluates the benefits of adopting variable rate technology (VRT), and explores the social optimum N rates. Using a biophysical model simulated dataset with over four million observations across 4,236 fields and 2,758 soil types in Illinois over 30 years, we compare optimal N rates and the corresponding utilities across three production functions, four weather beliefs, five objective functions, and two application methods. We find that farmers tend to overapply N when they are optimistic about the weather, and their risk preferences have no negative impact on N rates. However, farmers with other weather beliefs decrease N rate as their risk-averse level increases. Moreover, weather beliefs have a greater impact on N application rates than knowledge of spatial variation for utility maximizers. Additionally, we show that for highly risk-averse farmers, being optimistic about the weather and applying about 10 pounds per acre more N than those with random weather beliefs results in $6.3 per acre higher realized profits. Adopting VRT can decrease utility maximizers' realized profits by $0.8 - $4.8 per acre given different weather beliefs. The average social optimum N rate is approximately 63 pounds per acre less than the economic optimum N rate for farmers assuming random weather conditions.

1 Introduction

In 2024, farmers in the US produced approximately 31% of the world's corn (USDA-FAS, 2025). 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). Nevertheless, Sellars et al. (2020) found that about two-thirds of corn fields in Illinois received N fertilizer rates that are higher than the extension recommended rates. Additionally, Houser (2022) noted that over one-third of the farmers interviewed in Indiana, Iowa, and Michigan applied N at levels surpassing the economically optimal rate by at least 5 pounds per acre. Moreover, Wade et al. (2015) reported that farmers applied more N than the agronomic optimal rates on 36 percent of corn acres in the US. Furthermore, Zhang et al. (2015) highlighted the generally low global nitrogen use efficiency, suggesting widespread overuse. However, overapplication of N may reduce farmers' profits and also contribute to water contamination (Almasri & Kaluarachchi, 2004; Savci, 2012) and greenhouse gas emissions (Peel et al., 2013; Savci, 2012). The social costs associated with N fertilizer can be substantial, varying between \$1.7 and \$5.6 per pound of N throughout the state of Illinois (Goodkind et al., 2023), while in Europe, these costs range from \$0.21 to \$3.73 per pound of N (Van Grinsven et al., 2013). At their peak, the social costs of nitrogen can reach up to ten times the average price of N over multiple years.

The overuse of N could be due to technological reasons, including the use of different production functions compared to those used by agronomist or extension personnel and concerns regarding the accuracy of the recommendations based on regional average conditions. Sheriff (2005) suggested farmers may use quadratic production functions instead of linear plateau functions that are used by extension officers, which provide higher N application

recommendations. Additionally, the production functions used by farmers imply higher yield response to N, which also suggesting a higher N rate (SriRamaratnam et al., 1987). Besides, farmers may not trust that the recommendations based on regional average conditions can be suitable for their own soil and weather conditions (Sheriff, 2005), as following those rates can lead to overapplication in some parts of the field while underapplication in others. However, the adoption of variable rate technology (VRT) which enables variable rate fertilizer application across fields based on site-specific information remains relatively low at 28.2% (McFadden et al., 2023). This may be explained that risk aversion farmers are less willing to adopt VRT because of the greater variability of profits under uncertain weather and soil conditions (Isik & Khanna, 2003).

Additionally, many studies have focused on potential behavioral reasons that may lead to the overapplication of N, including farmers' perceptions of weather conditions and their risk preferences. Babcock (1992) suggests that farmers who are optimistic about the weather conditions tend to overapply N, and N is a risk-reducing input for risk-neutral farmers. A risk-neutral farmer who overapply N believes that overapplication of N can lead to higher expected profits across years, since the expected gains in good weather years can offset the expected losses in bad weather years (Sheriff, 2005). Moreover, due to concerns over yield penalties under unpredictable weather and soil conditions, risk-averse farmers may overapply N as an insurance to reduce downside risks (Babcock & Hennessy, 1996). Furthermore, some observational studies suggest that farmers believe N is risk reducing (SriRamaratnam et al., 1987) and overapplication of N can be used as a risk mitigation strategy (Houser, 2022). However, many production studies indicate that risk-averse farmers should reduce N rates because N is risk increasing (Chai et al., 2023; Rajsic et al., 2009). The mixed findings might be because these studies were based on

conceptual analysis or field trials conducted across different sites and time periods, which have not been well understood and explained.

In addition to research focusing on the overapplication of N relative to economic optimum levels, Gourevitch et al. (2018) and Van Grinsven et al. (2013) argue that social optimum N application rates should be lower than economic optimum rates. However, farmers seldom account for social costs when making N management decisions, as such information is typically not accessible to them, and they may lack concern for the environmental impacts associated with N use. Considering the significant social costs linked to N, it is valuable to investigate the social optimum N rates and simulate how farmers might respond under scenarios involving very low corn-to-N price ratios.

This study seeks to understand farmers' decisions regarding N application rates and provides insights on how to incentivize farmers to reduce N applications. Initially, we aim to investigate how technological and behavioral factors influence N application decisions and clarify the inconsistencies observed in prior findings. Next, we intend to assess the benefits associated with adopting VRT for nitrogen applications. Finally, we will analyze the social optimum levels of N application. To meet these objectives, we carried out an extensive analysis employing three distinct production functions, two N application methods, four different farmers' beliefs on weather conditions, and five objective functions.

Our study utilizes a simulated dataset (Mandrini, Archontoulis, et al., 2022), which includes over four million observations spanning a period of 30 years, encompassing 4236 fields of 98.9 acres each and representing 2744 soil types (mukey) across the northern, central, and southern regions of Illinois. This comprehensive dataset helps overcome the limitations of earlier studies that were largely theoretical or based on field trials conducted at limited sites and over short

durations. Previously, this dataset has been employed to compare the economic and environmental impacts of static versus dynamic N recommendation systems (Mandrini, Pittelkow, et al., 2021), assess various N management approaches using economic and environmental metrics (Mandrini, Bullock, et al., 2021), and estimate the effectiveness of policy interventions designed to reduce N use (Mandrini, Pittelkow, et al., 2022). However, none of these prior investigations considered the influence of risk attitudes of farmers on N application rates that are addressed in the current study.

The three production functions employed in this research include the general quadratic, linear plateau, and quadratic plateau production functions. The general quadratic function is derived by regressing nitrogen (N) application rates on corn yield using all available observations, incorporating weather and soil-related exogenous variables as well as interaction terms. For the linear plateau and quadratic plateau functions, data from each soil within each field are analyzed using a random effects model to generate distinct production functions tailored to various soil types.

Two nitrogen application strategies are considered in the analysis: uniform application at the field level and VRT guided by site-specific information at soil level. Field-level optimal N application rates are calculated based on aggregated production functions, which are obtained by averaging soil-level functions weighted by respective soil areas. Soil-level optimal N rates, in contrast, are derived directly from the corresponding soil-level production functions. These soil-specific optimal N rates can also be aggregated to the field level using soil area weights, allowing for direct comparison with the field-level optimal N rates.

When making decisions regarding N applications, farmers typically are uncertain about the upcoming year's weather conditions. We consider four different farmer beliefs about weather

variability: uniform distribution, normal distribution, left-skewed beta distribution, and right-skewed beta distribution. A uniform distribution implies that farmers perceive past weather patterns as occurring randomly with equal likelihood. A normal distribution reflects an expectation centered around average historical weather conditions. A left-skewed beta distribution represents a highly optimistic outlook, where farmers expect the most favorable weather conditions with the highest probability. Conversely, a right-skewed beta distribution indicates a pessimistic view, where the least favorable weather is anticipated to be most likely.

In evaluating N application strategies, we consider various decision-making objectives: yield maximization, utility maximization (both with and without accounting for the social costs of nitrogen), and value maximization (also evaluated with and without inclusion of these social costs). To model utility maximization, we apply the certainty equivalent method and assume risk parameters ranging from 0 to 0.01. A parameter of 0 means farmers are risk neutral, while a value of 0.01 corresponds to a risk premium amounting to approximately 40% of the standard deviation of revenue (Babcock & Hennessy, 1996). For value maximization, we employ cumulative prospect theory and incorporate four distinct combinations of risk and loss aversion parameters as specified in Babcock (2015, p. 201).

We find that linear plateau production functions offer the best fit to the data, and when linear production functions are aggregated from the soil level to the field level, they transform into quadratic functions, aligning with earlier research by Berck & Helfand (1990). Moreover, our results indicate that, when social costs of nitrogen (N) are not considered, linear plateau functions yield lower N application rate recommendations compared to quadratic functions for both yield maximizers and utility maximizers. However, this trend reverses, which means higher N rates are suggested by linear plateau when the social costs of N are factored in, particularly

under conditions of very low corn-to-N price ratios. The average field-level production functions also vary significantly across years, and the optimal N rates during the most favorable weather year are not necessarily the highest observed. In comparing uniform application methods with VRT, we find that, on average, total nitrogen fertilizer usage is quite similar between the two approaches. Nevertheless, for certain fields, the difference in recommended N rates at the soil level can exceed 100 pounds per acre, shedding light on farmers' concerns about the appropriateness of generalized recommendations for their specific fields.

Aligned with Babcock's (1992) research, which utilized conceptual framework and simulation analysis, our empirical results show that optimistic farmers tend to apply nitrogen at higher rates than their counterparts who hold different weather-related expectations for utility maximizers. Additionally, our study reveals that risk-averse farmers either maintain or increase their nitrogen application rates when they hold optimistic weather outlooks, whereas they tend to reduce these rates when their weather beliefs are not optimistic. This finding provides insight into the apparent contradiction where farmers tend to overapply nitrogen, yet some studies indicate that nitrogen increases risk. The discrepancy could arise from variations in the assumptions about weather patterns; prior research often assumes uniform weather conditions, whereas our analysis also incorporates a left-skewed beta distribution.

Some risk-averse farmers may be optimistic about the weather and consequently worry about insufficient nitrogen supply under favorable growing conditions. This behavior is supported by survey findings indicating that risk-averse farmers prefer low probabilities of high yields over low probabilities of crop failure, even when expected yields are equal (Paulson & Babcock, 2010). Furthermore, our analysis shows that, regardless of their optimization goals or risk preferences, optimistic farmers consistently achieve the highest expected utility levels compared

to those with alternative weather beliefs. This is consistent with the argument in Sheriff (2005) that farmers believe that overapplication of N can lead to higher expected average profits across good and bad years. Moreover, our findings indicate that farmers who hold an optimistic view about the weather and apply more N fertilizers uniformly than those based on other weather beliefs can get almost equivalent or even higher realized profits on average across years.

In addition, our findings suggest that considering corn and N price ratios in decision-making has the biggest impact on N rates. We also find that farmers' beliefs about weather have a bigger impact on N application rates than the application method used for profit-maximizers. Moreover, heterogeneous impacts of these factors are found across more than 4,000 fields across Illinois state.

Our findings suggest that the realized profits for utility maximizers are higher than those for yield maximizers. The rationale for some farmers to overapply N to maximize yield might be to get a higher Actual Production History (APH) to receive higher compensation when experiencing extreme bad weather events. This may explain why some farmers overapply N even if they have crop insurance though studies show that N and crop insurance are substitute (Babcock & Hennessy, 1996).

Regardless of whether farmers aim to achieve higher APH or being optimistic regarding weather conditions, their tendency to overapply nitrogen (N) serves as a strategy to seek upside potential, aiming for higher yields or profits while simultaneously lower downside risks under crop insurance. This behavior highlights two potential policy approaches to reduce N application rates: first, directly compensating farmers for profit losses and possible reductions in insurance payouts that may result from lowering N usage; second, offering insurance coverage that protects

against the risk of falling short of upside yield potential, which may be calculated based on the five highest yields recorded over the past decade.

To prevent moral hazard, it would be essential to require participating farmers to adhere to recommended N application rates and provide verifiable evidence of compliance. Calculating individual compensation would likely involve predictive models estimating counterfactual yields, which could raise concerns among farmers about fairness and accuracy. Additionally, some farmers might resist standardized compensation schemes based on average conditions, preferring more tailored arrangements. Therefore, the effectiveness of such a policy would hinge on farmers' willingness to disclose their current N application practices and their confidence in the yield prediction models used. Regarding the insurance mechanism designed to safeguard against upside yield risks, the reference point can be obtained from APH. However, key challenges would include determining appropriate coverage levels and premium rates, as well as accounting for the long-term economic impacts associated with reduced N application. Further research is necessary to refine and develop these policy tools effectively.

We also investigated the potential benefits of using VRT by comparing the expected and realized profits associated with VRT and uniform application methods. We find that using VRT can lead to an increase of $3.5 per acre and a reduction of $3.9 per acre in realized profits across years, respectively, for yield maximizers who assume a uniform and an lbeta distribution of weather conditions. Our findings suggest that while adopting VRT could potentially enhance expected profits, it might lead to lower realized profits. Specifically, when farmers are risk-averse and weather conditions are assumed to follow uniform or rbeta distribution, those using VRT may experience $0.8 or $4.8 per acre lower realized profits compared to those employing the uniform application method. In our analysis, variable rates were determined based on

historical site-specific data, which may not align well with the nitrogen requirements under actual weather conditions. This may potentially result in greater discrepancies than those seen with uniform rates derived from average data. This indicates that the effectiveness of VRT can be compromised under uncertainties related to weather and soil conditions, which is consistent with findings from Isik & Khanna (2003). Consequently, combining real-time recommendation systems with VRT may be a more effective approach to enhance fertilizer application efficiency while reducing nitrogen runoff and greenhouse gas emissions.

When accounting for the social costs of N, the expected utility and realized profits decline significantly by around $250 per acre compared to scenarios that rely solely on the market price of N. This divergence is primarily due to lower crop yields resulting from reduced N application rates. From both policy and food security perspectives, it is not practical to expect farmers to cut N usage to reach a social optimum level. Instead, enhancing nitrogen use efficiency could offer a mutually beneficial outcome for both farmers and the society. Improving N efficiency could involve strategies such as genetic advancements in crops, selecting appropriate fertilizer types, optimizing application timing, and employing precision agriculture techniques guided by real-time data.

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

2 Methods and Data

2.1 Empirical Approach

We incorporate three production functions, consider four farmers' beliefs about weather conditions, employ two application methods, and define five objective functions to

comprehensively account for all potential factors influencing farmers' nitrogen application decisions.

2.1.1 Production functions

The three production functions utilized are: the general quadratic production function given in Equation (1), the linear plateau production function introduced in Equation (2), and the quadratic plateau production function displayed in Equation (3).

$$y_{my}^{gq} = a_{my}^{gq} + b_{my}^{gq}N + c_{my}^{gq}N^2, \quad (1)$$

where y_{my}^{gq} is the crop yield at mukey m and in year y used in general quadratic production function ; $a_{my}^{gq} = \beta_{my}^{gq}X^{gq}$; $b_{my}^{gq} = \gamma_{my}^{gq}X^{gq}$; $c_{my}^{gq} = \delta_{my}^{gq}X^{gq}$; a_{my}^{gq}, b_{my}^{gq}, and c_{my}^{gq} are coefficients which are dependent on the general quadratic transformation of exogenous variables X^{gq}; $X^{gq} = \sum_i x_i + \sum_i x_i^2 + \sum_j \sum_k x_j x_k$ where x includes planting dates, water holding capacity, clay content, sand content, soil water content, soil organic matter, soil N level, precipitation, temperature, and solar radiation; N represents the N application rate.

$$y_{my}^{lp} = \begin{cases} a_{my}^{lp} + b_{my}^{lp}N, N < xs_{my}^{lp} \\ a_{my}^{lp} + b_{my}^{lp}xs_{my}^{lp}, N \geq xs_{my}^{lp} \end{cases}, \quad (2)$$

$$y_{my}^{qp} = \begin{cases} a_{my}^{qp} + b_{my}^{qp}N + c_{my}^{qp}N^2, N < xs_{my}^{lp} \\ a_{my}^{qp} + b_{my}^{qp}xs_{my}^{lp} + c_{my}^{qp}xs_{my}^{lp\ 2}, N \geq xs_{my}^{lp} \end{cases} \quad (3)$$

where y_{my}^{lp} and y_{my}^{qp} is the yield at mukey m and in year y used in linear plateau and quadratic plateau production function, respectively; $a_{my}^{lp} = \beta_{my}^{lp}X^{lp}$; $b_{my}^{lp} = \gamma_{my}^{lp}X^{lp}$; $xs_{my}^{lp} = \theta_{my}^{lp}X^{lp}$; $X^{lp} = \sum_i x_i$; $a_{my}^{qp} = \beta_{my}^{qp}X^{qp}$; $b_{my}^{qp} = \gamma_{my}^{qp}X^{qp}$; $c_{my}^{qp} = \delta_{my}^{qp}X^{qp}$; $xs_{my}^{qp} = \theta_{my}^{qp}X^{qp}$; $X^{qp} = \sum_i x_i$; similarly a_{my}^{lp}, b_{my}^{lp}, xs_{my}^{lp}, a_{my}^{qp}, b_{my}^{qp}, c_{my}^{qp}, and xs_{my}^{qp} are coefficients which are dependent on the linear transformation of exogenous variables x; x include soil water

content, soil organic matter, soil N level, precipitation, temperature, and solar radiation; N represents the N application rate.

2.1.2 Farmers' beliefs about the distribution of weather conditions

We consider four farmers' beliefs about the distribution of weather conditions: uniform, normal, left-skewed beta, and right-skewed beta. The hypothetical distributions are presented in Figure 1. These distributions are based on fifteen weather years from the dataset. The weather year index is the figure presents 15 weather years, and the ranking is based on the highest yield in each year, ordered from the smallest yield to highest yield. Uniform distribution implies that each 15-year weather cycle is equally likely to occur, with a probability of 1/15. The normal distribution is derived by assuming the mean of this distribution is 7, and the standard deviation corresponds to the spread of the weather year index (ranging from zero to fourteen) around this mean. Under this distribution, farmers expect that average weather conditions are the most probable, while extremely favorable or unfavorable weather years have the lowest probabilities. The left-skewed beta distribution is derived by setting the alpha parameter to 8 and the beta parameter to 1, represented as Beta (8,1). Conversely, the right-skewed beta distribution takes the form Beta (1,8), which is the mirror image of the left-skewed version. The left-skewed beta distribution indicates a higher likelihood of experiencing the most favorable weather conditions and a lower chance of encountering the least favorable ones. As a result, farmers who consider the weather distribution to follow a left-skewed beta pattern tend to hold an optimistic view regarding weather conditions. In contrast, the right-skewed beta distribution implies the reverse scenario.

2.1.3 Fertilizer application methods

Two application methods were employed in this research: variable rate technology (VRT) based on soil-specific information and uniform application at the field level. The expected yield at the

field level for these two application methods is specified by equations (4) and (5) for VRT and equations (6) and (7) for uniform application method, respectively.

$$E(y_m) = \sum_{y}^{15} p_{my} f_{my}\ (N, s, w), \tag{4}$$

$$E(y_f^{vrt}) = \sum_{m} a_m E(y_m), \tag{5}$$

where $E(y_m)$ denotes the expected yield at the mukey level with considering the distribution of weather conditions; p_{my} indicates the likelihood of the weather conditions in year y occur at mukey m; $f_{my}\ (N, s, w)$ represents the corn production function at mukey m in year y that is dependent on nitrogen application rate N, soil characteristics s, and weather conditions w; and $E(y_f^{vrt})$ refers to the expected field-level yield under VRT application, calculated as a weighted average of the mukey-level expected yield by using mukey areas within each field as weights.

$$f_{fy}(N, s, w) = \sum_{m} a_m f_{my}\ (N, s, w), \tag{6}$$

$$E\left(y_f^{uniform}\right) = \sum_{y}^{15} p_{fy} f_{fy}\ (N, s, w) \tag{7}$$

where $f_{fy}(\cdot)$ is the aggregated production function of corn at the field level which is the weighted average of mukey-level production functions by using mukey areas within each field as weights; $E\left(y_f^{uniform}\right)$ represents the expected profits at the field level under uniform application with considering the weather distributions; and p_{fy} denotes the probability that the weather conditions in year y occur at field f.

2.1.4 Objective functions

The objective functions specified in this study are yield maximization, profit maximization, utility maximization considering farmers' risk preferences, value maximizations, profit, utility,

and value maximization with considering the social costs of N. The utility maximization is the same as profit maximization when farmers are risk neutral. These objective functions are specified in equations (8) – (14).

$$\max_N E(y), \tag{8}$$

$$\max_N E(\pi) = P_C E(y) - P_N N, \tag{9}$$

$$\max_N E(u) = E(\pi) - \frac{a}{2} var(\pi) = E(\pi) - \frac{a}{2} \times \sum\nolimits_y^{15} p_y (\pi_y - E(\pi))^2, \tag{10}$$

$$\max_N V(\pi) = \sum_{i=-m}^{n} v(x_i) r(p_i), \tag{11}$$

$$v(x) = \begin{cases} \left(\pi_y - E(\pi)\right)^{a_v} & \text{if } \pi_y - E(\pi) \geq 0 \\ -\lambda\left(-\left(\pi_y - E(\pi)\right)\right)^{a_v} & \text{if } \pi_y - E(\pi) < 0 \end{cases}; \; r(p_i) = p_y$$

$$\max_N E(\pi_{soc}) = P_C E(y) - P_N N - P_{soc} N, \tag{12}$$

$$\max_N E(u_{soc}) = E(\pi_{soc}) - \frac{a}{2} var(\pi_{soc}) = E(\pi_{soc}) - \frac{a}{2} \times \sum\nolimits_y^{15} p_y (\pi_{socy} - E(\pi_{soc}))^2, \tag{13}$$

$$\max_N V(\pi_{soc}) = \sum_{i=-m}^{n} v(x_i) r(p_i), \tag{14}$$

$$v(x) = \begin{cases} \left(\pi_{socy} - E(\pi_{soc})\right)^{a_v} & \text{if } \pi_{socy} - E(\pi_{soc}) \geq 0 \\ -\lambda\left(-\left(\pi_{socy} - E(\pi_{soc})\right)\right)^{a_v} & \text{if } \pi_{socy} - E(\pi_{soc}) < 0 \end{cases}; \; r(p_i) = p_y$$

where $E(y)$, $E(\pi)$, $E(u)$, and $V(\pi)$ represent the expected yield, profits, utility, and value, respectively; P_C and P_N refer to the prices of corn and nitrogen, while N indicates the rate of N application; a reflects farmers' risk aversion level which is nonnegative; $var(\pi)$ signifies the variance of expected profits; p_y denotes the probability of the weather conditions in year y occur; π_y represents the profits achieved under weather conditions in year y; a_v and λ is farmers' risk and loss aversion parameter used in value functions, respectively; $E(\pi_{soc})$, (u_{soc}),

and $V(\pi_{soc})$ correspond to farmers' expected profits, utility, and value when accounting for the social costs of N, with P_{soc} symbolizing the social costs of N.

2.1.5 Impacting factors

We conduct regression analysis to examine the impacts of the above factors on optimal N rates and the corresponding realized profits, respectively, in addition to illustrate the results of optimal N rates and utilities by using boxplots and tables with average values. The models are presented as follows:

$$Nitrogen_{if} = \beta X_{if} + \alpha_f + \mu_{if}, \quad (15)$$

$$Profits_{if} = \gamma X_{if} + \delta_f + \nu_{if}, \quad (16)$$

where $Nitrogen_{if}$ and $Profits_{if}$ are the optimal N rates for each individual decision at field f and its corresponding realized profits, respectively; X_{if} represents the influencing factors and interactions; α_f and δ_f denote the field fixed effect; and μ_{if} and ν_{if} are error terms.

2.2 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 3.85 percent of corn planting acreage in Illinois for the year 2025 (USDA-NASS, 2025).

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 following soybeans was considered when conducting the simulation. 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 encompasses 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, other exogenous variables consist of soil water content, soil organic carbon, and soil N (NO3 and NH4) 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. The social costs of N utilized in this research are derived from the dataset provided by Goodkind et al. (2023). These costs are calculated by dividing the social damage costs associated with anhydrous ammonia by the fertilizer application rate specific to each county. For each field and soil type (mukey), the assigned social cost of N is consistent with the corresponding county-level value.

