# EFFECTS OF NITROGEN RATE AND TIMING APPLIED AS ANHYDROUS AMMONIA ON CORN PRODUCTION AND PROFITABILITY

B.A. Link[1], J.D. Jones[1], E.D. Nafziger[1], D. Schaefer[2]
[1]University of Illinois, Urbana, IL
[2]Illinois Fertilizer and Chemical Association, Bloomington, IL
blakeal2@illinois.edu (630) 991-8398

## ABSTRACT

Nitrogen (N) application timing is a critical decision for Illinois corn (*Zea mays* L.) producers, balancing operational efficiency, economic return, and environmental stewardship. We compared agronomic and economic responses to N rates applied as anhydrous ammonia (AA) in the fall and in the spring at 19 central Illinois sites from 2013 to 2020. Yield response to N was modeled to determine agronomic optimum N rate (AONR), economic optimum N rate (EONR), and maximum return to N (MRTN). Averaged across sites, EONR values for fall- versus spring-applied AA were 178 and 160 lb N $ac^{-1}$, respectively; yield at the EONR averaged 229 bu $ac^{-1}$ for fall and 231 bu $ac^{-1}$ spring N; MRTN was \$424 $ac^{-1}$ for fall N and \$437 $ac^{-1}$ for spring N. Of the \$13 $ac^{-1}$ MRTN advantage to spring N, \$7 came from needing less N, and \$6 from slightly higher (2 bu $ac^{-1}$) yield at the EONR. When compared using a paired t-test, EONR differences between timings were statistically significant ($p$ = 0.007), but differences in YEONR and MRTN were not ($p$ > 0.1). Differences in N response were not consistently linked to soil or weather parameters, highlighting the complexity of N dynamics across environments. Current N rate guidelines in central Illinois (187 lb N $ac^{-1}$ at the N and corn grain prices used in the study) would be sufficient to meet the needs of the crop whether applied in the fall or spring, these results indicate that N losses (or unavailability) tend to be higher following fall application than following spring application, with lower yield possible from fall application in fields where fertilizer N requirements are high.

## INTRODUCTION

Anhydrous ammonia ($NH_3$, AA) is a widely used nitrogen (N) fertilizer for corn production in Illinois. In 2024, approximately 258,000 tons of AA were sold as fertilizer in Illinois, making it the single most prevalent N source used in Illinois (Illinois Department of Agriculture, 2024). While applications of AA in the spring have increased in popularity, fall applications remain common on medium-textured soils in the central Corn Belt. A retailer survey reported that 54% of fields in Illinois received some amount of AA applied in the fall (IFCA, 2024).

Few studies in the North Central Region have compared fall versus spring application with N applied over a range of rates. Touchton et al. (1979) included fall and spring applied AA at one central and one northern Illinois site in an investigation of the effectiveness of nitrapyrin, and found yield differences between fall and spring timing only at the lowest N rate (60 lb N $ac^{-1}$), with no yield differences at 120, 180, and 240 lb N $ac^{-1}$. Welch et al. (1971), using ammonium nitrate as the N source, found no differences from fall vs. spring in yield or N fertilizer efficiency above 120 lb N $ac^{-1}$ at three Illinois locations across four years. Research in Indiana, with AA as the N source, found grain yield differences between N timing only at N rates of 130 and 180 lb N $ac^{-1}$, but no differences at lower N rates, although such an analysis was conducted for spring preplant versus sidedress timing and did not include a fall timing treatment (Kovacs et al., 2015).

While some previous work comparing timing of AA applications has been done, results have been mixed, and the work has not typically included a full set of N rates to allow comparisons of optimum N rates, associated yields, and economic returns to N. Thus, the rationale for this study was clear: perform and analyze on-farm N rate trials focusing on application timing differences to determine optimum N rates that could help shape management-specific N guidelines for fall or spring use of AA, as well as to evaluate whether spring-applied AA is economically advantageous.

