LINKING SOIL AND WEATHER TO CORN NITROGEN RESPONSE WITH A BAYESIAN HIERARCHICAL MODEL

Y. Wang[1], J. Lory[2], C. Ransom[3], S. Anderson[1], and K. Shannon[2]
[1] School of Natural Resources, University of Missouri, Columbia, MO
[2] Plant Sciences and Technology, University of Missouri, Columbia, MO
[3] USDA-ARS Cropping Systems and Water Quality Research Unit, Columbia, MO
ywhkz@missouri.edu | 573-219-8292

ABSTRACT

The economic optimum nitrogen rate (EONR) is the fertilizer nitrogen (N) rate that maximizes economic return. Corn N response varies among site-years and within a site-year, making EONR difficult to estimate. Soil and weather information may help explain this variation. We used a Bayesian hierarchical model to examine these relationships across 12 Missouri on-farm site-years conducted from 2023 to 2025. The analysis combined preplant soil fertility and soil health measurements, N application records, and georeferenced harvest yields. The weather predictor was cumulative precipitation divided by cumulative reference evapotranspiration from planting to the day before the first sidedress application, calculated from daily gridMET data. Active carbon, organic matter, soil-test phosphorus, and this weather ratio entered a quadratic yield-response model as predictors of baseline yield and the linear N-response coefficient. The hierarchy allowed site-years to differ while sharing information. Joint posterior draws were used to calculate conditional EONR distributions under specified soil, weather, and price conditions. In the preliminary N2401 field example, EONR medians ranged from 141 to 256 lb N/ac at corn and N prices of $4.50/bu and $0.50/lb, respectively. Further analysis will evaluate indicator contributions and predictive performance across trials. The goal is to develop a model that can integrate soil and weather information for site-specific N management while quantifying uncertainty in EONR.

INTRODUCTION

Choosing a profitable fertilizer N rate remains a challenge in corn production. The economic optimum depends on the yield response to added N and the relative prices of fertilizer and grain (Morris et al., 2018). Corn N response varies among site-years and within a site-year, resulting in substantial spatial variation in EONR (Scharf et al., 2005). Weather and soil conditions also change the amount of fertilizer needed across years (Morris et al., 2018). In a comparison of 31 recommendation tools across eight Corn Belt states, Ransom et al. (2020) found that no tool was consistently reliable across all growing environments.

Soil and weather affect soil N availability and crop N uptake through their influence on N cycling and crop growth (Tremblay et al., 2012). Soil texture and moisture affect water movement and N retention, while temperature and rainfall influence organic matter decomposition, N mineralization, and N losses (Morris et al., 2018). Across 51 North American experiments, Tremblay et al. (2012) found that N response differed with soil texture and rainfall distribution. These results support using soil measurements and seasonal weather together to explain variation in crop response to fertilizer N.

Soil fertility tests and weather observations help describe conditions that regulate N cycling, but nutrient concentrations alone provide an incomplete estimate of N supply over a growing season (Morris et al., 2018). Organic matter, microbial activity, and mineral interactions jointly regulate the release and uptake of plant-available N (Grandy et al., 2022). Soil health measurements may provide information about these processes. Active carbon, for example, measures a readily oxidizable carbon fraction used to assess soil quality (Weil et al., 2003). Its usefulness for N management depends on how well it relates to crop response under field conditions.

Previous studies tested how soil health measurements can improve N-response estimates. McDaniel et al. (2020) found that combining biological and chemical soil tests improved prediction of maize N response across 56 Midwestern site-years. Wade et al. (2020) found that biologically healthier soils produced more corn per unit of fertilizer N, but soil biological health offered limited information about a site's responsiveness to added N. An indicator associated with higher yield therefore does not necessarily imply a lower fertilizer requirement. This distinction motivates examining soil indicators separately as predictors of baseline yield and fertilizer response.

Uncertainty in a fitted response curve also creates uncertainty in its economic optimum. Palmero et al. (2026) used Bayesian inference to carry uncertainty in corn N-response parameters into distributions of optimum N rates and evaluate yield-loss risks under alternative N scenarios. A probability distribution shows both the estimated optimum and the uncertainty around it. In a hierarchical model, site-years can share information while retaining local differences. Soil and weather predictors can then explain response variation, and joint posterior draws carry parameter uncertainty through to EONR under specified prices.