3 Results

3.1 Comparison among production functions

The regression outcomes for the three production functions are presented in Table A3 of the Appendix. These results include the average, minimum, and maximum values of the coefficients across all soil types within each field. The coefficients for the intercept, nitrogen (N), nitrogen

squared (N^2), and the plateau nitrogen rates are obtained by aggregating all effects based on the given soil-specific weather and soil-related variables. The fitness comparison of production functions to the data is presented in Figure 2. Each data point reflects the ratio of predicted yield—derived from a specific production function—to the actual yield recorded at the mukey level within each field. The rows and columns represent the respective production functions and N rates used for yield prediction.

Among the functions evaluated, the linear plateau model demonstrates the best fit, outperforming both the quadratic plateau and general quadratic models, which exhibit the lowest accuracy. When the soil-level linear plateau function is aggregated to the field level using mukey areas as weighting factors, it transforms into a quadratic plateau function at that scale. This indicates variability in production functions across different soils within the same field. This observation is consistent with earlier research conducted by Berck & Helfand (1990), which demonstrated that quadratic plateau functions can represent aggregated linear plateau production functions when multiple inputs are taken into account.

Furthermore, we calculated the average predicted yield across all fields and years at the field level and displayed these results in Figure 3. The figure illustrates that the relationship between N application rate and yield varies from year to year. Notably, the optimal N rate for maximizing yield does not necessarily coincide with the highest rate applied, particularly under favorable weather conditions.

3.2 Optimal N application rates

Figure 4 displays a comparison of the optimal N application rates across various production functions, farmers' beliefs about the weather conditions, and optimization objectives, assuming uniform N fertilizer application at the field level. The figure provides boxplots representing the

distribution of optimal N application rates across over 4000 fields. Each column and each row represent farmers' belief about the weather conditions and their optimization objective, respectively. The comparison of optimal N rates among the three production functions is shown within each grid. For the utility and social utility maximization, each boxplot demonstrates the distribution of optimal N application rates corresponding to a specific level of risk aversion. The risk aversion levels used for utility maximization range from 0 to 0.01 in increments of 0.001. A risk aversion coefficient of 0 indicates that farmers are risk neutral, while a value of 0.01 implies a risk premium equivalent to 40% of the standard deviation of revenue (Babcock & Hennessy, 1996).

On average, the N rates required for maximizing yield are higher than those for maximizing utility, which in turn are higher than those for maximizing social utility with considering the social costs of N. When farmers aim to maximize utility, both the general quadratic and quadratic plateau production functions suggest higher N application rates compared to the linear plateau function, regardless of farmers' weather-related beliefs. However, when the social costs of nitrogen are factored in, the linear plateau function suggests the highest N rates. Our findings also indicate that risk-averse farmers tend to reduce their N application rates when their risk aversion level increases if they hold weather expectations other than an optimistic outlook, whereas they maintain their N application levels under optimistic weather assumptions. Furthermore, the differences in optimal N rates between yield maximization and profit maximization are smaller when using general quadratic functions compared to linear plateau functions. Finally, the social optimum N rates are significantly lower than the utility-maximizing N rates.

The regression outcomes of the model, which regresses all the influencing factors along with the interaction terms against the optimal N rates using the entire dataset, are presented in Appendix Table A8. In this table, “Risk” stands for the risk aversion level. The coefficient estimates for risk and risk interaction terms indicate the impact of a 0.01 change in the risk aversion level. “normal,” “lbeta,” and “rbeta” represent the distribution of farmers' weather beliefs. “vrt” indicates that farmers employ variable rate technology. “utility” and “socutility” suggest that farmers are utility maximizers without and with taking into account the social costs of N, respectively. The benchmark optimal N rates are derived by assuming a general quadratic production function, yield maximization, random weather beliefs, and a uniform application method. The findings show that most of the factors and interaction terms have statistically significant effects on the optimal N rates, except for some factors and interaction terms related to the normal distribution of weather belief and the use of variable rate technology.

Figure 5 illustrates the optimal N application rates based on farmers' beliefs about weather conditions, optimization objectives, and application methods, derived using linear plateau production functions. Similar to the illustration in Figure 4, this figure also displays boxplots representing the distribution of optimal N application rates at the field level across more than 4000 fields. However, in this case, the comparison within each grid cell is based on different nitrogen application methods. Field-level outcomes for variable rate technology (VRT) were calculated by scaling up the mukey-level results, with each mukey's area serving as a weighting factor.

Our findings suggest considering corn and N price ratios in decision-making has the biggest impact on N rates based on analysis conducted using linear plateau production functions. As presented in Table 1, which shows the average optimal nitrogen application rates derived from

linear plateau functions, we observe that those aiming for maximum yield apply approximately 90 pounds of nitrogen per acre more than those seeking maximum profit when using linear plateau production functions. Table 3 presents the regression results of models that are based on subsets of the dataset and are respectively associated with linear plateau functions, quadratic plateau functions, and general quadratic functions. The coefficient estimate of utility in column (1) of Table 3 suggests that, under the assumption of uniform application method and random weather conditions, farmers who are profit-maximizers reduce about 91 pounds per acre nitrogen application compared to yield-maximizers. This finding is consistent with the result shown in Table 1. Moreover, the data in Table 1 also reveals that, assuming weather conditions occur randomly with equal probability, the socially optimal nitrogen application rates are approximately 60 pounds per acrelower than the profit-maximizing nitrogen application rates for farmers. The coefficient estimate of socutility in column (1) of Table 3 reflects a similar value.

Table 1 also shows that the differences in N rates between uniform application method and VRT are around 2 - 3 lbs per acre across maximization objectives and farmers' beliefs about weather except for yield maximizers with weather beliefs other than optimistic view which are about 12 lbs per acre. Moreover, the impact of weather beliefs on N rates are moderate, which are 0 – 4 lbs per acre for yield maximizers, 1 – 25 lbs per acre for profit maximizers without considering the social costs of N. Furthermore, the differences in N rates between risk-neutral farmers and high risk-averse farmers range from 1 to -17 lbs per acre, with increasing N rates for optimistic farmers while decreasing for other farmers when risk-averse level increasing. We also find that farmers' beliefs about weather have a bigger impact on N application rates than the application method used for profit-maximizers. Farmers who are optimistic about weather can

apply 6 – 15 lbs per acre higher N than farmers with other weather beliefs, while VRT can only lead to 2 – 3 lbs N per acre decrease compared to uniform application.

Table 5 displays the regression outcomes derived from models that utilize subsets of the dataset for yield maximization, utility maximization, and social utility maximization, respectively. These models employ linear plateau production functions. The benchmarks refer to the optimal N rates for farmers adopting the uniform application approach and assuming that weather conditions occur randomly.

Column (1) of Table 5 indicates that, for yield maximizers, only the coefficient estimates for optimistic weather beliefs, VRT, and their interactions are statistically significant. The coefficient estimates suggest that, compared to the benchmark levels, farmers decrease their N application rates by approximately 12 pounds per acrewhen they are optimistic about the weather or make use of VRT. On the other hand, if they are both optimistic about the weather and utilize VRT, they may increase the rates by around 9 pounds per acre.

Column (2) of Table 5 presents the regression results for utility maximization using linear plateau production functions. The parameter estimates that are statistically significant include those for the risk aversion level, weather beliefs, VRT, the interactions between the risk aversion level and weather beliefs, the interaction between the 'rbeta' weather distribution and VRT, and the interaction between the previous term and the risk aversion level.

The estimate of the risk aversion level indicates that when utility-maximizing farmers assume weather conditions occur randomly and apply nitrogen (N) uniformly across the field, a 0.01 increase in their risk aversion level leads to a reduction of approximately 9 pounds per acre in N application. In addition, we discover that a 0.01 increase in the risk aversion level can cause an increase of 5.9 pounds per acre and 10 pounds per acre in N application for farmers with normal

and lbeta weather beliefs respectively, but a reduction of 11.1 pounds per acre for those with rbeta weather beliefs.

For risk-neutral farmers, altering their beliefs about weather conditions from uniform to normal and rbeta can result in a reduction of N application rates by 1.6 pounds per acre and 18.5 pounds per acre respectively. Conversely, when their weather beliefs change to lbeta, the N application rate increases by 4.9 pounds per acre. Furthermore, for risk-neutral farmers who assume the weather distribution follows uniform and rbeta, adopting VRT can reduce N application by 1.9 pounds per acre and 1.1 pounds per acre respectively. Nevertheless, for farmers who adopt VRT and have a rbeta belief about weather, a 0.01 increase in the risk aversion level can lead to a 0.9 pounds per acre increase in the N application rate.

Table 5's Column (3) shows the regression results for utility maximization when taking into account the social costs of N by using linear plateau production functions. The statistically significant parameter estimates are comparable to those in Column (2). However, there are some differences. Specifically, the interaction term between lbeta and VRT turns out to be significant, while the interaction term between risk, rbeta and VRT becomes insignificant. Additionally, compared with the estimates in Column (2), the magnitudes of these estimates are larger. The signs of the estimates for normal, VRT, the interaction between lbeta and VRT, the interaction between risk and rbeta, and the interaction between rbeta and VRT have changed to positive. This indicates that these regressors have positive effects on the optimal N rates.

As shown in Figure 6, which compares optimal N application rates between VRT and uniform application approaches, the average application rates under both methods are quite similar. Nevertheless, spatial variability among fields results in either higher or lower optimal N rates at the individual field level when compared to uniform application rates. Among farmers

who prioritize yield maximization and maintain an optimistic view of weather conditions, the differences in N application rates between VRT and uniform methods are smallest. In contrast, for utility maximizers, regardless of whether social costs are considered, the differences in application rates are greater for optimistic farmers than for those who assume that weather conditions follow a uniform or normal distribution.

3.3 Expected utilities

The expected utilities, considering farmers' beliefs about weather conditions, optimization objectives, and application methods based on linear plateau production functions, are illustrated in Figure 7 and Table 1. On average, the expected profits for utility maximizers are approximately $30 per acre greater than those for yield maximizers, regardless of weather beliefs and application methods. Farmers who hold optimistic views about weather have the highest expected utility compared to those with other weather-related beliefs, irrespective of their optimization objectives and application methods.

The use of VRT results in expected profits that are $1 to $5 per acre higher than those expected through the uniform application. For optimistic farmers, the shift from risk neutrality to a risk aversion level of 0.01 leads to a decrease in expected utility by roughly $5 per acre. In contrast, this reduction can reach up to $80 per acre for farmers who hold uniform beliefs about weather conditions. When farmers exhibit risk aversion and assume a uniform distribution of weather conditions, their expected utilities using the uniform application method are approximately $1 per acre higher than those obtained through VRT.

3.4 Realized profits

The comparisons of the realized profits obtained by using linear plateau production functions are presented in Figure 8 and Table 1. The realized profits refer to the profits achieved under a

specific year's weather and soil conditions through the application of optimal N rates. On average, utility maximizers achieve realized profits that are approximately $30 per acre higher than those of yield maximizers. Yield maximizers achieve their highest profits when they maintain an optimistic outlook on the weather. Their profit levels are nearly identical whether they use VRT or the uniform application method. However, yield maximizers with weather beliefs other than optimistic views can gain $3 to $4 per acre more by utilizing VRT. The regression results shown in column (1) of Table 4 indicate similar findings. The benchmark profits in Table 4 are obtained by assuming yield maximization, a uniform distribution regarding the weather, and a uniform application method. For yield maximizers, being optimistic about the weather and using VRT increase the realized profits by around $5.3 per acre and $3.5 per acre, respectively, compared to the benchmark profits.

For both utility and social utility optimizers, employing VRT results in realized profits that are $1 to $8 per acre lower compared with the uniform application, regardless of weather beliefs, as shown in Table 1. Column (1) of Table 4 suggests an average of $4.3 per acre and $6.3 per acre reduction, respectively, for utility maximizers and social utility maximizers who adopt VRT. Columns (2) and (3) of Table 6 break down the impacts of weather beliefs on realized profits further. For farmers assuming that the distribution of weather conditions is uniform, adopting VRT can reduce their realized profits by around $0.8 per acre and $2.8 per acre, respectively, for risk-neutral utility maximizers and social utility maximizers. While for risk-aversion utility maximizers, the reduction can be $1.8 per acre. In addition, the estimates for interaction terms between rbeta and VRT, and between lbeta and VRT are statistically significant for utility maximization and social utility maximization, respectively. The results suggest a $4.8 per acre and a $2 per acre reduction in realized profits for utility maximizers having a pessimistic

view on weather and social utility maximizers with an optimistic view on weather, respectively, compared with those assuming random weather occurrences.

Utility maximizers who are risk-neutral may experience roughly $1 per acre and $2.4 per acre less in profits, respectively, when they assume the distribution of weather is normal and lbeta compared to those assuming a uniform distribution of weather conditions, as illustrated in column (2) of Table 6. Conversely, if these farmers are risk-averse, their realized profits could be approximately $3.9 per acre and $6.3 per acre higher under risk aversion levels of 0.01, respectively. Farmers who are pessimistic about weather obtain $14 per acre and $35 per acre lower realized profits for risk-neutral and risk-averse utility maximizers, respectively, compared to those assuming that weather conditions are uniformly distributed.

The significance and signs of the parameter estimates shown in column (3) of Table 6 for social utility maximization are similar to those for utility maximization. The exceptions include that the estimates for the interaction between risk and VRT and the interaction between rbeta and VRT become insignificant, the estimate for the interaction between lbeta and VRT becomes significant, and the sign of the estimate for the interaction between risk and rbeta flips to positive. Moreover, the magnitudes of most estimates are larger for social utility maximization.

Figure 9 illustrates the comparison of realized profits and expected utilities among farmers with different weather beliefs, based on their maximization objectives under the assumptions of a linear plateau production function and uniform application. The expected utilities for optimistic farmers consistently exceed their realized profits regardless of the optimization objective. In contrast, for farmers with non-optimistic weather beliefs, realized profits are consistently equal to or greater than their expected utilities across all optimization objectives. In the case where

farmers are risk-neutral and assume a uniform distribution of weather conditions, their expected and realized utilities become identical.

3.5 Heterogenous effects across fields

We plotted the differences in optimal N rates and realized profits between weather beliefs and application methods at the field level on a state map to show the heterogeneous effects of these factors on N rates and the realized profits. The values in the state maps were obtained by using linear plateau production functions for more than 4,200 fields. The comparison maps are presented in Figures 11 – 16. Each figure has three maps that show the differences for yield maximization, utility maximization under risk-neutral (risk-aversion level = 0), and utility maximization under a risk-aversion level of 0.01.

Figure 11 represents the differences in optimal N rates between two weather beliefs – lbeta and uniform. For yield maximization, the non-zero differences, ranging from -100 to 200 pounds per acre, are spread across the states, with more negative differences, while there are a few significant positive differences in the northern region of Illinois. For utility maximization, there are more positive differences among the non-zero ones, which range from -50 to 180 pounds per acre. And the increase in the risk aversion level leads to more positive differences and greater gaps. It is worth noting that the high positive differences are clustered in the southern region of the state and the east-central Illinois for utility maximization under a risk aversion level of 0.01. Meanwhile, most of the differences in the southern region of Illinois are positive, and a few negative differences are spread in the other two regions, with more significant negative differences in the northern region.

Figures 12 and 13, respectively, show the differences in optimal N rates between two application methods – VRT and uniform – under the assumption of uniform distribution and

lbeta distribution in weather conditions. For yield maximization, the differences range from -200 to 100 pounds per acre. Most of the positive differences are located in the northern region of Illinois, and most of the negative differences are located in the other two regions under either weather belief. The differences become less negative but more positive when the weather belief changes from uniform to lbeta, with a range from -130 to 120 pounds per acre. For utility maximization, the differences become smaller compared to yield maximization for both risk aversion levels under uniform weather distribution. The ranges are from -40 to 20 pounds per acre and from -60 to 30 pounds per acre for risk neutral and a risk aversion level of 0.01, respectively. The ranges of differences become larger under lbeta distribution, which are from -70 to 100 pounds per acre and -40 to 100 pounds per acre. In addition, most of the differences in the northern region become negative.

The differences in realized profits between two weather beliefs – lbeta and uniform are presented in Figure 14. For yield maximization, the lbeta weather belief yields higher realized profits in more fields, and the maximum profit gaps can be up to more than $50 per acre. However, some fields in the northern region of Illinois have lower realized profits, which can be up to around $90 per acre. For risk-neutral utility maximization, most of the non-zero differences between lbeta and uniform are negative, and the maximum difference is located in the central region and can be up to -$70 per acre. However, when the risk aversion level is 0.01, the differences range from around -$50 per acre to $100 per acre, and most of the non-zero differences become positive and are located in the southern and eastern central regions.

The comparisons of differences in realized profits between VRT and uniform application under uniform and lbeta weather beliefs are displayed in Figures 15 and 16, respectively. The differences between the comparisons under uniform and lbeta weather beliefs are quite similar.

For yield maximization, VRT can yield higher realized profits in more fields among those fields that have non-zero differences. However, the situation is opposite for utility maximization. And the ranges of the differences are also similar across objectives, which are between -$100 per acre and around $150 per acre.

3.6 Results suggested by using cumulative prospect theory

Similar results were found based on cumulative prospect theory compared to those obtained by using certainty equivalent. Figure 10 shows the comparison of value-maximization optimal N rates across weather beliefs, application methods used, and N prices with and without considering the social cost of N by using linear plateau production functions. The N rates are highest for optimistic farmers among all farmers with different weather beliefs. Risk-averse and loss-neutral farmers decrease their N application rates compared to risk-neutral and loss-neutral farmers across all weather beliefs.

When farmers are optimistic about weather conditions, loss-averse farmers apply higher N rates compared to loss-neutral farmers. Among loss averse farmers, risk averse leads to N rate reduction. However, loss aversion leads to a greater increase in the N rate than the reduction in the N rate caused by risk aversion. The findings further emphasize that optimistic farmers who are unwilling to give up the potential gains under favorable weather conditions tend to overapply N. While the opposite is true for farmers with other weather beliefs.

On average, the impact of loss aversion is larger than that of risk aversion on N rates. Moreover, the optimal N rates for farmers using VRT are higher than those using the uniform application method for most of the decision combinations. Furthermore, the optimal N rates are similar between scenarios without and with consideration of the social costs of N.

The results and patterns obtained from using general quadratic functions and quadratic plateau functions are similar, which can be found in Figure A7 and Figure A8, respectively.

3.7 Analysis by using general quadratic and quadratic production functions

Figures A1 to A3 in the Appendix present a comparison of optimal N application rates, expected utility, and realized utility under the general quadratic production function. The observed trends are largely consistent with those derived from linear plateau functions, with a few notable exceptions. When yield maximizers are optimistic about weather conditions, their optimal N rates are 1 to 4 pounds per acre higher than those of farmers with different weather outlooks. Furthermore, the variation in optimal N rates between variable rate technology (VRT) and uniform application remains below 1 pounds per acre for both yield and utility maximizers across all weather belief categories. However, the expected utility values are lower when general quadratic functions are used. Utility maximizers achieve expected profits that exceed those of yield maximizers by approximately $5 to $15 per acre, regardless of weather beliefs or application methods. Additionally, VRT leads to expected profits that are roughly $1 per acre higher compared to the uniform application. With respect to realized profits, utility maximizers earn $3 to $8 more per acre than yield maximizers, irrespective of application method or weather outlook. Interestingly, yield maximizers using the uniform application tend to realize higher profits than those employing VRT, regardless of their weather-related expectations.

Figures A4 to A6 in the Appendix show the comparison of optimal N rates, expected utility, and realized profits under the quadratic plateau production function. The observed trends are quite like those obtained using the linear plateau function, although certain distinctions should be highlighted. For farmers aiming to maximize yield, adopting variable rate technology (VRT) results in a reduction of 15 to 18 pounds of nitrogen per acre compared to the uniform

application, regardless of weather beliefs. Farmers with optimistic weather expectations tend to apply over 20 pounds more nitrogen per acre than those with other outlooks when making decisions based on utility maximization, both with and without accounting for the social costs of nitrogen. In terms of profitability, the use of VRT leads to expected profits that are approximately $1 per acre higher than with uniform application. Furthermore, for yield-maximizers, the realized profits from implementing VRT are around $5 per acre greater than those achieved through uniform N application, across all weather belief scenarios.

4 Conclusions

Nitrogen fertilizer plays a crucial role in corn production in the United States. However, the overapplication of nitrogen fertilizer can result in potential profit losses and environmental damage. This study aims to understand the factors that lead farmers to apply excessive nitrogen and explore strategies to encourage the reduction of N. To achieve this, we analyzed 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. Our analysis involved the use of three different production functions, two application methods, four farmers' beliefs about weather, and five objective functions.

We find that linear plateau functions result in lower nitrogen (N) application rate recommendations than quadratic functions, whether the goal is yield maximization or utility maximization. Additionally, our analysis reveals that for certain fields, the difference between VRT and uniform application rates at the soil level can be significant. These observations provide empirical validation for the technological factors raised in earlier research. Consistent with prior findings, we find evidence that farmers who hold optimistic beliefs about weather conditions are more likely to apply excessive amounts of nitrogen. Importantly, we offer insights

into the inconsistent results reported in previous studies by demonstrating how risk-averse farmers make distinct N application decisions depending on their beliefs about weather patterns.

Furthermore, our study presents empirical support indicating that overapplication of nitrogen may stem from the fact that the average expected benefits over good and bad weather years are greater. Our results also show that farmers who have optimistic weather outlooks and apply higher levels of nitrogen uniformly, compared to those with other weather perspectives, tend to achieve nearly equal or even greater average realized profits across years. This implies that, for farmers using uniform application methods, holding an optimistic view about weather conditions does not necessarily harm their overall profitability.

Additionally, our study indicates that incorporating the price ratio of corn to N into decision-making exerts the most significant influence on determining optimal N application rates. We also observe that farmers' expectations and perceptions of weather conditions have a greater effect on N application rates than the specific application methods employed by profit-maximizers. Moreover, utility maximizers tend to achieve higher realized profits compared to those maximizing yield. The motivation behind excessive N application by some farmers aimed at boosting yield could be from a desire to increase their APH, thereby securing larger compensation payouts in the event of extreme bad weather occurrences. Whether driven by the goal of enhancing APH or by maintaining optimistic outlooks on weather conditions, farmers' inclination to overuse nitrogen functions as a risk mitigation strategy, seeking upside potentials under favorable weather conditions while minimizing losses during unfavorable ones.

Our findings suggest two possible policy interventions to help deal with excessive N use: one involves directly compensating farmers for any income loss or reduced insurance benefits that could result from lowering N inputs; the other could be providing insurance products that

safeguard against upside yield potential derived from the five best yields recorded within the past ten years. The success of the first approach would largely depend on farmers' readiness to share their current N application practices and their trust in the accuracy of yield forecasting models. As for the second policy option, critical challenges would involve setting suitable coverage levels and premium costs, along with assessing the long-term economic implications of reductions in nitrogen usage. Further investigation is needed to enhance and implement these policy instruments efficiently.

Our results indicate that although the adoption of VRT may increase expected profits, it could result in decreased realized profits. This implies that the performance of VRT may be undermined by uncertainties arising from weather and soil variability, a conclusion that aligns with the research of Isik & Khanna (2003). Therefore, integrating real-time recommendation systems with VRT could serve as a more effective strategy to improve fertilizer use efficiency while mitigating nitrogen runoff and greenhouse gas emissions.

When the social costs of nitrogen are considered, both expected utility and realized profits drop notably compared to scenarios based only on the market price of nitrogen. This decrease is largely attributed to lower crop yields caused by reduced nitrogen application rates. From the standpoint of policy and food security, it is unrealistic to expect farmers to significantly reduce nitrogen usage to achieve social optimum levels. Rather, improving nitrogen use efficiency could generate win-win outcomes for both agricultural producers and society at large.

