CORN ECONOMIC OPTIMUM NITROGEN RATES ACROSS FOUR DECADES AFFECTED BY CROP ROTATION

M.M.D. Betta, M. B. Villamil, E. D. Nafziger and J.D. Jones,
University of Illinois Urbana-Champaign, Urbana, IL
marinad4@illinois.edu (402) 713-4991

ABSTRACT

Inorganic and organic nitrogen (N) are essential for high and increasing corn production. The economic optimum N rate (EONR) varies considerably across years and locations and is influenced by previous crop, with corn following soybean generally requiring less fertilizer N than corn following corn. Long-term studies have been used to investigate temporal variability and changes in corn N requirements, but evidence from long-term trends within a consistent N production system remains limited. We used a 43-year long-term experiment to understand how corn N demand has changed under a consistently managed continuous corn versus corn-soybean rotation. Five N fertilizer rates (0, 60, 120, 180, and 240 lb N ac^{-1}) were evaluated annually from 1983 to 2025. N response models were fitted by year and rotation to estimate the EONR and the yield at the EONR (YEONR). EONR was calculated using a 10:1 corn price to N fertilizer cost ratio (\$5 bu^{-1} and \$0.50 lb N^{-1}. Temporal trends in yield without fertilizer N (YN0), EONR, YEONR, Nitrogen Use Efficiency (NUE), and Nitrogen Fertilizer Efficiency (NFE) were evaluated using simple linear regressions, and t-tests were performed to test regression slopes against zero using $\alpha = 0.05$. Y0N did not change across the 43-year study period for both corn after corn and corn after soybean, while YEONR increased by 0.13 Mg ha^{-1} $year^{-1}$ in both rotations. EONR did not change for corn after corn and increased by 1.3 lb N ac^{-1} $year^{-1}$ in corn after soybean. NUE did not change across the years in both rotations, while NFE increased by 0.012 and 0.009 bu yield (lb N)$^{-1}$ $year^{-1}$. These results provide long-term quantified evidence of how corn N requirements can be used to guide future N recommendations in Illinois.

INTRODUCTION

Inorganic and organic nitrogen (N) inputs are essential for high and increasing corn production. However, excessive use of N fertilizer comes with an economic and environmental cost, hence, optimal N fertilizer use is imperative. The economic optimum N rate (EONR) is the N fertilizer rate that maximizes economic return to N by considering the rate to produce the maximum yield and adjusting for the prices of corn grain and N fertilizer per unit (Sawyer et al., 2006). The EONR is known to vary substantially across years and locations, mainly due to weather uncertainty and its interactions with dynamic soil and crop N processes (Correndo et al., 2021; Dhital & Raun, 2016; Puntel et al., 2016). Therefore, despite many years of research, optimum N rates for corn are still difficult to predict. In the North Central U.S., crop rotation influences soil carbon (C) and N inputs, corn yield, and fertilizer N requirement (Bundy et al., 1993; Stanger & Lauer, 2008; Vanotti & Bundy, 1995); however, identifying

empirical differences between maize fertilizer N demand following common previous crops of soybean and corn is needed to guide N rate selection.

Current N recommendation systems, such as the Maximum Return to Nitrogen (MRTN), use empirical N response to generate optimum N rates (Nafziger et al., 2022) in six Midwest states. The optimum rates are estimated from many N response trials conducted for corn following corn and corn following soybean. The results can be accessed via the Corn N rate calculator (CNRC) https://www.cornnratecalc.org/calculator and support interpretation of the data by previous crop as one of the main features. Generally, N fertilizer recommendations across the Corn Belt states recommend lower N rates for corn following soybean than for corn following corn (Sawyer et al., 2006). Hence, it is relevant that current recommendations recognize previous crop as an important determinant of corn N requirement, as it is known as a major factor affecting optimal N rates (Baum et al., 2025).

The N benefit of rotating corn with soybeans is well documented and reported to reduce the need for N by about 50 lb N ac^{-1}. This benefit is partially caused by soybean residue that increases soil N supply via net N mineralization, thereby reducing the need for N fertilization (Baum et al., 2025; Mallarino & Pecinovsky, 2024; Puntel et al., 2016, Puntel et al., 2018). However, current recommendations suggest a smaller rotation benefit. For 2026, data from the CNRC recommend approximately 25 lb N ac^{-1} less N for corn following soybean than for corn following corn in Illinois. Although the rotation N benefit is well established, considerably less is known about whether its magnitude has remained stable as corn productivity has changed over time.

Long-term experiments have been used to investigate temporal variability and changes in corn N requirements, but evidence from long-term trends within a consistent N production system remains limited. Arnall et al. (2013) examined temporal variability in N responsiveness using long-term experiments but did not quantify trends in optimum N rates. Similarly, Mallarino and Pecinovsky (2024) used long-term data from 1979 to 2024 to understand corn N needs under seven different rotations, but no quantification of optimum rates over time is shown. More recently, Baum et al. (2025) combined long-term and short-term studies from different locations in Iowa and Illinois and demonstrated that EONR has increased over time in both continuous corn and corn after soybean. They further found that the EONR difference between rotations narrowed from 39 lb N ac^{-1} in 2000 to 29 lb N ac^{-1} in 2020, suggesting that the rotation N benefit may be changing over time. However, this analysis integrates studies across locations and production environments, and therefore long-term changes in N demand and the rotation N benefit with a single, consistently managed production system remain less well characterized.

Long-term field experiments provide a unique value for evaluating the interactions between treatment and environment that short-term studies may not capture (Schlegel & Havlin, 2017). When conducted at a common site and under consistent treatments over time, long-term studies minimize confounding effects from soil, location and experimental design that may occur when combining independent experiments across sites and years. In this study, we used a 43-year long-term experiment to understand how corn N demand has changed over four decades under a consistently managed continuous corn versus corn-soybean rotation. Specifically, we

evaluated temporal trends in yield at zero N, EONR, and YEONR; quantified differences between rotations; and determined whether the EONR benefit associated with corn after soybean rotation has changed or not over time.

MATERIALS AND METHODS

Site Description and Experimental Design

The study was conducted at the Northwestern Ag R&D Center in Monmouth, IL. The soil series is a Muscatune silt loam formed in deep loess parent material with 4.5% soil organic matter (SOM) in the surface layer. The trial was conducted from 1983 until 2025, and a Randomized Complete Block Design (RCBD) with three replications was used. Main plots were the rotations and subplots were five N rates tested: 0, 60, 120, 180, and 240 lb N ac^{-1} applied as UAN injected pre-plant. Other nutrients were managed to be nonlimiting, and hybrids were changed every 2 or 3 years.