## MATERIALS AND METHODS

Field trials were conducted from 2013 to 2020 in farmers' fields across central Illinois, mostly on Mollisols with silt loam or silty clay loam textures, and included locations in Vermillion, Sangamon, Piatt, DeWitt, Logan, Douglas, Pike, and Edgar counties from 2013 to 2020. The previous crop grown was soybean [*Glycine max* (L.) Merr.] on all sites except Site 3, where corn was the previous crop. Fall AA applications were made in November, and spring applications were made before planting at fifteen sites, and as early sidedress at four sites. Additional fertilizer nitrogen was applied as base rates over the entire trial at fifteen sites, with rates ranging from 14 to 72 lb N $ac^{-1}$, as dry ammoniated phosphate (P source), urea-ammonium nitrate (UAN) solution applied with the planter or as herbicide carrier, or both. Trials were structured as a randomized complete block design with three or four replications. Main plots were assigned N rates of 0, 50, 100, 150, 200, or 250 lb N $ac^{-1}$, with application timing (fall or spring) as subplots split within N rate; there was a single 0-N strip in each block. Base N rates were added to the treatment rates. Subplots were 8 to 12 30-inch rows (20 to 30 ft) wide and ranged in length from 300 to 1200 ft. Yield data were collected by harvesting the center four to twelve rows of each subplot, with weight and moisture recorded using calibrated yield monitors on combines, or, in a few cases, using weigh wagons. Grain yields were adjusted to 15.0% moisture. Yield monitor data were cleaned based on criteria such as combine distance traveled, harvest width, and grain moisture content as described by Luck and Fulton (2015). Weather data for each site was obtained from the PRISM gridded dataset (PRISM Group, 2025). Historical AA and corn grain price information was retrieved from USDA-AMS

Economic optimum N rates were determined by setting the first derivative of the response model to an N price ($ lb $N^{-1}$) to corn price ($ $bu^{-1}$) ratio and solving for N rate (Equation 1 and 2). Prices of $0.40 lb $N^{-1}$ and $4.00 $bushel^{-1}$ were used for this purpose, resulting in a price ratio (PR) of 0.10 bu lb $N^{-1}$.

Equation 1: $QP\ EONR\ (lb\ N\ ac^{-1}) = \frac{\mathrm{PR}-b}{2c}$

Equation 2: $LP\ EONR\ (lb\ N\ ac^{-1}) = \begin{cases} X_N, & b \geq PR \\ 0, & b < PR \end{cases}$

Where c [(bu $ac^{-1}$) (lb $N^2$)$^{-1}$] is the quadratic coefficient in Equation 1, b (bu lb $N^{-1}$) is the linear coefficient in Equation 1 and 2, and $X_N$ is the joint point (linear-plateau model) of the best fit response models. Once the EONR was calculated, YEONR was obtained by solving each best fit yield response function for yield. The RTN value is defined as the economic partial return received due to the increase in yield when applying nitrogen fertilizer at a certain rate ($Y_N$) as compared to a zero-nitrogen application ($Y_0$) minus the cost of the nitrogen fertilizer applied (Equation 3).

Equation 3: $RTN\ (\$\ ac^{-1}) = [(Y_N - Y_0) \times \$\ bu\ corn^{-1}] - (N \times \$\ lb\ N^{-1})$

For sites that received a base rate of N, RTN was calculated using the average of the estimated $Y_0$ values for each timing.

## RESULTS AND DISCUSSION

Figure 1 shows the modeled yield responses to N rate and application timing at each site. The best-fitting model was chosen for each N timing combination on the basis of the $R^2$ values adjusted for degrees of freedom, pairwise F-tests of the model's residual sums of squares, and observation of the distribution of residuals. Those best fit models are listed in Table 1. All yield responses were best described by fitting a quadratic-plateau model, except for three instances where the linear-plateau model best fit. All N rate responses were statistically significant for both N application timings at all sites ($p \leq 0.05$) with $R^2$ values ranging from 0.54 to 0.96. Paired t-tests indicate that model coefficients were significantly different ($p < 0.05$) between timings. The capacity of quadratic-plateau models to explain yield responses to N rate was notably high.

### Nitrogen Rate and Timing Effects on Yield

Yield response to N rate was observed for both N application timings (spring and fall) at all sites, though yield increase with incrementally higher N rates was not always consistent, even for different N application timings at the same site. As expected, the lowest N rate treatment to produce the statistically highest corn yield varied by site, ranging from 50 to 230 lb N $ac^{-1}$. Corn yield increases from the lowest N treatments to the statistically maxima treatments ranged from 41 to 190 bu $ac^{-1}$ with an average of 84 bu $ac^{-1}$ increase for both N timings. Yield response to N rate differed by site to a greater degree than by N application timing. Variance (coefficient of variation) of corn yield across N rates for individual site x N timing combinations ranged from 2.2 to 10.4%.