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References

Almasri, M. N., & Kaluarachchi, J. J. (2004). Assessment and management of long-term nitrate pollution of ground water in agriculture-dominated watersheds. *Journal of Hydrology*, *295*(1), 225–245. https://doi.org/10.1016/j.jhydrol.2004.03.013

Babcock, B. A. (1992). The Effects of Uncertainty on Optimal Nitrogen Applications. *Applied Economic Perspectives and Policy*, *14*(2), 271–280. https://doi.org/10.2307/1349506

Babcock, B. A. (2015). Using Cumulative Prospect Theory to Explain Anomalous Crop Insurance Coverage Choice. *American Journal of Agricultural Economics*, *97*(5), 1371–1384. https://doi.org/10.1093/ajae/aav032

Babcock, B. A., & Hennessy, D. A. (1996). Input Demand under Yield and Revenue Insurance. *American Journal of Agricultural Economics*, *78*(2), 416–427. https://doi.org/10.2307/1243713

Berck, P., & Helfand, G. (1990). Reconciling the von Liebig and Differentiable Crop Production Functions. *American Journal of Agricultural Economics*, *72*(4), 985–996. https://doi.org/10.2307/1242630

Chai, Y., J. Pannell, D., & G. Pardey, P. (2023). Nudging farmers to reduce water pollution from nitrogen fertilizer. *Food Policy*, *120*, 102525. https://doi.org/10.1016/j.foodpol.2023.102525

Goodkind, A. L., Thakrar, S. K., Polasky, S., Hill, J. D., & Tilman, D. (2023). Managing nitrogen in maize production for societal gain. *PNAS Nexus*, *2*(10), pgad319. https://doi.org/10.1093/pnasnexus/pgad319

Gourevitch, J. D., Keeler, B. L., & Ricketts, T. H. (2018). Determining socially optimal rates of nitrogen fertilizer application. *Agriculture, Ecosystems & Environment*, *254*, 292–299. https://doi.org/10.1016/j.agee.2017.12.002

Houser, M. (2022). Farmer Motivations for Excess Nitrogen Use in the U.S. Corn Belt. *Case Studies in the Environment*, *6*(1), 1688823. https://doi.org/10.1525/cse.2022.1688823

Iowa State University Extension and Outreach. (n.d.). *Corn Growth Stages | Integrated Crop Management*. Retrieved April 18, 2024, from https://crops.extension.iastate.edu/encyclopedia/corn-growth-stages

Isik, M., & Khanna, M. (2003). Stochastic Technology, Risk Preferences, and Adoption of Site-Specific Technologies. *American Journal of Agricultural Economics*, *85*(2), 305–317.

Just, R. E., & Pope, R. D. (1979). Production Function Estimation and Related Risk Considerations. *American Journal of Agricultural Economics*, *61*(2), 276–284. https://doi.org/10.2307/1239732

Mandrini, G., Archontoulis, S. V., Pittelkow, C. M., Mieno, T., & Martin, N. F. (2022). Simulated dataset of corn response to nitrogen over thousands of fields and multiple years in Illinois. *Data in Brief*, *40*, 107753. https://doi.org/10.1016/j.dib.2021.107753

Mandrini, G., Bullock, D. S., & Martin, N. F. (2021). Modeling the economic and environmental effects of corn nitrogen management strategies in Illinois. *Field Crops Research*, *261*, 108000. https://doi.org/10.1016/j.fcr.2020.108000

Mandrini, G., Pittelkow, C. M., Archontoulis, S., Kanter, D., & Martin, N. F. (2022). Exploring Trade-Offs Between Profit, Yield, and the Environmental Footprint of Potential Nitrogen Fertilizer Regulations in the US Midwest. *Frontiers in Plant Science*, *13*. https://www.frontiersin.org/articles/10.3389/fpls.2022.852116

Mandrini, G., Pittelkow, C. M., Archontoulis, S. V., Mieno, T., & Martin, N. F. (2021). Understanding differences between static and dynamic nitrogen fertilizer tools using simulation modeling. *Agricultural Systems*, *194*, 103275. https://doi.org/10.1016/j.agsy.2021.103275

McFadden, J., Njuki, E., & Griffin, T. (2023). *Precision Agriculture in the Digital Era: Recent Adoption on U.S. Farms* (Economic Information Bulletin No. Number 248). U.S. Department of Agriculture Economic Research Service.

Nelson, C. H., & Preckel, P. V. (1989). The Conditional Beta Distribution as a Stochastic Production Function. *American Journal of Agricultural Economics*, *71*(2), 370–378. https://doi.org/10.2307/1241595

Paulson, N. D., & Babcock, B. A. (2010). Readdressing the Fertilizer Problem. *Journal of Agricultural and Resource Economics*, *35*(3), 368–384.

Peel, J. L., Haeuber, R., Garcia, V., Russell, A. G., & Neas, L. (2013). Impact of nitrogen and climate change interactions on ambient air pollution and human health. *Biogeochemistry*, *114*(1), 121–134. https://doi.org/10.1007/s10533-012-9782-4

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

Savci, S. (2012). An Agricultural Pollutant: Chemical Fertilizer. *International Journal of Environmental Science and Development*, 73–80. https://doi.org/10.7763/IJESD.2012.V3.191

Sellars, S. C., Schnitkey, G. D., & Gentry, L. F. (2020). Do Illinois Farmers Follow University-Based Nitrogen Recommendations? *2020 Annual Meeting, July 26-28, Kansas City, Missouri*, Article 304617. https://ideas.repec.org//p/ags/aaea20/304617.html

Sheriff, G. (2005). Efficient Waste? Why Farmers Over-Apply Nutrients and the Implications for Policy Design. *Review of Agricultural Economics*, *27*(4), 542–557. https://doi.org/10.1111/j.1467-9353.2005.00263.x

SriRamaratnam, S., Bessler, D. A., Rister, M. E., Matocha, J. E., & Novak, J. (1987). Fertilization under Uncertainty: An Analysis Based on Producer Yield Expectations. *American Journal of Agricultural Economics*, *69*(2), 349–357. Scopus. https://doi.org/10.2307/1242285

USDA-AMS. (2024). *Report-Illinois Production Cost Report (Bi-weekly) | MMN*. https://mymarketnews.ams.usda.gov/viewReport/3195

USDA-FAS. (2025). *Corn 2024 World Production*. https://ipad.fas.usda.gov/cropexplorer/cropview/commodityView.aspx?cropid=0440000

USDA-NASS. (2024). *USDA/NASS QuickStats Ad-hoc Query Tool*. https://quickstats.nass.usda.gov/

USDA-NASS. (2025). *USDA/NASS QuickStats Ad-hoc Query Tool*. https://quickstats.nass.usda.gov/results/0E74BEB9-0AC1-38FB-BBF3-D2FE6A55EB2B

Van Grinsven, H. J. M., Holland, M., Jacobsen, B. H., Klimont, Z., Sutton, M. a., & Jaap Willems, W. (2013). Costs and Benefits of Nitrogen for Europe and Implications for Mitigation. *Environmental Science & Technology*, *47*(8), 3571–3579. https://doi.org/10.1021/es303804g

Wade, T., Claassen, R., Bowman, M., & Wallander, S. (2015). *Conservation-Practice Adoption Rates Vary Widely by Crop and Region* (No. EIB-147; p. 40). U.S. Department of Agriculture, Economic Research Service.

Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., & Shen, Y. (2015). Managing nitrogen for sustainable development. *Nature*, *528*(7580), Article 7580. https://doi.org/10.1038/nature15743

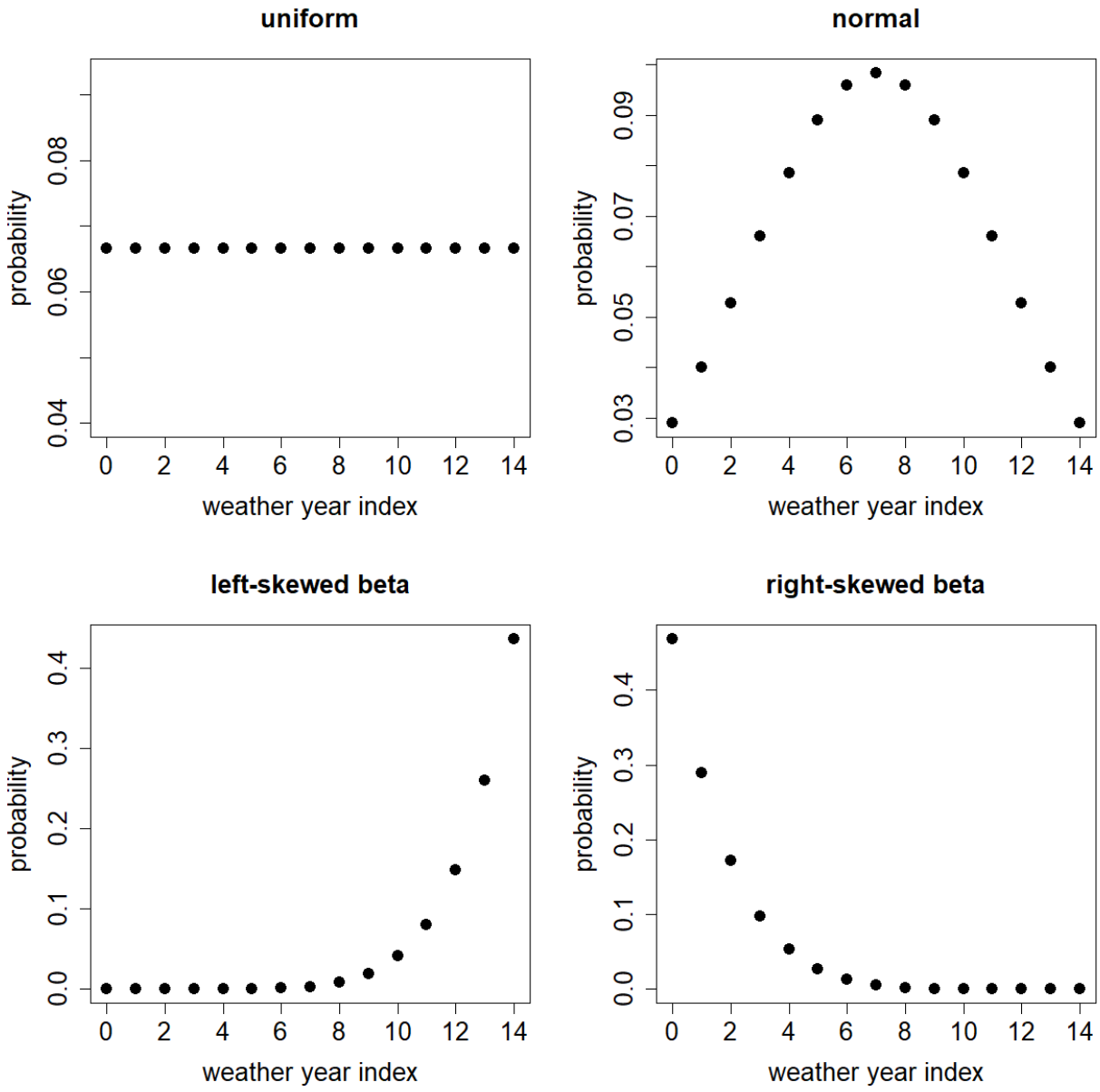


Figure 1. Farmers' beliefs about the distribution of the weather conditions

Notes: the weather year index presents 15 weather years, and the ranking is based on the highest yield in that year.

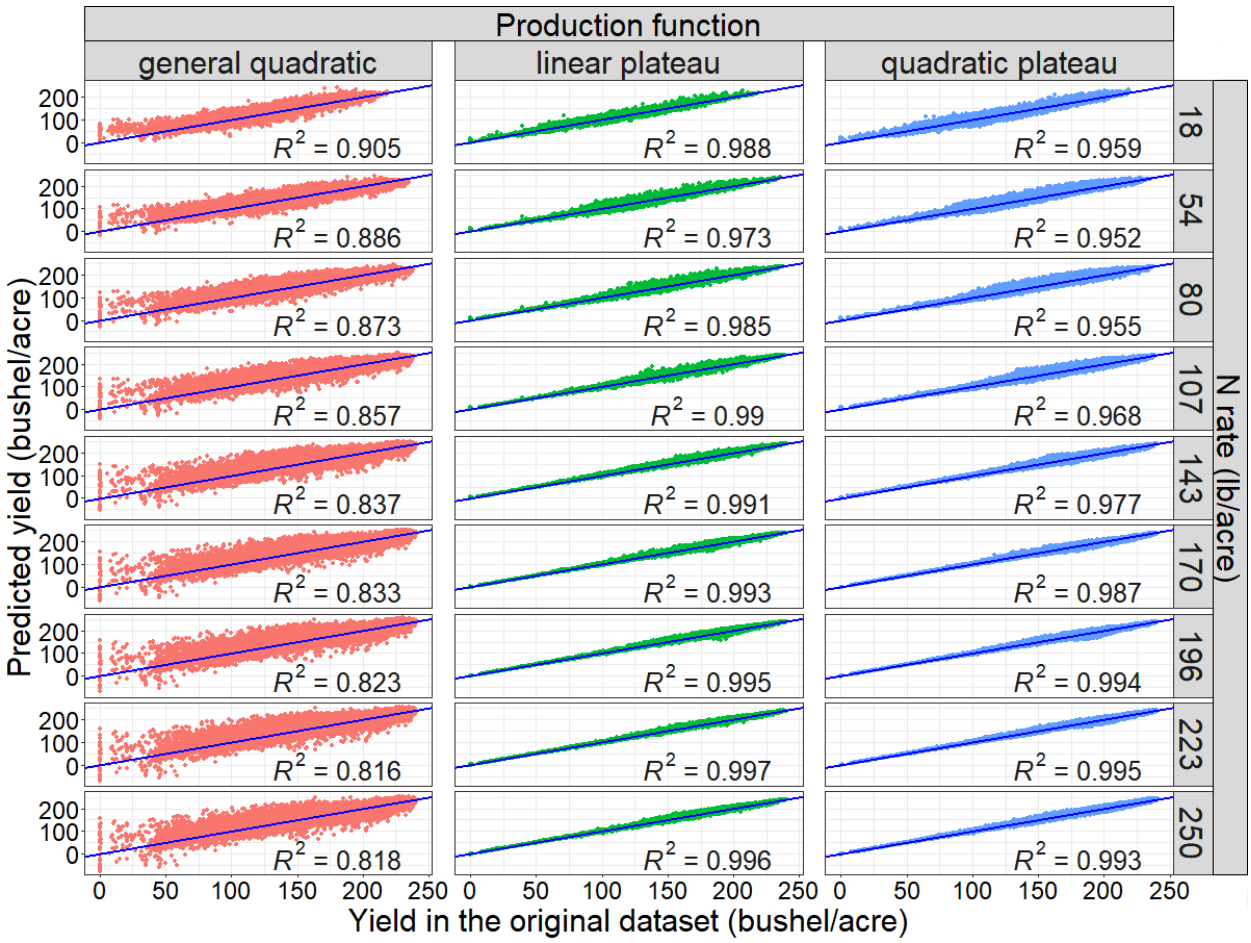


Figure 2. Comparison among production functions

Notes: each data point represents the ratio of the predicted yield calculated using the corresponding production function to the yield in original dataset at mukey level within each field. Each column and row show the corresponding production function and N rate used for yield prediction.

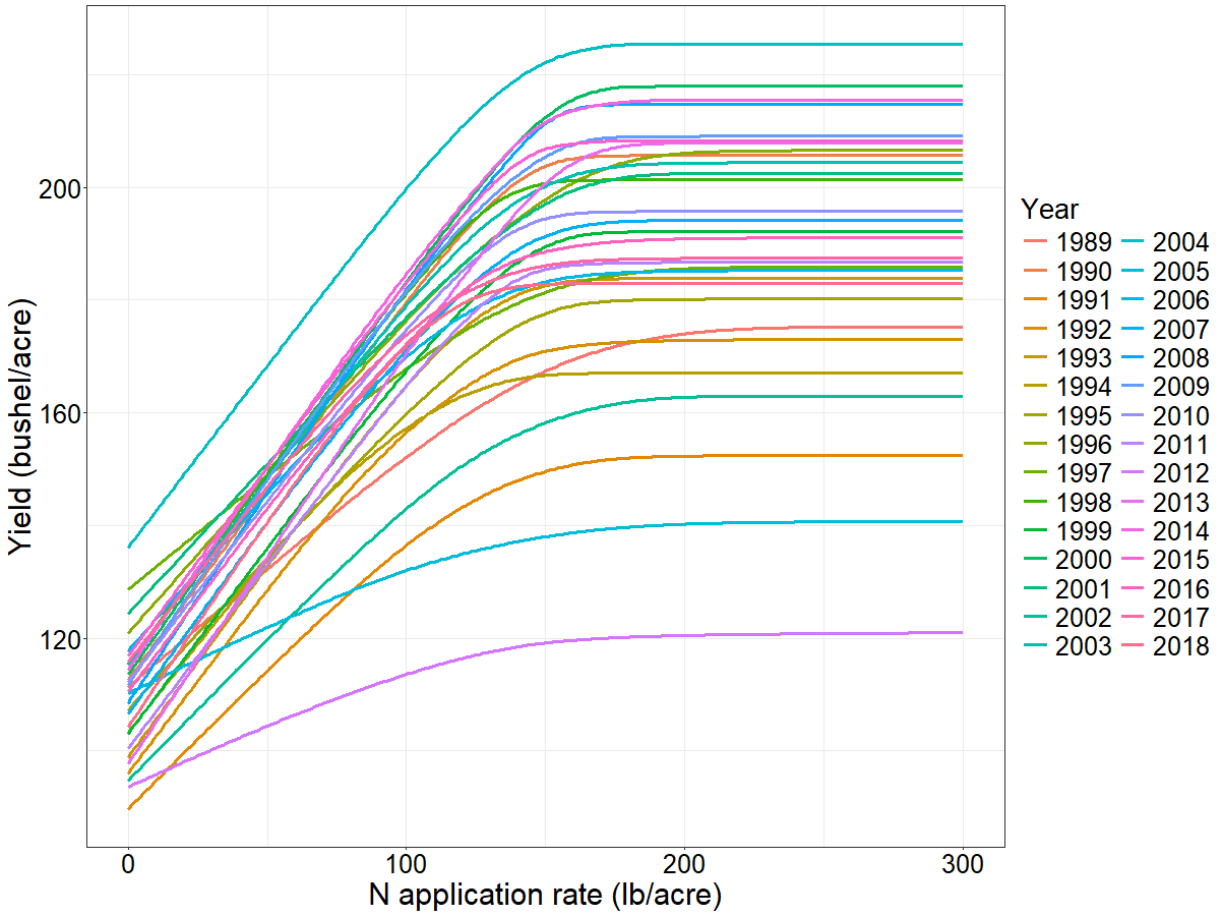


Figure 3. Yield responses to N curves across 30 years

Notes: yield on the y-axis is obtained by first aggregating mukey-level predicted yield using a linear plateau function to the field level, weighting by the mukey area within each field, and then averaging the yields across more than 4,000 fields.

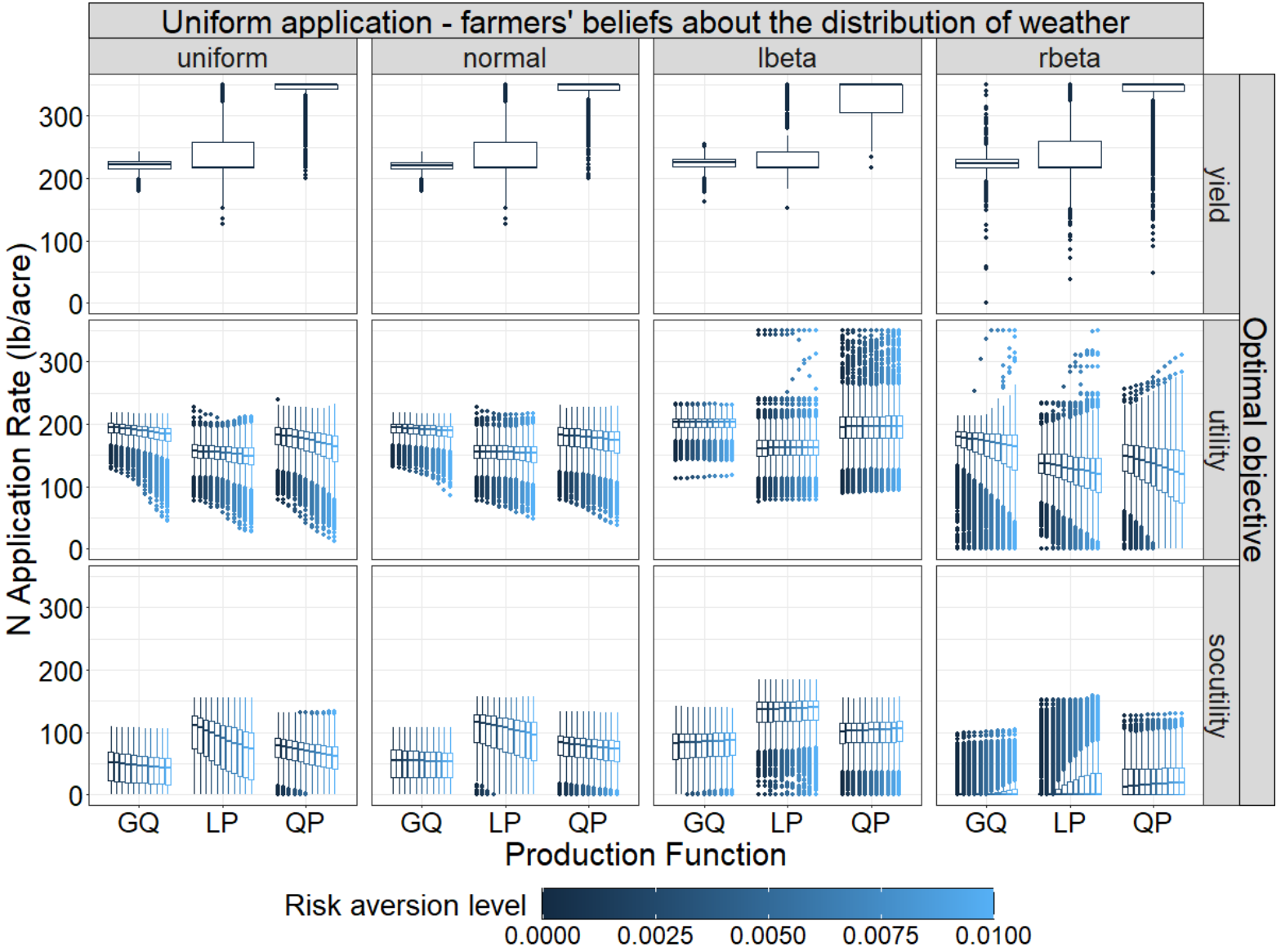


Figure 4. Optimal N rates for farmers following uniform application

Notes: The figure presents the boxplots for optimal N application rate at the field level across more than 4000 fields. GQ represents general quadratic; LP denotes linear plateau; QP is quadratic plateau; socutility indicates social optimal; lbeta means farmers are optimistic about the weather.

