EFFECTS OF SOIL PHOSPHORUS AND POTASSIUM LEVELS ON CORN YIELD RESPONSE TO NITROGEN FERTILIZATION, NITROGEN USE EFFICIENCY, AND PROFITABILITY

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ABSTRACT

Annual investment in nitrogen (N) fertilizer for corn production represents a significant portion of annual input costs. Yield response to N fertilization is affected by soil N supply, crop N demand, and interacting factors that affect crop N use, such as phosphorus (P) and potassium (K) supply. To investigate the effects of soil-test P and K levels on corn yield response to N fertilizer, a four-year study was conducted at two southern Wisconsin sites. Soil-test P and K were maintained at low, optimum, and high levels corresponding with currently used interpretation class ranges for fertilizer guidelines in Wisconsin. Ranges of low, optimum, and high soil-test (Bray-1 P) levels for P were 6 to 17, 16 to 27, and 31 to 51 ppm P, respectively, across both sites. Ranges of low, optimum, and high soil-test (Mehlich-3 K) levels for K were 50 to 104, 120 to 173, and 164 to 262 ppm K, respectively, across both sites. Six N rates (0, 40, 80, 120, 160, and 200 lb. N/a) were applied to each corn crop in a corn-soybean rotation. Agronomic optimum N rate (AONR), economic return to N (RTN), economic optimum N rate (EONR), and partial factor productivity nitrogen use efficiency (NUE) were identified using grain yield response to N and multiple N:grain price ratios ($ lb N and $ bu corn grain). Corn yield response to N fertilization varied by soil-test P and K level. In optimum and high soil-test P and K soils, corn grain yield increased to a plateau with increasing N rates and an EONR (0.1 ratio) of 130 lb N/a was observed across all site-years, with no difference in AONR or yield at the AONR (240 to 242 bu/a) between optimum and high levels. Low soil-test P and K led to inconsistent yield responses to N and reduced profitability regardless of N rate. Results suggest that optimum ranges of soil-test P and K, confirmed with identification of critical soil-test concentrations in this study, of 16 to 23 ppm Bray-1 P and 138 to 182 ppm Mehlich-3 K resulted in maximized corn grain yield and profitability response to N fertilization.

INTRODUCTION

Annual investment in nitrogen (N) fertilizer for corn (Zea Mays) grain systems represents a significant portion of annual input costs. Yield response to N fertilization is affected by soil N supply, crop N demand, and interacting factors that affect crop N use, such as phosphorus (P) and potassium (K) supply. Decades of research has addressed N, P, and K management for corn individually, but published information on the interaction of these nutrients is scarce. Schlegel and Havlin (2017) showed positive effect of N and P interaction on corn grain yield and fertilizer N recovery in a 50-year study in Western Kansas. Hirniak and Mallarino (2017) identified positive interactions of

N and K fertilization on corn yield in continuous corn rotations in Iowa. Other Iowa work showed significant interactions of N and K on corn yield, but no interactions among other nutrients (Mallarino and Rueber, 2003). Research summaries or reviews highlight the importance of macronutrient interactions, and suggest that N uptake and use requires adequate P and K supply (Dibb and Thompson, 1985; Usherwood and Segars, 2001). Many studies investigating N, P, or K interactions focus on applied fertilizer rates as experimental variables or treatments. Rarely are soil-test levels of P and/or K used as treatment levels. To align nutrient interaction research with assessments of soil-test interpretation classes (Low, Optimum, or High), target soil-test ranges must be maintained as treatment levels with N fertilization then randomized in a factorial design.

Recent pressure from either high or volatile fertilizer prices has posed questions regarding priority of macronutrients for corn production and if fertilization of nutrients such as P and K can be avoided. Alternatively, discussions of nutrient interactions can lead to ideas that higher P and K testing soils will require high N fertilization rates, or vice versa, with little data supporting this approach. Regardless, if yield or profitability is the metric used to assess nutrient management and fertilization planning, clear relationships between soil-test P and K levels and corn yield response to N fertilization would inform on-farm decisions.