The objective of this ongoing study is to quantify how soil fertility, soil health, and early-season weather relate to corn N response within a site-year and among site-years, and to estimate conditional EONR distributions. The current model was developed using 12 Missouri on-farm site-years from 2023 to 2025. This paper describes the methodology and presents N2401 as a preliminary site-year example. Broader evaluation of indicator contributions and predictive performance is ongoing.

MATERIALS AND METHODS

On-Farm Trials and Predictor Information

The analysis included 12 Missouri on-farm site-years from 2023 to 2025 in Chariton, Shelby, Ralls, Callaway, and Morgan counties (Table 1). Preplant soil measurements from the 0–6-inch depth were linked to recorded N application rates and harvest yields. N2401 was used to illustrate model-based EONR and economic calculations.

The soil indicators selected for this model were active carbon (AC), organic matter (OM), and soil-test phosphorus (P), obtained from preplant soil fertility and soil health testing on one-acre grids. Soil predictors were centered and scaled within each trial. A value of zero represented the trial mean, and one represented one within-site-year standard deviation above the mean. Farmers applied five to six N rates with at least two rates above and below their typical rate, primarily as sidedress applications (Table 1).

Farmers harvested corn using their equipment. As-applied N records and yield data were spatially aligned, screened, and summarized as area-weighted means within retained plots. Each retained plot was required to contain at least 20 yield records and one complete harvest pass within a single N treatment. Daily gridMET precipitation and reference evapotranspiration were obtained at approximately 2.5-mile resolution. Cumulative precipitation was divided by cumulative reference evapotranspiration for the period from planting to the day before the first sidedress application. This ratio was standardized among site-years to obtain the weather predictor, W. All plots within a site-year shared the same W. Soil predictors described variation among plots within each site-year, while W described differences among site-years.

Table 1. At-planting and target sidedress N rates for the 12 site-years

Site-year	County	At planting in lb N/ac	Target sidedress rates in lb N/ac
N2302	Ralls	70	Irrigation: 60, 120, 180, 240, 300; No irrigation: 0, 60, 120, 180, 240
N2303	Chariton	60	0, 30, 60, 100, 140
N2304	Callaway	60	0, 30, 60, 90, 150
N2305	Callaway	60	0, 30, 60, 90, 150
N2401	Chariton	50	0, 50, 100, 150, 200, 250
N2403	Callaway	50	0, 30, 60, 90, 120, 150
N2405	Ralls	90	0, 95, 140, 190, 240, 290
N2406	Shelby	50	0, 50, 100, 150, 200
N2407	Shelby	50	0, 50, 100, 150, 200
N2502	Chariton	80	0, 50, 75, 100, 125
N2504	Shelby	50	0, 50, 100, 150, 200
N2506	Morgan	40	0, 60, 90, 120, 150

Bayesian Hierarchical Response Model

Measured corn yield was modeled as:

$$Y_{ij} = A_{ij} + B_{ij}N_{ij} + C_jN_{ij}^2 + \varepsilon_{ij}$$

where Y_{ij} is yield in bu/ac for plot i in site-year j, and N_{ij} is the recorded trial N rate in lb N/ac divided by 100, and the term εij represents residual variation. The intercept A is the modeled yield at trial sidedress-N = 0. Other fertilizer or N inputs before sidedress may still be present. The coefficient B is the N linear response, expressed as bu/ac per 100 lb N/ac. Curvature C describes how the slope changes as N increases.

The response components A, B, and C were specified as follows, with k indexing soil indicators: AC, OM, and P:

$$A_{ij} = a_0 + u_{Aj} + \sum_k \alpha_{kj} X_{kij} + \alpha_W W_j$$

$$B_{ij} = b_0 + u_{Bj} + \sum_k \beta_{kj} X_{kij} + \beta_W W_j$$

$$C_j = -exp(c_0 + u_{Cj})$$

$$\alpha_{kj} = \alpha_k + \delta_{A,kj}$$

$$\beta_{kj} = \beta_k + \delta_{B,kj}$$

For soil indicator k, X_{kij} is its standardized value for plot i in site-year j. Site-year adjustment terms u_{Aj}, u_{Bj}, and u_{Cj} allow the response intercept, linear coefficient, and curvature to differ. Each soil coefficient is the sum of an overall association and a site-year deviation. Hierarchical priors link these deviations through shared distributions, allowing partial pooling while retaining local differences.

