APPLICATION TIMING, CEREAL RYE, AND RESPONSE-MODEL SELECTION AFFECT SITE-SPECIFIC ECONOMIC OPTIMUM NITROGEN RATES AND NITRATE-N LEACHING IN CORN

A. Sadeghpour[1], O. Guzel[1], S. Koduru[1], M. Guzel[2], G. Williams[1], Y. Samadi[3], S. Armstrong[4], E.C. Brevik[1,5]

[1]School of Agricultural Sciences, Southern Illinois University, Carbondale, IL
[2]Faculty of Agriculture, Tokat Gaziosmanpasa University, Tokat, Türkiye
[3]School of Mathematical and Statistical Sciences, Southern Illinois University, Carbondale, IL
[4]Department of Agronomy, Purdue University, West Lafayette, IN
[5]School of Earth Systems and Sustainability, Southern Illinois University, Carbondale, IL

ABSTRACT

Nitrogen (N) management in corn (*Zea mays* L.) must balance profitability with nitrate-N losses. The Maximum Return to N (MRTN) approach provides regionally robust recommendations but does not explicitly account for site-specific differences in N application timing, cover crops, or uncertainty in the yield-response model used to estimate the economic optimum N rate (EONR). We evaluated these factors using N-rate trials conducted in southern Illinois. Eight N rates (0 to 352 lb N ac^{-1}) were applied upfront across 12 site-years and compared with sidedress application across 10 site-years. Six N rates (0 to 250 lb N ac^{-1}) were evaluated with and without cereal rye (*Secale cereale* L.) across six site-years, and nitrate-N leaching was measured in three site-years. Upfront EONR ranged from 149 to 322 lb N ac^{-1}, and the MRTN point estimate fell within the profitable EONR range in only 16% of site-year × price scenarios. Sidedress N reduced EONR by 13%, increased grain yield at EONR from 192 to 200 bu ac^{-1}, and reduced mean deviation from MRTN from 51 to 44 lb N ac^{-1}. Cereal rye increased EONR from 201 to 209 lb N ac^{-1} without reducing grain yield at EONR. Nitrate-N leaching increased exponentially with N rate. Partial factor productivity, apparent N recovery, and N use efficiency declined when N rates exceeded EONR. Bootstrap multi-model aggregation using an expanded candidate model set produced the lowest EONR estimation error among the multi-model approaches evaluated and confidence intervals that incorporated model uncertainty. These results indicate that N application timing and cover crop use can shift site-specific EONR relative to regional MRTN recommendations and that multi-model approaches can improve EONR estimation by accounting for uncertainty in yield-response model selection.

INTRODUCTION

Illinois corn N recommendations are based on the Maximum Return to N (MRTN) approach, which pools yield response to N across many trials within a region and returns a single recommended rate and a profitable range for a given N:grain price ratio (Sawyer et al., 2006). The MRTN estimates the average economic optimum N rate (EONR) for the region. The EONR of an individual field and season, however, depends on soil N supply, rainfall timing, and management, so a regional rate can be accurate on average but too high in some site-years and too low in others (Scharf et al., 2005;

Morris et al., 2018; Ransom et al., 2020). In southern Illinois, claypan and fragipan soils restrict internal drainage, and wet springs increase the risk of N loss between application and crop uptake.

Two management factors common in the region are not separated in the MRTN database. First, many Illinois growers apply all of their N at or before planting, which lengthens the period between N availability and peak crop uptake. Sidedress application places N closer to the period of rapid uptake and can reduce N losses (Morris et al., 2018; Preza-Fontes et al., 2022). Second, cereal rye is the most widely used cover crop before corn, but its high C:N residue can immobilize soil N after termination. Reported effects of cereal rye on corn EONR range from none to substantial increases (Pantoja et al., 2015; Quinn et al., 2023; Marcillo et al., 2024).

