Economic and Environmental Impacts of Long-Term Nitrogen and Phosphorus Fertilization

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Nitrogen and P fertilizers are needed for optimum production and economic returns from irrigated continuous corn (*Zea mays* L.) However, excessive application of N must be avoided to minimize adverse environmental impacts. The objectives of this study were to determine: (i) the economic optimum rate of N for irrigated continuous corn, (ii) how sensitive optimal N rates were to corn and N prices as well as yield potential, and (iii) the relationship of optimal N rate to profile nitrate-N accumulation. Yield data from a long-term study were used to estimate quadratic production functions, with and without P, for corn yield as a function of N rate. Six rates of N (0, 40, 80, 120, 160, and 200 lb/acre) and two rates of P_2O_5 (0 and 40 lb/acre) were applied annually from 1961 to 1991 on a Ulysses silt loam (fine silty, mixed, mesic, Aridic Haplustoll) near Tribune, KS. Without fertilizer P, soil P levels declined to deficient levels of about 7 ppm Bray 1-P. The economic optimal N rate, with P, was 159 lb/acre. Phosphorus fertilization increased the economic optimal N rate by about 15 lb/acre, while increasing maximum yields by almost 60 bu/acre, increasing maximum net revenue more than $130/acre, and decreasing minimum cost of production by $0.56/bu. The economic optimal N rate was similar for low-, medium-, and high-yielding years and application of insurance N reduced profitability. The economic optimal N rate was relatively insensitive to changing N and corn prices. Profile nitrate-N content was relatively low and essentially the same when N was applied with P at the economic optimal N rate or less. This indicates that applying N to maximize profit does not cause nitrate accumulation or leaching concerns. However, accumulation and movement of nitrate below the crop root zone increased when N was applied in excess of the economic optimal rate or without adequate P fertilizer.

ACCURATELY QUANTIFYING the economic optimum fertilizer rate is essential to maximize profitability and minimize potential negative environmental impacts of fertilizer N use. Nitrogen fertilizer requirements depend on many factors including yield goal, inorganic soil N concentration, N mineralization, soil type, and numerous environmental factors (Powers and Schepers, 1989). In the Great Plains, N recommendation models generally are based on yield goal and preplant nitrate-N concentration in the soil profile (Onken et al., 1985; Hergert, 1987; Vanotti and Bundy, 1994a,b). For example, fertilizer N recommendations for irrigated corn in western and south central Nebraska varied between 50 and 164 lb/acre and depended on soil profile N concentration and nitrate-N content of irrigation water (Ferguson et al., 1991).

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When yield goals are overestimated or profile nitrate-N concentration is underestimated, the recommended N rate may be greater than that required for optimum grain yield, which can dramatically increase residual fertilizer N in the soil profile (Hooker et al., 1983; Schepers et al., 1986; Vanotti and Bundy, 1994a). Schepers et al. (1986) reported that some irrigated corn producers used yield goals that were 38 bu/acre greater than yields actually achieved, thereby overestimating fertilizer N requirement by 40 lb/acre.

Many studies have reported minimal carryover of residual fertilizer N when the N application rate was nearly equivalent to crop need (Dahnke and Johnson, 1990; Bundy and Malone, 1988; Oberle and Keeney, 1990a). Broadbent (1980) showed that residual profile nitrate-N concentration increased in direct proportion to increasing fertilizer N applied in excess of 200 lb/acre. Above this N rate, corn grain yield and fertilizer N in the grain remained relatively constant. Vanotti and Bundy (1994a) reported similar results with N rates exceeding 160 lb/acre.

When making fertilizer N recommendations, failure to consider residual profile nitrate-N content may result in overapplication of N and accumulation of potentially leachable nitrate-N in the soil profile. Bundy and Malone (1988) observed no corn yield response to N when preplant profile nitrate-N (3-ft depth) exceeded 134 lb N/acre. In a 24-yr study of corn N rate, Vanotti and Bundy (1994a) reported corn yield response to fertilizer N only when preplant soil nitrate-N was less than 220 lb/acre (3-ft depth). Using 10 different soils, Oberle and Keeney (1990a) and Onken et al. (1985) showed that N rate required for maximum yield was related inversely to preplant profile nitrate-N content.