The weather predictor is Wj, where j indexes site-years. All plots within a site-year shared the same Wj. Weather coefficients α_W and β_W are shared across site-years. Soil coefficients α_{kj} and β_{kj} vary by site-year. Curvature is negative and common to plots within a site-year. Soil and weather modify A and B in the current specification.

For each joint posterior draw, we combined the sampled response parameters with local soil values and site-year weather to obtain a conditional yield-response curve. We then calculated EONR and economic outcomes from that curve. Repeating the calculation across joint draws retained dependence among the parameters and produced distributions summarized by medians and 95% credible intervals.

Economic Analysis

The economic comparison used corn and N prices of $4.50/bu and $0.50/lb, respectively. At an interior economic optimum, the value of the marginal yield response equals the marginal N cost. For each posterior draw, the corresponding rate in lb N/ac is:

$$R^* = 100\left(\frac{100p_N/p_Y - B}{2C}\right)$$

Here p_N is N price in $/lb and p_Y is corn price in $/bu. The factor of 100 converts the model's scaled N rate to lb N/ac. Plot-specific EONR was compared with a uniform trial N rate of 150 lb N/ac. Prices were held fixed across posterior draws.

PRELIMINARY RESULTS AND DISCUSSION

N2401 Site-Year Example

The Bayesian hierarchical model was fitted jointly to all 12 site-years. Model prediction was evaluated separately using three-fold spatial validation within site-years and three grouped site-year holdouts. N2401 is presented here as an example to illustrate variation among plots within a site-year in EONR and its potential economic implications.

Within N2401, plot-level posterior median EONRs ranged from 141 to 256 lb N/ac (Figure 1). The interpolated surface shows lower estimates in parts of the southwest and south-central parts of the field and higher estimates across much of the

northern area. These differences reflect local soil inputs under the same site-year weather and prices.

For the economic comparison, each plot's N rate was fixed at its posterior median EONR. This fixed strategy was compared with a uniform rate of 150 lb N/ac across 8,000 joint posterior draws. At corn and N prices of $4.50/bu and $0.50/lb, respectively, the mean partial-budget gain was $21.2/ac (95% credible interval: $0.04 to $42.31/ac), with a posterior probability of a positive gain of 97.55%. The calculation excluded additional variable-rate application and harvest costs.

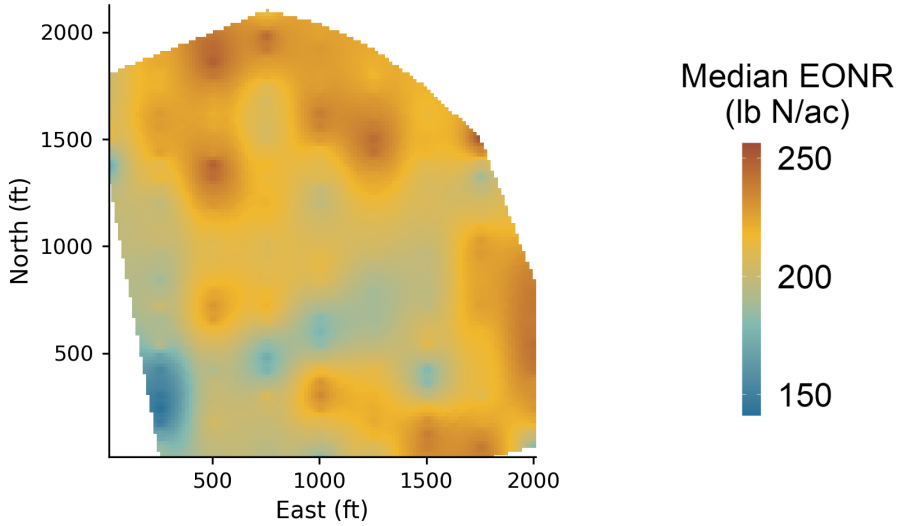


Figure 1. Interpolated posterior median EONR for N2401 at corn and N prices of $4.50/bu and $0.50/lb. The surface interpolates model estimates based on local soil inputs.