Effects of N application timing were inconsistent across sites and N rates. Averaged across all N rates, yield differences between fall and spring N application timing ranged from a 21 bu $ac^{-1}$ (8%) yield benefit to fall N (Site 17 at 115 lb N $ac^{-1}$) to a 45 bu $ac^{-1}$ (21%) yield benefit to spring N (Site 13 at 136 lb N $ac^{-1}$). Significant effects ($p \leq 0.1$) of N timing on yield were observed for at least one N application rate at ten of nineteen sites. However, N timing never affected yield at more than two N rates for any site, and when an N timing effect was significant at two N rates, no clear pattern of benefit to fall or spring application was observed in the context of yield. The general linear relationship between fall and spring yields at N rates above the lowest is strong and suggests yield differences between N timings were mostly within 10% of being equivalent. Evaluating yield at all N rates and sites in aggregate suggests that small to no yield differences would be expected between fall and spring applied AA. A significant ($p \leq 0.1$) N rate by N timing interaction was observed at two sites (16 and 17) of the nineteen. Site 16 exhibited a stronger yield response to spring-applied N as N rate increased, while spring N at site 17 optimized yield at a much lower N rate, albeit at a lower YEONR as compared to fall. No clear justification could be discerned for why fall or spring N timing affected yield response to N rate in these two sites.

**Table 1.** Equations describing relationships between fall or spring-applied N rate and yield for each site, optimum N rates and associated yields.