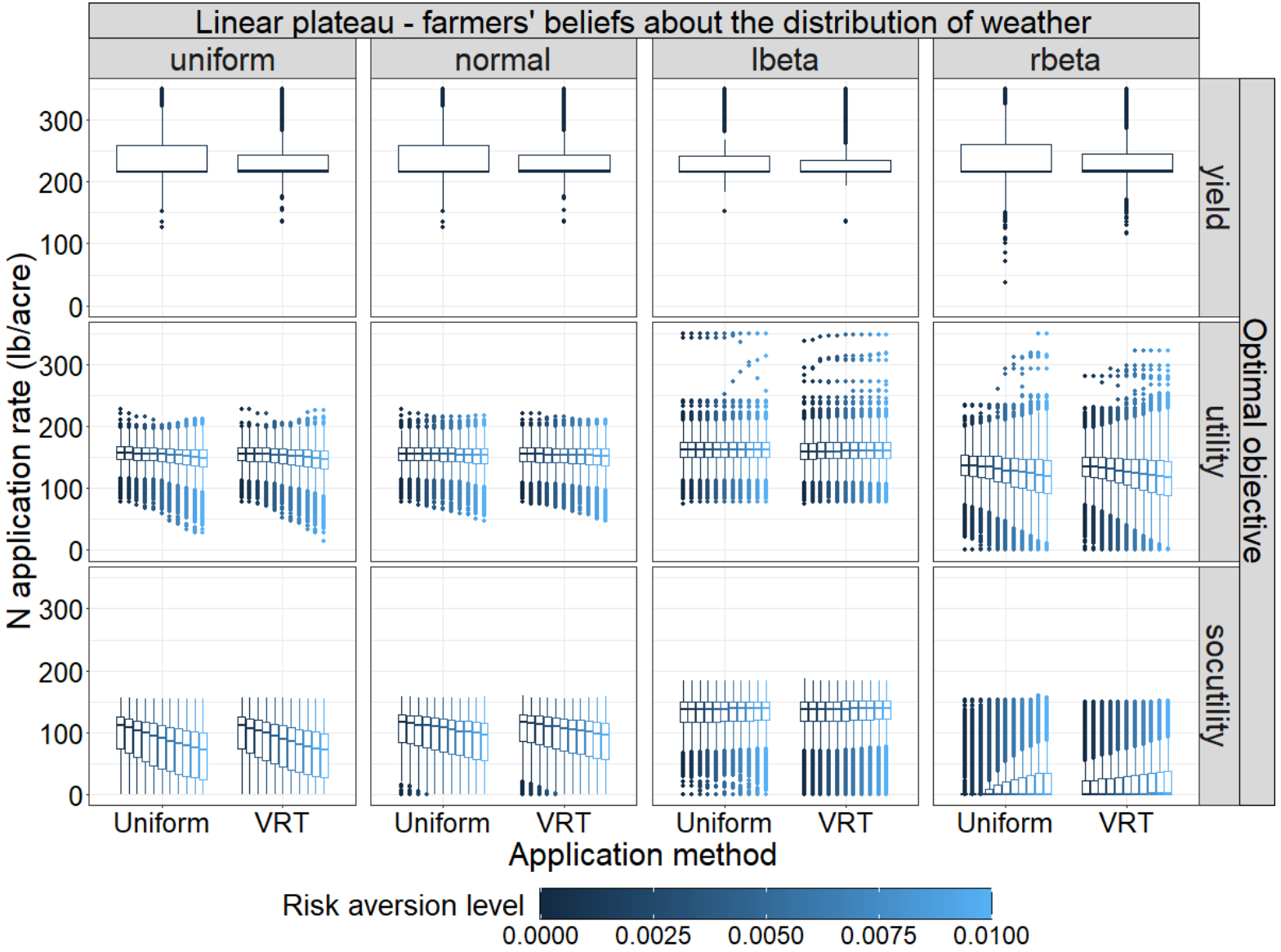


Figure 5. Optimal N rates for linear plateau production functions

Notes: The figure presents the boxplots for optimal N application rate at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

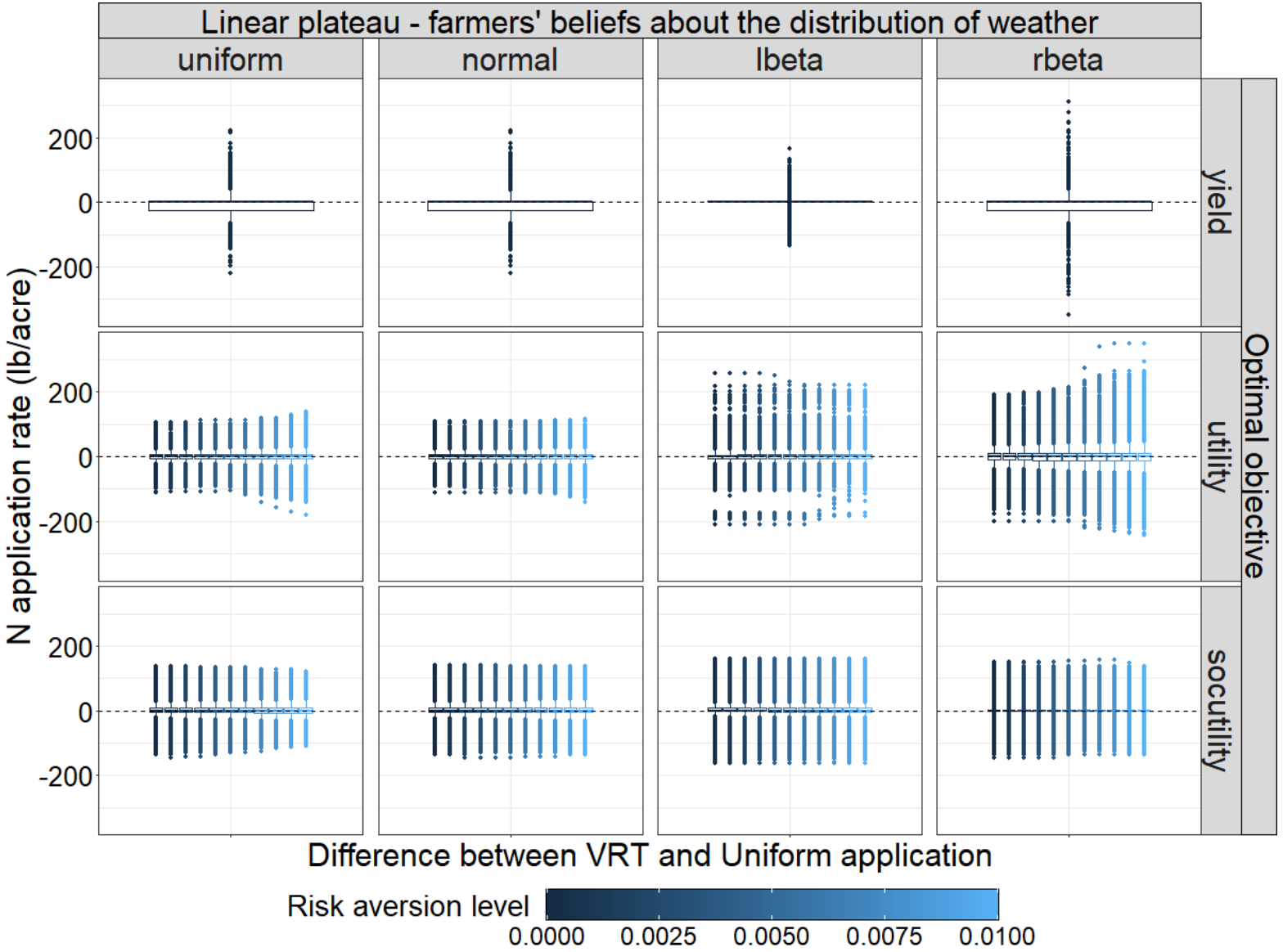


Figure 6. Optimal N rate differences between VRT and Uniform application for linear plateau functions

Notes: This figure illustrates the differences in N application rates between VRT and uniform application at the mukey level.

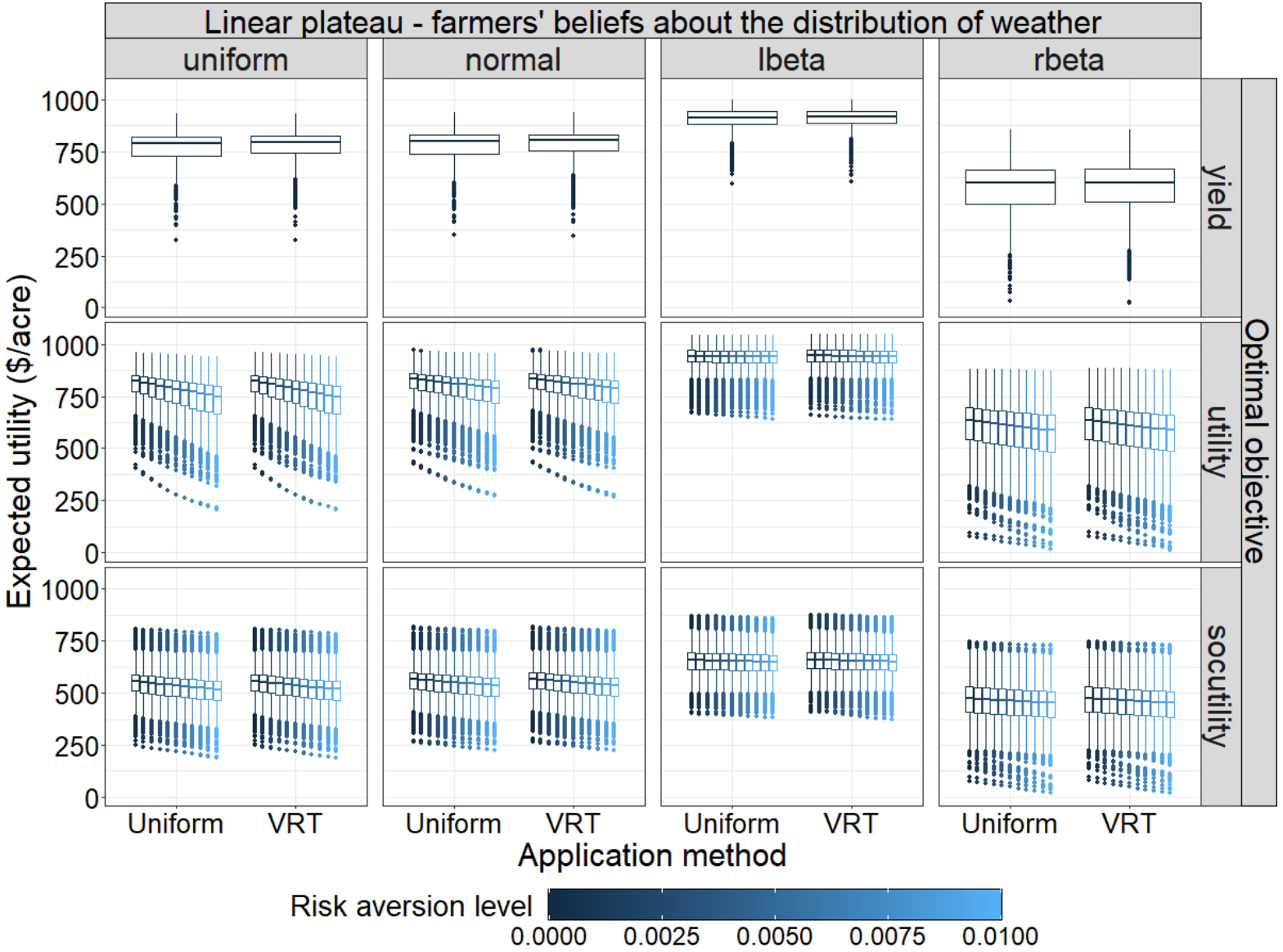


Figure 7. Expected utility for linear plateau functions

Notes: The figure presents the boxplots for expected utility at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

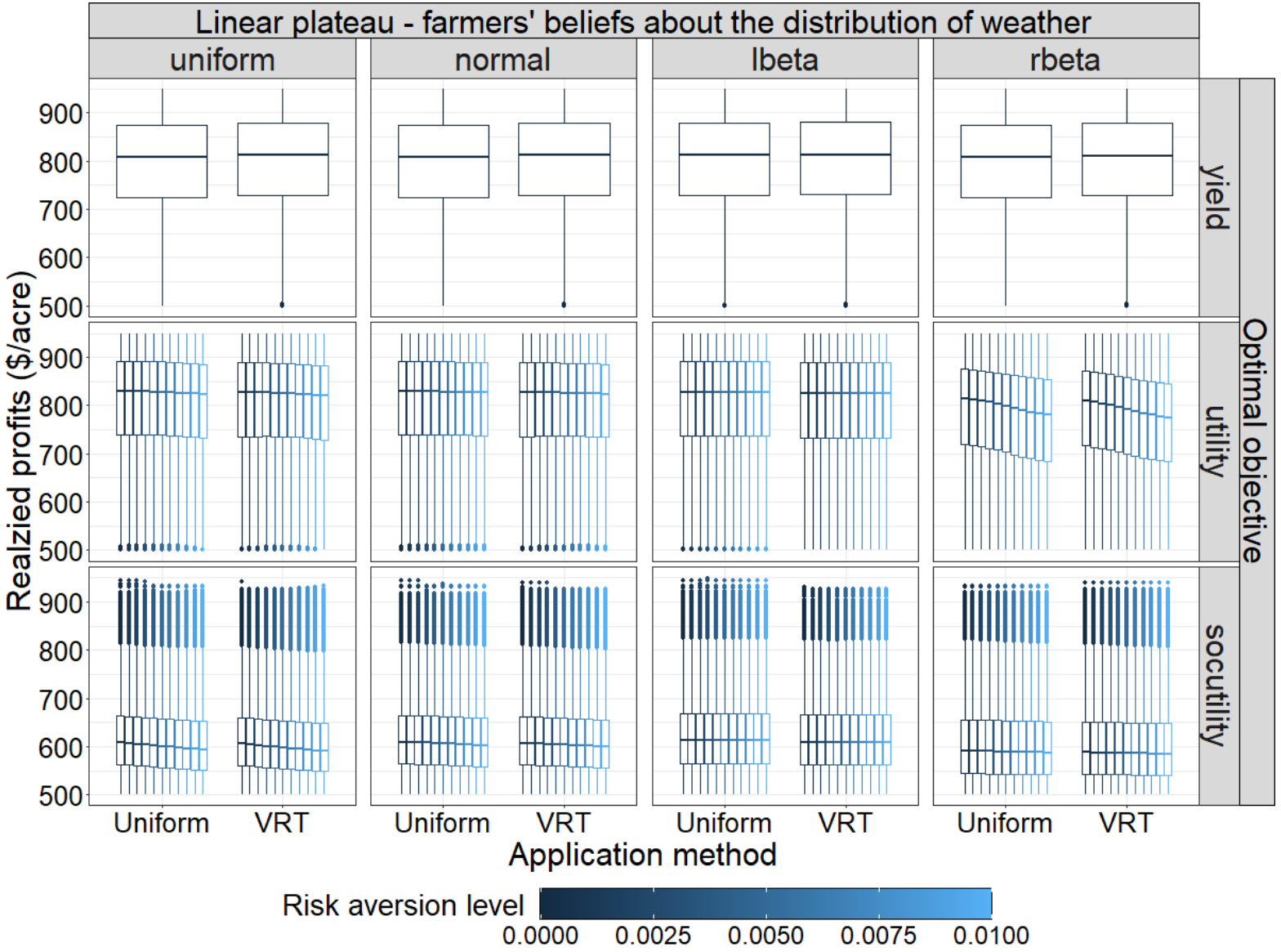


Figure 8. Realized profits for linear plateau functions

Notes: The figure presents the boxplots for realized profits at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

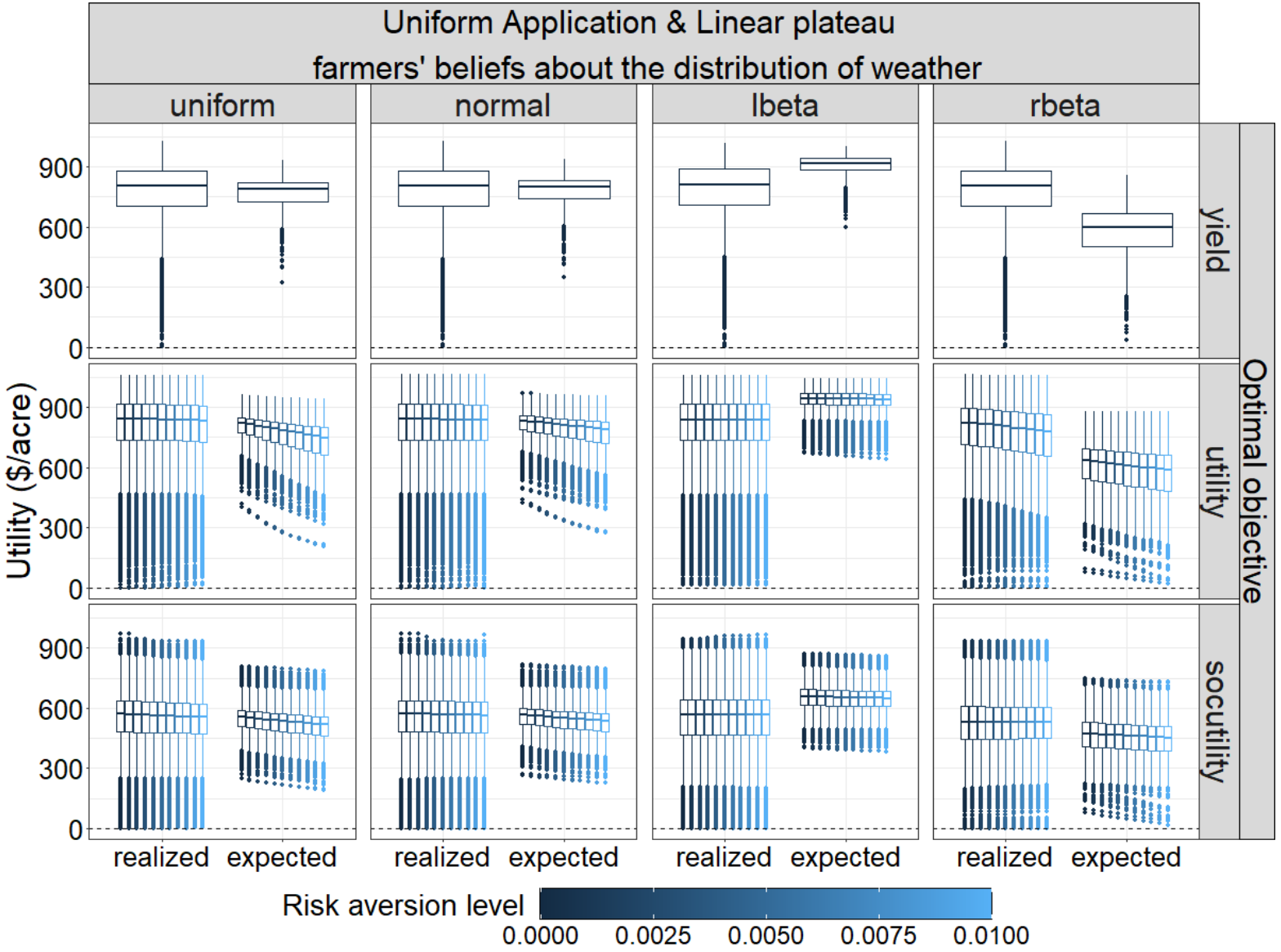


Figure 9. Comparison of utility between realized and expected for linear plateau functions

Notes: The figure presents the comparison of utility between realized and expected at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

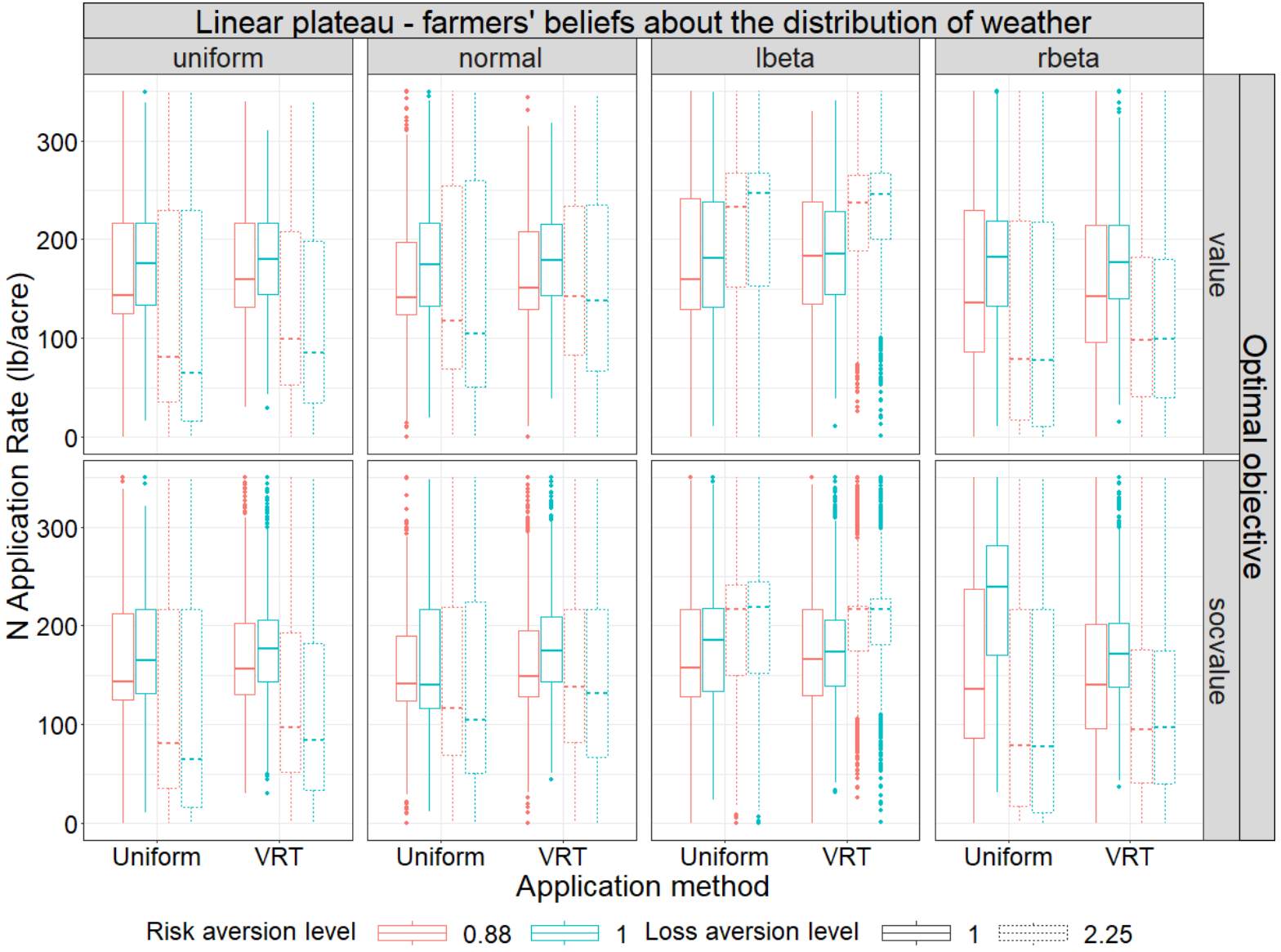


Figure 10. Comparison of value optimal N application rates for linear plateau functions

Notes: The figure presents the comparison of value maximization N application rates at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

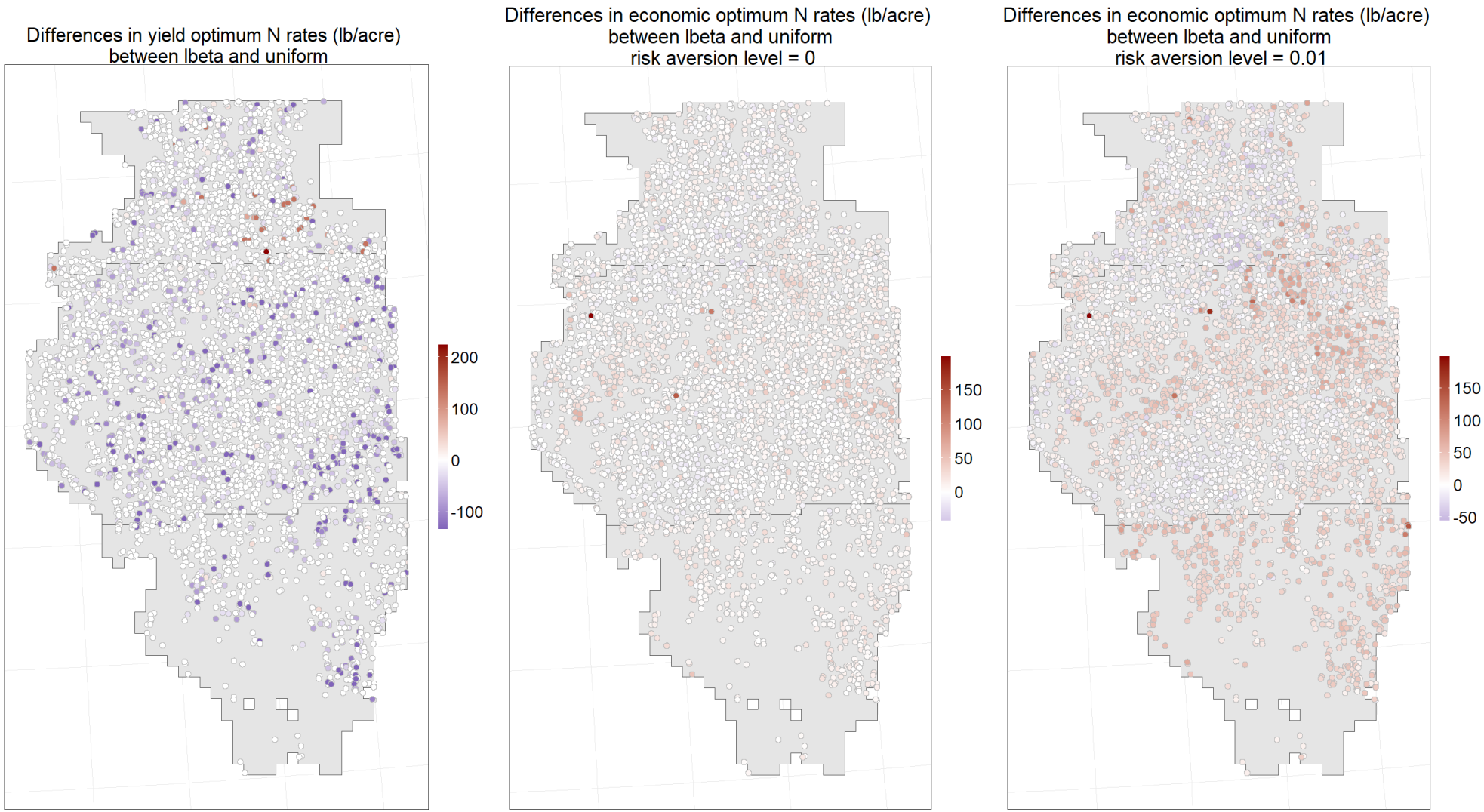


Figure 11. The comparison of the differences in optimum N rates between farmers holding different weather beliefs

Notes: The comprisons are among yield optimum N rates, economic optimum N rates assuming farmers are risk neutral, and economic optimum N rates assuming farmers' risk aversion level at 0.01 across approximately 4,200 fields in Illinois based on linear plateau production functions. "lbeta" and "uniform" represent farmers hold optimistic view on the weather conditions and assume weather conditions occur randomly, respectively. More farmers across three regions of Illinois are likely to increase the gap in N rates between being optimistic on weather and assuming random weather conditions when they are risk averse.