Previous Crop Mapping

Corn crop sequences for Illinois were mapped using the 2018–2025 Crop Sequence Boundaries dataset from the USDA National Agricultural Statistics Service (USDA-NASS, 2026). Polygons classified as corn in 2025 were grouped according to their annual Cropland Data Layer crop classifications for 2023, 2024 and 2025. Three sequences were highlighted: corn–corn–corn, soybean–corn–corn, and corn–soybean–corn, corresponding to CCC, CCS, and CSC. Acreage within each sequence was calculated by summing the polygon acreage attribute (CSBACRES). Data processing and mapping were performed in RStudio (R Core Team, 2024) using the packages *sf*, *dplyr* and *ggplot2*.

Weather Data

Precipitation and temperature were obtained from the PRISM Climate Group at Oregon State University using the PRISM Data Explorer. Weather conditions were summarized for the growing season, defined as April through October, by calculating cumulative precipitation and mean air temperature for each year. Long-term averages were calculated across the 43 growing seasons and used as thresholds to classify each year into one of four weather categories: warm and dry, warm and wet, cool and dry, or cool and wet. Warm and cool conditions were defined by seasonal mean temperatures above and below the long-term average, respectively, whereas wet and dry conditions were defined by seasonal precipitation totals above and below the long-term average, respectively.

Data analysis

Repeated measures Analysis of Variance (ANOVA) was used to evaluate the effect of N rate and rotation on corn grain yield across the years and by year. Corn grain yield response was evaluated using ANOVA and testing four different statistical models: linear, quadratic, linear-plateau, and quadratic-plateau. The best models were selected based on Akaike Information Criterion (AIC) and adjusted R^2. For non-significant years, contrasts were run testing the unfertilized against fertilized treatments. The EONR was calculated using a 10:1 corn price to N fertilizer cost ratio (\$5 bu^{-1} and \$0.50 lb N^{-1}).

Changes over time for Y0N (yield at zero N), EONR, YEONR (yield at the EONR), NUE (N Use Efficiency) and NFE (N fertilizer Efficiency) were evaluated using simple linear regression and t-tests to test regression slopes against zero at $\alpha = 0.05$. Response model fits were done in SAS ODA (SAS Institute, Cary, NC), while statistical analysis, EONR calculation and plotting was done in R.

RESULTS AND DISCUSSION

Previous Crop Mapping

The crop sequence maps illustrate three common cropping sequences across Illinois (Figure 1). Corn–soybean–corn occupied approximately 8.41 million acres, compared with 1.06 million acres under corn–corn–corn and 0.81 million acres under soybean–corn–corn. Together, these sequences accounted for 10.28 million acres, equivalent to approximately 92% of the 11.2 million acres planted to corn reported by USDA-NASS (2026). The remaining difference may reflect corn acreage associated with crop sequences not included in the maps (e.g., corn following wheat or other crops), as well as differences between the satellite-derived crop sequence estimates and USDA-NASS survey estimates. Although corn–soybean–corn was the predominant sequence among those mapped, the substantial acreage planted to corn in consecutive years and the emerging soybean-corn-corn rotation shows the importance of evaluating N management in both crop sequences.

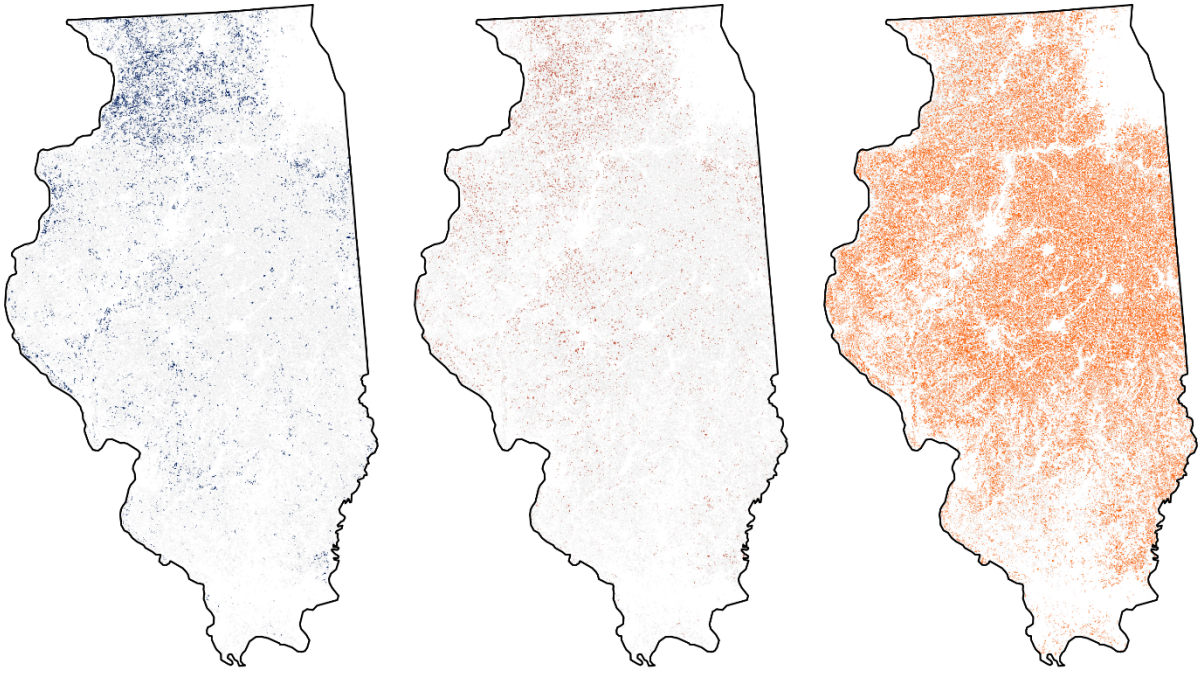


Figure 1. Corn areas in Illinois in 2025 by crop sequence a) corn-corn-corn, b) soybean-corn-corn and c) corn-soybean-corn**.** Crop sequences are listed in chronological order (2023–2024–2025).

Growing season weather and corn yield variability

Precipitation and temperature varied considerably during the 43 years of study (Figure 2). Precipitation ranged from 13 inches in 1988 to 43 inches in 2010, with a study period average of 27 in. Temperature ranged from 61.1°F in 2009 to 66.2°F in 2025, with a study period average of 64°F. These extremes corresponded to precipitation deviations of -14 and +16°F in and temperature deviations of -2.9 and +2°F from their respective study period averages. Despite wide ranges in precipitation and temperature, years were relatively evenly distributed among the four categories, with 13 warm and dry, 11 cool and dry, nine warm and wet, and 10 cool and wet years.