| Site Index | Year | N Timing | Model | Equation Coefficients and Statistics[1] | | | | | EONR | YEONR | MRTN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $Y_0$ | b | c | RMSE | $R^2$ | | | |
| | | | | | | | | | lb N ac$^{-1}$ | bu ac$^{-1}$ | \$ ac$^{-1}$ |
| 1 | 2013 | Fall | QP | 22.8 | 1.422 | -0.0039 | 8.58 | 0.93 | 170 | 151.9 | 443 |
| | | Spring | QP | 25.4 | 1.361 | -0.0036 | 8.50 | 0.94 | 177 | 154.8 | 452 |
| 2 | 2014 | Fall | LP | 171.5 | 0.493 | | 6.09 | 0.94 | 133 | 237.2 | 211 |
| | | Spring | QP | 170.9 | 0.760 | -0.0025 | 10.59 | 0.80 | 139 | 230.1 | 180 |
| 3 | 2014 | Fall | QP | 162.0 | 0.859 | -0.0019 | 8.18 | 0.88 | 200 | 258.0 | 307 |
| | | Spring | QP | 160.4 | 0.918 | -0.0022 | 9.65 | 0.83 | 187 | 255.3 | 302 |
| 4 | 2014 | Fall | QP | 139.7 | 0.888 | -0.0019 | 9.73 | 0.89 | 206 | 241.6 | 322 |
| | | Spring | QP | 141.2 | 0.860 | -0.0020 | 10.89 | 0.83 | 189 | 231.8 | 290 |
| 5 | 2015 | Fall | QP | 53.1 | 2.170 | -0.0058 | 16.39 | 0.87 | 177 | 254.2 | 765 |
| | | Spring | QP | 37.1 | 2.668 | -0.0080 | 16.05 | 0.88 | 161 | 259.7 | 794 |
| 6 | 2015 | Fall | LP | 100.3 | 0.471 | | 24.85 | 0.54 | 164 | 177.5 | 236 |
| | | Spring | LP | 104.2 | 0.626 | | 16.24 | 0.78 | 130 | 185.8 | 282 |
| 7 | 2016 | Fall | QP | 137.6 | 1.069 | -0.0031 | 6.04 | 0.94 | 157 | 229.5 | 316 |
| | | Spring | QP | 132.2 | 1.290 | -0.0042 | 5.47 | 0.95 | 142 | 230.7 | 327 |
| 8 | 2016 | Fall | QP | 103.7 | 0.893 | -0.0027 | 8.40 | 0.85 | 145 | 175.6 | 218 |
| | | Spring | QP | 109.3 | 0.886 | -0.0026 | 7.87 | 0.88 | 149 | 183.0 | 246 |
| 9 | 2017 | Fall | QP | 101.1 | 1.523 | -0.0039 | 20.44 | 0.70 | 183 | 249.7 | 568 |
| | | Spring | QP | 77.8 | 2.120 | -0.0066 | 17.93 | 0.75 | 153 | 247.4 | 571 |
| 10 | 2017 | Fall | QP | 110.8 | 1.210 | -0.0026 | 11.73 | 0.91 | 217 | 253.2 | 480 |
| | | Spring | QP | 112.3 | 1.227 | -0.0028 | 14.06 | 0.85 | 202 | 246.4 | 458 |
| 11 | 2017 | Fall | QP | 83.5 | 1.010 | -0.0021 | 21.01 | 0.80 | 213 | 201.7 | 390 |
| | | Spring | QP | 82.1 | 0.904 | -0.0016 | 16.50 | 0.87 | 250 | 209.0 | 405 |
| 12 | 2017 | Fall | QP | 177.2 | 0.741 | -0.0018 | 15.05 | 0.75 | 175 | 250.9 | 230 |
| | | Spring | QP | 174.5 | 0.867 | -0.0023 | 12.95 | 0.84 | 170 | 256.8 | 256 |
| 13 | 2017 | Fall | QP | 70.0 | 1.436 | -0.0033 | 16.15 | 0.83 | 236 | 230.9 | 678 |
| | | Spring | QP | 5.5 | 3.423 | -0.0122 | 20.31 | 0.85 | 136 | 245.2 | 775 |
| 14 | 2017 | Fall | QP | 146.8 | 0.476 | -0.0009 | 8.61 | 0.78 | 199 | 204.0 | 169 |
| | | Spring | QP | 136.7 | 0.767 | -0.0023 | 7.69 | 0.81 | 145 | 199.3 | 172 |
| 15 | 2018 | Fall | QP | 64.5 | 1.456 | -0.0030 | 11.65 | 0.87 | 225 | 236.4 | 748 |
| | | Spring | QP | -10.4 | 2.877 | -0.0086 | 8.01 | 0.92 | 162 | 231.4 | 752 |
| 16 | 2018 | Fall | QP | 90.0 | 1.944 | -0.0042 | 11.56 | 0.96 | 217 | 308.0 | 795 |
| | | Spring | QP | 85.0 | 2.105 | -0.0045 | 14.38 | 0.96 | 223 | 330.8 | 884 |
| 17 | 2018 | Fall | QP | 171.1 | 1.232 | -0.0054 | 6.50 | 0.90 | 105 | 240.9 | 270 |
| | | Spring | QP | 154.7 | 2.573 | -0.0217 | 5.95 | 0.89 | 57 | 230.9 | 249 |
| 18 | 2018 | Fall | QP | 109.6 | 1.099 | -0.0024 | 13.95 | 0.80 | 207 | 233.9 | 448 |
| | | Spring | QP | 92.8 | 1.531 | -0.0042 | 13.50 | 0.81 | 171 | 232.3 | 456 |
| 19 | 2020 | Fall | QP | 100.3 | 1.721 | -0.0057 | 10.84 | 0.92 | 142 | 229.3 | 460 |
| | | Spring | QP | 100.0 | 1.787 | -0.0062 | 8.64 | 0.95 | 137 | 228.9 | 461 |

[1] Coefficients for best fit models according to the general equation $Y = cx^2 + bx + Y_0$

