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Spatial and Temporal Factors Impacting Incremental Corn Nitrogen Fertilizer Use Efficiency

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Abstract. *For corn (Zea mays L.), nitrogen (N) fertilizer use is often summarized from field to global scales using average N use efficiency (NUE). But expressing NUE as averages can be misleading because grain increase to added N diminishes near optimal yield. We use empirical datasets obtained in North America of corn grain yield response to N fertilizer (n=189) to create and interpret incremental NUE (iNUE), or the change in NUE with change in N fertilization. For those last units of N applied to reach economic optimal N rate (EONR) iNUE for N removed with the grain is only about 6%. As N fertilizer costs increase relative to grain prices, this value increases, but remains under 10% using typical modern pricing. Results also showed iNUE decrease averaged 0.63% for medium-textured soils and 0.37% for fine-textured soils, attributable to fine-textured soils being more predisposed to denitrification and/or lower mineralization. Characteristics of iNUE were also shown to vary within fields. Further analysis demonstrated the critical nature growing season water amount and distribution has on iNUE. Conditions with too much rainfall and/or uneven rainfall produced low iNUE. Producers realize this from experience, and it is uncertain weather that largely drives insurance fertilizer additions. Nitrogen fertilization creating low iNUE is environmentally challenging. Our results show that with modest sub-EONR fertilization and minor forgone profit, average NUE improvements of ~10% can be realized. Precision agriculture technologies may be the key for quantifying field and sub-field iNUE and implementing strategies for improving overall NUE.*

Keywords. *Crop Nitrogen Use Efficiency, corn, environmental nitrogen loss*

Introduction

Corn accounts for more than 40% of the global production of the six leading grain crops. Corn N budgets show global fertilizer NUE ranges between 25 and 40% (Conant et al. 2013; McLellan et al. 2018; Raun and Johnson 1999), which implies that N fertilizer application rates require two to four times more N than contained in the harvested grain. Nitrogen fertilizer rates applied to corn are typically higher than for other grains because corn yields are typically higher. Further, no autoregulation exists to deter overapplications of N in corn since excess fertilization has little or no negative impact on crop performance, as can occur with other crops (e.g., lodging in wheat (*Triticum aestivum* L.)). The only major disincentive to corn producers for over applying N fertilizer is economical as related to N fertilizer costs.

Expressing NUE as an average over-simplifies the relationship between N rate and NUE. The reality is each additional unit of N fertilizer induces a smaller and smaller yield response and at some point, environmental risks may exceed economic benefits. In this analysis we expand on the previously introduced idea of iNUE (A. Dobermann and Cassman 2005; A. R. Dobermann 2005). Incremental NUE means to express NUE over small increments of N fertilizer. The objective of this investigation was to: 1) quantify iNUE over typical fertilization rates; and 2) relate iNUE to agronomic, edaphic, and weather factors.

Materials and Methods

Three corn N response datasets were used for this analysis (Table 1). Combined, this dataset provided 189 site-years of corn N quadratic-plateau response curves from varying soil spatial scales (i.e., regional responses throughout North America to multiple within field responses), temporal climates, corn hybrids, and management practices.

Table 1. Summary information of the three datasets used in this analysis.

Study	Summary	Years	Site-years used in analysis	Crop Rotation	Time of N application	N Source	Citation
North America (NA)	Study from Mexico to Canada	2006 to 2010	28	All but a few were corn following soybean	V4 to V10	Urea based fertilizer	(Tremblay et al. 2012)
Nebraska (NE)	Continuous plot research with fixed rotation	1991 to 2004	75	39 site-years were corn following corn, and the rest were corn following soybean	V9	Urea-ammonium nitrate	(Varvel et al. 2007)
Missouri (MO)	Study measuring within field variability	2004 to 2007	86	All but a few were corn following soybean	V7 to V11	Urea-ammonium nitrate + Agrotain	(Kitchen et al. 2010)