The EONR is also a model-based estimate. Quadratic, quadratic-plateau, linear-plateau, and Mitscherlich models often fit the same N-rate data similarly well but give different EONR values (Cerrato & Blackmer, 1990; Kyveryga et al., 2007). Choosing one model discards this uncertainty. Bootstrap-based multi-model aggregation (BbMA) fits several candidate models to resampled data and summarizes the resulting distribution of EONR estimates (Palmero et al., 2026). The objectives of this study were to: i) determine site-specific EONR for upfront N and compare it with the MRTN recommendation; ii) quantify how sidedress timing and cereal rye change EONR and grain yield at EONR; iii) quantify nitrate-N leaching across N rates and application timings; and iv) evaluate whether BbMA with an expanded set of candidate models improves EONR estimation. We hypothesized that sidedress N would lower EONR, that cereal rye would raise it, and that EONR would deviate from the MRTN rate in both directions.

MATERIALS AND METHODS

Site Description

Nitrogen rate trials were conducted from 2018 to 2024 at the Southern Illinois University Agronomy Research Center, Carbondale, IL (ARC), the Belleville Research Center, Belleville, IL (BRC), and at sites near Shawneetown and Dowell, IL. Soils were mainly silt loams with restricted internal drainage. Growing-season (May to November) precipitation ranged from 13.0 to 36.5 inches across site-years. The cereal rye trials were conducted from 2019 to 2021 at ARC and BRC (five site-years) and at one site in Indiana. Trials were mainly in a corn–soybean [*Glycine max* (L.) Merr.] rotation.

Experimental Design and Treatments

The N timing trials used a randomized complete block design with five replications. Eight N rates (0, 55, 104, 153, 203, 252, 302, and 352 lb N ac^{-1}) were applied as urea ammonium nitrate (UAN; 32-0-0), either upfront at planting (12 site-years) or as an in-season sidedress (10 of these site-years). Corn was planted in 30-inch rows. The cereal rye trials used a split-plot randomized complete block design, with cover crop (cereal rye vs. no cover) as the main plot and six N rates (0, 50, 100, 150, 200, and 250 lb N ac^{-1}) as subplots. Cereal rye was drilled in mid-October to mid-November and terminated between mid-April and mid-May before corn planting.

Measurements

Corn grain yield was determined at maturity and is reported in bu ac^{-1} at 15.5% moisture. Grain N removal was measured or estimated from yield (Tenorio et al., 2019), and N balance (N applied minus grain N removal), partial factor productivity (PFP), apparent N fertilizer recovery (ANFR), and N use efficiency (NUE) were calculated for each N rate. Cereal rye aboveground biomass was sampled at termination. Growing-season nitrate-N leaching was measured in three upfront and sidedress site-years (BRC-2023, ARC-2024, and BRC-2024) with ion-exchange resin lysimeters (Susfalk & Johnson, 2002; Leon et al., 2024). Three lysimeters per plot were installed at 16 inches, or directly above the claypan where it was shallower, before planting and retrieved after harvest. Yield-scaled leaching was calculated as nitrate-N leached per bushel of grain (Pittelkow et al., 2017).

EONR Estimation and Statistical Analysis

Quadratic-plateau and linear-plateau models were fitted to grain yield for each site-year, and EONR was calculated from the best-fitting model using a grain price of \$5.08 bu^{-1} and an N price of \$0.59 lb^{-1} N (price ratio 0.12), the average prices during the study period. Profitability was also evaluated at grain and N prices 20% above and below these values (nine price scenarios per site-year). The profitable EONR range included N rates with net return within \$1 ac^{-1} of the maximum. Grain yield, N removal, N balance, and N use metrics were analyzed with mixed models in SAS 9.4 (SAS Institute, 2017), with block as a random effect. Leaching responses to N rate were described with exponential models.

For BbMA, each site-year data set was resampled with replacement, one candidate model was selected at random and fitted, and EONR was calculated from the fitted curve. The median of the bootstrap EONR values was the point estimate, and the 2.5th and 97.5th percentiles gave a 95% confidence interval (Palmero et al., 2026). Aggregation was run with four standard models (quadratic, quadratic-plateau, linear-plateau, and Mitscherlich; BbMA-4) and with the inverse quadratic of Nelder (1966) added as a fifth candidate (BbMA-5). Because the true EONR of a field trial is unknown, estimation error was evaluated in a simulation that reproduced the field design (eight N rates, five replications) with known true EONR, and both methods were then applied to the 12 upfront site-years.