Therefore, the objectives of this study were to: (1) determine and compare the economically optimum N rate, nitrogen use efficiency, and partial profit for corn at varying soil-test P and K levels, and (2) corroborate critical soil-test P and K concentrations with optimum levels for corn N response and examine crop removal of macronutrients in grain.

MATERIALS AND METHODS

Two field experiments with corn-soybean rotations harvested for grain were conducted from 2019 to 2022. Selected soil information and properties for each site is shown in Table 1. One site was located at the Arlington Agricultural Research Station near Arlington, Wisconsin in Columbia County on a Plano silt loam soil (fine-silty, mixed, superactive, mesic Typic Argiudolls). The second site was located at the Lancaster Agricultural Research Station near Lancaster, Wisconsin in Grant County on a Fayette silt loam soil (fine-silty, mixed, superactive, mesic Typic Hapludalfs). Each site was managed with chisel-plow/disk tillage and a 30-inch row spacing. Treatments replicated four times at both sites were the factorial combinations of three maintained soil-test P and K levels (Low, Optimum, and High; see Table 1) and six N rates applied to corn (0, 40, 80, 120, 160, and 200 lb N/a). Treatments and replications were arranged as a randomized complete block (RCBD) design. Phosphorus and potassium fertilizer were broadcast applied and incorporated as triple super phosphate (0-46-0) and potassium chloride (0-0-60), respectively, in the fall after harvest and soil sampling to maintain specific soil-test ranges (Table 1). Initial soil-test values for P and K at each site are also shown in Table 1. Nitrogen fertilizer was applied as urea treated with a urease inhibitor (NBPT) in spring and incorporated prior to corn planting.

Each year soil samples were collected (6-inch depth) and analyzed for pH (1:1 ratio of soil to deionized water), soil organic matter (loss on ignition), for P by the Bray-1 test, and for K by the Mehlich-3 test following the procedures suggested by the NCERA-13 north-central region soil testing committee (Frank et al., 1998). Beginning in 2021, soil samples were collected after corn harvest to a depth of 0 to 3-feet and analyzed for nitrate. Nitrate-N was determined from 0.2M KCl extracts and analyzed using the Cadmium 40 reduction method (Gelderman and Beegle, 1998) with a modified Technicon Auto-Analyzer (SEAL Analytical, Inc., Fareham, UK). Grain yield was collected and adjusted to 15.5% moisture. Grain samples were collected from each plot and analyzed for P and K concentration using (Zarcinas et al., 1987). Grain removal of nutrients with harvest was calculated by using the measured nutrient concentration multiplied by the plot-level grain yield and adjusted for consistent moisture.

Corn grain yield response to N fertilizer rate for each soil-test P and K level was evaluated with a segmented polynomial quadratic-plateau model for all site-years combined using PROC NLIN in SAS ODA (SAS Institute, Cary, NC). The agronomic optimum N rate (AONR) was identified as the joint point where the quadratic and plateau portions of the model joins and where no statistical difference between treatments above the model joint point were observed. Economic optimum N rates (EONR) were identified by setting the first derivative of the response model to an N ($/ lb. N fertilizer) to corn price ($/ bushel) ratio of 0.05, 0.1, 0.15, and 0.2 and solving for N rate. Additionally, EONR was calculated when considering the added price of P and K fertilizer to maintain the optimum and high soil-test levels. Static P and K fertilizer prices of \$0.85/ lb. P_2O_5 and \$0.55/ lb. K_2O, respectively, were used, in addition to the yield increases over the low soil-test category, to calculate partial profit or maximum return to N, P, and K fertilizer.

Relative corn grain yield was calculated for each site-year-treatment by expressing the mean yield (across replication) without fertilization as the percentage of the mean yield of treatments produced by the statistically maximum yield (the mean of all treatments, including the control, was used as maximum yield when there was no P or K response). Each relative yield value was calculated for every N rate and is expressed as such to avoid distortion of the relative yield term. This method of relative yield determination is termed “STATMAX” (Pearce et al., 2022). Critical soil-test P and K concentration ranges were identified by the range of linear-plateau and quadratic-plateau model joint points (Jones et al, 2022, Clover and Mallarino, 2013). All statistical analysis, response model fits, and critical concentration identification was done in SAS ODA (SAS Institute, Cary, NC).