Determining the economic optimally N rates

For each site-year of data, the grain yield in response to fertilizer rates was calculated using a quadratic-plateau modeling method. For site-years to be included in the analysis, the quadratic-plateau model had to meet several criteria. First, the *F*-test needed to be significant ($\alpha = 0.10$). Second, the quadratic-plateau model had to have r^2 values ≥ 0.30. Third, the joint point for the plateau had to occur at N rates lower than the highest N rate applied for that site. For sites that meet these criteria, the EONR values were calculated using the first derivative of the quadratic-plateau model:

$$\mathbf{EONR} = \frac{\mathbf{ratio - b}}{\mathbf{2a}} \tag{1}$$

Where a [in (kg grain * ha) (kg N^2)$^{-1}$] and b [in (kg grain) (kg N)$^{-1}$] were the quadratic and linear coefficients, respectively. The ratio was fixed at 5.6 and derived using the cost of N fertilizer ($0.88 kg N^{-1}; or $0.40 lb N^{-1}) divided by the price of corn ($0.158 kg grain^{-1}; or $4.00 bu grain^{-1}).

Calculating incremental N use efficiency and related metrics

For each site-year, two N use efficiency (NUE) values were calculated: an incremental NUE (iNUE) and an average NUE. Both values were based on the ratio of grain-N removal to applied fertilizer (kg grain N) (kg N)$^{-1}$. The grain-N removed was calculated as the crop yield (kg ha^{-1}) multiplied by a fixed grain N content of 0.0115 (kg grain N) (kg grain)$^{-1}$. We used the grain N content coefficient that was reported by (Tenorio et al. 2019) which were the average values measured across the US North Central region.

The iNUE, or the rate of increase in NUE for each unit of fertilizer applied, was calculated using the first derivative of the quadratic-plateau model as shown in equation 2 for each 1 kg N ha^{-1} increment from 0 kg N ha^{-1} to EONR.

$$\mathbf{Incremental\ NUE} = \frac{(\mathbf{b} \times \mathbf{0.0115}) + (\mathbf{2} \times \mathbf{a} \times \mathbf{0.0115} \times \mathbf{Nrate})}{\mathbf{1\ kg\ N\ ha^{-1}}} \tag{2}$$

The average NUE values were calculated as the increase in grain-N over corn that received no fertilizer per unit of fertilizer applied:

$$\mathbf{NUE} = \frac{\mathbf{Grain\ N_{Nrate} - Grain\ N_0}}{\mathbf{Nrate}} \tag{3}$$

where $GrainN_{Nrate\ and}$ $GrainN_{N0}$ were the predicted grain N (kg grain N ha^{-1}) for each of the N rates between 0 and EONR.

Calculating forgone profit relative to EONR

A partial profit was calculated using the total profit ($0.158 kg grain^{-1}) minus the cost of N ($0.88 kg N^{-1}) for each N rate from 0 kg N ha^{-1} to EONR. For each N rate, forgone profit was calculated by dividing the partial profit at each N rate by the partial profit at EONR.

Predicting incremental NUE with soil and weather factors

For predicting the rate of decrease for iNUE with added N fertilizer, the slope term of each site-year was classified as either “High” or “Low” based on the overall all-site median value of 0.608. For all models the slopes were predicted as a function of weather and soil information. Weather and soil information were collected from publicly available datasets using Daymet [1 km gridded weather; via the ‘daymetr’ r package] and NRCS SSURGO [via the ‘soilDB’ r package]. For each unique site-year, the daily minimum and maximum daily temperature (°C) and daily precipitation (mm) were downloaded from April 15th to September 15th. Using the daily temperature and precipitation values, additional features were derived as described by (Tenorio et al. 2019)that included the total precipitation, a Shannon Diversity Index [SDI; a measurement of evenness], an abundant and well distributed rainfall (AWDR), corn heat units (CHU), and growing degree days (GDD; base of 10 °C). These features were calculated for three additional crop growing season time periods: the establishment phase (April 15 - June 1), growth phase (June 2 - July 15), and grain filling phase (July 16 - September 15). Soil variables for each site-year included texture (percent sand and clay) to a depth of 30 cm, texture classification, drainage class (6 different classification ranging from poor to well drained), and taxonomic order. In addition, site management variables were also included such as irrigation (“yes” or “no”), tillage (“yes” or “no”), and crop rotation (“continuous corn”, or “corn-soybean”).