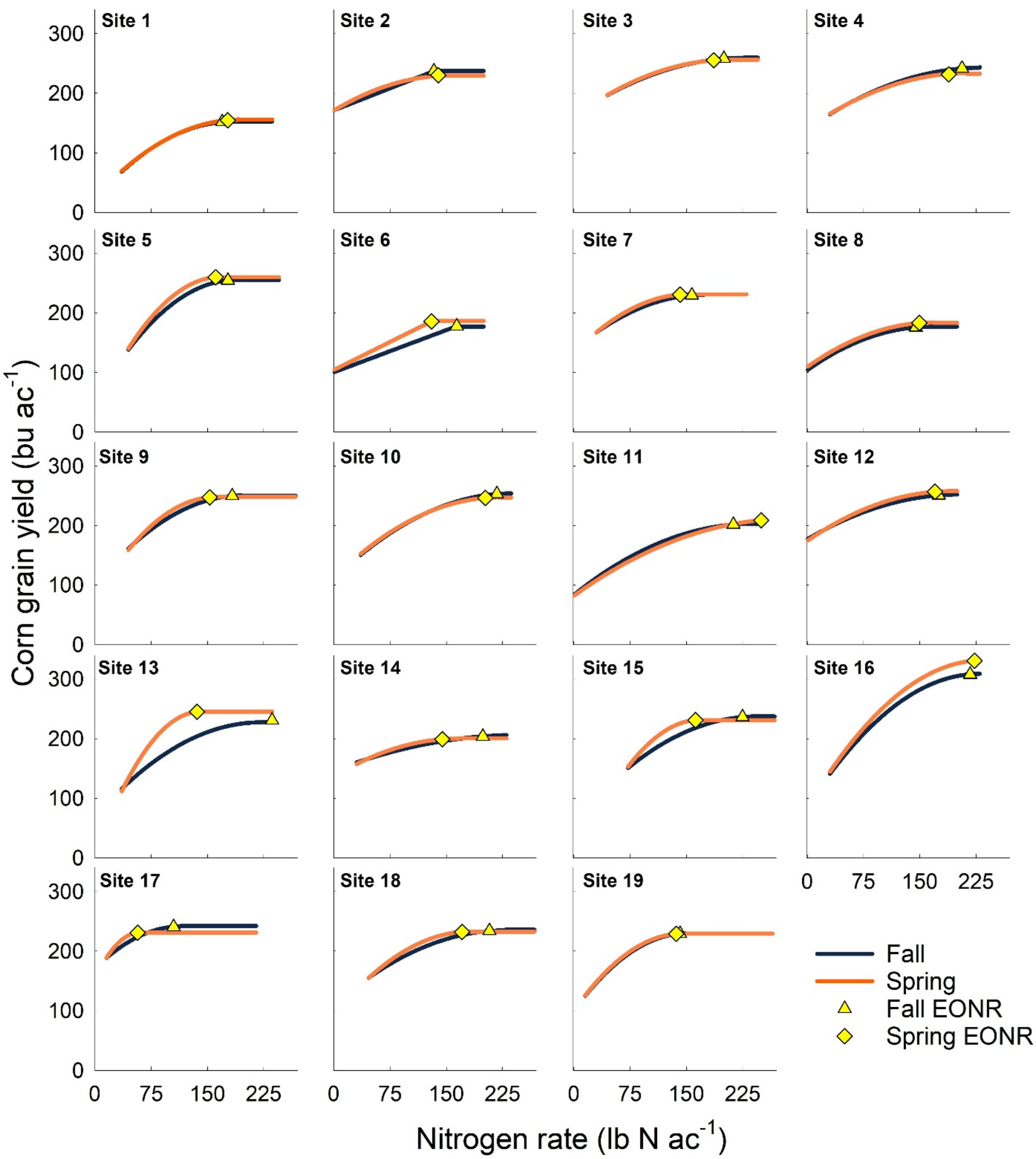


**Figure 1.** Relationship between N fertilizer rate and corn grain yield for both fall and spring anhydrous ammonia application timing at each site.

## Economic Optimum Nitrogen Rates and Return to Nitrogen

The range of EONR values with fall application was 103 to 222 lb N ac$^{-1}$, with a mean of 178 lb N ac$^{-1}$. The range of spring EONR values was 56 to 248 lb N ac$^{-1}$, with a mean of 160 lb N ac$^{-1}$. YEONR values ranged from 151 to 331 bu ac$^{-1}$, with a mean of 229 bu ac$^{-1}$ and 231 bu ac$^{-1}$ for fall and spring respectively. Maximum return to N

(MRTN) values at the EONR ranged from \$166 $ac^{-1}$ to \$892 $ac^{-1}$ across the sites and timings. Across all sites, mean MRTN values were \$424 $ac^{-1}$ and \$437 $ac^{-1}$ for fall and spring, respectively – a \$13 $ac^{-1}$ benefit to spring application. Of the \$13 $ac^{-1}$ MRTN advantage to spring N, \$7 came from needing less N, and \$6 from slightly higher (2 bu $ac^{-1}$) yield at the EONR. When treating all sites as random, paired *t*-tests indicated the EONR for fall-applied AA was 18 lb N $ac^{-1}$ greater ($p = 0.007$) compared to spring with no significant difference in YEONR. Using the same analysis on the MRTN values showed that those values were not significantly different ($p = 0.133$), and adjusting the PR from 50% to 150% of the PR used did not result in any significant differences.