Model Assumptions and Further Evaluation

The model assumed a quadratic response with negative curvature, linear soil associations within A and B, and shared weather associations across site-years. Its EONR distributions are conditional on these assumptions and the observed inputs. In particular, weather after sidedress and future price variation are not represented in the N2401 comparison.

This is a working model in an ongoing study. Further analysis will evaluate additional indicators, check whether estimated optima are supported by the experimental N range, and compare EONR estimates with conventional regression. Evaluation across trials is needed before using the model for recommendations. The posterior draws can also support future comparisons of the probability and magnitude of yield or return changes under alternative N strategies, as illustrated by Palmero et al. (2026).

CONCLUSIONS

The Bayesian hierarchical model links soil and weather information with corn N response and carries parameter uncertainty into conditional EONR estimates. The N2401 example shows how local soil inputs produce spatially varying EONR estimates and a distribution of modeled economic outcomes. The 12 site-years support model

development. Further evaluation will determine how well these relationships predict N response and EONR in other trials.

REFERENCES

Grandy, A.S., A.B. Daly, T.M. Bowles, A.C.M. Gaudin, A. Jilling, A. Leptin, M.D. McDaniel, J. Wade, and H. Waterhouse. 2022. The nitrogen gap in soil health concepts and fertility measurements. Soil Biology and Biochemistry 175:108856. https://doi.org/10.1016/j.soilbio.2022.108856

McDaniel, M.D., D.T. Walters, L.G. Bundy, X. Li, R.A. Drijber, J.E. Sawyer, M.J. Castellano, C.A.M. Laboski, P.C. Scharf, and W.R. Horwath. 2020. Combination of biological and chemical soil tests best predict maize nitrogen response. Agronomy Journal 112:1263–1278. https://doi.org/10.1002/agj2.20129

Morris, T.F., T.S. Murrell, D.B. Beegle, J.J. Camberato, R.B. Ferguson, J. Grove, Q. Ketterings, P.M. Kyveryga, C.A.M. Laboski, J.M. McGrath, J.J. Meisinger, J. Melkonian, B.N. Moebius-Clune, E.D. Nafziger, D. Osmond, J.E. Sawyer, P.C. Scharf, W. Smith, J.T. Spargo, H.M. van Es, and H. Yang. 2018. Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. Agronomy Journal 110:1–37. https://doi.org/10.2134/agronj2017.02.0112

Palmero, F., E.A. Davidson, K. Guan, A.J. Eagle, H.E. Birgé, P.V.V. Prasad, T.J. Hefley, J.R. Schussler, and I.A. Ciampitti. 2026. Environmental and societal costs of maize production decrease by addressing the uncertainty in nitrogen rate recommendations. Nature Communications 17:2375. https://doi.org/10.1038/s41467-026-68988-y

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

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

Tremblay, N., Y.M. Bouroubi, C. Bélec, R.W. Mullen, N.R. Kitchen, W.E. Thomason, S. Ebelhar, D.B. Mengel, W.R. Raun, D.D. Francis, E.D. Vories, and I. Ortiz-Monasterio. 2012. Corn response to nitrogen is influenced by soil texture and weather. Agronomy Journal 104:1658–1671. https://doi.org/10.2134/agronj2012.0184

Wade, J., S.W. Culman, J.A.R. Logan, H. Poffenbarger, M.S. Demyan, J.H. Grove, A.P. Mallarino, J.M. McGrath, M. Ruark, and J.R. West. 2020. Improved soil biological health increases corn grain yield in N fertilized systems across the Corn Belt. Scientific Reports 10:3917. https://doi.org/10.1038/s41598-020-60987-3

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. American Journal of Alternative Agriculture 18(1):3–17. https://doi.org/10.1079/AJAA200228