Target soil-test P and K level ranges to maintain throughout the study roughly relate to soil-test interpretation classes from University of Wisconsin-Madison Recommendations (Laboski and Peters, 2012). Low, Optimum, and High designations shown in Table 1 relate to the Very Low to Low, Optimum, and High classes of Laboski and Peters (2012). After study initiation, STP for the Low, Optimum, and High categories was maintained at 6 to 11, 16 to 23, and 31 to 42 ppm Bray-1 P, respectively, at Arlington; and 6 to 17, 18 to 27, and 34 to 51 ppm Bray-1 P, respectively, at Lancaster. Soil-test K for the Low, Optimum, and High levels was maintained at 50 to 90, 120 to 160, and 164 to 236 ppm Mehlich-3 K, respectively, at Arlington; and at 80 to 104, 143 to 173, and 182 to 262 ppm Mehlich-3 K, respectively, at Lancaster. These Optimum ranges are similar to the critical STP and STK concentrations for the Bray-1 and Mehlich-3 tests, respectively, reported by Jones et al. (2022) on similar soils.

RESULTS AND DISCUSSION

Corn Yield Response to Nitrogen and Soil-test Level

The relationship between corn grain yield and N rate for each soil-test level for all site-years combined is shown in Figure 1. For the Low, Optimum, and High soil-test levels, corn yield ranged from 154 to 236, 189 to 263, and 178 to 259 bu/a across all N rates. Nitrogen rated affected corn yield each site-year of the study when soil-test levels were Optimum and High ($p \le 0.05$), and inconsistently affected corn yield when soil-test levels were Low. The only significant ($p \le 0.05$) effect of N rate on corn yield for the Low soil-test level was in 2021 at Arlington between zero and 200 lb. N/a rates (not shown). Orthogonal comparisons between the zero N rate and all other rates indicated an N fertilization effect across all site-years, thus the AONR was set to the lowest experimental N rate, 40 lb. N/a (Fig. 1). Corn yield increased incrementally to a plateau with higher N rates when soil-test levels were both Optimum and High. Across all site-years, the AONR and yield at AONR (YAONR) were 188 lb. N/a and 240 bu/a for Optimum soil-test level, and 164 lb. N/a and 242 bu/a when soil-test P and K were High (Fig. 1). The 95% confidence intervals for each ANOR are shown in Fig. 1 and were calculated using a bootstrapping approach. Practically, the AONR and YAONR for both Optimum and High soil-test levels do not differ if using the 95% confidence intervals to differentiate, however the AONR at Optimum soil-test levels was 24 lb. N/a lower. The lower AONR for Optimum may also be a result of lower corn yield levels at lower N rates in the High soil-test level compared to Optimum (Fig. 1). The relative yield increase with added N fertilizer was greater at High soil-test levels, as seen by the larger quadratic coefficient of the quadratic-plateau response model function seen in Figure 1. Across site-years and at each N rate, corn yield for the Optimum and High soil-test level did no differ and were always greater than the Low soil-test levels. At 0, 40, 80, 120, 160, and 200 lb. N/a rates, the corn yield mean of Optimum and High level was 29, 47, 48, 59, 58, and 48 bu/a greater than if the soil-test P and K were in the Low range.

Soybean grain yield within the corn-soybean rotation of this study is not shown. Across site-years, no significant effect of the N rate applied to the previous corn crop on soybean grain yield was observed ($p \le 0.05$). Soil-test P and K level did affect soybean yield, with Low, Optimum, and High levels resulting in 61, 75, and 77 bu/a yield, respectively. Soybean yields at Optimum and High levels did not differ across the study and were significantly greater than yields at Low levels every site-year (not shown).