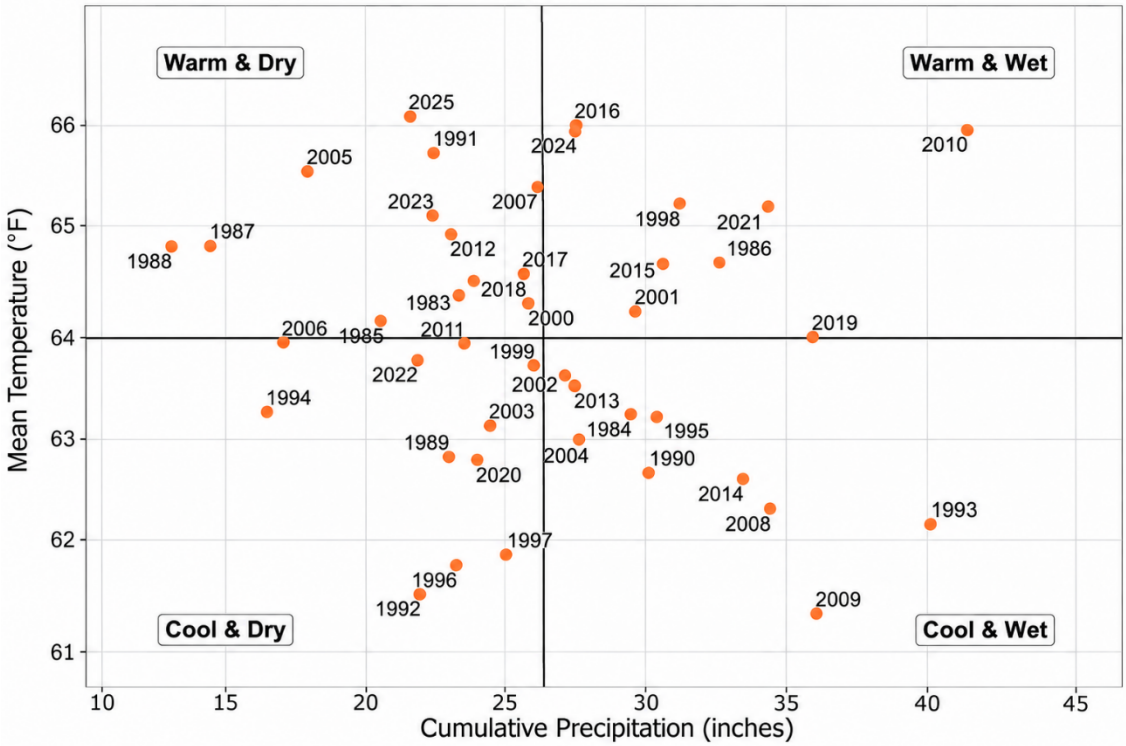


Figure 2. Cumulative precipitation and mean temperature in Monmouth, Illinois, USA from April to October for the years 1983 to 2025. Vertical and horizontal lines represent the long-term average cumulative precipitation and temperature, respectively. These average values were used to classify quadrants as warm, cool, dry, and wet.

Corn grain yield at the EONR (YEONR) varied substantially across the study period in both corn after corn (CC) and corn after soybean (CS) rotation (Table 1, supplementary material). For significant years, the YEONR in CC ranged from 80 in 2005 to 245 bu a^{-1} in both 2015 and 2025 with a median of 182 bu a^{-1}. In CS, YEONR ranged from 151 in 1995 to 272 bu ac^{-1} in 2023 with a median of 213 bu ac^{-1}. The YEONR was higher in CS than CC in 38 of the 40 significant years, with an average difference of 33 bu ac^{-1} across significant years. YEONR was higher in CC in 2016 and equal between rotations in 2017. Variability between years was greater in CC than CS, with coefficients of variation of 25.1% and 16.2%, respectively. The year county yield for Warren County, IL, where the study is located, ranged from 67 bu ac^{-1} in 1988 to 247 bu ac^{-1} in 2017, averaging 166 bu ac^{-1} across the study period. The lowest yields in both rotations and Warren County occurred in 1988, the year with the lowest growing-season

precipitation and above-average temperature. The YEONR was lower than the corresponding county yield in 15 of the 43 years for CC and for five years for CS, with mean differences above county yield of 8% and 28%, respectively. These percentages reflect the high productive soil where the study is located.

Corn yield response to N fertilizer and crop rotation

Corn grain yield was significantly affected by N fertilizer rate ($p < 0.0001$) and rotation ($p = 0.0014$) across the 43-year study period (Table 1). A significant N fertilizer rate by rotation interaction ($p < 0.0001$) indicated that yield response to N differed between rotations. These differences varied among years, as indicated by the significant N fertilizer rate by rotation by year ($p < 0.0001$).

Table 1. Tests of fixed effects on corn grain yield from the mixed-effects repeated measures ANOVA.

Effect	Num DF	Den DF	F-value	P-value
N rate	4	849	710.971	<0.0001
Rotation	1	2	696.998	0.0014
Year	42	849	220.322	<0.0001
N rate x Rotation	4	849	80.065	<0.0001
Rotation x Year	42	849	15.365	<0.0001
N rate x Year	168	849	9.010	<0.0001
N rate x Rotation x Year	168	849	2.528	<0.0001

Within individual years, N fertilizer rate significantly affected corn grain yield in 40 of 43 years, with no significant effect in 1988, 1989, and 2003 (Table 2). Crop rotation significantly affected 41 years, with no significant effect in 1989 and 2004. The N fertilizer rate and rotation interaction was significant in 28 years, including every year from 2006 through 2020, indicating that yield response to N frequently differed between the rotations during this period. Significant interactions occurred across all four weather categories, with the highest frequency in warm and wet years (89%), followed by cool and wet (70%), warm and dry (62%), and cool and dry years (45%).

Table 2. *P*-values for the effects of rotation, N fertilizer rate and their interaction on corn grain yield in individual years from 1983 to 2025.