Maximizing the quantity of fertilizer N recovered by the crop, or minimizing the quantity of residual fertilizer N after harvest, generally will reduce the potential for groundwater contamination (Keeney, 1987; Bock, 1984). Recovery of N from applied fertilizer generally ranges between 30 and 70% (Legg and Meisinger, 1982), depending on residual soil N, fertilizer N rate, and other N management factors (Bock, 1984; Walters and Malzer, 1990). Generally, fertilizer N recovery is greater on soils with low residual N (Onken et al., 1985; Bock, 1984) and decreases with increasing fertilizer N rates (Oberle and Keeney, 1990b).

Numerous studies have reported the importance of identifying the optimum N rate to increase both short- and long-term net returns (Stoecker and Onken, 1989; Vanotti and Bundy, 1994a). In general, the average economic optimum N rate over years represents a reliable first estimate of the fertilizer N recommendation (Bock and Hergert, 1991). Using quadratic response functions and a 1:10 fertilizer N:corn price ratio, Oberle and Keeney (1990a) reported economic optimum N rates between 160 and 210 lb/acre on irrigated sandy soils and between 90 and 150 lb/acre on finer textured soils. In Wisconsin, the fertilizer N rate required to maximize net

Table 1. Ordinary least squares regression for corn grain yield on N rate with and without P (1961–1991) with base year of 1991.

Variable	Parameter estimate	Standard error	T-statistic
	With P		
Constant	94.2716	1.6564	56.915***
N	1.1007	0.0313	35.161***
N^2	−0.0033	0.0002	−21.698***
(Yr-1991)	1.0850	0.0660	16.438***
$R^2 = 0.651$			
	Without P		
Constant	70.7998	2.2680	31.217***
N	0.7416	0.0429	17.302***
N^2	−0.0023	0.0002	−11.382***
(Yr-1991)	−0.3477	0.0904	−3.848***
$R^2 = 0.425$			

*** Indicates coefficients are statistically significant using a 99.9% confidence level.

return with corn was 160 to 170 lb/acre in both high-yielding and low-yielding years (Vanotti and Bundy, 1994a).

In addition, management of other inputs can affect crop yield potential and optimum N rate. Generally, any factor that limits yield potential will reduce the quantity of N required for optimum yield. For example, in P-deficient soils, adequate P fertilization increases yield response to fertilizer N (Black, 1970; Halvorson and Black, 1985; Halvorson and Havlin, 1992).

Most studies of N and P fertilization of corn cover less than 10 yr and focus on the agronomic aspect of fertilization. There is less information available that relates economic and environmental impacts of long-term fertilization. The objectives of the present study were to (i) quantify the economic optimum N rate for irrigated continuous corn over 30-yr, (ii) analyze the sensitivity of the economic optimum N rate to fertilizer N:corn price ratio and yield potential, and (iii) evaluate the relationship between the economic optimum N rate, with and without P, and residual nitrate-N accumulation in the soil profile.

MATERIALS AND METHODS

Nitrogen and P fertilizers were applied annually from 1961 to 1991 to irrigated continuous corn grown on a Ulysses silt loam (fine silty, mixed, mesic, Aridic Haplustoll) at the Tribune Unit, Southwest Research-Extension Center in west central Kansas. The initial soil properties were pH of 7.9, organic matter of 1.4%, and Bray 1-P of 17 ppm (Hooker et al., 1983). Without P application, soil P levels declined to about 7 ppm Bray 1-P after 5 yr and then stabilized at this lower level. With P fertilization, soil P levels increased at low N rates and gradually decreased at higher N rates to about 11 ppm Bray 1-P in 1991. Annual yield data and cultural practices were reported previously (Hooker et al., 1983; Schlegel and Havlin, 1995). A factorial of six N rates (0, 40, 80, 120, 160, and 200 lb/acre) and two P rates (0 and 18 lb/acre) was arranged in a randomized complete block design replicated five times. All treatments were hand broadcast to the same plot each year in the spring and incorporated. Plot size was 12 by 60 ft.

The study area was flood irrigated each year to minimize water stress. Irrigation amounts depended upon growing season rainfall and varied from about 14 to 22 in. annually. The quality of the irrigation water was excellent, containing about 2 ppm nitrate-N (0.45 lb/acre-in.) with a pH of 7.9. The irrigation water supplied less than 10 lb N/acre annually.

Table 2. Ordinary least squares regression for corn grain yield on N rate (with P) for low-, medium-, and high-yielding years (1991 base year).