RESULTS AND DISCUSSION

Upfront EONR and the MRTN Recommendation

Grain yield response to upfront N was best described by a quadratic-plateau model in seven site-years and a linear-plateau model in five. EONR ranged from 149 to 322 lb N ac^{-1}. The price-specific MRTN rate came within 10% of the site-year EONR in only 3 of 12 site-years, and the MRTN point estimate fell within the profitable EONR range in 16% of the 108 site-year × price scenarios. The MRTN rate was too low in most site-years with high EONR, which tended to have wet or cool early seasons that limited mineralization and increased fertilizer N loss, and too high in site-years with low EONR (data now shown). These results agree with reports that current recommendation tools do not reliably separate site-years of low and high N response (Ransom et al., 2020).

PFP, ANFR, and NUE declined as N rate increased above EONR, and N balance was positive at EONR in all site-years. Fertilizer N applied above the EONR therefore contributed little to grain yield and increased the N surplus left in the soil after harvest.

Sidedress N Timing

Across the 10 site-years with both timings, mean EONR was 13% lower with sidedress than with upfront N (206 vs. 237 lb N ac^{-1}), and grain yield at EONR increased from 192 to 200 bu ac^{-1} (Table 1). The mean absolute deviation of site-year EONR from the reference MRTN rate decreased from 51 to 44 lb N ac^{-1}. Applying N closer to rapid crop uptake shortens the period in which fertilizer N is exposed to leaching and denitrification on these restrictively drained soils. Sidedress did not lower EONR in every site-year, however, and EONR was more closely related to soil organic matter under sidedress than under upfront N. Sidedress applications also depend on field access during early vegetative growth, which can be limited in wet years (data now shown).

Cereal Rye

Cereal rye biomass at termination ranged from about 720 to 2,890 lb ac^{-1}, and residue C:N exceeded 25 in most site-years. Averaged over six site-years, cereal rye increased EONR from 201 to 209 lb N ac^{-1} (4%), whereas grain yield at EONR was similar with and without the cover crop (184 vs. 187 bu ac^{-1}; Table 1). Corn plant population was lower after cereal rye than after no cover, and the increase in EONR is consistent with N immobilization by high C:N residue and reduced early-season N supply (Pantoja et al., 2015; Quinn et al., 2023). The increase was smaller than the 21 lb N ac^{-1} reported in a recent synthesis (Marcillo et al., 2024) and varied among site-years with rye biomass and termination date.

Table 1. Mean economic optimum N rate (EONR), grain yield at EONR, deviation of EONR from the MRTN rate, and yield-scaled nitrate-N leaching at EONR as affected by N application timing and cereal rye in southern Illinois.

Factor	Treatment	Site-years	EONR (lb N ac^{-1})	Grain yield at EONR (bu ac^{-1})	Deviation from MRTN† (lb N ac^{-1})	Yield-scaled leaching‡ (lb N bu^{-1})
N timing	Upfront	10	237	192	51	0.45
	Sidedress	10	206	200	44	0.22
Cover crop	No cover	6	201	187	–	–
	Cereal rye	6	209	184	–	–

EONR values are the means of site-year EONR for the N timing comparison and were derived from a quadratic-plateau model fitted across site-years for the cover crop comparison. EONR was calculated at \$5.08 bu^{-1} grain and \$0.59 lb^{-1} N. Grain yield is reported at 15.5% moisture. †Mean absolute deviation of site-year EONR from the reference MRTN rate of 203 lb N ac^{-1}. ‡Growing-season nitrate-N leached per bushel of grain at EONR, measured at 16 inches in three site-years.