Year	N rate	Rotation	N rate × Rot.	Year	N rate	Rotation	N rate × Rot.
1983	<0.0001	0.0229	0.1377	2005	<0.0001	0.0031	0.5776
1984	<0.0001	0.0033	0.0011	2006	<0.0001	0.0125	0.0351
1985	<0.0001	0.0085	<0.0001	2007	<0.0001	0.0995	0.0002
1986	<0.0001	0.0089	<0.0001	2008	<0.0001	0.0155	<0.0001
1987	<0.0001	0.0274	0.1678	2009	<0.0001	0.0302	0.0557
1988	0.2706	0.0181	0.8776	2010	<0.0001	0.0291	0.0089
1989	0.2823	0.1661	0.2792	2011	<0.0001	0.0110	0.0207
1990	<0.0001	0.0251	<0.0001	2012	<0.0001	0.0071	0.0081

1991	<0.0001	0.0067	<0.0001	2013	<0.0001	0.0067	0.0097
1992	0.0071	0.0156	0.3711	2014	<0.0001	0.0641	0.0011
1993	<0.0001	0.0224	0.1166	2015	<0.0001	0.0079	<0.0001
1994	<0.0001	0.0105	0.1285	2016	<0.0001	0.0216	<0.0001
1995	<0.0001	0.0083	0.3081	2017	<0.0001	0.0152	<0.0001
1996	<0.0001	0.0203	0.3545	2018	<0.0001	0.0076	<0.0001
1997	<0.0001	0.0182	0.3333	2019	<0.0001	0.0406	0.0938
1998	<0.0001	0.0364	0.0267	2020	<0.0001	0.0266	0.0329
1999	<0.0001	0.0189	0.0459	2021	<0.0001	0.0385	0.7002
2000	<0.0001	0.0066	<0.0001	2022	<0.0001	0.0337	0.0411
2001	<0.0001	0.0141	0.0003	2023	<0.0001	0.0065	0.4679
2002	0.0051	0.0059	0.8870	2024	<0.0001	0.0088	<0.0001
2003	0.2572	0.0068	0.4671	2025	<0.0001	0.0330	<0.0001
2004	<0.0001	0.4839	0.0159				

Corn yield response to N fertilizer rate varied in shape and magnitude between rotations and among years (Table 1, supplementary material; Figure 3). Across years with significant response models, quadratic-plateau models described the most responses, occurring in 25 years in CC and 17 years in CS. Quadratic models described the response in six years in CC and 12 years in CS, while linear-plateau models occurred in seven and nine years, respectively. Linear models described CC responses in four years and CS in one.

Corn grain yield was generally higher in CS than in CC (Figure 3). The EONR was also lower in CS in most years, except in 1991, 1996, 1999, 2002, 2003, 2004, 2007, 2014, 2019, 2020, and 2023. Median AONR and EONR were 166 and 153 lb N ac^{-1} in CC, respectively, with corresponding grain yields of 182 bu ac^{-1} at both rates. In CS, median AONR and EONR were 150 and 125 lb N ac^{-1}, with corresponding grain yields of both 213 bu ac^{-1}. Mean yield increases from N0 to EONR were greater in CC (92 bu ac^{-1}) than in CS (55 bu ac^{-1}). The difference between EONR and AONR was 10 lb-N ac^{-1} in CC and 15 lb N a^{-1} in CS, while yield differences were 0 and 1 bu a^{-1}, respectively. Mean NUE was higher in CS than in CC (1.7 and 1.2, respectively), while fertilizer NUE was higher in CC than in CS (0.7 versus 0.5).

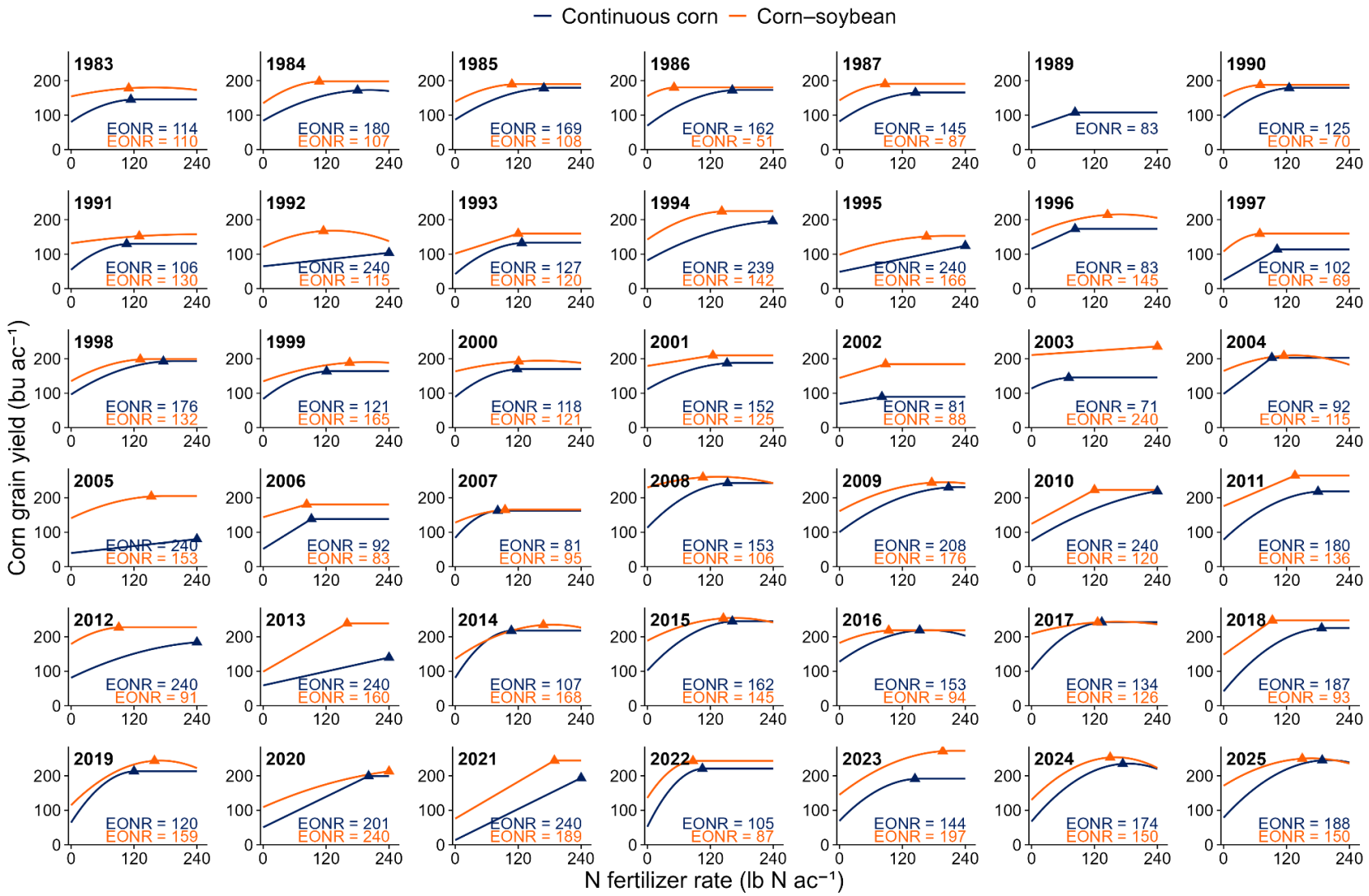


Figure 3. Relationship between N fertilizer rate and corn grain yield for corn after corn (blue) and corn after soybean (orange) from 1983 to 1025. Triangles represent the EONR calculated using a 10:1 corn price to nitrogen fertilizer cost ratio ($5 bu^{-1} and $0.50 lb N^{-1}). Continuous orange and blue lines are the fitted models. Nonsignificant models were excluded: 1988 CC and 1988, 1989 CS.