We trained the models on 60% of the data (n = 113) (randomly selected) and validated the models on the remaining 40% (n = 75). One site-year (from Mexico) was excluded because the soil information was inaccessible. Training the models included tunning the hyperparameters (parameters used to optimize learning) using a 10-fold cross validation repeated five times. Where the dataset was randomly divided into 10 equal sized folds. Using nine of the ten folds, multiple models were trained using each possible hyperparameter and then tested on the tenth fold. This was repeated until every fold was used as a testing fold. The process was further repeated five more times—each time the data was randomly divided into ten new folds—until there were 50 testing folds. Optimal hyperparameter values were selected based on the highest average accuracy across all 50 testing folds. The accuracy of the models was determined based on the number of correct predictions divided by the total number of observations. For the random forest model, we used the ‘randomforest’ and ‘caret’ packages with the R statistical software to tune the number of variables considered at each split. The most important variables were determined using the mean decrease in the Gini index.

To provide an example of how these variables could predict the slope terms, a recursive partitioning decision tree was fit in the same manner as the random forest (i.e., same training dataset, random seed, and variables) using the “rpart” and “mlr” packages. The hyperparameters optimized for this model included the complexity parameter (determines how much improvement to accuracy is required to keep a split), the minimum number of observations required to attempt additional splits, the minimum number of observations allowed in each terminal node, and the maximum depth of the tree. The accuracy of the trained and tunned models was tested using the validation dataset. The accuracy was again calculated as the number of correct predictions divided by the total number of observations.

Results

Insights examining EONR and iNUE

Economic optimal N rate occurs when marginal profit equals zero. At this fertilization rate the increased return from grain sales equals the increased fertilizer cost. On average, EONR was 132, 104, and 147 kg ha^{-1} for the North America (NA), Nebraska (NE) and Missouri (MO) datasets, respectively (weighted mean = 127 kg ha^{-1}; Fig. 1A). EONR values of these datasets were comparable others (Wang et al. 2014).

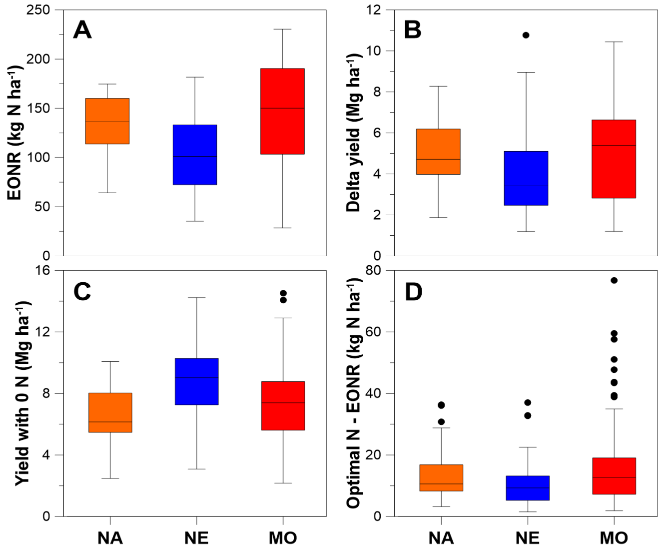

Fig 1. Maize productivity is highly dependent on nitrogen fertilization. Contrasted across the three datasets: (A) EONR, (B) yield increase or delta yield from EONR fertilization, (C) yield without nitrogen fertilization, and (D) the difference between optimal nitrogen rate and EONR. Box limits indicate the first and third quartile, whiskers indicate 1.5 times the interquartile range, points indicate outliers, and box line is the median.

Utilizing EONR values obtained from quadratic-plateau relationships for these three datasets, iNUE was calculated and graphed as a function of N rates (Fig. 2, A-C) with each site-year shown as an individual line on the graphs. Features amongst these site-year lines are quite variable, yet they have both agronomic and environmental meaning. When the amount of N applied was near 0 (e.g., ~1 kg ha^{-1} since undefined at 0) iNUE for that site-year was highest. Average iNUE from the first unit of fertilization was 82%, 85%, and 79% for the NA, NE, and MO datasets, respectively (weighted mean = 82%). These values show that even when a minor amount of N fertilizer is applied, typically an amount well-under N needed for optimal corn growth, an average of ~18% will be unrecovered in the harvested grain for that growing season. Many site-years had initial iNUE exceeding 100%. These represent conditions where initial amounts of fertilization stimulated N availability from organic sources through mineralization, a well-known priming-effect (Jenkinson et al. 1985). In contrast, some site-years had initial iNUE values below 40%. We presume initial low iNUE are the result excessive rainfall during the growing season causing significant fertilizer N loss (e.g., denitrification, leaching), high amounts of residual mineral N prior to fertilization, and/or other yield-limiting factors creating crop stress (e.g., pest, other nutrient deficiencies) suppressing yield response to N.