Economic Optimum N Rates and Partial Profit

Figure 3 shows the economic return to N fertilizer and N, P, and K fertilizer at four different price ratios of N fertilizer to corn grain for all soil-test levels. No return to NPK fertilization is shown for the Low testing range. Economic return to fertilization lines are calculated using the quadratic-plateau yield response function and applying the price scenarios for N, P, and K. Return to fertilization increased to a maximum economic return value, which corresponded with an N rate, the EONR (Fig. 3). Figures 3a to 3c show only the return to N fertilization for each soil-test level. When the price of N fertilizer and corn grain was considered, no N rate produced a profitable return to fertilizer N for the Low testing category (Fig. 3a). The EONR for the 0.05, 0.1, 0.15, and 0.2 price ratios for Optimum testing P and K soils was 157, 130, 101, and 72 lb. N/a with maximum return to N values of 160, 88, 44, and 18 $/a, respectively (Fig. 3b). For High testing P and K soils, the maximum return to N occurred at 146, 129, 112, and 95 lb. N/a rates (Fig. 3c). Similar to the yield response results, the higher economic return to N for High testing soils is a function of the lower yielding zero N rate compared to the Optimum level. At the 0.1 price ratio, $0.6/ lb. N and $6/bu corn, the EONR values for the Optimum and High soil-test P and K levels were similar (130 and 129 lb. N/a), though the return to N was greater if soil-tests were High.

Figures 3d and 3e show the economic return to N fertilizer and the P and K fertilizer needed to maintain either Optimum or High soil-test ranges. Phosphorus and K fertilizer prices were held static and the four aforementioned N fertilizer and corn grain price scenarios are shown. When taking P and K fertilizer into consideration, economic returns were higher for the Optimum level for each price ratio scenario. The EONR for the 0.05, 0.1, 0.15, and 0.2 price ratios for Optimum testing P and K soils was 147, 120, 91, and 62 lb. N/a with maximum return to N values of 278, 171, 104, and 53 $/a, respectively (Fig. 3d). At the 0.1 price ratio, maintaining Optimum soil-test P and K levels led to a $32/a greater return to fertilization and a 3 lb./N lower EONR compared to High soil-test levels (Fig 3d, 3e). Overall, the increased price of maintaining High soil-test levels reduces partial profit while using similar or more N fertilizer compared to targeted Optimum soil-test P and K ranges. This supports the approach of monitoring soil-test levels so that avoiding applying unneeded P or K fertilizer to high testing soils, and optimizing a response to N, can be accomplished.

Nitrogen Use Efficiency and Residual Soil N

Nitrogen use efficiency (NUE) is expressed as the ratio of bushels of corn grain to pounds of N applied (as fertilizer), thus the units of NUE in this paper are bu/lb. N. As expected, across soil-test levels as N rate increased NUE decreased. Low soil-test P and K levels led to lower NUE at each N rate; however, there was no difference in NUE between Optimum and High levels (Fig. 2a). At the 0.1 price ratio EONR for both Optimum and High soil-test levels (130 lb. N/a), the NUE would be 1.1 bu/ lb. N or 0.90 lb. N per bushel of corn grain. Results of post-harvest residual soil N (RSN) samples analyzed for nitrate, expressed at NO_3-N, are shown in Figure 2b. Residual soil N for 3-

foot depths are shown for each soil-test level and N rate. Two-way segmented linear models fit to the data showed change in RSN for N rates of zero to 80 lb. N/a (Fig. 2b). For the 120 lb. N/a and higher N rates, the Low soil-test level had higher RSN compared to the Optimum and High levels. Maintaining a Low soil-test P and K level led to a mean RSN 21 lb NO_3-N/a higher than Optimum or High for N rates of 120, 160, and 200 lb. N/a. At the 0.1 price ratio EONR, RSN was 32 lb. NO_3-N/a for Optimum or High levels, compared to 48 lb. NO_3-N/a for Low soil-test levels. Overall, with increasing N rates, NUE was lower and RSN higher for Low testing P and K soils and generally did not differ for Optimum or High soil-test levels.