Temporal trends in Y0, YEONR, EONR and NUE

Results from the 43-year experiment showed that temporal trends in corn yield and EONR differed between variables and crop rotations (Figure 4). EONR increased significantly in corn after soybean by 1.3 lb N ac^{-1} $year^{-1}$, while in corn after corn the increase was 0.8 lb N ac^{-1} $year^{-1}$ and not statistically significant. The different slopes of these trends indicate that the difference in EONR between rotations over the years is closing from 42 lb N ac^{-1} in 1983 to 16 lb N ac^{-1} in 2025. This is due to the corn after soybean N demand has increased more rapidly over time than corn following corn. Yields at the zero N rate did not change significantly over the years (p = 0.569 and p = 0.646). In contrast, both yields at the EONR increased significantly over the years at a rate of 2.1 bu ac^{-1} $year^{-1}$. Yield gains in corn after corn occurred without a statistically significant increase in N demand. This finding implies that increasing corn grain yields do not necessarily require a corresponding increase in N fertilizer and can be associated with other factors. Baum et al. (2025), for example, attributed increasing EONR partly to increasing N losses. DeBruin et al. (2017) associated yield improvements at unchanged N application rates with traits including reduced grain N concentration and increased kernel number and mass. These mechanisms warrant consideration, although they were not directly evaluated in the study.

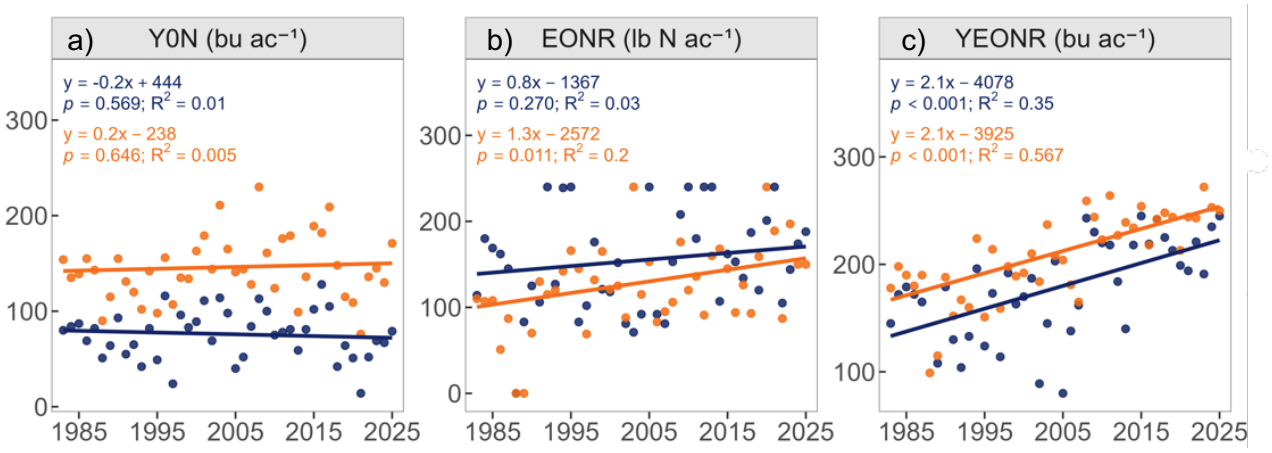


Figure 4. Long-term temporal trends in a) yield at the zero N fertilizer rate (Y0N), b) Economic Optimum N rate (EONR), and c) yield at the EONR (YEONR) for corn after corn (CC; blue) and corn after soybean (CS, orange) across 43 years. Points are the year values, and solid lines are separate linear regressions for each rotation. Regression equations and coefficients of determination (R^2) are shown; p-values are the results of testing the regression slopes against zero. Years with non-significant model fit were not included in the regression analysis (1988 CC, 1988 and 1989 CS).

Temporal changes for the two NUE metrics were contrasting (Figure 5). NUE which accounts for both N provided by the soil and by the fertilizer showed no change in either rotation. Differently, NFE (which subtracts zero-N yield before dividing by EONR) increased significantly by 0.012 and 0.009 bu yield lb N $^{-1}$$year^{-1}$ in corn after corn and corn after soybean, respectively. NUE provides a convenient indicator for farmers

because it requires only grain yield and fertilizer N rate; however, it includes yield supported by the soil N and therefore does not distinguish the yield response to fertilizer. The importance of accounting for soil N contributions when interpreting fertilizer requirements has also been emphasized by Vanotti and Bundy (1995). By accounting for zero-N yield, NFE revealed increasing yield gains per unit of fertilizer N that were not evident from the total yield to N rate ratio. Similarly, Baum et al. (2025) also reported increasing fertilizer N use efficiency despite an unchanged N rate to yield ratio. These results demonstrate that the two metrics provide complementary information and that a stable NUE ratio can mask improvements in the yield response to applied N, although it is a convenient way to measure efficiency.

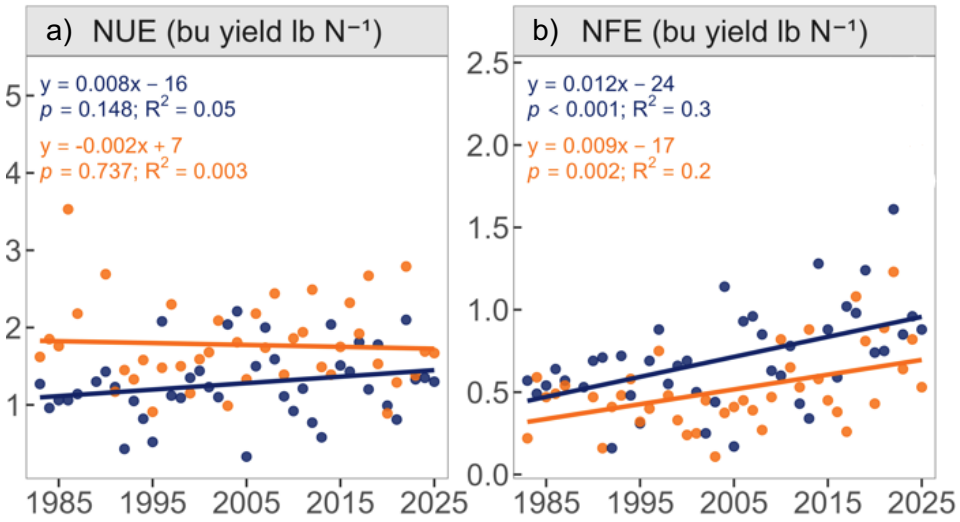


Figure 5. Long-term temporal trends in a) Nitrogen Use Efficiency (NUE), and b) Nitrogen Fertilizer Efficiency (NFE) for corn after corn (CC; blue) and corn after soybean (CS, orange) across 43 years. Points are the year values, and solid lines are separate linear regressions for each rotation. Regression equations and coefficients of determination (R^2) are shown; *p*-values are the results of testing the regression slopes against zero. Years with non-significant model fit were not included in the regression analysis (1988 CC, 1988 and 1989 CS).