Nitrate-N Leaching

Nitrate-N leaching increased exponentially with N rate under both application timings. Because the exponential response has no breakpoint, each additional pound of N above the EONR increased leaching more than the previous pound. Under upfront N,

leaching at the EONR (238 lb N ac^{-1} averaged over the three site-years) was 73 lb N ac^{-1}, and leaching at the MRTN rate was 39% lower than at the EONR. Leaching was greatest at BRC-2024, the wettest site-year. Sidedress N reduced nitrate-N leaching in two of three site-years, and yield-scaled leaching at EONR was 0.22 lb N bu^{-1} with sidedress compared with 0.45 lb N bu^{-1} with upfront N (Table 1). Resin lysimeters measure nitrate-N moving below 16 inches, above the restrictive layer, and these values should not be read as tile or watershed loads. The results show that site-years with a high upfront EONR also carried high leaching at that rate, so the most profitable upfront rate and the environmentally preferred rate were not the same.

Response-Model Selection and Multi-Model Aggregation

Candidate models often disagreed on EONR. At one site-year, the five models gave EONR values from 65 to 194 lb N ac^{-1} from the same data. In the simulation, each single model had its lowest error only when it was the model that generated the data. The linear-plateau model, for example, had root mean squared error (RMSE) as large as 75 lb N ac^{-1} when the true response curved gradually, because it forced a sharp join point (Cerrato & Blackmer, 1990). Adding the inverse quadratic to the candidate set reduced BbMA mean RMSE across simulated response shapes from 32 to 29 lb N ac^{-1} and reduced worst-case RMSE from 53 to 49 lb N ac^{-1}, giving BbMA-5 the lowest error among the multi-model approaches evaluated. The single inverse quadratic model also performed well in simulation, but it gave unstable estimates in some field site-years and, like any single model, provides no measure of model-selection uncertainty.

In the 12 field site-years (upfront N trials), BbMA-5 estimates fell within the range of the individual models and never at its extremes. The 95% confidence intervals averaged about 150 lb N ac^{-1} in width, wider than those from a single fitted model, because they include disagreement among models in addition to sampling variability. A wide interval indicates how little a single N-rate trial constrains the EONR and is useful information for risk-based N decisions and for variable-rate prescriptions that otherwise report a rate without any measure of confidence (Jaynes, 2011; Miguez & Poffenbarger, 2022).

CONCLUSIONS

Upfront EONR in southern Illinois varied more than twofold among site-years, and the regional MRTN rate seldom fell within the site-year profitable range. Sidedress N lowered EONR by 13%, increased grain yield at EONR, brought EONR closer to the MRTN rate, and halved yield-scaled nitrate-N leaching. Cereal rye raised EONR by about 8 lb N ac^{-1} without reducing grain yield at EONR. Nitrate-N leaching increased exponentially with N rate, so N applied above the EONR carried a large environmental cost for little or no economic gain. Including application timing and cover crop use in MRTN-based recommendations, and reporting EONR with a confidence interval from multi-model aggregation rather than from a single response model, would improve site-specific N recommendations for corn.

ACKNOWLEDGEMENTS

This research was supported by the Illinois Nutrient Research and Education Council (NREC).

REFERENCES

Cerrato, M. E., & Blackmer, A. M. (1990). Comparison of models for describing corn yield response to nitrogen fertilizer. *Agronomy Journal*, 82(1), 138–143. https://doi.org/10.2134/agronj1990.00021962008200010030x

Jaynes, D. B. (2011). Confidence bands for measured economically optimal nitrogen rates. *Precision Agriculture*, 12(2), 196–213. https://doi.org/10.1007/s11119-010-9168-3

Kyveryga, P. M., Blackmer, A. M., & Morris, T. F. (2007). Disaggregating model bias and variability when calculating economic optimum rates of nitrogen fertilization for corn. *Agronomy Journal*, 99(4), 1048–1056. https://doi.org/10.2134/agronj2006.0339

Leon, P., Nakayama, Y., & Margenot, A. J. (2024). Field-scale evaluation of struvite phosphorus and nitrogen leaching relative to monoammonium phosphate. *Journal of Environmental Quality*, 53(1), 23–34. https://doi.org/10.1002/jeq2.20522