Variable	Parameter estimate	Standard error	T-statistic
	Low-yielding years		
Constant	76.1345	2.1977	34.644***
N	0.8985	0.0454	19.787***
N^2	−0.0026	0.0002	−11.845***
$R^2 = 0.728$			
	Medium-yielding years		
Constant	91.2763	1.5790	57.805***
N	1.2054	0.0291	41.354***
N^2	−0.0036	0.0001	−25.467***
$R^2 = 0.845$			
	High-yielding years		
Constant	115.7721	3.0604	37.829***
N	1.0812	0.0483	22.362***
N^2	−0.0033	0.0002	−14.159***
$R^2 = 0.715$			

*** Indicates coefficients are statistically significant using a 99.9% confidence level.

Soil samples to a depth of 10 ft were collected after harvest in 1990 and analyzed for nitrate-N by extraction with 1M KCl and colorimetric analysis (Technicon Industrial Systems, 1977).

Yield data from 1961 to 1991 (1974 was excluded because of hail) were used to estimate quadratic production functions, with and without P fertilizer, with grain yield as a function of N. A time variable was included in the analysis to account for

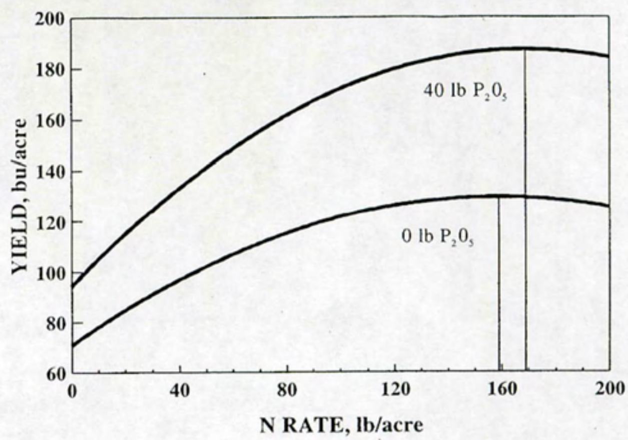

Fig. 1. Grain yield response to N and P. Vertical lines indicate economic optimal N rates.

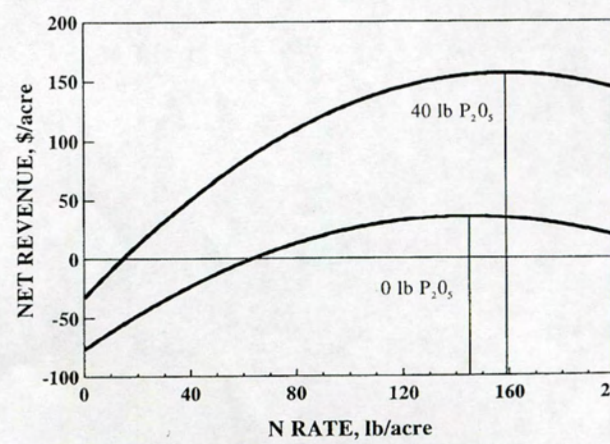

Fig. 2. Net revenue response to fertilizer N and P. Vertical lines indicate economic optimal N rates.

general trends that occurred over the 30 yr. With P, the coefficient for the time variable was positive, accounting for technological improvements; however, without P, the coefficient was negative, representing greater P deficiency. Although other functional relationships are possible, a quadratic function was used because yields increased at a decreasing rate over the range of N rates and declined at the highest N rate. Quadratic production functions have been used by others to estimate yields (Mjelde et al., 1991; Arce-Diaz et al., 1993; Vanotti and Bundy, 1994a).

The general form of the function is:

$$Y_i = \beta_0 + \beta_1 N + \beta_2 N^2 + \beta_3(\text{Yr-1991}) + e \qquad [1]$$

where:

- Y = grain yield of corn, bu/acre,
- N = N rate, lb/acre
- (Yr-1991) = linear time trend,
- e = error term, and
- β = parameters to be estimated.

The model is estimated using ordinary least squares techniques (SAS, 1988). A year variable is included to estimate the linear increase in yields during the study (Table 1). The N rate, with and without P, required for maximum grain yield was found by equating the first derivative of the respective production functions to zero and solving for N.

Once the production function is estimated, net returns (NR) are calculated using the following equation [2].

$$NR = (Y \times P_c) - (N \times P_n) - (P \times P_p) - PC \qquad [2]$$

where:

- Y = grain yield of corn in bu/acre from the production function in equation [1].
- P_c = price of corn, \$/bu,
- N = N rate, lb/acre,
- P_n = price of N, \$/lb,
- P = P rate, lb/acre,
- P_p = price of P, \$/lb,
- PC = production costs per acre other than N and P costs.