CONCLUSION

In 2025, Illinois cropland area in corn following corn in 2024 and 2023 was 1.06 million acres, following corn in 2024 and soybean in 2023 was 0.81 million acres and following soybean in 2024 and corn in 2023 was 8.41 million acres. This highlights the importance of previous crop for corn areas in the state of Illinois and the need for assessments regarding N demand in both crop sequences.

The experiment showed that the EONR for corn after soybean is increasing 1.3 lb N ac^{-1} $year^{-1}$, while is not changing for corn after corn. This is causing therecommended N rate gap between the two rotations to close or being smaller, from 42 lb N ac^{-1} in 1983 to 16 lb N ac^{-1} in 2025. While N demand is increasing only for corn after soybean, yields at the EONR are getting higher across the years in both rotations at the rate of 2.1 bu ac^{-1} $year^{-1}$. On the other hand, yields from the unfertilized plots are found to be stable over time with no significant changes in either ration. The study also

compared efficiency metrics and found contrasting results over time with fertilizer efficiency showing significant increasing trends over time, while NUE was stable. Overall, these results provide long term evidence useful for future guidance on corn N recommendations in Illinois accounting for the well-known effects of previous crop on N requirements.

Acknowledgements
The authors would like to thank Greg Steckel and Marty Johnson for their work and support in the study discussed in this paper. This research is supported by the Illinois Nutrient Research and Education Council (NREC; project number 2025-4-360378-579) and Nutrien Ltd.

Supplementary Material

Table 1. Model coefficients, goodness-of-fit statistics, optimum N rates, corn grain yields, and N efficiency in continuous corn (CC) and corn-soybean (CS) from 1983 to 2025.

Year	Prev. crop	Model[1]	Equation Coefficients and Statistics						AONR[3]	YAONR[4]	EONR[5]	YEONR[6]	Δ yield[7]	Δ yield opt. N rate[8]	Δ N rate[9]	NUE[10]	NFE[11]
			a	b	c	AdjRSQ	AIC	p-value[2]									
1983	CC	QP	80	1.039	-0.0041	0.62	91.9	0.0012	126	146	114	145	65	1	12	1.27	0.57
1983	CS	Quad	154	0.331	-0.001	0.36	75.2	0.0257	157	180	110	178	24	2	47	1.62	0.22
1984	CC	Quad	84	0.879	-0.0021	0.96	57.6	< 0.10	202	173	180	172	88	1	22	0.96	0.49
1984	CS	QP	135	1.087	-0.0046	0.93	59.4	< 0.10	117	198	107	198	63	0	10	1.85	0.59
1985	CC	QP	87	0.984	-0.0026	0.95	66.2	< 0.10	188	179	169	179	92	0	19	1.06	0.54
1985	CS	QP	139	0.831	-0.0033	0.94	51.4	< 0.10	123	190	108	190	51	0	15	1.76	0.47
1986	CC	QP	69	1.173	-0.0033	0.96	64	< 0.10	177	173	162	172	103	1	15	1.06	0.64
1986	CS	QP	155	0.887	-0.0076	0.52	70.1	0.0044	58	181	51	180	25	1	7	3.53	0.49
1987	CC	QP	82	1.049	-0.0032	0.7	94.2	0.0003	160	166	145	165	83	1	15	1.14	0.57
1987	CS	QP	143	0.987	-0.005	0.75	74.1	0.0001	97	191	87	190	47	1	10	2.18	0.54
1988	CC	Lin	51	0.057		0.05	81.5	0.2072 ns	0	65	0	65	14	0	0	-	-
1988	CS	QP	90	0.339	-0.0032	0.09	62.6	0.2124 ns	0	99	0	99	9	0	0	-	-
1989	CC	LP	64	0.526		0.41	90.7	0.0157	83	108	83	108	44	0	0	1.3	0.53
1989	CS	Quad	115	0.178	-0.0009	0	94.1	0.3862 ns	0	115	0	115	0	0	0	-	-
1990	CC	QP	93	1.28	-0.0047	0.87	79.8	< 0.10	136	179	125	179	86	0	11	1.43	0.69
1990	CS	QP	155	0.847	-0.0053	0.82	57.1	< 0.10	79	188	70	188	33	0	9	2.69	0.47
1991	CC	QP	55	1.311	-0.0056	0.95	60.2	< 0.10	115	130	106	130	75	0	9	1.23	0.71
1991	CS	QP	131	0.221	-0.0004	0.56	66.4	0.0028	236	158	130	152	21	6	106	1.17	0.16
1992	CC	Lin	65	0.163		0.19	98.9	0.0551	240	104	240	104	39	0	0	0.43	0.16
1992	CS	Quad	120	0.716	-0.0026	0.59	82.2	0.0018	134	168	115	167	47	1	19	1.45	0.41
1993	CC	QP	42	1.323	-0.0048	0.9	76.3	< 0.10	137	133	127	133	91	0	10	1.05	0.72
1993	CS	LP	102	0.481		0.7	84	0.0002	120	160	120	160	58	0	0	1.33	0.48
1994	CC	QP	82	0.855	-0.0015	0.9	82.1	< 0.10	240	196	239	196	114	0	1	0.82	0.48
1994	CS	QP	142	1.055	-0.0033	0.81	84.5	< 0.10	157	225	142	224	82	1	15	1.58	0.58
1995	CC	Lin	49	0.315		0.88	71.3	< 0.10	240	124	240	124	75	0	0	0.52	0.31
1995	CS	QP	98	0.537	-0.0013	0.73	78.9	0.0002	204	153	166	151	53	2	38	0.91	0.32
1996	CC	LP	116	0.696		0.73	80.5	0.0001	83	173	83	173	57	0	0	2.08	0.69
1996	CS	Quad	156	0.697	-0.002	0.66	84.4	0.0006	170	215	145	214	58	1	25	1.48	0.4
1997	CC	LP	24	0.872		0.68	97.7	0.0004	102	114	102	114	90	0	0	1.12	0.88