Critical Soil-test Concentrations and Removal

As a *post hoc* assessment of corn grain yield at the three maintained soil-test levels, critical soil-test concentrations were identified for corn using all site-years. Important to note is that relative yield was calculated individually for each N rate so that this evaluation could be done. Figure 4 shows the relationship of relative corn grain yield with Bray-1 soil-test P and Mehlich-3 soil-test K. Critical soil-test P concentrations were 16-22 ppm P and 138-182 ppm K (Fig. 4). These ranges align with those reported by Jones et al. (2022) on similar soils using the same soil test methods. No differences were observed in critical concentrations above or below the EONR values for the entire study, indicating that independent of N fertilizer applied, target optimum soil-test ranges for P and K should be the same. Crop nutrient removal of P and K is commonly used to guide fertilization rates where soil-test levels are being maintained (ideally not increased or decreased). Table 2 shows the mean removal of N, P, and K with corn grain harvest across all site-years. Grain removal of N is used in some NUE calculations, but is only reported as lb. N removed per acre here. Nitrogen rate affected removal of all nutrients at each soil-test P and K level except for grain N removal at the Low level (Table 2). An interaction between N rate and soil-test level was observed for each nutrient, with larger amounts of N, P, and K being removed as corn yield increased. No differences in removal of N, P, or K were observed between the Optimum and High soil-test levels for any N rate, indicating that effects of removal on the soil-test level following corn grain harvest would be similar. Small or no differences in removal were observed at the 120 lb. N/a rate or higher, suggesting that applying N above the EONR would not draw down soil-test levels any faster than applying at the economically optimum rates. Overall, corn yield linearly and positively correlated with removal of N, P, and K, as expected.

Conclusions

The results of this study should be interpreted in context of the soils and physiographic region of Wisconsin where they were conducted. The soils in southcentral and southwest Wisconsin can provide significant amounts of inorganic N from soil organic N mineralization and are considered high yield potential soils for corn grain in Wisconsin. Nevertheless, results from this work indicate that when determining N rates to apply in corn-soybean rotations, considering soil-test P and K levels is important for optimizing yield and profitability. Low soil-test P and K levels led to an inefficient use of applied N fertilizer and did not support profitable corn production. Additionally, maintaining soil-test P and K at optimum ranges between 16-27 ppm Bray-1 P and 120-173 ppm Mehlich-3 K led to maximum corn grain yield and economic return to the N, P, and K fertilizer needed to both supply annual N to the corn crop and maintain soil-test levels. Soil-test levels above the critical concentration ranges identified in this study resulted in lower economic return to fertilization. Overall, investments of N fertilizer can be partially safeguarded by closely monitoring soil-test P and K levels and maintaining them where yield is optimized. These results can aid farmers and agronomists working with similar soils to assess how balancing optimum soil-test levels with profitable N rates can affect corn production profitability.

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Tables and Figures

Table 1. Site descriptions and selected soil properties.

	Arlington		Lancaster	
County	Columbia		Grant	
Soil series	Plano (Typic Argiudoll)		Fayette (Typic Hapludalf)	
Surface texture	silt loam		silt loam	
Parent material	loess over glacial till		deep loess	
Drainage class	well drained		well drained	
Soil pH	6.0		6.3	
Soil organic matter, %	4.85		2.33	
Initial Bray-1 P, ppm	6.0		8.6	
Initial Mehlich-3 K, ppm	72		78	
	Phosphorus	Potassium	Phosphorus	Potassium
Low soil-test range, ppm[1]	6 – 11	50 – 90	6 – 17	80 – 104
Optimum soil-test range, ppm[1]	16 – 23	120 – 160	18 – 27	143 – 173
High soil-test range, ppm[1]	31 - 42	164 – 236	34 - 51	182 - 262

[1] Low, Optimum, and High soil-test ranges maintained throughout the study.

Table 2. Corn grain crop macronutrient removal as affected by soil-test P and K level, and nitrogen rate.

	Nitrogen				
	Soil-test P and K level				
Nitrogen rate	Low	Optimum	High	*p*	LSD (0.05)[1]
lb. N/a	---------- lb. N/a ----------				
0	106	114	113	0.244	NS
40	107	122	126	< 0.001	11
80	109	129	129	< 0.001	15
120	105	131	136	< 0.001	16
160	111	141	147	< 0.001	16
200	115	142	139	0.001	19
p	0.332	< 0.001	< 0.001		
LSD (0.05)	NS	14	15		
	Phosphorus				
	Soil-test P and K level				
Nitrogen rate	Low	Optimum	High	*p*	LSD (0.05)
lb. N/a	---------- lb. P_2O_5/a ----------				
0	51	60	63	0.003	9.2
40	49	70	78	< 0.001	13
80	48	75	76	< 0.001	9.1
120	45	73	80	< 0.001	14
160	52	80	81	< 0.001	10
200	55	70	77	< 0.001	14
p	0.074	< 0.001	< 0.001		
LSD (0.05)	13	13	13		
	Potassium				
	Soil-test P and K level				
Nitrogen rate	Low	Optimum	High	*p*	LSD (0.05)
lb. N/a	---------- lb. K_2O/a ----------				
0	30	35	37	< 0.001	4.5
40	29	40	43	< 0.001	6.3
80	29	42	43	< 0.001	4.4
120	27	41	45	< 0.001	7.2
160	30	43	45	< 0.001	5.4
200	33	39	43	< 0.001	6.6
p	0.060	< 0.001	0.008		
LSD (0.05)	5.8	6.8	6.0		