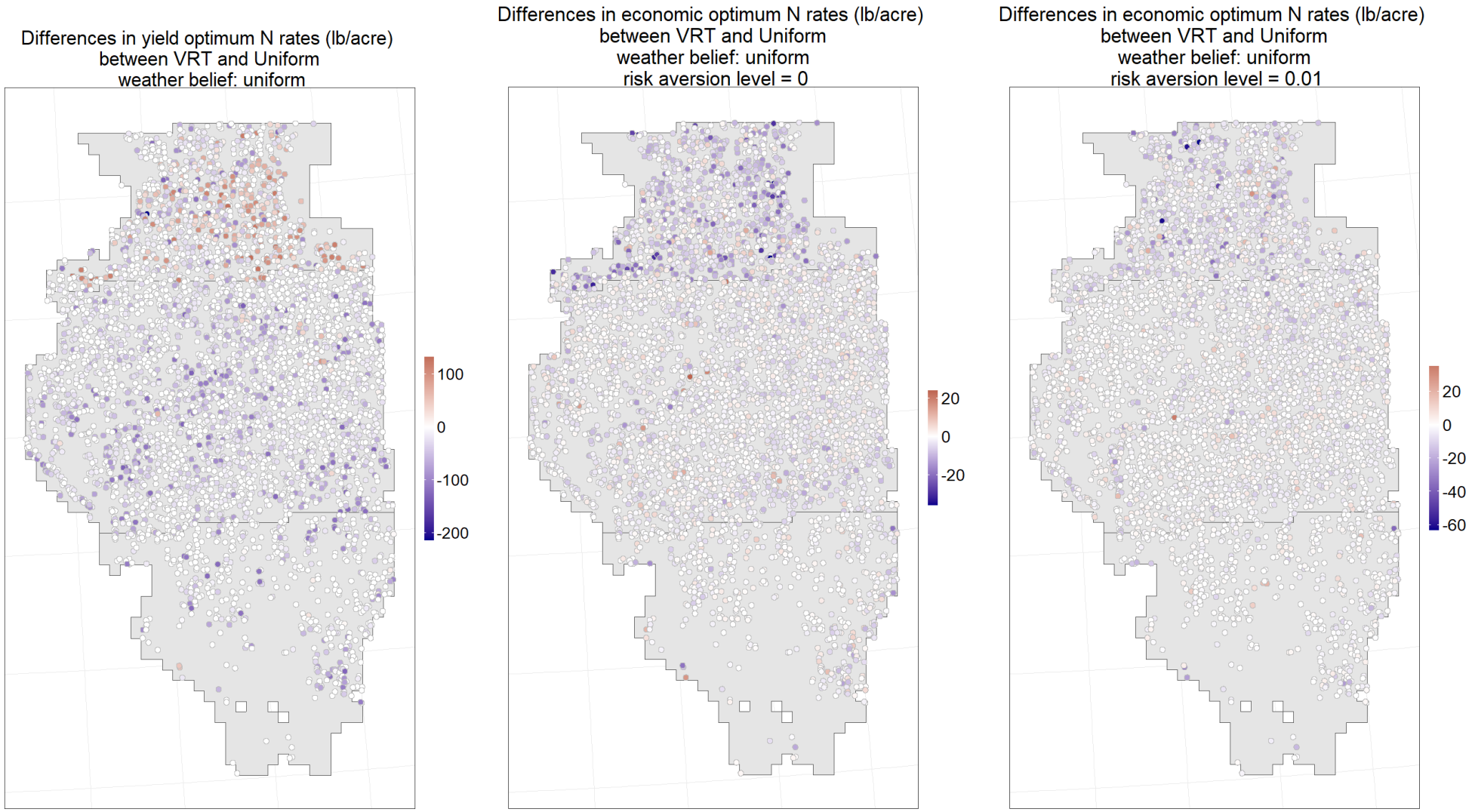


Figure 12. The comparison of the differences in optimum N rates between farmers using different application methods by assuming uniform weather distribution

Notes: The comprisons are among yield optimum N rates, economic optimum N rates assuming farmers are risk neutral, and economic optimum N rates assuming farmers' risk aversion level at 0.01 across approximately 4,200 fields in Illinois based on linear plateau production functions. "VRT" and "Uniform" denote variable rate technology and uniform application, respectively. "uniform" represents farmers assume weather conditions occur randomly.

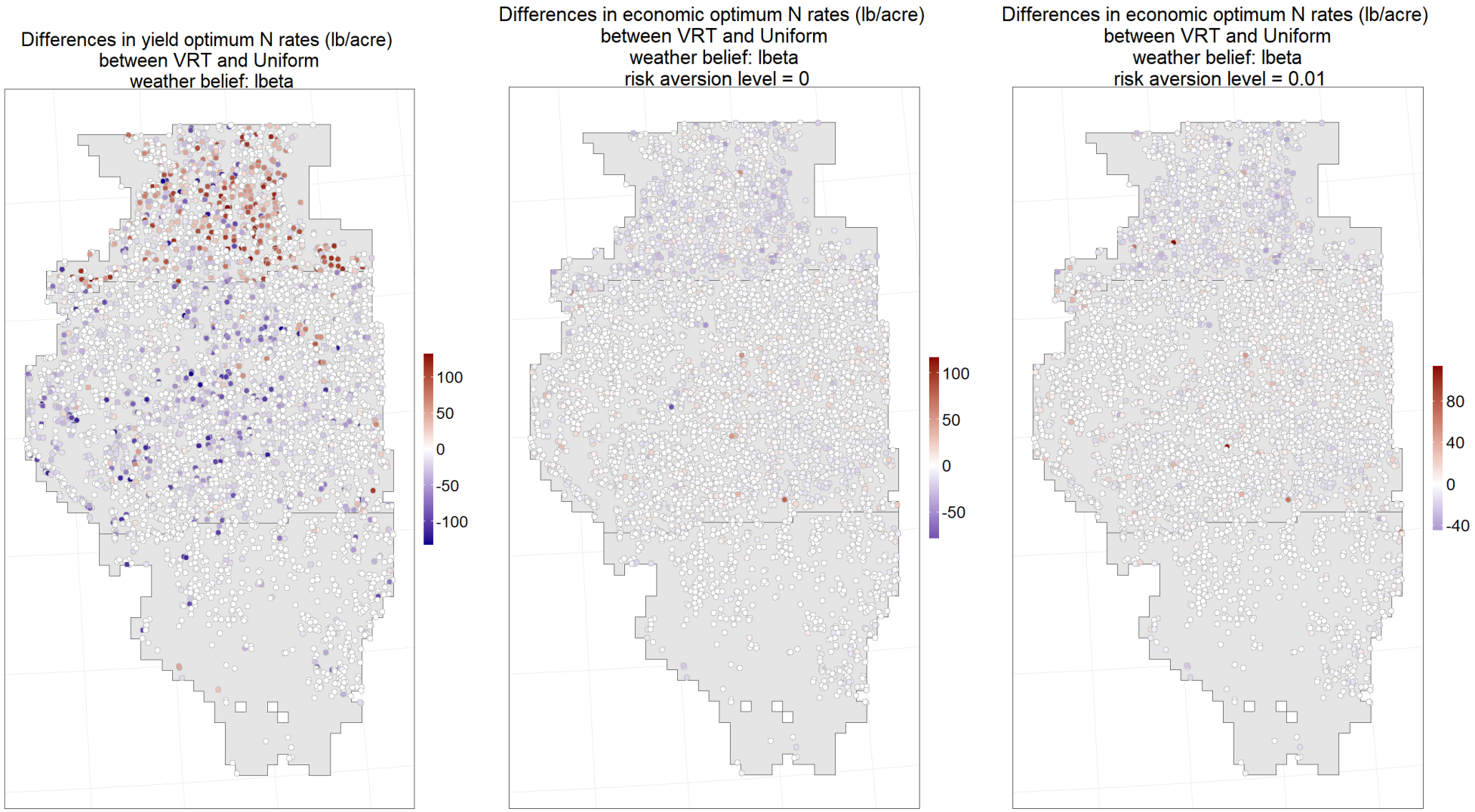


Figure 13. The comparison of the differences in optimum N rates between farmers using different application methods by assuming farmers are optimistic about the weather conditions

Notes: The comprisons are among yield optimum N rates, economic optimum N rates assuming farmers are risk neutral, and economic optimum N rates assuming farmers' risk aversion level at 0.01 across approximately 4,200 fields in Illinois based on linear plateau production functions. "VRT" and "Uniform" denote variable rate technology and uniform application, respectively. "lbeta" represents farmers hold optimistic view on the weather conditions.

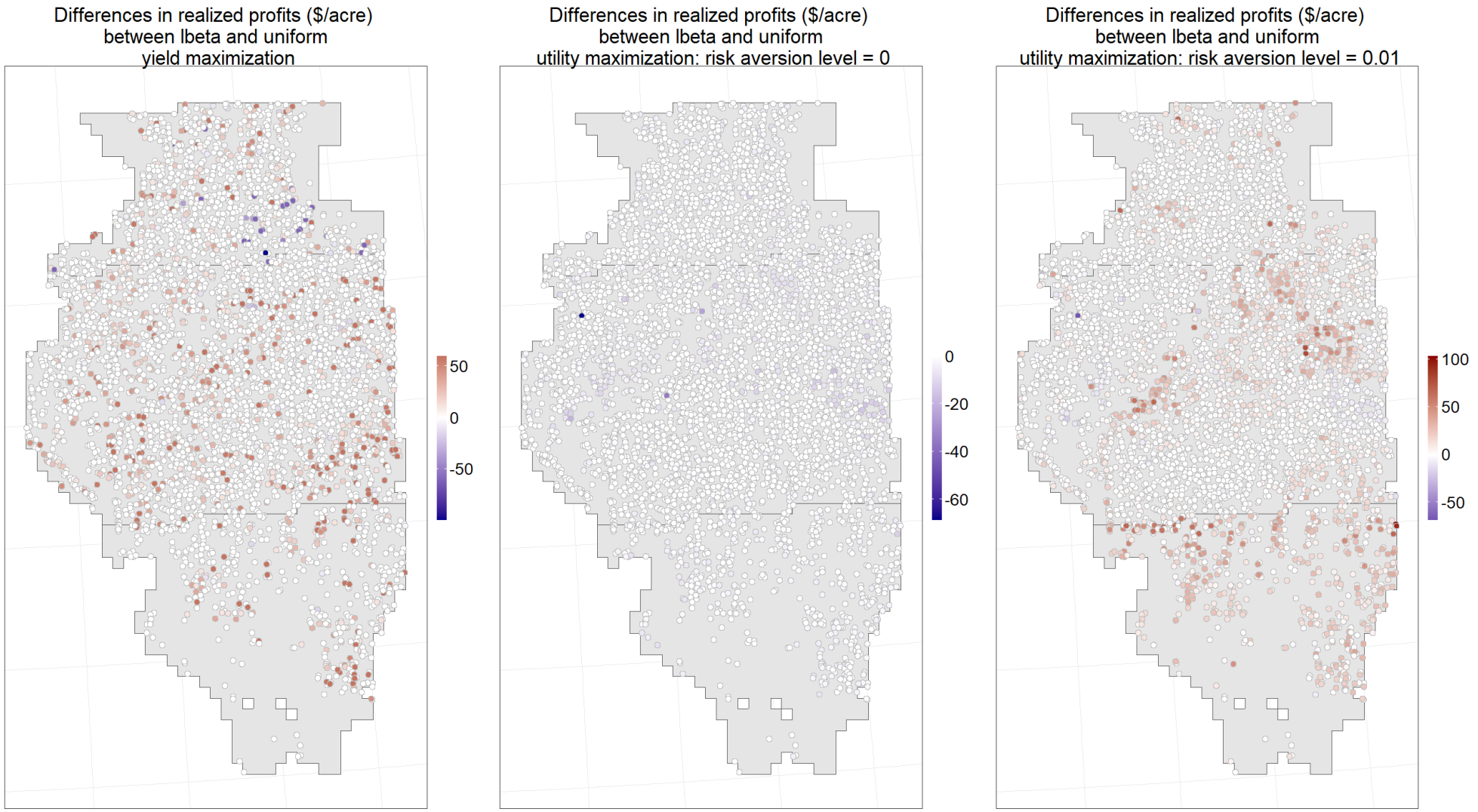


Figure 14. The comparison of the differences in realized profits between farmers holding different weather beliefs

Notes: The comprisons are among realized profits obtained by following yield optimum N rates, economic optimum N rates assuming farmers are risk neutral, and economic optimum N rates assuming farmers' risk aversion level at 0.01 across approximately 4,200 fields in Illinois based on linear plateau production functions. "VRT" and "Uniform" denote variable rate technology and uniform application, respectively. "lbeta" and "uniform" represent farmers hold optimistic view on the weather conditions and assume weather conditions occur randomly, respectively.

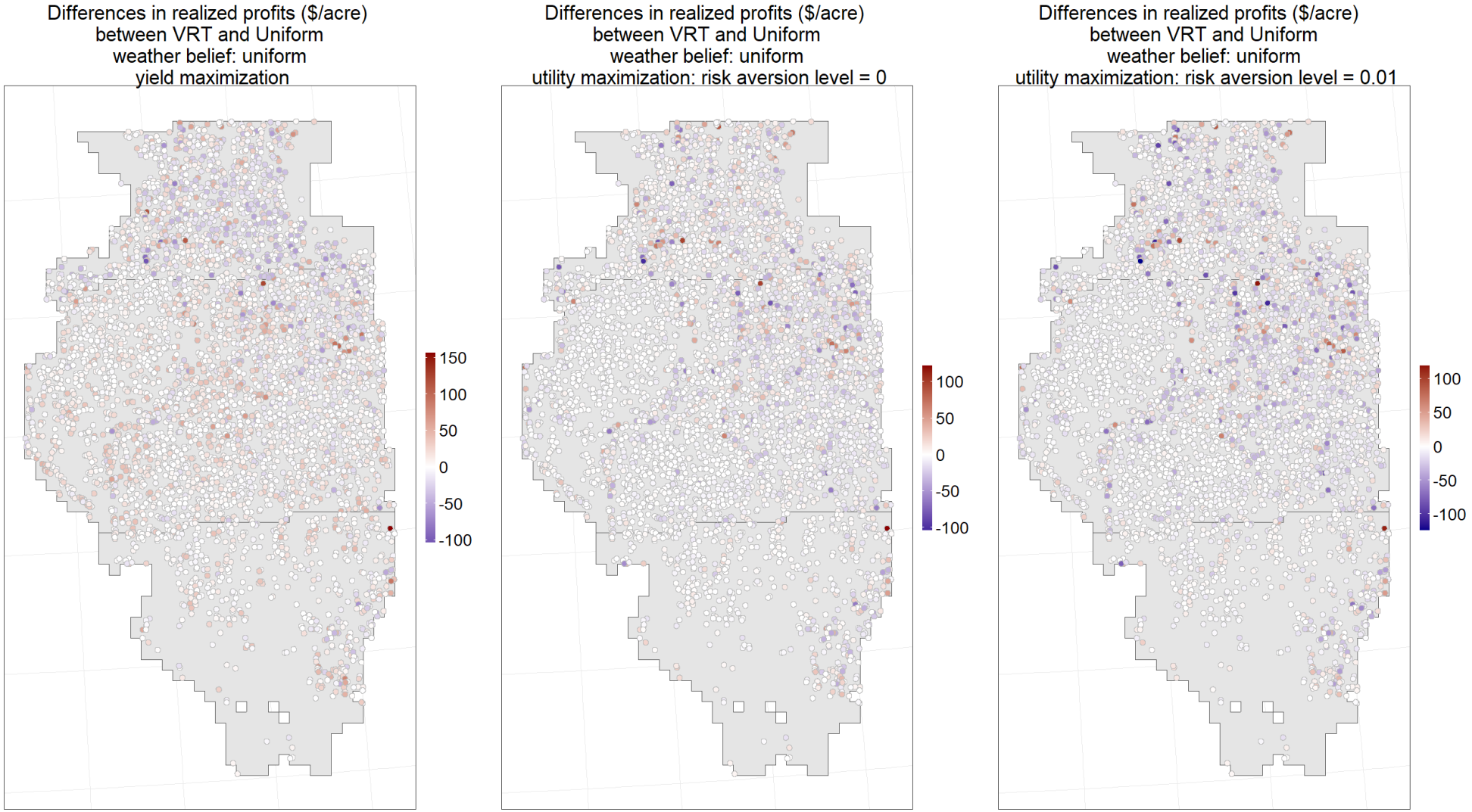


Figure 15. The comparison of the differences in realized profits between farmers using different application methods by assuming uniform weather distribution

Notes: The comprisons are among realized profits obtained by following yield optimum N rates, economic optimum N rates assuming farmers are risk neutral, and economic optimum N rates assuming farmers' risk aversion level at 0.01 across approximately 4,200 fields in Illinois based on linear plateau production functions. "VRT" and "Uniform" denote variable rate technology and uniform application, respectively. "uniform" represents farmers assume weather conditions occur randomly.

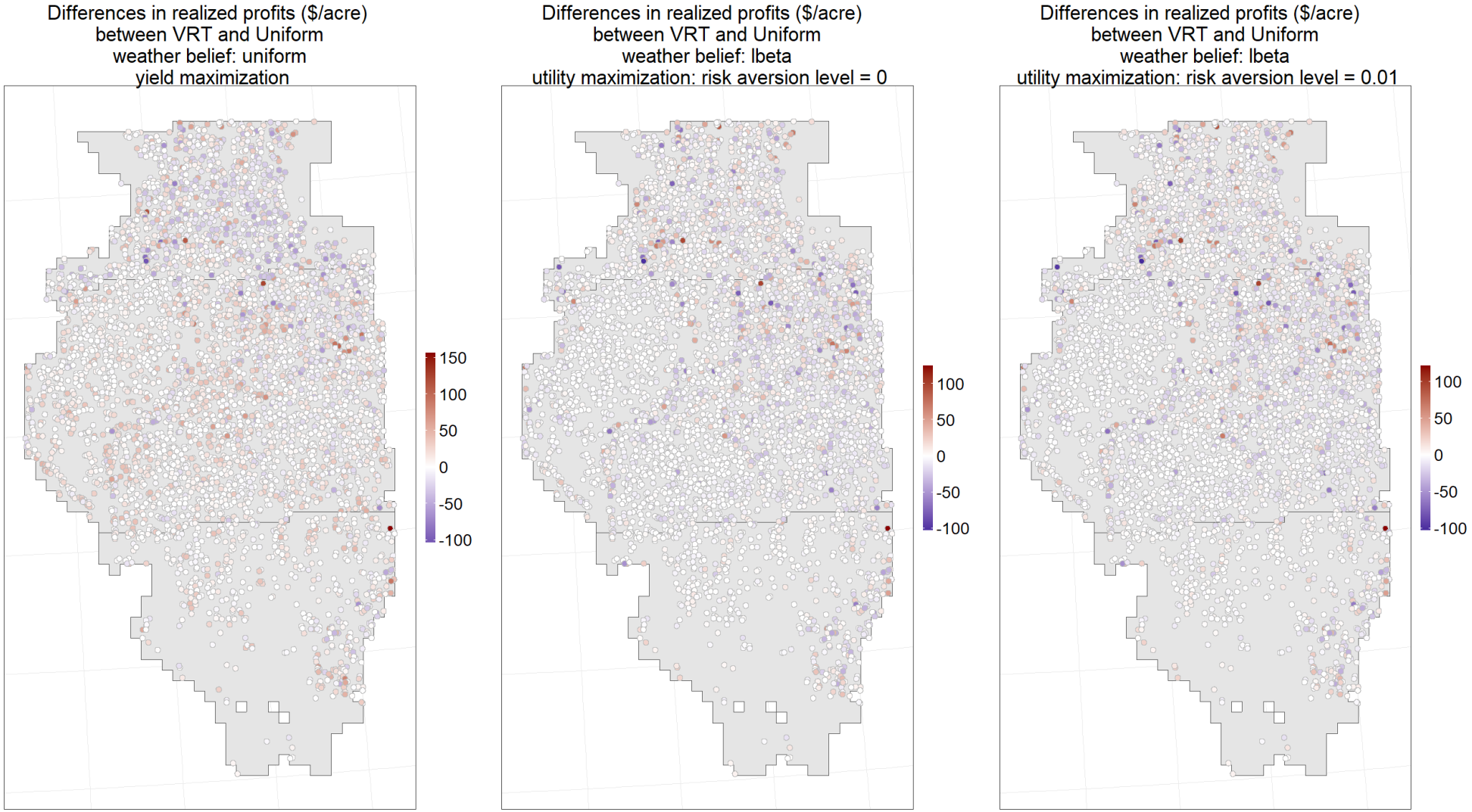


Figure 16. The comparison of the differences in realized profits between farmers using different application methods by assuming farmers are optimistic about the weather conditions

Notes: The comprisons are among realized profits obtained by following yield optimum N rates, economic optimum N rates assuming farmers are risk neutral, and economic optimum N rates assuming farmers' risk aversion level at 0.01 across approximately 4,200 fields in Illinois based on linear plateau production functions. "VRT" and "Uniform" denote variable rate technology and uniform application, respectively. "lbeta" represents farmers hold optimistic view on the weather conditions.