1997	CS	QP	107	1.396	-0.0093	0.61	86	0.0013	75	160	69	159	52	1	6	2.3	0.75
1998	CC	QP	96	0.987	-0.0025	0.92	74	< 0.10	196	193	176	192	96	1	20	1.09	0.55
1998	CS	QP	135	0.858	-0.0028	0.86	71.1	< 0.10	150	199	132	198	63	1	18	1.5	0.48
1999	CC	QP	83	1.221	-0.0046	0.89	75.3	< 0.10	132	164	121	163	80	1	11	1.35	0.66
1999	CS	Quad	134	0.556	-0.0013	0.85	68.3	< 0.10	202	190	165	189	55	1	37	1.15	0.33
2000	CC	QP	89	1.26	-0.0049	0.93	66.7	< 0.10	128	170	118	170	81	0	10	1.44	0.69
2000	CS	Quad	163	0.374	-0.0011	0.76	57.8	0.0001	165	194	121	192	29	2	44	1.59	0.24
2001	CC	QP	111	0.893	-0.0026	0.91	69.8	< 0.10	172	188	152	187	76	1	20	1.23	0.5
2001	CS	LP	179	0.244		0.41	80.9	0.0159	125	210	125	210	31	0	0	1.68	0.25
2002	CC	LP	69	0.252		0.56	53.1	0.006	81	89	81	89	20	0	0	1.1	0.25
2002	CS	LP	144	0.456		0.57	80.2	0.0024	88	184	88	184	40	0	0	2.09	0.45
2003	CC	QP	114	0.783	-0.0047	0.46	79.7	0.0097	82	146	71	145	31	1	11	2.04	0.44
2003	CS	Lin	211	0.103		0.19	78.9	0.0676	240	236	240	237	26	1	0	0.99	0.11
2004	CC	LP	98	1.141		0.91	79.4	< 0.10	92	203	92	203	105	0	0	2.21	1.14
2004	CS	Quad	165	0.671	-0.0024	0.3	63.4	0.116	135	210	115	208	43	2	20	1.81	0.37
2005	CC	Lin	40	0.169		0.4	87.3	0.0067	240	80	240	80	40	0	0	0.33	0.17
2005	CS	QP	141	0.727	-0.002	0.61	91.4	0.0013	178	205	153	204	63	1	25	1.33	0.41
2006	CC	LP	52	0.942		0.74	92.5	0.0001	92	138	92	138	86	0	0	1.5	0.93
2006	CS	LP	144	0.447		0.68	66.6	0.0007	83	181	83	181	37	0	0	2.18	0.45
2007	CC	QP	84	1.846	-0.0107	0.86	78.3	< 0.10	86	163	81	162	78	1	5	2	0.96
2007	CS	QP	128	0.677	-0.003	0.82	60.4	< 0.10	111	166	95	165	37	1	16	1.74	0.39
2008	CC	QP	113	1.599	-0.0049	0.91	85.6	< 0.10	163	243	153	243	130	0	10	1.59	0.85
2008	CS	Quad	230	0.457	-0.0016	0.41	78.4	0.0164	136	261	106	259	29	2	30	2.44	0.27
2009	CC	Quad	100	1.151	-0.0025	0.87	90.8	< 0.10	227	231	208	230	130	1	19	1.11	0.63
2009	CS	Quad	161	0.839	-0.002	0.91	70.7	< 0.10	200	245	176	244	83	1	24	1.39	0.47
2010	CC	QP	75	0.942	-0.0014	0.85	94.6	< 0.10	240	220	240	220	145	0	0	0.92	0.6
2010	CS	LP	124	0.821		0.9	80.6	< 0.10	120	223	120	223	99	0	0	1.86	0.82
2011	CC	QP	78	1.448	-0.0037	0.86	95.1	< 0.10	194	219	180	218	140	1	14	1.21	0.78
2011	CS	LP	176	0.651		0.87	81.2	< 0.10	136	264	136	264	88	0	0	1.94	0.65
2012	CC	QP	81	0.736	-0.0012	0.85	85.7	< 0.10	240	184	240	184	103	0	0	0.77	0.43
2012	CS	QP	179	0.966	-0.0047	0.49	90.1	0.0064	101	228	91	227	48	1	10	2.49	0.53
2013	CC	Lin	59	0.336		0.55	99.3	0.0009	240	140	240	140	81	0	0	0.58	0.34
2013	CS	LP	99	0.876		0.95	78.7	< 0.10	160	239	160	239	140	0	0	1.49	0.88

2014	CC	QP	81	2.463	-0.011	0.93	83.4	< 0.10	111	218	107	218	137	0	4	2.04	1.28
2014	CS	Quad	136	1.07	-0.0028	0.94	69.5	< 0.10	185	235	168	234	98	1	17	1.39	0.58
2015	CC	QP	102	1.665	-0.0048	0.99	49.1	< 0.10	172	245	162	245	143	0	10	1.51	0.88
2015	CS	Quad	189	0.796	-0.0023	0.88	67.4	< 0.10	166	255	145	254	65	1	21	1.75	0.45
2016	CC	Quad	128	1.091	-0.0032	0.95	64.2	< 0.10	169	220	153	219	91	1	16	1.43	0.59
2016	CS	QP	182	0.67	-0.003	0.75	66.4	0.0001	110	219	94	218	36	1	16	2.32	0.38
2017	CC	QP	105	1.944	-0.0068	0.97	68.7	< 0.10	141	242	134	242	137	0	7	1.81	1.02
2017	CS	Quad	209	0.433	-0.0013	0.63	70.3	0.001	163	244	126	242	33	2	37	1.92	0.26
2018	CC	QP	42	1.857	-0.0046	0.97	76.7	< 0.10	198	226	187	225	183	1	11	1.2	0.98
2018	CS	LP	148	1.072		0.89	81.7	< 0.10	93	248	93	248	100	0	0	2.67	1.08
2019	CC	QP	64	2.392	-0.0095	0.97	71.8	< 0.10	125	213	120	213	149	0	5	1.78	1.24
2019	CS	Quad	115	1.523	-0.0044	0.89	87	< 0.10	170	244	159	244	129	0	11	1.53	0.81
2020	CC	LP	51	0.739		0.96	73.9	< 0.10	201	199	201	199	148	0	0	0.99	0.74
2020	CS	QP	109	0.671	-0.0009	0.81	89	< 0.10	240	213	240	213	104	0	0	0.89	0.43
2021	CC	Lin	14	0.75		0.94	78	< 0.10	240	194	240	194	180	0	0	0.81	0.75
2021	CS	LP	76	0.891		0.94	58.2	< 0.10	189	244	189	244	168	0	0	1.29	0.89
2022	CC	QP	52	3.114	-0.0143	0.94	82.2	< 0.10	108	221	105	221	169	0	3	2.1	1.61
2022	CS	QP	136	2.362	-0.0129	0.82	77.4	0.0001	91	243	87	243	107	0	4	2.79	1.23
2023	CC	QP	69	1.593	-0.0051	0.91	83.2	< 0.10	154	192	144	191	122	1	10	1.33	0.85
2023	CS	QP	145	1.188	-0.0027	0.87	84.9	< 0.10	215	273	197	272	127	1	18	1.38	0.64
2024	CC	Quad	67	1.822	-0.0049	0.98	67.3	< 0.10	184	235	174	235	168	0	10	1.35	0.96
2024	CS	Quad	130	1.548	-0.0048	0.96	67.6	< 0.10	160	254	150	253	123	1	10	1.69	0.82
2025	CC	Quad	79	1.673	-0.0041	0.89	89.6	< 0.10	200	246	188	245	166	1	12	1.3	0.88
2025	CS	Quad	171	0.95	-0.0028	0.94	61.4	< 0.10	167	251	150	250	79	1	17	1.67	0.53
Median	CC	-	-	-	-	-	-	-	166	182	153	182	92	0	10	1.2	0.7
Median	CS	-	-	-	-	-	-	-	150	213	125	213	55	1	15	1.7	0.5