[1]LSD(0.5), least significant difference at the 0.05 significance level

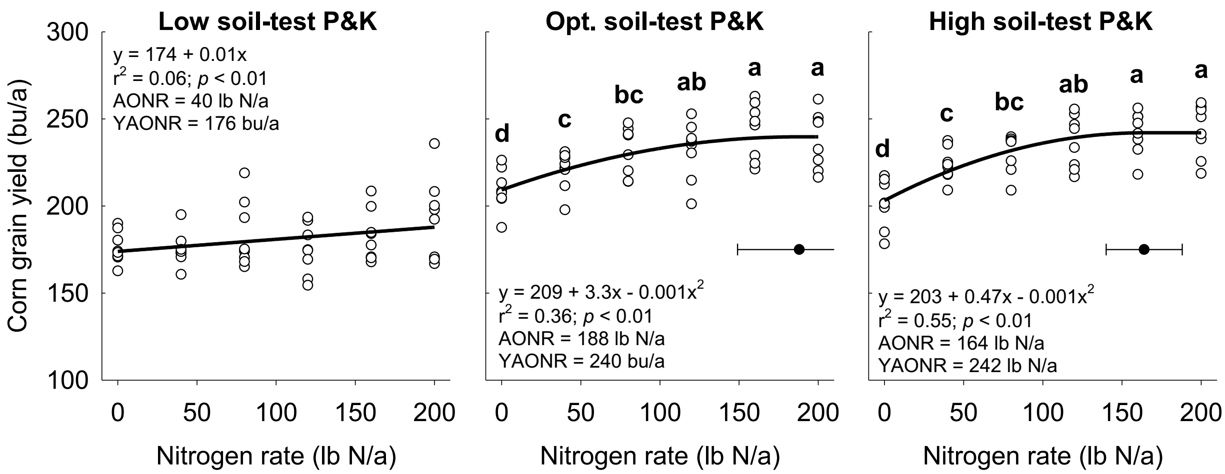

Figure 1. Relationship between corn yield and nitrogen rate when soil-test P and K levels are maintained at Low, Optimum, and High ranges for all site-years of the study. Agronomic optimum N rate (AONR), yield at the AONR, and mean separation by N rate is shown. Letters represent significant differences ($p \leq 0.05$).