Table 1. The mean values of optimal N rates and corresponding utilities by using linear plateau production functions

	Application method	*Risk averse level*	*Yield optimal*				*Utility optimal*				*Social utility optimal*			
			uniform	normal	lbeta	rbeta	uniform	normal	lbeta	rbeta	uniform	normal	lbeta	rbeta
N rate pounds per acre	VRT	0	235	235	231	235	152	151	158	133	94	100	125	19
		0.005					149	149	158	124	77	92	126	21
		0.01					143	148	159	116	65	83	127	23
	Uniform	0	247	247	234	246	154	153	160	136	93	99	123	17
		0.005					151	152	160	127	76	91	124	19
		0.01					145	149	160	114	64	82	126	22
Expected utility $/acre	VRT	0	777	788	910	581	808	820	942	616	555	565	658	470
		0.005					765	793	939	588	532	548	652	458
		0.01					727	767	936	567	514	533	648	446
	Uniform	0	772	783	907	577	807	818	938	615	554	563	655	470
		0.005					766	793	936	589	532	547	650	457
		0.01					728	768	933	566	514	533	646	447
Realized utility $/acre	VRT	0	776	776	777	775	806	805	804	786	551	550	535	523
		0.005					804	805	804	767	548	550	535	524
		0.01					797	802	804	743	544	549	534	525
	Uniform	0	772	772	777	772	807	807	806	791	554	553	540	526
		0.005					806	806	806	774	551	553	539	527
		0.01					800	804	806	751	547	552	538	528

Table 2. The mean values of optimal N rates and corresponding values by using linear plateau production function

	Application method	*Risk averse level*	*Loss averse level*	*Value optimal*				*Social value optimal*			
				uniform	normal	lbeta	rbeta	uniform	normal	lbeta	rbeta
N rate pounds per acre	VRT	1	1	180.47	180.77	186.15	178.09	174.39	174.61	172.21	170.35
		0.88	1	171.78	166.18	177.43	149.98	164.35	159.25	161.29	143.21
		1	2.25	112.60	146.14	227.60	112.24	106.62	138.28	205.80	108.96
		0.88	2.25	123.72	153.70	221.99	113.43	117.60	145.98	200.82	109.84
	Uniform	1	1	175.83	174.93	178.77	177.15	171.11	157.00	176.90	228.28
		0.88	1	165.87	160.07	168.49	150.67	160.29	154.59	160.37	153.39
		1	2.25	108.60	144.78	221.85	112.90	103.97	138.00	210.10	114.05
		0.88	2.25	118.65	150.74	213.73	114.66	113.97	144.08	202.48	115.85
Expected value $/acre	VRT	1	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.88	1	2.24	1.83	0.83	0.08	2.24	1.83	0.84	0.08
		1	2.25	-40.26	-33.36	-12.17	-33.52	-40.14	-33.31	-12.13	-33.58
		0.88	2.25	-22.16	-18.19	-7.39	-20.95	-22.10	-18.16	-7.37	-20.99
	Uniform	1	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.88	1	2.21	1.80	0.82	0.07	2.21	1.80	0.82	0.07
		1	2.25	-39.45	-32.91	-11.97	-33.47	-39.42	-32.88	-11.95	-33.47
		0.88	2.25	-21.72	-17.94	-7.27	-20.94	-21.71	-17.92	-7.25	-20.94

Table 3. The relationship between optimal N rates and influential factors for different production functions

	Optimal N rates				Optimal N rates		
	(1) - linear plateau	(2) - quadratic plateau	(3) - general quadratic		(1) - linear plateau	(2) - quadratic plateau	(3) - general quadratic
risk	-28.922***	-15.460***	-6.814***	lbeta*socutility	43.262***	31.938***	23.487***
	(0.379)	(0.304)	(0.271)		(0.645)	(0.517)	(0.462)
normal	-0.04	-0.116	-1.008**	rbeta*socutility	-75.133***	-46.808***	-43.104***
	(0.562)	(0.451)	(0.402)		(0.645)	(0.517)	(0.462)
lbeta	-12.059***	-8.879***	3.414***	risk*normal*vrt	0.033	-0.139	2.263***
	(0.562)	(0.451)	(0.402)		(0.758)	(0.608)	(0.542)
rbeta	-0.079	-2.870***	2.816***	risk*normal*utility	-6.117***	3.860***	2.722***
	(0.562)	(0.451)	(0.402)		(0.758)	(0.608)	(0.542)
vrt	-12.039***	-15.044***	-0.220	risk*vrt*utility	0.399	-0.981	5.502***
	(0.562)	(0.451)	(0.402)		(0.758)	(0.608)	(0.542)
utility	-91.652***	-157.689***	-27.870***	normal*vrt*utility	-0.249	-0.252	-0.035
	(0.456)	(0.366)	(0.326)		(0.912)	(0.732)	(0.653)
socutility	-154.885***	-263.093***	-175.121***	risk*lbeta*vrt	-0.242	-0.003	5.921***
	(0.456)	(0.366)	(0.326)		(0.758)	(0.608)	(0.542)
risk*normal	12.024***	6.336***	4.197***	risk*lbeta*utility	-21.813***	1.475**	2.428***
	(0.536)	(0.430)	(0.383)		(0.758)	(0.608)	(0.542)
risk*vrt	-0.416	-0.077	-6.218***	lbeta*vrt*utility	-9.112***	4.752***	-0.002
	(0.536)	(0.430)	(0.383)		(0.912)	(0.732)	(0.653)
normal*vrt	0.116	-0.009	0.015	risk*rbeta*vrt	-0.118	-0.106	6.912***
	(0.795)	(0.637)	(0.569)		(0.758)	(0.608)	(0.542)
risk*utility	19.534***	-3.299***	-6.182***	risk*rbeta*utility	-45.680***	-28.166***	-23.780***
	(0.536)	(0.430)	(0.383)		(0.758)	(0.608)	(0.542)
normal*utility	-1.596**	-1.358***	0.369	rbeta*vrt*utility	-1.281	-2.319***	-0.508
	(0.645)	(0.517)	(0.462)		(0.912)	(0.732)	(0.653)
vrt*utility	10.177***	14.340***	-0.062	normal*vrt*socutility	0.277	0.163	-0.112
	(0.645)	(0.517)	(0.462)		(0.912)	(0.732)	(0.653)
risk*lbeta	31.870***	18.433***	10.336***	lbeta*vrt*socutility	-7.737***	2.372***	-1.280**
	(0.536)	(0.430)	(0.383)		(0.912)	(0.732)	(0.653)
lbeta*vrt	8.761***	-2.554***	0.039	rbeta*vrt*socutility	0.877	1.084	-10.941***
	(0.795)	(0.637)	(0.569)		(0.912)	(0.732)	(0.653)

	Optimal N rates				Optimal N rates		
	(1) - linear plateau	(2) - quadratic plateau	(3) - general quadratic		(1) - linear plateau	(2) - quadratic plateau	(3) - general quadratic
lbeta*utility	16.951***	23.280***	3.907***	risk*normal*vrt*utility	0.169	0.771	-1.886**
	(0.645)	(0.517)	(0.462)		(1.071)	(0.859)	(0.767)
risk*rbeta	34.531***	18.093***	10.536***	risk*lbeta*vrt*utility	0.786	1.053	-5.216***
	(0.536)	(0.430)	(0.383)		(1.071)	(0.859)	(0.767)
rbeta*vrt	0.214	-0.375	-0.505	risk*rbeta*vrt*utility	1.048	3.704***	-5.829***
	(0.795)	(0.637)	(0.569)		(1.071)	(0.859)	(0.767)
rbeta*utility	-18.408***	-31.032***	-22.539***	Observations	785,864	785,864	785,864
	(0.645)	(0.517)	(0.462)	R2	0.791	0.918	0.937
normal*socutility	7.510***	4.179***	4.506***	Adjusted R2	0.79	0.918	0.937
	(0.645)	(0.517)	(0.462)	F Statistic	75,972.540***	226,214.600***	299,165.600***
vrt*socutility	12.860***	15.210***	20.948***		(df = 39; 784601)	(df = 39; 784601)	(df = 39; 784601)
	(0.645)	(0.517)	(0.462)				

Notes: *p<0.1; **p<0.05; ***p<0.01. 'Risk' represents the risk aversion level, the coefficent estimates for risk and risk interaction terms suggest the effect of the change of 0.01 in risk aversion level; 'normal', 'lbeta', and 'rbeta' denotes the distribution of farmers' weather beliefs; 'vrt' implies farmers adopt variable rate technology; utility and socutility suggest farmers are utility maximizers without and with considering the social costs of N, respectively. The benchmark optimal N rates are obtained by assuming yield maximization, random weather beliefs, uniform application method.

Table 4. The relationship between realized profits and influential factors for different production functions

	Realized profits				Realized profits		
	(1) - linear plateau	(2) - quadratic plateau	(3) - general quadratic		(1) - linear plateau	(2) - quadratic plateau	(3) - general quadratic
risk	-7.206***	-4.328***	-3.841***	lbeta*socutility	-19.766***	-12.051***	4.411***
	(0.592)	(0.586)	(0.588)		(1.007)	(0.999)	(1.001)
normal	0.018	0.052	0.435	rbeta*socutility	-28.295***	-36.669***	-33.591***
	(0.877)	(0.870)	(0.872)		(1.007)	(0.999)	(1.001)
lbeta	5.293***	3.925***	-1.770**	risk*normal*vrt	0.267	0.183	-0.340
	(0.877)	(0.870)	(0.872)		(1.183)	(1.173)	(1.176)
rbeta	-0.067	1.064	-2.498***	risk*normal*utility	-1.875	0.068	-0.503
	(0.877)	(0.870)	(0.872)		(1.183)	(1.173)	(1.176)
vrt	3.509***	4.540***	-1.580*	risk*vrt*utility	-1.287	-1.016	-1.576
	(0.877)	(0.870)	(0.872)		(1.183)	(1.173)	(1.176)
utility	35.898***	57.986***	6.884***	normal*vrt*utility	-0.201	-0.186	-0.064
	(0.712)	(0.706)	(0.708)		(1.425)	(1.412)	(1.416)
socutility	-217.683***	-180.465***	-248.641***	risk*lbeta*vrt	1.073	0.351	-2.132*
	(0.712)	(0.706)	(0.708)		(1.183)	(1.173)	(1.176)
risk*normal	5.775***	3.628***	2.609***	risk*lbeta*utility	0.617	2.360**	-0.892
	(0.837)	(0.829)	(0.831)		(1.183)	(1.173)	(1.176)
risk*vrt	-0.481	-0.318	1.040	lbeta*vrt*utility	3.388**	-1.959	-0.106
	(0.837)	(0.829)	(0.831)		(1.425)	(1.412)	(1.416)
normal*vrt	-0.064	0.006	-0.010	risk*rbeta*vrt	0.066	-0.001	-1.575
	(1.241)	(1.230)	(1.233)		(1.183)	(1.173)	(1.176)
risk*utility	0.908	-0.971	1.168	risk*rbeta*utility	-44.537***	-46.374***	-33.628***
	(0.837)	(0.829)	(0.831)		(1.183)	(1.173)	(1.176)
normal*utility	-0.979	-0.803	-0.849	rbeta*vrt*utility	-4.632***	-4.149***	-0.810
	(1.007)	(0.999)	(1.001)		(1.425)	(1.412)	(1.416)
vrt*utility	-4.345***	-5.882***	0.083	normal*vrt*socutility	0.053	-0.018	-1.513
	(1.007)	(0.999)	(1.001)		(1.425)	(1.412)	(1.416)
risk*lbeta	5.671***	2.772***	3.635***	lbeta*vrt*socutility	1.915	-1.605	-9.840***
	(0.837)	(0.829)	(0.831)		(1.425)	(1.412)	(1.416)
lbeta*vrt	-3.880***	1.055	-0.015	rbeta*vrt*socutility	0.022	0.167	5.019***
	(1.241)	(1.230)	(1.233)		(1.425)	(1.412)	(1.416)

	Realized profits				Realized profits		
	(1) - linear plateau	(2) - quadratic plateau	(3) - general quadratic		(1) - linear plateau	(2) - quadratic plateau	(3) - general quadratic
lbeta*utility	-7.691***	-6.912***	0.587	risk*normal*vrt*utility	0.727	0.705	0.755
	(1.007)	(0.999)	(1.001)		(1.673)	(1.659)	(1.663)
risk*rbeta	9.223***	6.746***	8.409***	risk*lbeta*vrt*utility	0.594	0.997	2.678
	(0.837)	(0.829)	(0.831)		(1.673)	(1.659)	(1.663)
rbeta*vrt	-0.199	-0.035	-0.174	risk*rbeta*vrt*utility	-1.522	0.058	1.108
	(1.241)	(1.230)	(1.233)		(1.673)	(1.659)	(1.663)
rbeta*utility	-14.252***	-12.536***	-2.087**	Observations	785,864	785,864	785,864
	(1.007)	(0.999)	(1.001)	R2	0.908	0.898	0.911
normal*socutility	-0.680	-0.574	0.767	Adjusted R2	0.908	0.898	0.911
	(1.007)	(0.999)	(1.001)	F Statistic (df = 39; 784601)	198,695.300***	177,699.700***	206,248.600***
vrt*socutility	-6.319***	-8.047***	3.073***				
	(1.007)	(0.999)	(1.001)				

Notes: *p<0.1; **p<0.05; ***p<0.01. 'Risk' represents the risk aversion level, the coefficent estimates for risk and risk interaction terms suggest the effect of the change of 0.01 in risk aversion level; 'normal', 'lbeta', and 'rbeta' denotes the distribution of farmers' weather beliefs; 'vrt' implies farmers adopt variable rate technology; utility and socutility suggest farmers are utility maximizers without and with considering the social costs of N, respectively. The benchmark realized profits are obtained by assuming yield maximization, random weather beliefs, uniform application method.

Table 5. The relationship between optimal N rates and influential factors for linear plateau production functions

Linear plateau production functions	Optimal N rates		
	(1) - yield maximization	(2) - utility maximization	(3) - socutility maximization
risk		-9.388***	-28.922***
		(0.281)	(0.371)
normal	-0.04	-1.636***	7.470***
	(0.667)	(0.235)	(0.310)
lbeta	-12.059***	4.891***	31.203***
	(0.667)	(0.235)	(0.310)
rbeta	-0.079	-18.488***	-75.212***
	(0.667)	(0.235)	(0.310)
vrt	-12.039***	-1.862***	0.821***
	(0.667)	(0.235)	(0.310)
risk*normal		5.907***	12.024***
		(0.398)	(0.525)
risk*vrt		-0.017	-0.416
		(0.398)	(0.525)
normal*vrt	0.116	-0.133	0.393
	(0.944)	(0.333)	(0.439)
risk*lbeta		10.057***	31.870***
		(0.398)	(0.525)
lbeta*vrt	8.761***	-0.350	1.025**
	(0.944)	(0.333)	(0.439)
risk*rbeta		-11.149***	34.531***
		(0.398)	(0.525)
rbeta*vrt	0.214	-1.067***	1.091**
	(0.944)	(0.333)	(0.439)
risk*normal*vrt		0.202	0.033
		(0.563)	(0.742)
risk*lbeta*vrt		0.544	-0.242
		(0.563)	(0.742)
risk*rbeta*vrt		0.931*	-0.118
		(0.563)	(0.742)
Observations	34,168	375,848	375,848
R2	0.04	0.322	0.695
Adjusted R2	0.004	0.320	0.694
F Statistic	197.326***	11,860.090***	56,824.710***
	(df = 7; 32937)	(df = 15; 374609)	(df = 15; 374609)

Notes: *p<0.1; **p<0.05; ***p<0.01. 'Risk' represents the risk aversion level, the coefficent estimates for risk and risk interaction terms suggest the effect of the change of 0.01 in risk aversion level; 'normal', 'lbeta', and 'rbeta' denotes the distribution of farmers' weather beliefs; 'vrt' implies farmers adopt variable rate technology; utility and socutility suggest farmers are utility maximizers without and with considering the social costs of N, respectively. The benchmark optimal N rates are obtained by assuming linear plateau production function, random weather beliefs, uniform application method.

Table 6. The relationship between realized profits and influential factors for linear plateau production functions

Linear plateau production functions	Realized profits		
	(1) - yield maximization	(2) - utility maximization	(3) - socutility maximization
risk		-6.298***	-7.206***
		(0.579)	(0.469)
normal	0.018	-0.962**	-0.663*
	(0.758)	(0.485)	(0.392)
lbeta	5.293***	-2.398***	-14.473***
	(0.758)	(0.485)	(0.392)
rbeta	-0.067	-14.319***	-28.362***
	(0.758)	(0.485)	(0.392)
vrt	3.509***	-0.836*	-2.810***
	(0.758)	(0.485)	(0.392)
risk*normal		3.900***	5.775***
		(0.819)	(0.663)
risk*vrt		-1.768**	-0.481
		(0.819)	(0.663)
normal*vrt	-0.064	-0.265	-0.011
	(1.072)	(0.686)	(0.555)
risk*lbeta		6.288***	5.671***
		(0.819)	(0.663)
lbeta*vrt	-3.880***	-0.493	-1.965***
	(1.072)	(0.686)	(0.555)
risk*rbeta		-35.314***	9.223***
		(0.819)	(0.663)
rbeta*vrt	-0.199	-4.831***	-0.177
	(1.072)	(0.686)	(0.555)
risk*normal*vrt		0.995	0.267
		(1.159)	(0.938)
risk*lbeta*vrt		1.667	1.073
		(1.159)	(0.938)
risk*rbeta*vrt		-1.457	0.066
		(1.159)	(0.938)
Observations	34,168	375,848	375,848
R2	0.004	0.155	0.100
Adjusted R2	-0.034	0.152	0.097
F Statistic	17.482***	4,569.149***	2,769.003***
	(df=7;32937)	(df=15;374609)	(df=15;374609)

Notes: *p<0.1; **p<0.05; ***p<0.01. 'Risk' represents the risk aversion level, the coefficent estimates for risk and risk interaction terms suggest the effect of the change of 0.01 in risk aversion level; 'normal', 'lbeta', and 'rbeta' denotes the distribution of farmers' weather beliefs; 'vrt' implies farmers adopt variable rate technology; utility and socutility suggest farmers are utility maximizers without and with considering the social costs of N, respectively. The benchmark optimal N rates are obtained by assuming linear plateau production function, random weather beliefs, uniform application method.

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 pounds per acre)	36.44	30.40	0.00	14.81	50.50	320.20
N application rate (N pounds per 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 – production functions

	(1) General Quadratic Mean Estimate (Min, Max)	(2) Linear Plateau Mean Estimate (Min, Max)	(3) Quadratic Plateau Mean Estimate (Min, Max)
Intercept	105.768 (9.095, 240.029)	110.236 (0.006, 211.98)	104.393 (0.105, 226.009)
N rate	0.792 (-0.589, 1.546)	0.6065 (-0.755, 8.736)	0.950 (-7.988, 28.143)
N rate ^2	-0.0018 (-0.0033, 0.0010)	-	-0.00361 (-14.071, 6.214)
Plateau N rate	-	135.338 (0.112, 349.933)	198.138 (0.010, 349.984)
Number of regressors	752	8 - 15	8 - 15
Observations	4,786,650	495	495
Adjusted R-squared	0.9062	-	-
Residual standard error	12.61	-	-

Notes: The number of regressors presented here reflect 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.

Table A4. The mean values of optimal N rates and corresponding utilities by using general quadratic production functions

	Application method	*Risk averse level*	*Yield optimal*				*Utility optimal*				*Social utility optimal*			
			uniform	normal	lbeta	rbeta	uniform	normal	lbeta	rbeta	uniform	normal	lbeta	rbeta
N rate pounds per acre	VRT	0	221	220	224	223	192	192	200	172	67	70	92	15
		0.005					186	189	200	159	60	66	94	17
		0.01					178	185	200	146	54	63	95	19
	Uniform	0	221	220	224	224	192	192	200	173	46	49	72	5
		0.005					187	189	200	160	42	48	74	7
		0.01					179	186	200	147	39	47	76	9
Expected utility $/acre	VRT	0	797	807	927	610	804	813	932	621	554	559	645	468
		0.005					767	791	929	597	536	547	641	458
		0.01					732	770	926	576	520	536	637	448
	Uniform	0	797	807	926	610	803	813	931	621	447	451	515	392
		0.005					768	792	928	597	436	443	511	384
		0.01					733	770	925	576	426	435	508	376
Realized utility $/acre	VRT	0	796	796	794	793	802	802	801	796	550	549	543	519
		0.005					801	802	801	783	549	549	542	521
		0.01					798	801	801	767	547	549	541	523
	Uniform	0	797	798	795	795	803	803	803	798	548	550	551	512
		0.005					803	803	803	786	547	549	551	515
		0.01					801	803	803	771	545	548	551	517

Table A5. The mean values of optimal N rates and corresponding utilities by using quadratic plateau production functions

	Application method	*Risk averse level*	*Yield optimal*				*Utility optimal*				*Social optimal*			
			uniform	normal	lbeta	rbeta	uniform	normal	lbeta	rbeta	uniform	normal	lbeta	rbeta
N rate pounds per acre	VRT	0	321	321	309	317	176	175	194	141	73	77	96	24
		0.005					168	171	195	127	65	72	97	25
		0.01					157	166	195	115	58	68	99	26
	Uniform	0	336	336	327	333	177	176	192	144	73	77	96	23
		0.005					169	173	193	130	65	72	97	24
		0.01					158	168	194	116	58	68	99	25
Expected utility $/acre	VRT	0	746	757	882	552	797	809	924	610	559	567	643	474
		0.005					756	784	921	584	539	553	637	463
		0.01					719	759	919	565	522	539	632	454
	Uniform	0	739	750	872	547	796	808	922	609	558	566	643	473
		0.005					757	783	920	584	539	552	638	463
		0.01					720	760	917	564	522	539	633	454
Realized utility $/acre	VRT	0	744	744	749	745	795	794	792	778	555	554	546	519
		0.005					793	794	792	758	553	554	546	521
		0.01					788	792	792	733	550	554	545	522
	Uniform	0	739	739	743	740	796	796	794	783	558	558	550	523
		0.005					795	796	794	765	557	558	550	524
		0.01					791	794	794	739	554	557	549	525

Table A6. The mean values of optimal N rates and corresponding values by using general quadratic production functions

	Application method	*Risk averse level*	*Loss averse level*	*Value optimal*				*Social value optimal*			
				uniform	normal	lbeta	rbeta	uniform	normal	lbeta	rbeta
N rate pounds per acre	VRT	1	1	176.96	177.57	174.01	172.28	176.59	177.98	173.98	171.92
		0.88	1	184.24	180.98	208.32	184.46	184.24	180.99	208.32	184.46
		1	2.25	49.83	73.93	188.32	74.66	49.83	73.93	188.32	74.66
		0.88	2.25	63.39	88.87	193.06	77.44	63.39	88.87	193.06	77.44
	Uniform	1	1	176.83	177.78	174.01	175.95	170.99	159.52	179.21	228.76
		0.88	1	184.12	181.10	211.70	185.46	184.12	181.10	211.70	185.46
		1	2.25	47.98	73.62	188.37	73.61	47.98	73.62	188.37	73.62
		0.88	2.25	62.57	88.87	194.32	74.75	62.57	88.86	194.32	74.75
Expected value $/acre	VRT	1	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.88	1	1.71	1.34	0.94	0.42	1.71	1.34	0.94	0.42
		1	2.25	-32.80	-27.60	-13.12	-24.25	-32.80	-27.60	-13.12	-24.25
		0.88	2.25	-19.10	-16.00	-7.85	-15.50	-19.10	-16.00	-7.85	-15.50
	Uniform	1	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.88	1	1.72	1.34	0.93	0.41	1.72	1.34	0.93	0.41
		1	2.25	-32.63	-27.43	-12.94	-24.29	-32.63	-27.43	-12.94	-24.29
		0.88	2.25	-19.01	-15.93	-7.74	-15.51	-19.01	-15.93	-7.74	-15.51

Table A7. The mean values of optimal N rates and corresponding values by using quadratic plateau production functions

	Application method	*Risk averse level*	*Loss averse level*	*Value optimal*				*Social value optimal*			
				uniform	normal	lbeta	rbeta	uniform	normal	lbeta	rbeta
N rate pounds per acre	VRT	1	1	176.44	177.57	176.27	174.07	176.28	177.28	173.97	172.13
		0.88	1	180.24	173.23	171.55	169.84	179.64	172.68	170.23	169.05
		1	2.25	77.25	113.35	226.89	110.55	76.63	112.86	225.33	110.02
		0.88	2.25	88.82	125.92	218.23	109.61	87.93	125.00	216.12	108.86
	Uniform	1	1	176.63	175.34	173.01	177.28	173.01	160.43	179.63	229.33
		0.88	1	181.92	175.36	174.21	174.87	181.90	175.31	174.08	175.12
		1	2.25	76.77	110.95	229.33	110.14	76.77	110.80	229.00	110.29
		0.88	2.25	86.30	123.97	222.73	109.42	86.17	123.79	222.35	109.53
Expected value $/acre	VRT	1	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.88	1	2.12	1.70	0.86	0.17	2.12	1.70	0.86	0.17
		1	2.25	-34.93	-30.16	11.58	-29.61	-34.92	-30.15	-11.58	-29.61
		0.88	2.25	-19.95	-17.04	-7.01	-18.66	-19.94	-17.04	-7.01	-18.66
	Uniform	1	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.88	1	2.09	1.67	0.83	0.17	2.09	1.67	0.83	0.17
		1	2.25	-34.48	-29.59	-11.61	-29.01	-34.48	-29.59	-11.61	-29.01
		0.88	2.25	-19.66	-16.71	-7.05	-18.32	-19.66	-16.71	-7.05	-18.32