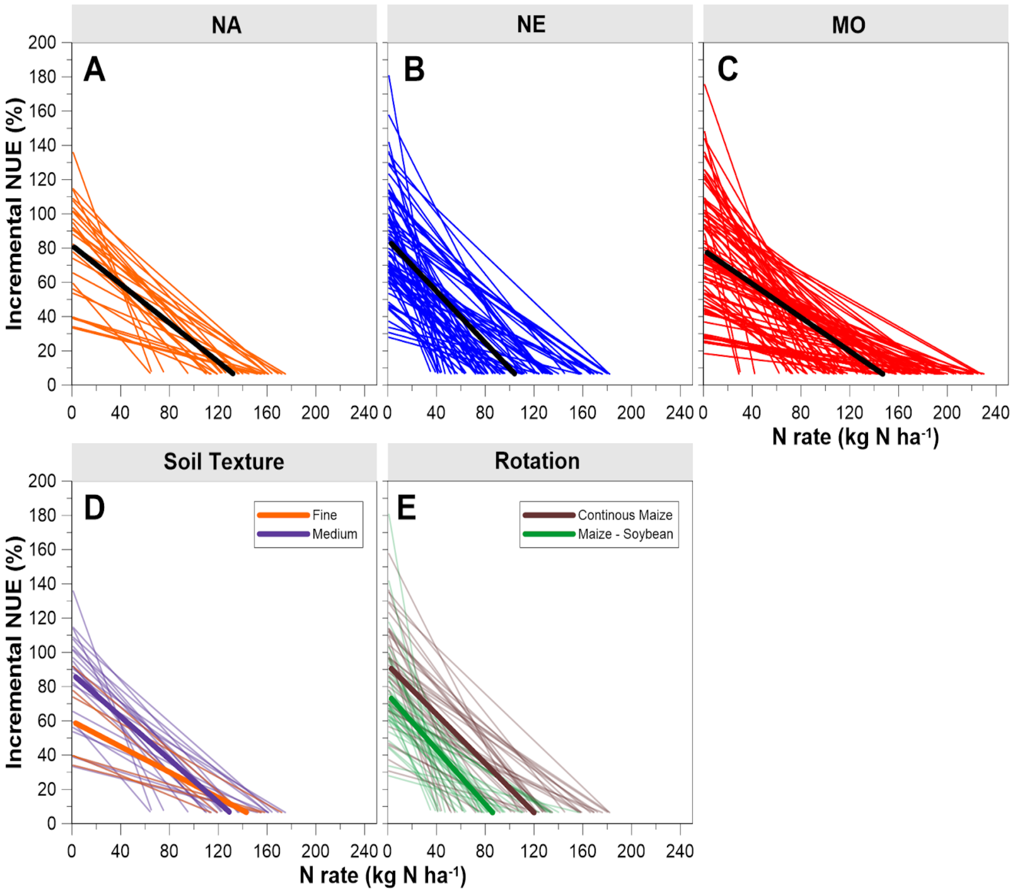

Fig. 2. For maize, iNUE relative to increasing nitrogen fertilizer rate is not static. (A-C) iNUE shown for three datasets. (D) For the NA dataset, iNUE at low nitrogen rates was higher for medium-textured vs fine-textured soils. (E) For the NE dataset, iNUE was higher for continuous maize compared to maize rotated with soybean. With each graph, a line represents one site-year. The black and solid colored lines indicate the best-fit linear lines.