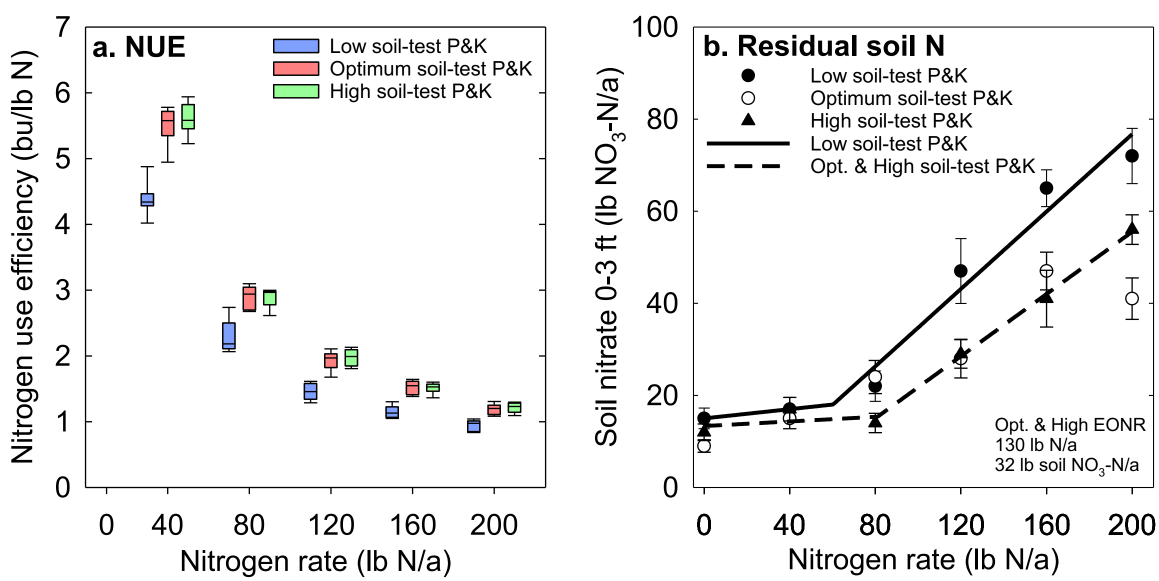

Figure 2. (a) Relationship between nitrogen rate and partial factor productivity nitrogen use efficiency and (b) residual soil nitrate from 3-foot depth collected after corn harvest as affected by nitrogen rate for each soil-test P and K level.