Production expenses, other than N and P costs, are constant for all fertilizer treatments. The cost assumptions used were N at \$0.15/lb, P at \$0.55/lb, corn at \$2.30/bu, and production costs at \$240/acre (Dhuyvetter, 1994). The economic optimal N rates were calculated by equating the first derivatives of the yield functions to the fertilizer N/corn price ratio and solving for N.

The cost per bushel, with and without P, was calculated for N rates between 0 and 200 lb/acre (1-lb increments) using Eq. 3 and an electronic spreadsheet to determine the N rate where cost is minimized.

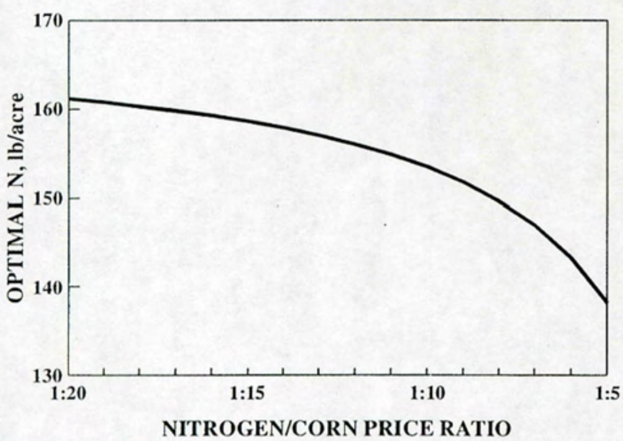

Fig. 3. Relationship of fertilizer N:corn price ratio on economic optimal N rate.

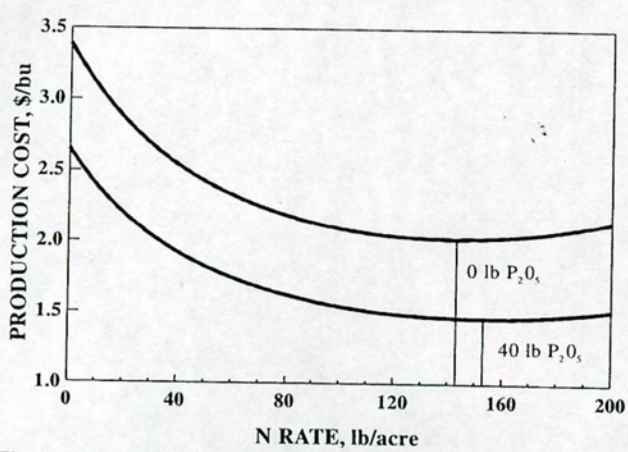

Fig. 4. Cost of corn production with and without P. Vertical lines indicate least cost production.

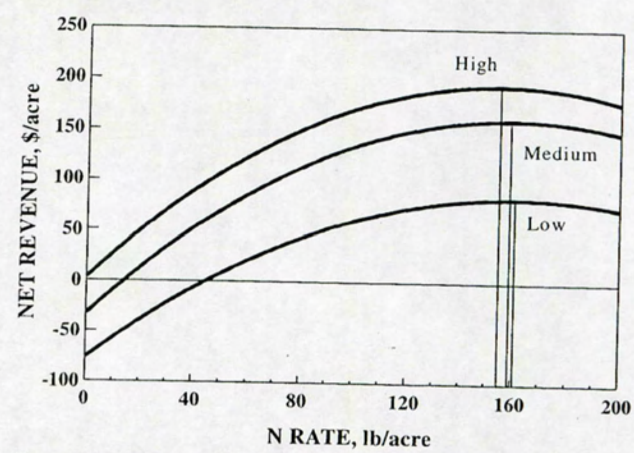

Fig. 5. Economic optimal N rate in low-, medium-, and high-yielding years. Vertical lines indicate economic optimal N rates.

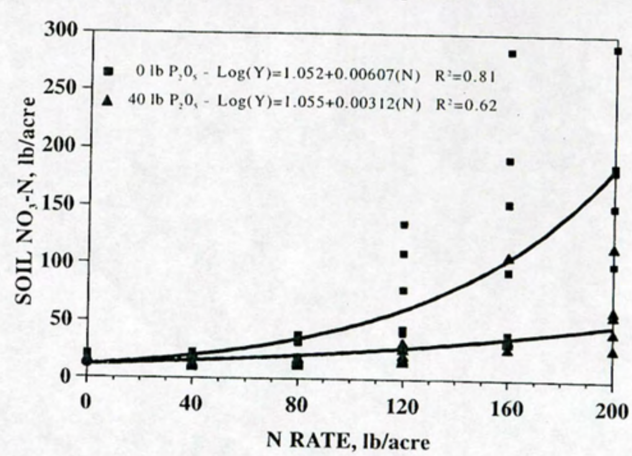

Fig. 6. Nitrate-N content in the soil profile (10 ft) after 30 yr of N and P applications. Coefficients in regression equations are statistically significant at the 99% confidence level.