Relative to increasing N rate, each line (Fig. 2, A-C) ends at each site-year's respective EONR value. Further, each line ends at an iNUE value of 6.4%, a value set by the fixed corn and fertilizer prices used for determining EONR. Adjusting typical prices has a nominal impact on this ending iNUE value. For example, adjusting the price of N fertilizer 40% less than that used here (but keeping corn price the same) would alter the ending iNUE to 3.8%. If N prices were 40% more, then the ending iNUE would be 9.0%. Since in the recent decade fertilizer N prices often track corn grain prices, the ratio of corn to grain prices remains relatively constant, and for our analysis, the 6.4% value would be typical for US corn production. This demonstrates how low iNUE is when full fertilization is at EONR and at common corn and fertilizer prices. Stated differently, for those last few kg of N fertilizer applied to reach EONR in corn, the equivalent of less than 10% of added N would be removed in the grain. Conversely, over 90% was either lost to the environment during the growing season, remains in the soil as inorganic N subject to environmental loss without intervention, or has been captured within corn stover and roots or soil organic matter pools.

Initial iNUE and EONR define the line that represents the decrease in iNUE with fertilization. For each of the three datasets, using the average initial iNUE and average EONR provides an average rate of decrease in iNUE for each additional kg of N applied of 0.57, 0.75, and 0.49% for NA, NE, and MO, respectively. Soil, weather, and management practices that produce crop N responses with higher initial iNUE (e.g., >80%) and relative lower EONR (e.g., < 100 kg ha^{-1}) are scenarios where a greater percentage of fertilizer N is captured into the harvested grain. In contrast, low initial iNUE tended to have higher EONR, and therefore lower rates of decrease in iNUE. These scenarios cause overall low NUE and knowing causal factors for such would be helpful in targeting management practices and public policy.

Importantly, the interpretation for these varying rates of decrease in iNUE is that NUE is not a static concept, though typically presented as such. Declining iNUE with fertilization stems from increased transformation and/or loss opportunities with higher concentrations of reactive soil N.

iNUE by soil texture and crop rotation

Corn response to N fertilizer and environmental loss depends on soil properties (including soil N supply and water storage), management, and weather factors (Bullock and Bullock 1994a; Cambouris et al. 2016; McLellan et al. 2018). How these factors influence iNUE is illustrated with two examples using these same datasets. Within the NA dataset, soils as previously classified were found to have an average initial iNUE of 88% for medium-textured soils (n=22) and 60% for fine-textured soils (n=6) (Fig. 2D). Only sites with medium-textured soils resulted in initial iNUE greater than 95%. Incremental NUE decrease averaged 0.63% for medium-textured soils and 0.37% for fine-textured soils. Average EONR was 116 and 140 kg N ha^{-1} for medium- and fine-textured soils, respectively. This demonstrates that with fine-textured soils, a greater equivalent portion of fertilization near EONR is unrecovered in the grain. As explained in previous work (Cambouris et al. 2016; Tremblay et al. 2012), fine-textured soils are those with higher clay content and consequently, more predisposed to denitrification losses and/or lower mineralization. Furthermore, drainage with these soils is often poor, causing an anaerobic condition which leads to stunted early-season root development that limits late-season water uptake31. We attribute these as reasons iNUE differed by soil texture.

The second example contrasts corn response to N fertilization with two common crop rotations that include corn: continuous corn and corn rotated with soybean (*Glycine max*; Fig. 2E). Using the NE dataset, continuous corn averaged 93% for initial iNUE, 0.72% for iNUE decrease with fertilization and 120 kg ha^{-1} for EONR. These same metrics for corn in rotation with soybean were 76%, 0.80%, and 86 kg ha^{-1}. respectively. When soybean is included in a crop rotation with corn, multiple benefits have been found, including N fixation, net soil mineralization, improved conditions for seed germination, diversified microorganism community, disrupted disease cycles, and increased pest resistance (Gentry et al. 2013). Here, including soybean in the rotation translated into lower EONR and greater rates of decrease in iNUE (i.e., more efficient system). Additionally, when evaluating long-term impacts of N fertilization on NUE over many growing seasons, it is notable that fields with a corn-soybean rotation receive N fertilization half the time.