[1]LP, linear plateau; QP, quadratic-plateau; Quad, quadratic; Lin, linear
[2]p-value refers to the overall model F-test. Models considered statistically significant at $p < 0.10$ and ns: non-significant model fit.
[3]Agronomic Optimum N Rate
[4]Yield at the Agronomic Optimum Nitrogen Rate
[5]Economic Optimum Nitrogen Rate calculated using a N to corn grain price ratio of 0.10 ($5 bu^{-1} and $0.50 lb N^{-1})
[6]Yield at the Economic Optimum N Rate
[7]The a coefficient subtracted from the YEONR
[8]The yield at the EONR subtracted from the yield at the EONR
[9]The EONR subtracted from the AONR
[10]The YEONR divided by the EONR
[11]The Y0N subtracted from the YEONR and divided by the EONR

REFERENCES

Arnall, D. B., Mallarino, A. P., Ruark, M. D., Varvel, G. E., Solie, J. B., Stone, M. L., Mullock, J. L., Taylor, R. K., & Raun, W. R. (2013). Relationship between grain crop yield potential and nitrogen response. Agronomy Journal, 105(5), 1335–1344. https://doi.org/10.2134/agronj2013.0034

Baum, M. E., Sawyer, J. E., Nafziger, E. D., Castellano, M. J., McDaniel, M. D., Licht, M. A., Hayes, D. J., Helmers, M. J., & Archontoulis, S. V. (2025). The optimum nitrogen fertilizer rate for maize in the US Midwest is increasing. Nature Communications, 16(1). https://doi.org/10.1038/s41467-024-55314-7

Bundy, L. G., Andraski, T. W., & Wolkowski, R. P. (1993). Nitrogen credits in soybean-corn crop sequences on three soils. Agronomy Journal, 85(5), 1061–1067. https://doi.org/10.2134/agronj1993.00021962008500050020x

Correndo, A. A., Tremblay, N., Coulter, J. A., Ruiz-Diaz, D., Franzen, D., Nafziger, E., Prasad, V., Rosso, L. H. M., Steinke, K., Du, J., Messina, C. D., & Ciampitti, I. A. (2021). Unraveling uncertainty drivers of the maize yield response to nitrogen: A Bayesian and machine learning approach. Agricultural and Forest Meteorology, 311. https://doi.org/10.1016/j.agrformet.2021.108668

DeBruin, J. L., Schussler, J. R., Mo, H., & Cooper, M. (2017). Grain yield and nitrogen accumulation in maize hybrids released during 1934 to 2013 in the US Midwest. Crop Science, 57(3), 1431–1446. https://doi.org/10.2135/cropsci2016.08.0704

Dhital, S., & Raun, W. R. (2016). Variability in optimum nitrogen rates for maize. Agronomy Journal, 108(6), 2165–2173. https://doi.org/10.2134/agronj2016.03.0139

Mallarino, A. P., & Pecinovsky, K. T. (2024). Corn, soybean, oat, and alfalfa yields as affected by the rotation and nitrogen fertilization for corn in northeast Iowa—1979–2024 summary. Iowa State University Research and Demonstration Farms Progress Reports, 1(1).

Nafziger, E., Sawyer, J., Laboski, C., & Franzen, D. (2022). The MRTN approach to making nitrogen rate recommendations: Background and implementation. Crops & Soils, 55(2), 4–11. https://doi.org/10.1002/crso.20180

Puntel, L. A., Sawyer, J. E., Barker, D. W., Dietzel, R., Poffenbarger, H., Castellano, M. J., Moore, K. J., Thorburn, P., & Archontoulis, S. V. (2016). Modeling long-term corn yield response to nitrogen rate and crop rotation. Frontiers in Plant Science, 7, 1630. https://doi.org/10.3389/fpls.2016.01630

Puntel, L. A., Sawyer, J. E., Barker, D. W., Thorburn, P. J., Castellano, M. J., Moore, K. J., VanLoocke, A., Heaton, E. A., & Archontoulis, S. V. (2018). A systems modeling approach to forecast corn economic optimum nitrogen rate. Frontiers in Plant Science, 9, 436. https://doi.org/10.3389/fpls.2018.00436

R Core Team. (2024). R: A language and environment for statistical computing (Version 4.2.2). R Foundation for Statistical Computing. https://www.r-project.org/

Sawyer, J., Nafziger, E., Randall, G., Bundy, L., Rehm, G., & Joern, B. (2006). Concepts and rationale for regional nitrogen guidelines for corn (PM 2015). Iowa State University Extension.

Schlegel, A. J., & Havlin, J. L. (2017). Corn yield and grain nutrient uptake from 50 years of nitrogen and phosphorus fertilization. Agronomy Journal, 109(1), 335–342. https://doi.org/10.2134/agronj2016.05.0294

Stanger, T. F., & Lauer, J. G. (2008). Corn grain yield response to crop rotation and nitrogen over 35 years. Agronomy Journal, 100(3), 643–650. https://doi.org/10.2134/agronj2007.0280

United States Department of Agriculture, National Agricultural Statistics Service. (2026). Crop sequence boundaries. https://www.nass.usda.gov/research-and-science/crop-sequence-boundaries

Vanotti, M. B., & Bundy, L. G. (1995). Soybean effects on soil nitrogen availability in crop rotations. Agronomy Journal, 87(4), 676–680. https://doi.org/10.2134/agronj1995.00021962008700040012x