$$\text{Cost per bushel} = [(N \times P_n) + (P \times P_p) + PC]/Y \quad [3]$$

where:

N = N rate, lb/acre,
P_n = price of N, $/lb,
P = P rate, lb/acre,
P_p = price of P, $/lb,

PC = all production costs per acre other than N and P costs,
Y = grain yield of corn in bu/acre from the production function in Eq. [1].

Yield data, with P, also was partitioned into low-, medium-, and high-yielding years based on average annual yields compared with the 30-yr average. Years classified as medium yielding had average annual yields within about 10% of the 30-yr average yield. This partitioning described 7 yr as low-yielding (average maximum yield of 156 bu/acre), 15 yr as medium-yielding (average maximum yield of 189 bu/acre), and 8 yr as high-yielding (average maximum yield of 203 bu/acre). Quadratic production functions then were estimated for each of the yield categories (Table 2).

RESULTS AND DISCUSSION

Grain yield of irrigated corn was increased significantly by fertilizer N and P in this long-term study (Fig. 1, Table 1). The treatment yields for each year were reported previously (Hooker et al., 1983; Schlegel and Havlin, 1995). The N rate, with P, to maximize yield was 169 lb/acre, which is consistent with the optimum N rate observed in the first 21 yr of the study (Hooker et al., 1983). Irrigation water can be a significant source of applied N (Ferguson et al., 1991); however, in this study, it supplied less than 10 lb N/acre annually.

The economic optimal N rate (with P) on this silt loam soil at a fertilizer N:corn price ration of 1:15 was 159 lb/acre (Fig. 2). This was only 10 lb N/acre less than the N rate required to maximize grain yield. This is in contrast to Oberle and Keeney (1990a) who reported that, on silt loam soils in Wisconsin, the economic optimal N rate was 28 to 78 lb/acre less than the N rate required to maximize yield when the fertilizer N:corn price ratio was also 1:15.

Changes in relative fertilizer N and corn grain prices influence the economic optimum N rate. In this study, the economic optimum N rate was relatively insensitive to changes in the fertilizer N:corn price ratio. For example, when the fertilizer N:corn price ratio decreased from 1:5 to 1:20, the economic optimum N rate increased only 23 lb/acre from 138 to 161 lb/acre (Fig. 3). With the same decrease in fertilizer N:corn price ratio, Oberle and Keeney (1990a) reported that the economic optimum N rate increased 29 to 39 lb/acre on irrigated sandy soils and from 64 to 122 lb/acre on finer textured soils.

Phosphorus increased N fertilizer demand by about 10 lb/acre, while increasing maximum corn yields by almost 60 bu/acre (Fig. 1). This indicates that fertilizer P allows the plant to use available N more efficiently rather than substantially increasing N demand. Application of P increased net revenue by $130/acre with only a small increase in the economic optimal N rate (Fig. 2).

Production costs per bushel were minimized at a N rate of 153 lb/acre (Fig. 4) which was slightly less than the economic optimal N rate of 159 lb/acre. This shows that fertilizer N rates that minimize production costs do not maximize profitability. Phosphorus fertilization reduced production costs by more than $0.50/bu at the economic optimal N rate.

The economic optimal N rate remained in the range of 154 to 161 lb/acre for low- to high-yielding years (Fig. 5). The yields produced by the economic optimal N rates ranged from 155 bu/acre in the low-yielding years to 203 bu/acre in the high-yielding years. This indicates that the optimum N rate for a particular field is relatively constant from year to year and should not be adjusted based on expected growing conditions. Vanotti and Bundy (1994a) obtained similar results from a 24 yr study of corn in Wisconsin. They reported that the economic optimum N rate was 160 to 170 lb/acre in both low- and high-yielding years and that the economic optimum N rate was not related to grain yield. Therefore, the practice of applying insurance N should be discouraged as it reduces profitability, even in high-yielding years, and increases the risk of N loss to the environment (Broadbent, 1980; Ferguson et al., 1991; Legg and Meisinger, 1982; Vanotti and Bundy, 1994a).