iNUE Decrease Related To Soil and Weather

The combined three datasets were further examined using decision tree analysis for how the decrease in iNUE was influenced by soil and weather factors (Fig. 3). Two quadratic response models provide examples to contrast how corn N responses differ at the same location over two years, even under irrigation (Fig. 3A). Characteristics of a response curve vary spatially and temporally based on the soil properties, weather conditions, management practices, and crop genotypes. Response model terms (Fig. 3B) are not only related to each other, but also can be used to understand causal relationships of multiple weather and soil factors to iNUE decrease (Fig. 3C). Precipitation factors dominated in importance (blue), but soil (brown) and temperature (red) factors also helped explain iNUE decrease. For this analysis, management information availability was minimal, and therefore contributed little. The example decision tree (Fig. 3D) demonstrates the critical nature water amount and distribution have on iNUE decrease. Conditions with too much rainfall and/or uneven rainfall produced a “Low” decrease in iNUE. Producers realize this from experience, and it is uncertain weather that largely drives adding extra N fertilizer as insurance (A. Dobermann and Cassman 2005). Since the forecasted weather trends for the US Midwest are for greater annual precipitation, more of the annual total in the spring, and more variable summer rainfall (Hayhoe et al. 2018), improved weather forecasting offers one of the best options for improving N management and subsequently improving NUE. Doing so will require producers embrace more adaptive practices.

Profit relative to iNUE

EONR is characterized by low iNUE. There is no forgone profit from N rate decisions when fertilization is at EONR and iNUE is 6.4%. Forgone profit increases exponentially as iNUE increases. For these datasets iNUE relative to forgone profit were determined (data not included). The most significant change in iNUE is with the first \$20 ha^{-1} (\$8.10 ac^{-1}) step of forgone profit, with iNUE increasing by 14.3 percentage points, from 6.4% to 20.7% (weighted mean). The interpretation of this is that minor sub-EONR fertilization eliminates the lowest iNUE values for the smallest forgone profit; further deviation from EONR eliminates less iNUE for the same amount of forgone profit. On average, forgone profit of \$20 ha^{-1} from sub-EONR fertilization effectively excludes all iNUE values from 6.4% up to 20.7%.