Critics of determining N rates using maximum economic returns have suggested concerns of grain yield reductions. For all site and N timing combinations, estimated yield was on average 2 bu $ac^{-1}$ less at the EONR compared to estimated yield at the AONR, where the maximum yield from best fit response function was determined. Furthermore, this negligible yield difference coincided with an average 18 lb N $ac^{-1}$ lower N rate when economic returns were maximized (EONR) compared to yield maximized (AONR). We found no evidence to suggest that yield would be compromised when focusing on economic return to N to guide N rates for both N times.

**Price Scenarios and Relationship with Economic Optimum Nitrogen Rate**

Over the period of this study, the price ratio (\$ lb $N^{-1}$:\$ $bu^{-1}$) ranged between 0.07 and 0.13, with an average of 0.09 (USDA-AMS). This is equivalent to a range of 70% to 125% of the expected 0.10 ratio, with the average at 94% of the default ratio; a slightly lower ratio produces slightly higher EONR values. The seasonality of pricing also affects producer decisions regarding N timing. But over the period of this study, the average price ratio during the fall application months of October through December was within 0.01 of the average price ratio between the months of March through May (USDA-AMS). Such a small difference would do little to affect the decision on when to apply AA, at least compared to fall weather and application conditions.

**Site Weather Characterization of Response to Application Timing**

Weather is often a causal factor pointed to for observed N timing effects. The four sites with EONR values higher for fall- than for spring-applied N, were not consistently above or below the normal temperature or precipitation amounts. Additionally, they spanned four different counties, and each occurred in a different year. In fact, similar statements can be made about the sites with greater EONR values for spring N compared to fall. There were no consistent weather factors analyzed that displayed a relationship with fertilizer application timing performance.

## CONCLUSION

Despite some general trends, this study's site-specific variability was considerable, and no strong relationships were observed between application timing performance and environmental parameters such as precipitation or soil characteristics. Some sites showing a greater advantage to spring applications may have had greater precipitation-induced losses after fall application, while other sites showed no such advantage. The majority of sites showed little or no difference in response to N rate between fall- and spring-applied N; most of the benefit to spring-applied N came from two sites. Across sites, yields at the economic optimum did not significantly differ, whereas the EONR was reduced by 18 lb N $ac^{-1}$ by moving from fall to spring application. These results indicate producers can maintain optimal yields while lowering total N inputs by managing to economic return, thereby reducing input costs and the pool of nitrogen susceptible to loss**.**

## REFERENCES


Illinois Department of Agriculture. (2024). *Fertilizer Tonnage Report*. https://agr.illinois.gov/plants/fertilizer/fertilizer-reports.html

Illinois Fertilizer and Chemical Association. (2024). *Illinois Ag Retail Survey*. https://lsc-pagepro.mydigitalpublication.comhttps://lsc-pagepro.mydigitalpublication.com/article/Update+on+the+Illinois+Ag+Retail+Survey/4900895/837136/article.html

Kovács, P., Van Scoyoc, G. E., Doerge, T. A., Camberato, J. J., & Vyn, T. J. (2015). Anhydrous Ammonia Timing and Rate Effects on Maize Nitrogen Use Efficiencies. *Agronomy Journal*, *107*(4), 1205–1214. https://doi.org/10.2134/agronj14.0350

Luck, J. D., Mueller, N., & Fulton, J. P. (n.d.). *Improving Yield Map Quality by Reducing Errors through Yield Data File Post-Processing*.

PRISM Group, Oregon State University. (n.d.). *PRISM*. https://prism.oregonstate.edu

Touchton, J. T., Hoeft, R. G., Welch, L. F., Mulvaney, D. L., Oldham, M. G., & Zajicek, F. E. (1979). N Uptake and Corn Yield as Affected by Applications of Nitrapyrin with Anhydrous Ammonia. *Agronomy Journal*, *71*(2), 238–242. https://doi.org/10.2134/agronj1979.00021962007100020006x

USDA-AMS. (n.d.). *Illinois Production Reports* [Dataset]. https://mymarketnews.ams.usda.gov

Welch, L. F., Mulvaney, D. L., Oldham, M. G., Boone, L. V., & Pendleton, J. W. (1971). Corn Yields with Fall, Spring, and Sidedress Nitrogen. *Agronomy Journal*, *63*(1), 119–123. https://doi.org/10.2134/agronj1971.00021962006300010037x