Long term application of N fertilizer does not necessarily cause accumulation of nitrate-N in the soil. Profile nitrate-N was less than 50 lb/acre (10-ft profile) after 30 yr of applying the economic optimal N rate with P (Fig. 6). Profile nitrate-N increased with higher N rates, but was less in 1990 than earlier in the study. Hooker et al. (1983) reported 203 lb nitrate-N/acre in a 6-ft profile in 1979 from application of 160

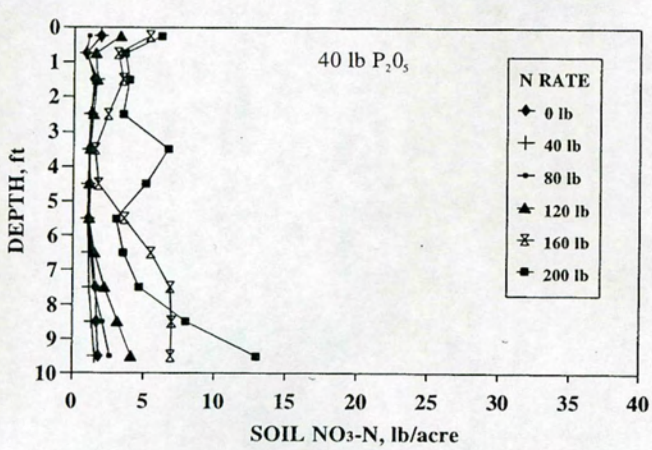

Fig. 7. Distribution of nitrate-N in the soil profile after 30 yr of N applied with P.

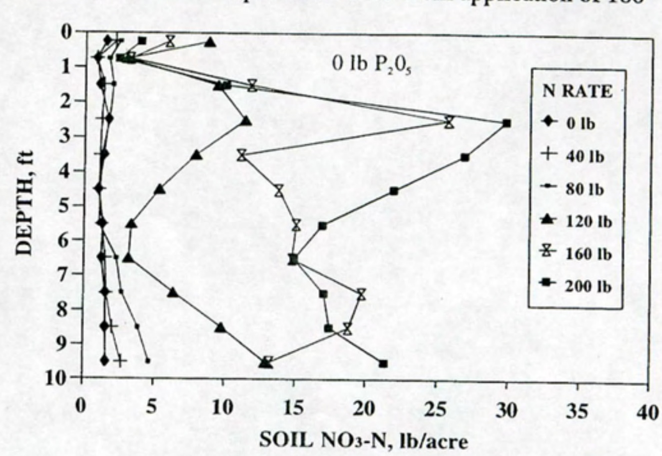

Fig. 8. Distribution of nitrate-N in the soil profile after 30 yr of N applied without P.

lb N/acre with P. This depletion of residual N may eventually result in increased requirements for fertilizer N.

Application of P increased grain yield and N removal, thereby reducing residual soil N. At the economic optimal N rate, profile nitrate-N was over four times greater without P than with P. This emphasizes the importance of applying P, if needed, along with N in a balanced fertility program to reduce environmental risk of groundwater contamination by nitrate-N.

Nitrate-N is very low throughout the profile with N rates below 160 lb N/acre with P (Fig. 7). At the 10 ft depth, nitrate-N levels are twice as great with 200 than 160 lb N/acre, indicating a much greater potential for nitrate leaching when N rates exceed the economic optimal. Detection of considerable nitrate-N at the deepest sampling depth (10 ft) indicated movement of nitrate-N further into the profile. The amount of nitrate-N that may have leached below 10 ft was not measured in this study.

Nitrate-N levels were greater at lower N rates without P (Fig. 8) than with P. For example, nitrate-N levels below 5 ft were similar for 120 lb N/acre without P as that of 200 lb N/acre with P. Without P, nitrate-N also accumulated in the 3 to 5 ft depth when N was applied at 120 lb N/acre and greater. However, this nitrate-N remains available for crop use since it is within the corn root zone, typically about 5 ft in this soil. Residual nitrate-N below the root zone is susceptible to further leaching, which increases the potential for nitrate-N to enter the groundwater (Bock, 1984; Keeney, 1987).

These data demonstrate that: (i) the economic optimum N rate for irrigated continuous corn was about 160 lb N/acre, (ii) that the economic optimum N rate is relatively insensitive to fertilizer N:corn price ratio, (iii) that the economic optimum N rate is relatively constant across low- to high-yielding years, (iv) that insurance N reduces profitability, and (v) that long term application of the economic optimum N rate with P, when needed, does not cause accumulation of nitrate-N in the soil profile.

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