Marcillo, G. S., Thapa, R., Mirsky, S. B., & Martin, N. (2024). The nitrogen value of cover crops: How much N can cover crops replace? *Agricultural & Environmental Letters*, 9(2), e70006. https://doi.org/10.1002/ael2.70006

Miguez, F. E., & Poffenbarger, H. (2022). How can we estimate optimum fertilizer rates with accuracy and precision? *Agricultural & Environmental Letters*, 7(1), e20075. https://doi.org/10.1002/ael2.20075

Morris, T. F., Murrell, T. S., Beegle, D. B., Camberato, J. J., Ferguson, R. B., Grove, J., … Yang, H. (2018). Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. *Agronomy Journal*, 110(1), 1–37. https://doi.org/10.2134/agronj2017.02.0112

Nelder, J. A. (1966). Inverse polynomials, a useful group of multi-factor response functions. *Biometrics*, 22(1), 128–141. https://doi.org/10.2307/2528220

Palmero, F., Ciampitti, I. A., & Hefley, T. J. (2026). Bootstrap multimodel aggregation for estimating optimum nitrogen rates in agricultural crops. *Agronomy Journal*, 118, e70476. https://doi.org/10.1002/agj2.70476

Pantoja, J. L., Woli, K. P., Sawyer, J. E., & Barker, D. W. (2015). Corn nitrogen fertilization requirement and corn–soybean productivity with a rye cover crop. *Soil Science Society of America Journal*, 79(5), 1482–1495. https://doi.org/10.2136/sssaj2015.02.0084

Pittelkow, C. M., Clover, M. W., Hoeft, R. G., Nafziger, E. D., Warren, J. J., Gonzini, L. C., & Greer, K. D. (2017). Tile drainage nitrate losses and corn yield response to fall and spring nitrogen management. *Journal of Environmental Quality*, 46(5), 1057–1064. https://doi.org/10.2134/jeq2017.03.0109

Preza-Fontes, G., Christianson, L. E., Greer, K., Bhattarai, R., & Pittelkow, C. M. (2022). In-season split nitrogen application and cover cropping effects on nitrous oxide

emissions in rainfed maize. *Agriculture, Ecosystems & Environment*, 326, 107813. https://doi.org/10.1016/j.agee.2021.107813

Quinn, D. J., Poffenbarger, H. J., Miguez, F. E., & Lee, C. D. (2023). Corn optimum nitrogen fertilizer rate and application timing when following a rye cover crop. *Field Crops Research*, 291, 108794. https://doi.org/10.1016/j.fcr.2022.108794

Ransom, C. J., Kitchen, N. R., Camberato, J. J., Carter, P. R., Ferguson, R. B., Fernández, F. G., Franzen, D. W., Laboski, C. A. M., Nafziger, E. D., Sawyer, J. E., Scharf, P. C., & Shanahan, J. F. (2020). Corn nitrogen rate recommendation tools' performance across eight US Midwest Corn Belt states. *Agronomy Journal*, 112(1), 470–492. https://doi.org/10.1002/agj2.20035

SAS Institute. (2017). The SAS system for Windows (Version 9.4). SAS Institute, Cary, NC.

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

Scharf, P. C., Kitchen, N. R., Sudduth, K. A., Davis, J. G., Hubbard, V. C., & Lory, J. A. (2005). Field-scale variability in optimal nitrogen fertilizer rate for corn. *Agronomy Journal*, 97(2), 452–461. https://doi.org/10.2134/agronj2005.0452

Susfalk, R. B., & Johnson, D. W. (2002). Ion exchange resin based soil solution lysimeters and snowmelt solution collectors. *Communications in Soil Science and Plant Analysis*, 33(7–8), 1261–1275. https://doi.org/10.1081/CSS-120003886

Tenorio, F. A. M., Eagle, A. J., McLellan, E. L., Cassman, K. G., Howard, R., Below, F. E., … Grassini, P. (2019). Assessing variation in maize grain nitrogen concentration and its implications for estimating nitrogen balance in the US North Central region. *Field Crops Research*, 240, 185–193. https://doi.org/10.1016/j.fcr.2018.10.017