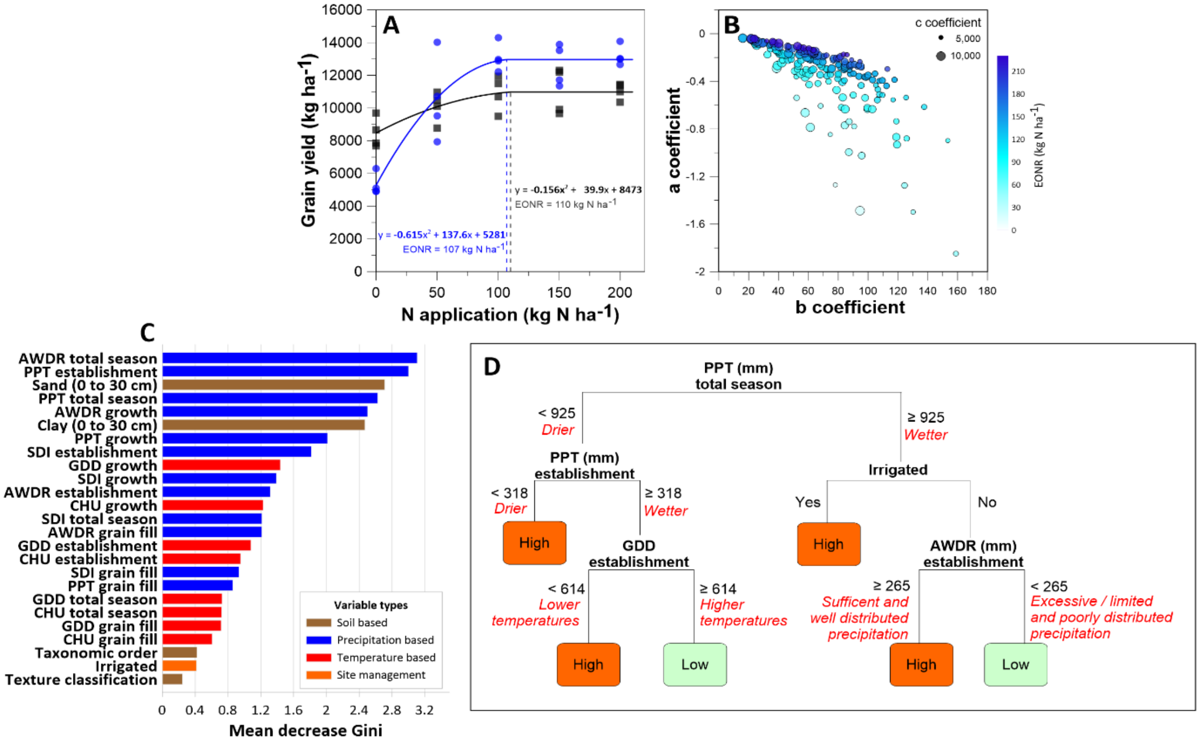

Fig. 3. Parameters of the quadratic response model are valuable for explaining weather and soil influence on iNUE. (A) Two examples from the same site (NE dataset) of maize yield response to nitrogen fertilization (black squares = 1999, blue circles = 2000). For both, the quadratic-plateau model fits the measured yield response well, yet differently; they have similar EONR values but different quadratic-plateau model coefficients. (B) Bubble plot of all three datasets combined showing the relationships between the quadratic-plateau model terms (a, b, and c) and EONR. Low values for "a" coincide with low values for "b" (r^2=0.46); and low values for "a" are related to high EONR (r^2=0.50). (C) The response model terms are valuable for understanding causal relationships of weather, soil, and management to iNUE. Using a random forest model, important weather and soil variables were identified that predict the rate of iNUE decrease (i.e., slope coefficients), classed as "High" or "Low" based on the median value of -0.608. Weather variables were calculated across different time periods: total season (April 15-September 15), emergence (April 15-June 1), growth (June 2-July 15), and grain fill (July 16-September 15). (D) An example of decision tree predicting slopes (68% accuracy on a withheld testing portion of the data) as "High" or "Low" using weather information, which included the PPT (cumulative precipitation) during establishment and for the entire season, GDD (growing degree days) during establishment, and AWDR (abundant and well distributed rainfall) during establishment.

How does removing low iNUE values change the average NUE [i.e., average NUE = [(grain Nx – grain N0)/x; x=N rate)]? Using the same foregone profit steps, distributions of average NUE was 44, 45, and 43% for NA, NE, and MO datasets, respectively, with an overall mean average of 44%. Average NUE increased to 50, 53, and 49% (weighted mean = 51%) with only \$20 ha^{-1} foregone profit, illustrating the impact of low iNUE values near EONR on overall average NUE.

Conclusions

We found that examining NUE incrementally helps expose the need for exploring more sustainable N fertilizer practices. Nitrogen management includes many interdependent choices (e.g., crop rotation, genetics, and fertilizer timing, source, placement, stabilizers), but when considering environmental implications, the choice of fertilizer amount is typically most impactful since the standard of supporting decision tools is to apply at EONR (Bullock and Bullock 1994b). The iNUE analysis provided shows that fertilization at EONR amounts is problematic environmentally, but also creates a unique perspective for influencing change.

Is EONR the right target for N fertilizer rate management? While held as the standard for decades, it ignores low iNUE, as illustrated. Yet, current N rate decision tools built upon economics as the standard could easily be modified to embrace environmental objectives. Corn producers are generally risk adverse, unlikely to embrace foregone profit from sub-EONR applications without compensatory incentives. Since all society would be beneficiaries of improved crop NUE, we encourage support of the development and enhancement of N decision support tools that allow consideration of incentive payments offered to producers to match anticipated foregone profit from sub-EONR applications. These tools should embrace adaptive N management practices that response to weather factors, respond to site-specific soil conditions, integrate weather and soil dynamics relative to crop N availability, and on a platform that is friendly to end users (Basso et al. 2009). Also, decision aids developed for producers for making fertilizer recommendations should incorporate anticipated iNUE. Utilizing precision agriculture technologies can greatly facilitate these tools, particularly using precision fertilization controllers along with combine yield-monitoring systems to help establish ENOR or even sub-EONR fertilization by field or farm.

As shown, influences of weather, soil, and management factors can easily be characterized within iNUE, giving site-specific sensitivity that N management requires. Such promotes efficiencies to be gained by utilizing newer technologies through precision agriculture (Finger et al. 2019; Martinez-Feria and Basso 2020; Stuart et al. 2014).

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