Table A8. The relationship between optimal N rates and influential factors

	Optimal N rates		Optimal N rates		Optimal N rates
risk	-6.814***	risk*vrt*utility	5.502***	lbeta*socutility*quadratic_plateau	8.451***
	(0.326)		(0.652)		(0.785)
normal	-1.008**	normal*vrt*utility	-0.035	rbeta*socutility*quadratic_plateau	-3.704***
	(0.483)		(0.785)		(0.785)
lbeta	3.414***	risk*normal*linear_plateau	7.827***	risk*normal*vrt*utility	-1.886**
	(0.483)		(0.652)		(0.922)
rbeta	2.816***	risk*vrt*linear_plateau	5.802***	risk*normal*vrt*linear_plateau	-2.230**
	(0.483)		(0.652)		(0.922)
vrt	-0.220	normal*vrt*linear_plateau	0.101	risk*normal*utility*linear_plateau	-8.840***
	(0.483)		(0.967)		(0.922)
utility	-27.870***	risk*utility*linear_plateau	25.716***	risk*vrt*utility*linear_plateau	-5.103***
	(0.392)		(0.652)		(0.922)
socutility	-175.121***	normal*utility*linear_plateau	-1.966**	normal*vrt*utility*linear_plateau	-0.214
	(0.392)		(0.785)		(1.110)
linear_plateau	25.796***	vrt*utility*linear_plateau	10.239***	risk*lbeta*vrt*utility	-5.216***
	(0.483)		(0.785)		(0.922)
quadratic_plateau	114.994***	risk*lbeta*vrt	5.921***	risk*lbeta*vrt*linear_plateau	-6.163***
	(0.483)		(0.652)		(0.922)
risk*normal	4.197***	risk*lbeta*utility	2.428***	risk*lbeta*utility*linear_plateau	-24.241***
	(0.461)		(0.652)		(0.922)
risk*vrt	-6.218***	lbeta*vrt*utility	-0.002	lbeta*vrt*utility*linear_plateau	-9.109***
	(0.461)		(0.785)		(1.110)
normal*vrt	0.015	risk*lbeta*linear_plateau	21.534***	risk*rbeta*vrt*utility	-5.829***
	(0.683)		(0.652)		(0.922)
risk*utility	-6.182***	lbeta*vrt*linear_plateau	8.722***	risk*rbeta*vrt*linear_plateau	-7.030***
	(0.461)		(0.967)		(0.922)
normal*utility	0.369	lbeta*utility*linear_plateau	13.044***	risk*rbeta*utility*linear_plateau	-21.900***
	(0.555)		(0.785)		(0.922)
vrt*utility	-0.062	risk*rbeta*vrt	6.912***	rbeta*vrt*utility*linear_plateau	-0.773
	(0.555)		(0.652)		(1.110)
risk*linear_plateau	-22.108***	risk*rbeta*utility	-23.780***	normal*vrt*socutility*linear_plateau	0.389
	(0.461)		(0.652)		(1.110)

	Optimal N rates		Optimal N rates		Optimal N rates
normal*linear_plateau	0.968	rbeta*vrt*utility	-0.508	lbeta*vrt*socutility*linear_plateau	-6.457***
	(0.683)		(0.785)		(1.110)
vrt*linear_plateau	-11.819***	risk*rbeta*linear_plateau	23.994***	rbeta*vrt*socutility*linear_plateau	11.817***
	(0.683)		(0.652)		(1.110)
utility*linear_plateau	-63.782***	rbeta*vrt*linear_plateau	0.719	risk*normal*vrt*quadratic_plateau	-2.402***
	(0.555)		(0.967)		(0.922)
risk*lbeta	10.336***	rbeta*utility*linear_plateau	4.130***	risk*normal*utility*quadratic_plateau	1.137
	(0.461)		(0.785)		(0.922)
lbeta*vrt	0.039	normal*vrt*socutility	-0.112	risk*vrt*utility*quadratic_plateau	-6.483***
	(0.683)		(0.785)		(0.922)
lbeta*utility	3.907***	normal*socutility*linear_plateau	3.004***	normal*vrt*utility*quadratic_plateau	-0.217
	(0.555)		(0.785)		(1.110)
lbeta*linear_plateau	-15.474***	vrt*socutility*linear_plateau	-8.088***	risk*lbeta*vrt*quadratic_plateau	-5.924***
	(0.683)		(0.785)		(0.922)
risk*rbeta	10.536***	lbeta*vrt*socutility	-1.280	risk*lbeta*utility*quadratic_plateau	-0.953
	(0.461)		(0.785)		(0.922)
rbeta*vrt	-0.505	lbeta*socutility*linear_plateau	19.775***	lbeta*vrt*utility*quadratic_plateau	4.754***
	(0.683)		(0.785)		(1.110)
rbeta*utility	-22.539***	rbeta*vrt*socutility	-10.941***	risk*rbeta*vrt*quadratic_plateau	-7.018***
	(0.555)		(0.785)		(0.922)
rbeta*linear_plateau	-2.896***	rbeta*socutility*linear_plateau	-32.029***	risk*rbeta*utility*quadratic_plateau	-4.386***
	(0.683)		(0.785)		(0.922)
normal*socutility	4.506***	risk*normal*quadratic_plateau	2.138***	rbeta*vrt*utility*quadratic_plateau	-1.811
	(0.555)		(0.652)		(1.110)
vrt*socutility	20.948***	risk*vrt*quadratic_plateau	6.142***	normal*vrt*socutility*quadratic_plateau	0.274
	(0.555)		(0.652)		(1.110)
socutility*linear_plateau	20.237***	normal*vrt*quadratic_plateau	-0.024	lbeta*vrt*socutility*quadratic_plateau	3.652***
	(0.555)		(0.967)		(1.110)
lbeta*socutility	23.487***	risk*utility*quadratic_plateau	2.883***	rbeta*vrt*socutility*quadratic_plateau	12.025***
	(0.555)		(0.652)		(1.110)
rbeta*socutility	-43.104***	normal*utility*quadratic_plateau	-1.728**	risk*normal*vrt*utility*linear_plateau	2.055
	(0.555)		(0.785)		(1.303)
risk*quadratic_plateau	-8.645***	vrt*utility*quadratic_plateau	14.402***	risk*lbeta*vrt*utility*linear_plateau	6.002***
	(0.461)		(0.785)		(1.303)

	Optimal N rates		Optimal N rates		Optimal N rates
normal*quadratic_plateau	0.892	risk*lbeta*quadratic_plateau	8.097***	risk*rbeta*vrt*utility*linear_plateau	6.877***
	(0.683)		(0.652)		(1.303)
vrt*quadratic_plateau	-14.824***	lbeta*vrt*quadratic_plateau	-2.594***	risk*normal*vrt*utility*quadratic_plateau	2.658***
	(0.683)		(0.967)		(1.303)
utility*quadratic_plateau	-129.819***	lbeta*utility*quadratic_plateau	19.373***	risk*lbeta*vrt*utility*quadratic_plateau	6.269***
	(0.555)		(0.785)		(1.303)
lbeta*quadratic_plateau	-12.294***	risk*rbeta*quadratic_plateau	7.556***	risk*rbeta*vrt*utility*quadratic_plateau	9.533***
	(0.683)		(0.652)		(1.303)
rbeta*quadratic_plateau	-5.686***	rbeta*vrt*quadratic_plateau	0.130	Observations	2,357,592
	(0.683)		(0.967)	R2	0.894
socutility*quadratic_plateau	-87.972***	rbeta*utility*quadratic_plateau	-8.493**	Adjusted R2	0.894
	(0.555)		(0.785)	F Statistic (df = 119, 2356249)	166,254.600***
risk*normal*vrt	2.263***	normal*socutility*quadratic_plateau	-0.326		
	(0.652)		(0.785)		
risk*normal*utility	2.722***	vrt*socutility*quadratic_plateau	-5.739***		
	(0.652)		(0.785)		

Notes: *p<0.1; **p<0.05; ***p<0.01. 'Risk' represents the risk aversion level, the coefficent estimates for risk and risk interaction terms suggest the effect of the change of 0.01 in risk aversion level; 'normal', 'lbeta', and 'rbeta' denotes the distribution of farmers' weather beliefs; 'vrt' implies farmers adopt variable rate technology; utility and socutility suggest farmers are utility maximizers without and with considering the social costs of N, respectively. The benchmark optimal N rates are obtained by assuming general quadratic production function, yield maximization, random weather beliefs, uniform application method.

Table A9. The relationship between realized profits and influential factors

	Realized profits		Realized profits		Realized profits
risk	-3.841***	risk*vrt*utility	-1.576	lbeta*socutility*quadratic_plateau	-16.462***
	(0.605)		(1.209)		(1.456)
normal	0.435	normal*vrt*utility	-0.064	rbeta*socutility*quadratic_plateau	-3.078**
	(0.897)		(1.456)		(1.456)
lbeta	-1.770**	risk*normal*linear_plateau	3.166***	risk*normal*vrt*utility	0.755
	(0.897)		(1.209)		(1.710)
rbeta	-2.498***	risk*vrt*linear_plateau	-1.521	risk*normal*vrt*linear_plateau	0.607
	(0.897)		(1.209)		(1.710)
vrt	-1.580*	normal*vrt*linear_plateau	-0.054	risk*normal*utility*linear_plateau	-1.372
	(0.897)		(1.793)		(1.710)
utility	6.884***	risk*utility*linear_plateau	-0.260	risk*vrt*utility*linear_plateau	0.289
	(0.728)		(1.209)		(1.710)
socutility	-248.641***	normal*utility*linear_plateau	-0.131	normal*vrt*utility*linear_plateau	-0.137
	(0.728)		(1.456)		(2.059)
linear_plateau	-25.053***	vrt*utility*linear_plateau	-4.428***	risk*lbeta*vrt*utility	2.678
	(0.897)		(1.456)		(1.710)
quadratic_plateau	-58.003***	risk*lbeta*vrt	-2.132*	risk*lbeta*vrt*linear_plateau	3.205*
	(0.897)		(1.209)		(1.710)
risk*normal	2.609***	risk*lbeta*utility	-0.892	risk*lbeta*utility*linear_plateau	1.508
	(0.855)		(1.209)		(1.710)
risk*vrt	1.040	lbeta*vrt*utility	-0.106	lbeta*vrt*utility*linear_plateau	3.493*
	(0.855)		(1.456)		(2.059)
normal*vrt	-0.010	risk*lbeta*linear_plateau	2.036*	risk*rbeta*vrt*utility	1.108
	(1.268)		(1.209)		(1.710)
risk*utility	1.168	lbeta*vrt*linear_plateau	-3.866**	risk*rbeta*vrt*linear_plateau	1.641
	(0.855)		(1.793)		(1.710)
normal*utility	-0.849	lbeta*utility*linear_plateau	-8.278***	risk*rbeta*utility*linear_plateau	-10.909***
	(1.029)		(1.456)		(1.710)
vrt*utility	0.083	risk*rbeta*vrt	-1.575	rbeta*vrt*utility*linear_plateau	-3.822*
	(1.029)		(1.209)		(2.059)
risk*linear_plateau	-3.365***	risk*rbeta*utility	-33.628***	normal*vrt*socutility*linear_plateau	1.566
	(0.855)		(1.209)		(2.059)

		Realized profits	Realized profits		Realized profits
normal*linear_plateau	-0.418	rbeta*vrt*utility	-0.810	lbeta*vrt*socutility*linear_plateau	11.756***
	(1.268)		(1.456)		(2.059)
vrt*linear_plateau	5.089***	risk*rbeta*linear_plateau	0.814	rbeta*vrt*socutility*linear_plateau	-4.997**
	(1.268)		(1.209)		(2.059)
utility*linear_plateau	29.014***	rbeta*vrt*linear_plateau	-0.025	risk*normal*vrt*quadratic_plateau	0.523
	(1.029)		(1.793)		(1.710)
risk*lbeta	3.635***	rbeta*utility*linear_plateau	-12.165***	risk*normal*utility*quadratic_plateau	0.571
	(0.855)		(1.456)		(1.710)
lbeta*vrt	-0.015	normal*vrt*socutility	-1.513	risk*vrt*utility*quadratic_plateau	0.560
	(1.268)		(1.456)		(1.710)
lbeta*utility	0.587	normal*socutility*linear_plateau	-1.448	normal*vrt*utility*quadratic_plateau	-0.122
	(1.029)		(1.456)		(2.059)
lbeta*linear_plateau	7.064***	vrt*socutility*linear_plateau	-9.392***	risk*lbeta*vrt*quadratic_plateau	2.483
	(1.268)		(1.456)		(1.710)
risk*rbeta	8.409***	lbeta*vrt*socutility	-9.840***	risk*lbeta*utility*quadratic_plateau	3.252*
	(0.855)		(1.456)		(1.710)
rbeta*vrt	-0.174	lbeta*socutility*linear_plateau	-24.177***	lbeta*vrt*utility*quadratic_plateau	-1.853
	(1.268)		(1.456)		(2.059)
rbeta*utility	-2.087***	rbeta*vrt*socutility	5.019***	risk*rbeta*vrt*quadratic_plateau	1.575
	(1.029)		(1.456)		(1.710)
rbeta*linear_plateau	2.432*	rbeta*socutility*linear_plateau	5.296***	risk*rbeta*utility*quadratic_plateau	-12.746***
	(1.268)		(1.456)		(1.710)
normal*socutility	0.767	risk*normal*quadratic_plateau	1.019	rbeta*vrt*utility*quadratic_plateau	-3.339
	(1.029)		(1.209)		(2.059)
vrt*socutility	3.073***	risk*vrt*quadratic_plateau	-1.358	normal*vrt*socutility*quadratic_plateau	1.494
	(1.029)		(1.209)		(2.059)
socutility*linear_plateau	30.959***	normal*vrt*quadratic_plateau	0.016	lbeta*vrt*socutility*quadratic_plateau	8.235***
	(1.029)		(1.793)		(2.059)
lbeta*socutility	4.411***	risk*utility*quadratic_plateau	-2.139*	rbeta*vrt*socutility*quadratic_plateau	-4.852**
	(1.029)		(1.209)		(2.059)
rbeta*socutility	-33.591***	normal*utility*quadratic_plateau	0.045	risk*normal*vrt*utility*linear_plateau	-0.028
	(1.029)		(1.456)		(2.418)
risk*quadratic_plateau	-0.487	vrt*utility*quadratic_plateau	-5.964***	risk*lbeta*vrt*utility*linear_plateau	-2.084
	(0.855)		(1.456)		(2.418)

	Realized profits		Realized profits		Realized profits
normal*quadratic_plateau	-0.384	risk*lbeta*quadratic_plateau	-0.862	risk*rbeta*vrt*utility*linear_plateau	-2.630
	(1.268)		(1.209)		(2.418)
vrt*quadratic_plateau	6.120***	lbeta*vrt*quadratic_plateau	1.069	risk*normal*vrt*utility*quadratic_plateau	-0.050
	(1.268)		(1.793)		(2.418)
utility*quadratic_plateau	51.101***	lbeta*utility*quadratic_plateau	-7.498***	risk*lbeta*vrt*utility*quadratic_plateau	-1.681
	(1.029)		(1.456)		(2.418)
lbeta*quadratic_plateau	5.695***	risk*rbeta*quadratic_plateau	-1.663	risk*rbeta*vrt*utility*quadratic_plateau	-1.050
	(1.268)		(1.209)		(2.418)
rbeta*quadratic_plateau	3.563***	rbeta*vrt*quadratic_plateau	0.139	Observations	2,357,592
	(1.268)		(1.793)	R2	0.901
socutility*quadratic_plateau	68.176***	rbeta*utility*quadratic_plateau	-10.448***	Adjusted R2	0.901
	(1.029)		(1.456)	F Statistic (df = 119; 2356249)	181,161.500***
risk*normal*vrt	-0.340	normal*socutility*quadratic_plateau	-1.341		
	(1.209)		(1.456)		
risk*normal*utility	-0.503	vrt*socutility*quadratic_plateau	-11.120***		
	(1.209)		(1.456)		

Notes: *p<0.1; **p<0.05; ***p<0.01. 'Risk' represents the risk aversion level, the coefficent estimates for risk and risk interaction terms suggest the effect of the change of 0.01 in risk aversion level; 'normal', 'lbeta', and 'rbeta' denotes the distribution of farmers' weather beliefs; 'vrt' implies farmers adopt variable rate technology; utility and socutility suggest farmers are utility maximizers without and with considering the social costs of N, respectively. The benchmark optimal N rates are obtained by assuming general quadratic production function, yield maximization, random weather beliefs, uniform application method.

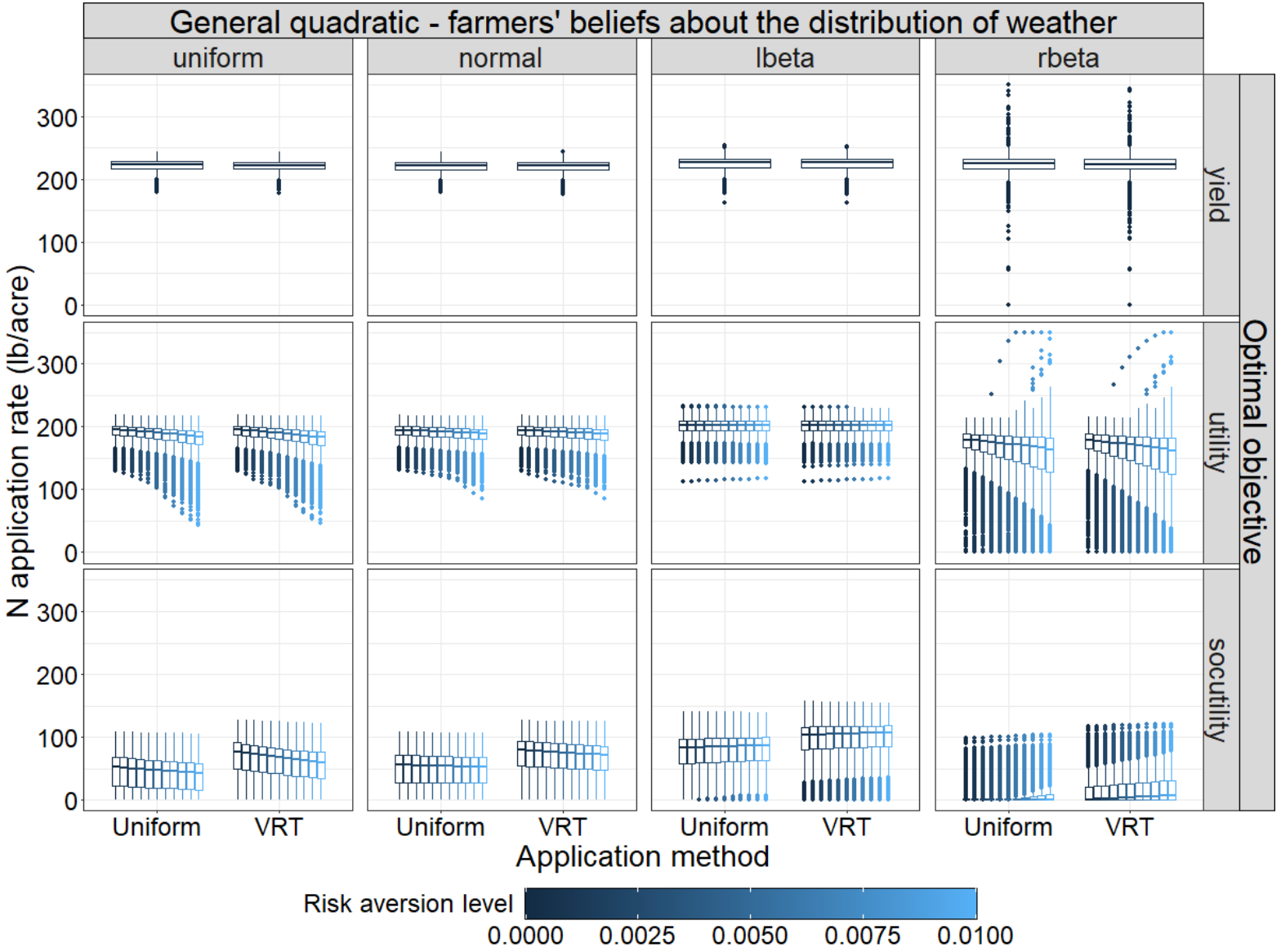


Figure A1. Optimal N application rates for general quadratic production functions

Notes: The figure presents the boxplots for optimal N application rate at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

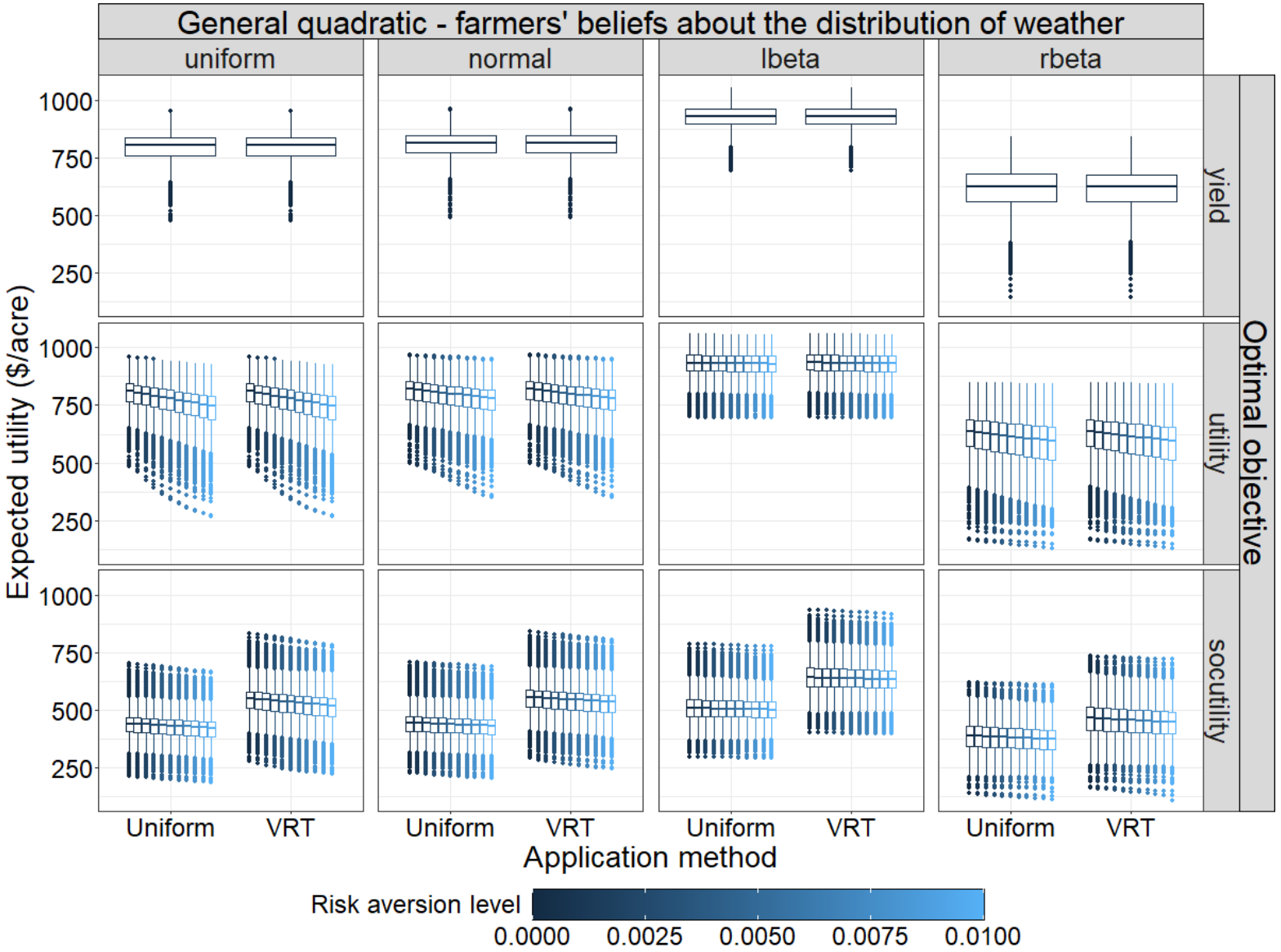


Figure A2. Expected utilities for general quadratic functions

Notes: The figure presents the boxplots for expected utility at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