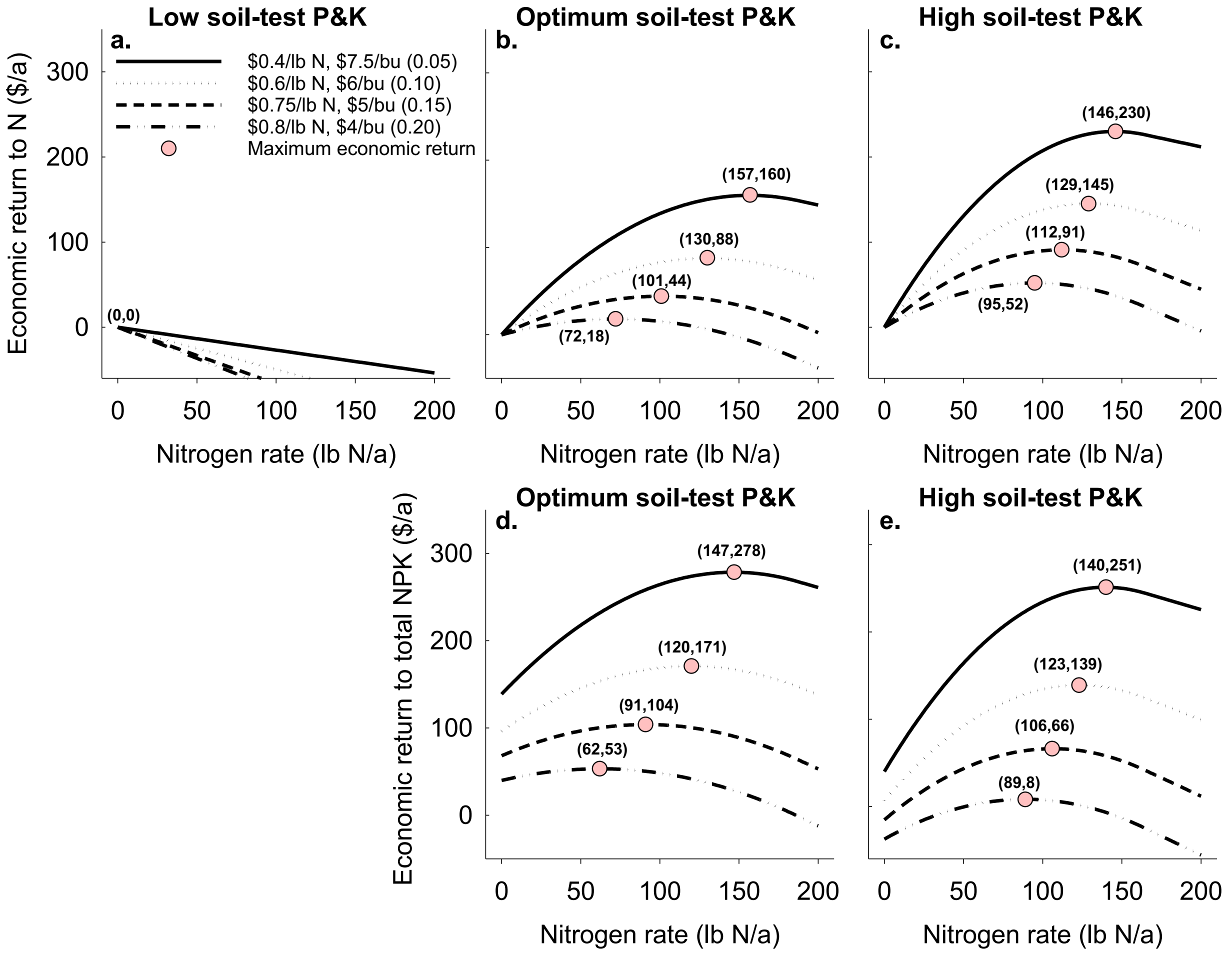

Figure 3. Relationship between nitrogen rate and economic return to fertilization of corn using four different ratios of the price of N fertilizer to the price of corn grain. Economic returns to only N fertilizer are shown in figures 3a-3c, Economic returns to N, and P and K fertilizer needed to maintain Optimum and High testing levels are shown in figures 3d and 3e. Phosphorus and potassium fertilizer price was set to $0.85/ lb. P_2O_5 and $0.55/ lb. K_2O. Values in parentheses are the nitrogen rate at where the maximum economic return to either only N or total N, P, and K was reached, and the value of the return in $/ac.

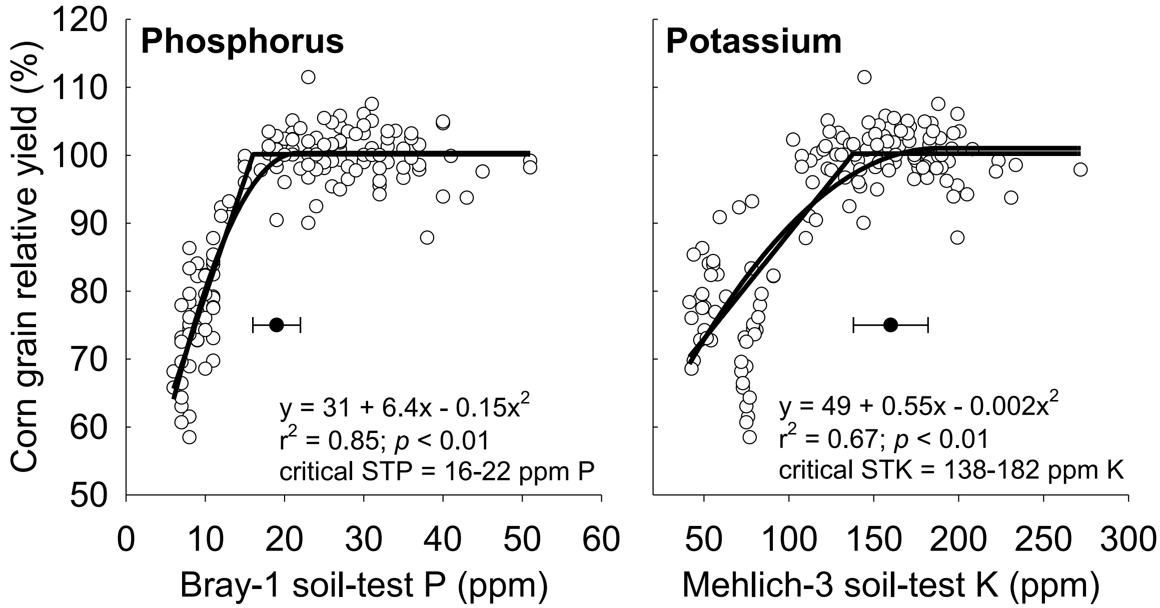

Figure 4. Relationship across all site-years between corn yield response to P or K and soil-test P or K. Critical concentration ranges for P and K are ranges of the linear-plateau and quadratic-plateau model joint points.