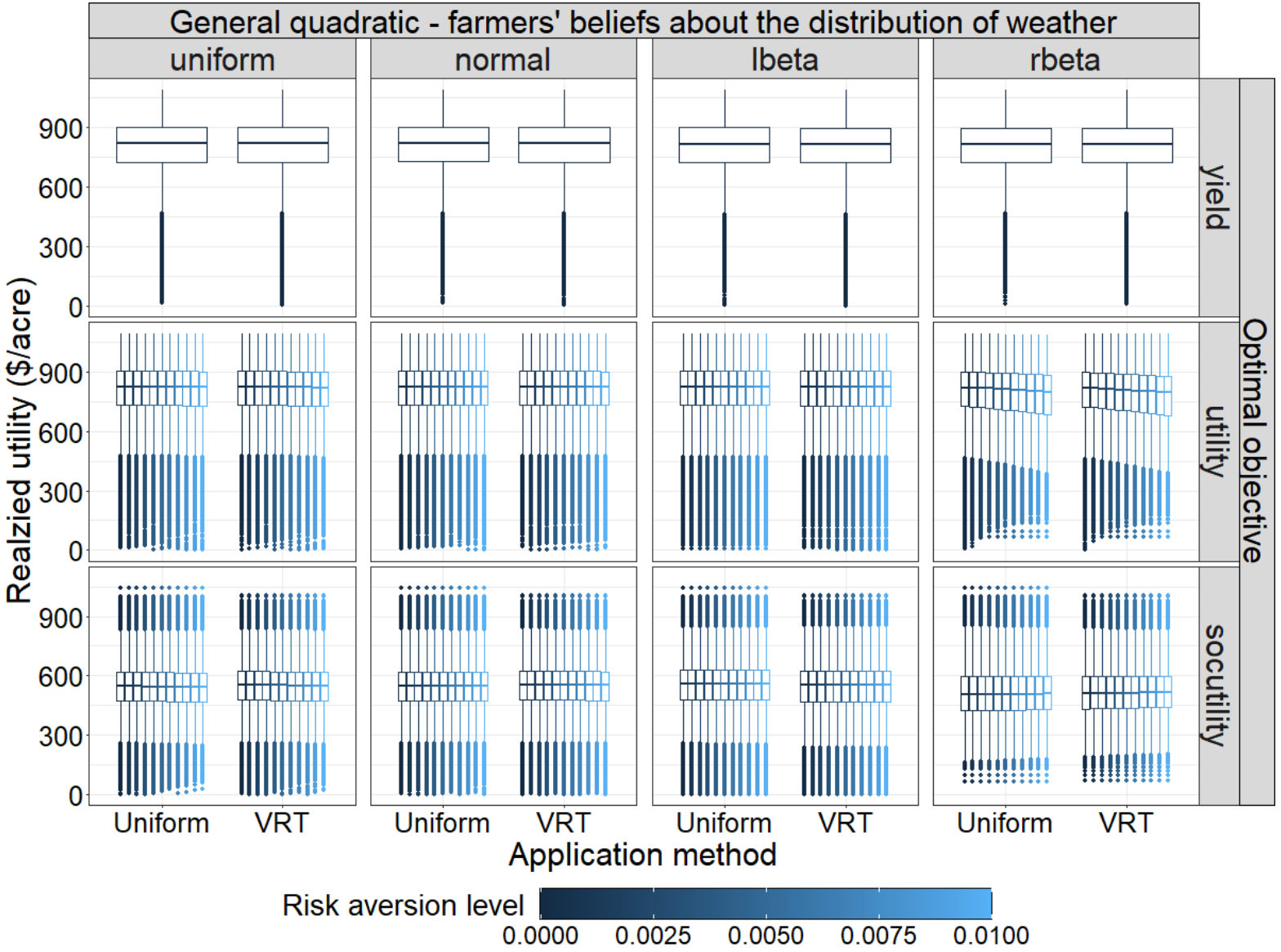


Figure A3. Realized profits for general quadratic functions

Notes: The figure presents the boxplots for realized utility at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

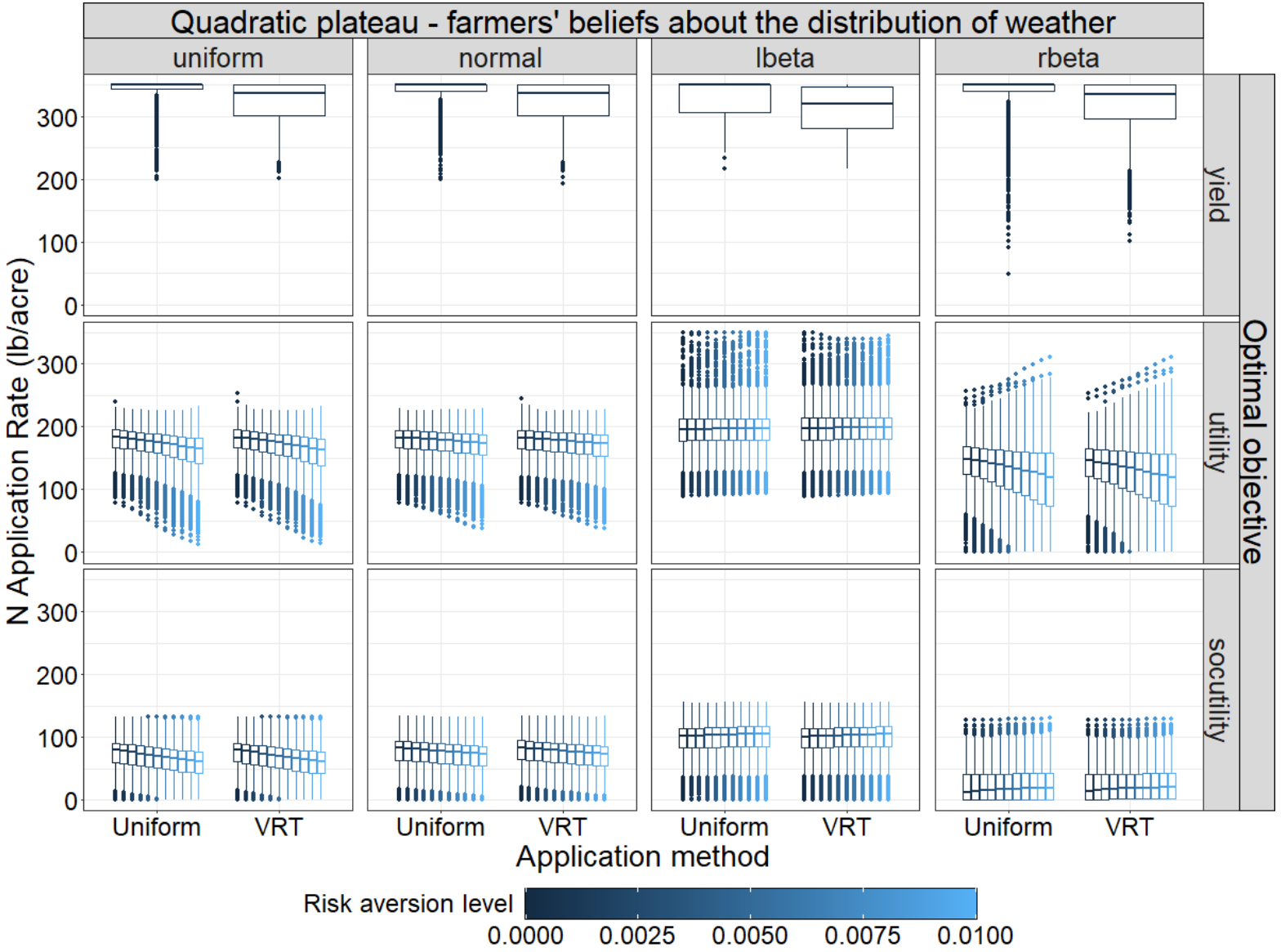


Figure A4. Optimal N application rates for quadratic plateau production functions

Notes: The figure presents the boxplots for optimal N application rate at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

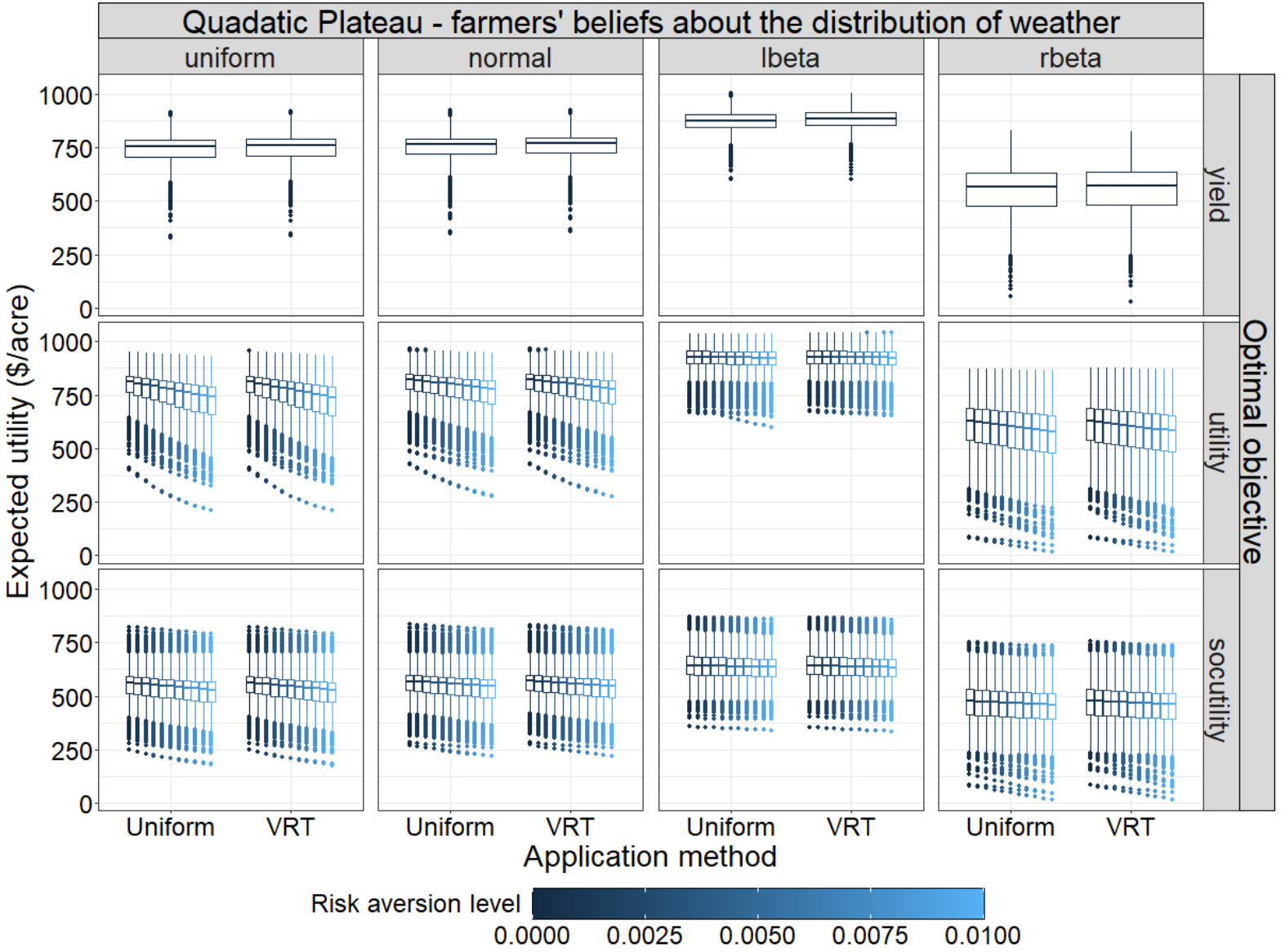


Figure A5. Expected utilities for quadratic plateau functions

Notes: The figure presents the boxplots for expected utility at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

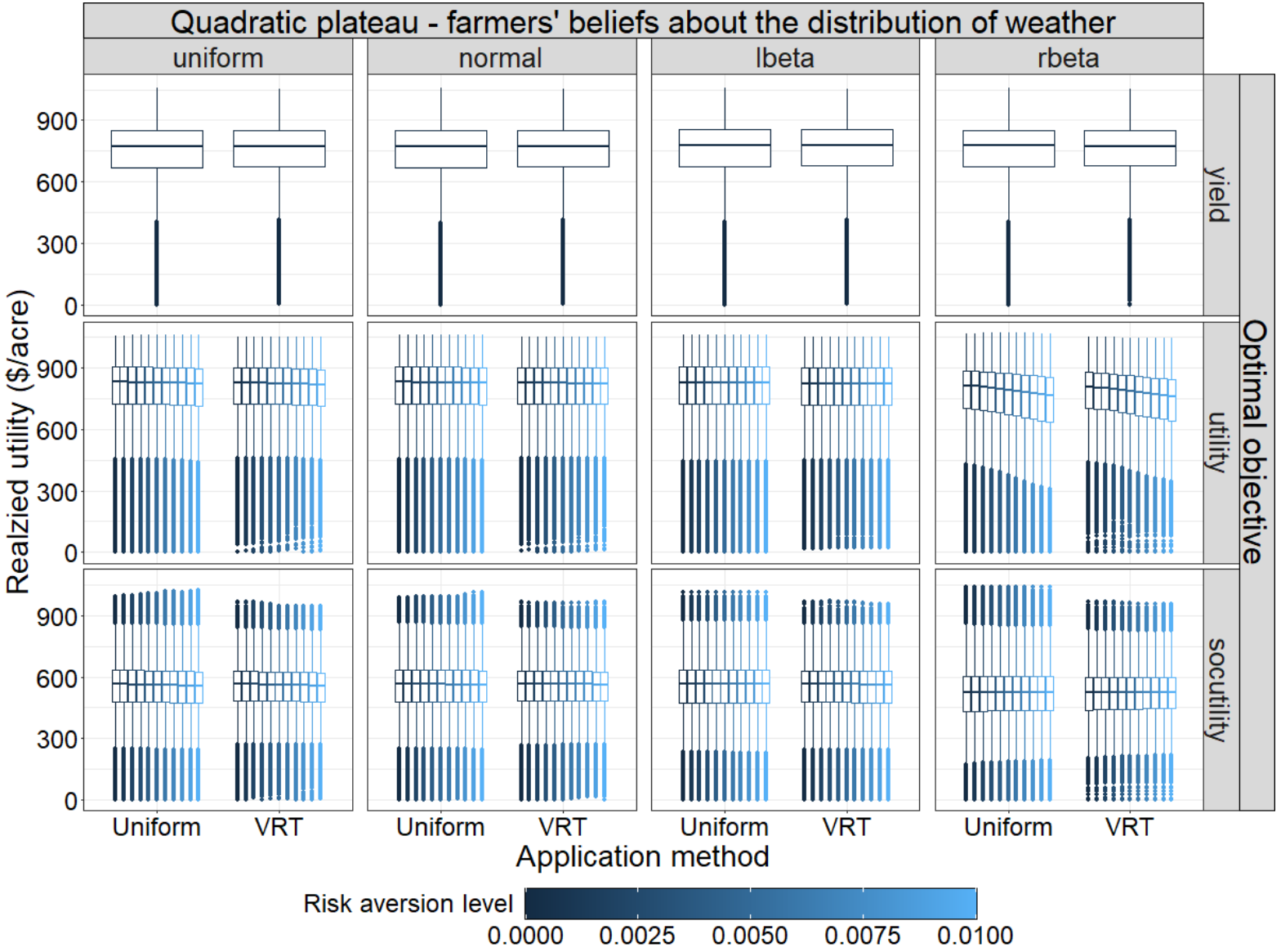


Figure A6. Realized profits for quadratic plateau functions

Notes: The figure presents the boxplots for realized utility at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

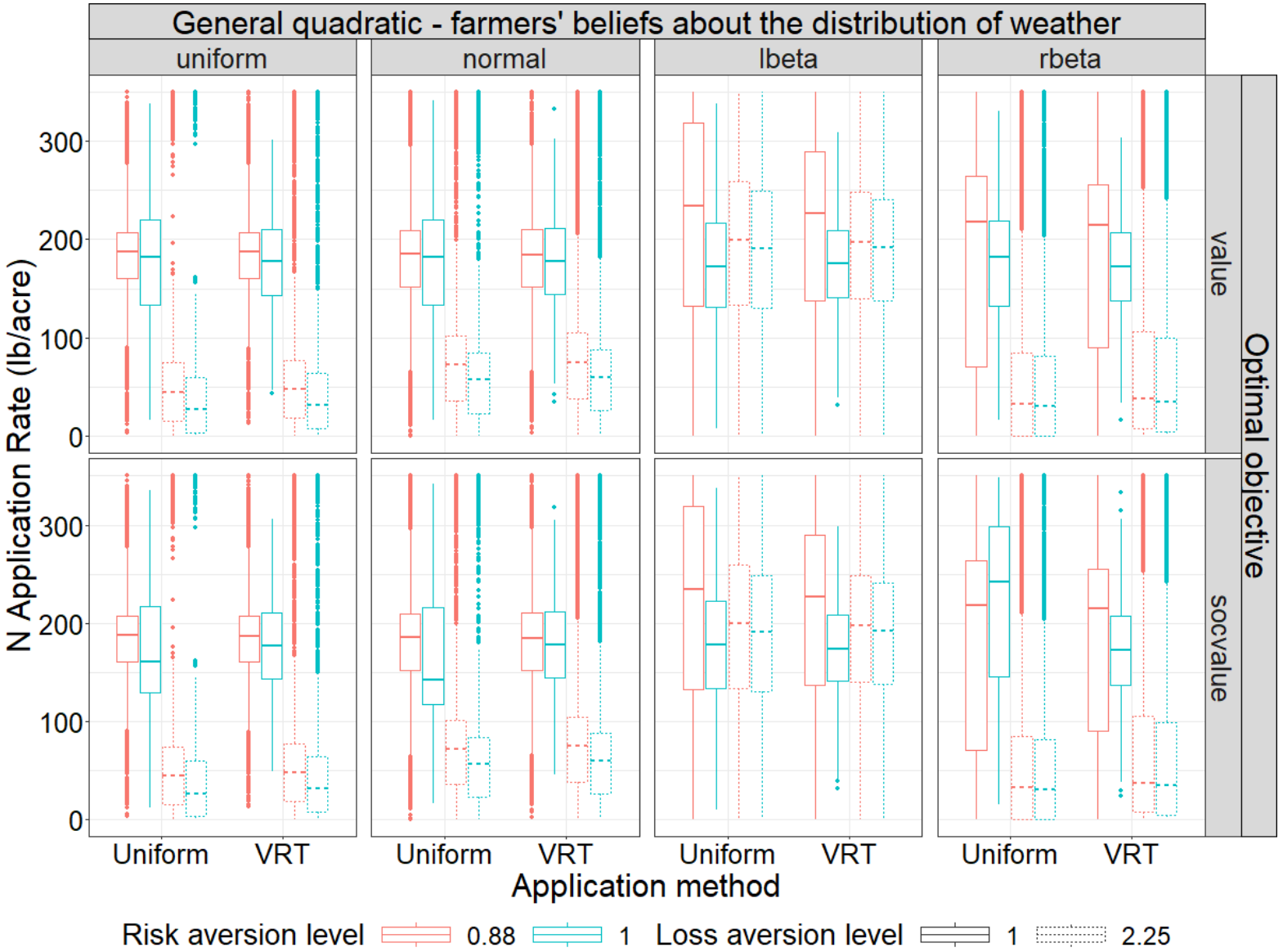


Figure A7. Comparison of value optimal N application rates for general quadratic functions

Notes: The figure presents the comparison of value maximization N application rates at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.

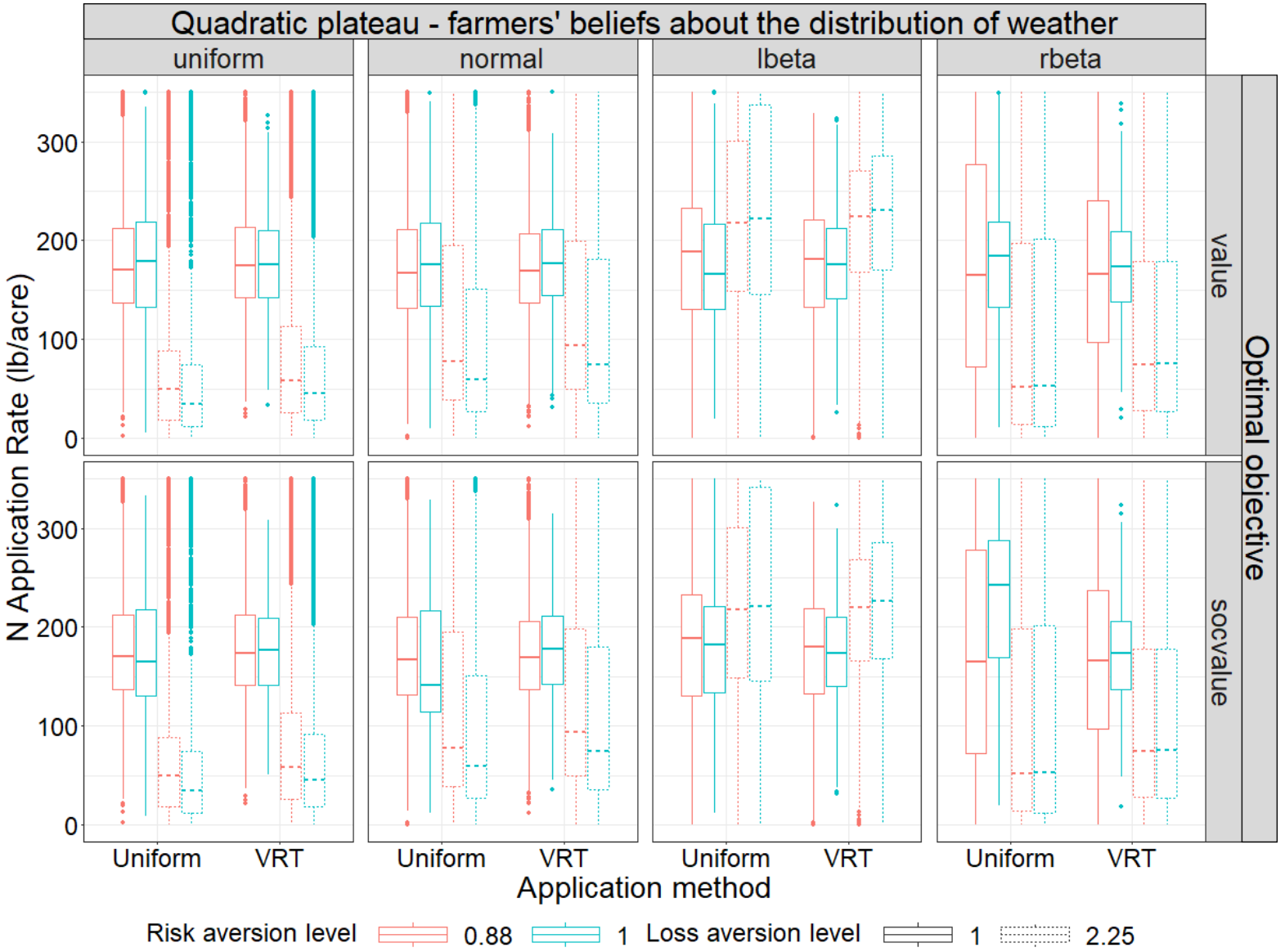


Figure A8. Comparison of value optimal N application rates for general quadratic functions

Notes: The figure presents the comparison of value maximization N application rates at the field level across more than 4000 fields. The field-level results for variable rate technology (VRT) are derived by aggregating the soil-level results to the field level, using the mukey area within each field as a weighting factor.