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Soil testing and plant analysis to optimize nitrogen management in manured cornfields

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Soil testing and plant analysis to optimize nitrogen management in manured cornfields

by

David Jay Hansen

A dissertation submitted to the graduate faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY

Co-majors: Soil Science (Soil Fertility); Water Resources

Major Professors: Alfred M. Blackmer and Robert Horton

Iowa State University

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GENERAL INTRODUCTION

Animal manures can provide N needed for corn production, but there is often great uncertainty in amounts of plant-available N supplied by a given application of animal manure (Bouldin et al. 1984; Bouldin and Klausner, 1998; Sharpley et al., 1998; Klausner et al., 1994). This uncertainty has been attributed to inaccurate estimates concerning amounts of manure applied, extreme variability in the N concentration of similar types of manure, and variability in amounts of N lost after application (Schepers and Fox, 1989). This uncertainty makes it difficult to decide how much commercially prepared N fertilizer should be applied in fields already treated with animal manure.

Commonly used methods for assessing N fertilizer needs on manured soils address this uncertainty by encouraging good record-keeping and laboratory analysis of manure (Midwest Planning Service, 1985; Bock and Hegert, 1991; Killorn, 1995; Schmidt et al., 1997). Predicted losses of N are incorporated into estimates of plant-available N based on rate of manure-N application, timing of application, and method of application. However, these losses are difficult to predict for a given site because of variability in soils, management practices, and weather. An increased ability to recognize and quantify these losses is needed to improve site-specific management of N.

Concentrations of nitrate in the surface 30-cm layer of soil in late spring can be used to assess whether soils have sufficient nitrogen for growth of corn (Magdoff et al., 1984; Blackmer et al., 1989; Fox et al., 1989; Magdoff et al., 1990; Binford et al., 1992). Studies across a wide range of conditions show remarkable agreement that the critical concentration of soil nitrate-N (i.e., the concentration that distinguishes soils that should be fertilized from those that should
not) occurs between 20 and 25 mg N/kg (Magdoff, 1990; Sims et al., 1995). There is widespread agreement that additional N should not be applied to soils testing above the critical concentration (Fox et al., 1989; Meisinger et al., 1992; Schepers and Meisinger, 1994; Lory et al., 1995). However, the ability of soil nitrate tests to predict optimal rates of N fertilization at low-testing sites has not been established. Soil test calibrations that predict amounts of fertilizer N that should be applied for any given soil test value are needed to improve site-specific management of N.

Concentrations of nitrate in cornstalks at the end of the season provide the basis for a tissue test that can be used to make after-the-fact assessments of N sufficiency for corn growth (Binford et al., 1990, 1992; Sims et al., 1995; Varvel et al., 1997). The test has been used in surveys to evaluate N management practices within a region (El-Hout and Blackmer, 1990). It has been used to help interpret results of N-response studies conducted on small plots (Binford et al., 1992; Morris et al., 1993). It also has been used to give site-specific assessments of N sufficiency when characterizing spatial variability in N fertilizer needs within fields (Blackmer and White, 1998). This test is unique among tissue tests for corn in that it characterizes degrees of N excess as well as degrees of N deficiencies.

The cornstalk test was calibrated by using pooled data from many response trials having 10 rates of fertilizer applied (Binford et al., 1992). The calibrations showed that commonly observed cornstalk nitrate concentrations ranged from <100 to >10,000 mg N/kg. Current Iowa guidelines for using the test divide cornstalk nitrate concentrations into four categories: low, 0 to 250 mg N/kg; marginal, 250 to 700 mg N/kg; optimal, 700 to 2000 mg N/kg; and above optimal, >2000 mg N/kg (Blackmer and Mallarino, 1996). Low
concentrations indicate a high probability that greater availability of N would have resulted in higher yields. Marginal concentrations, while indicative of a high probability that N availability was in the range needed to maximize profits, are considered to be "too close" to low to serve as a target concentration. Optimal concentrations indicate a high probability that N availability was in the range needed to maximize profits for producers. Above-optimal concentrations indicate a high probability that N availability was greater than if fertilizer N had been applied at rates that maximized profits for producers. Although these qualitative definitions are useful when interpreting results of cornstalk testing, more quantitative definitions would increase the usefulness of this test for corn producers.

Trials were conducted in 205 Iowa cornfields from 1992 through 1997. All fields had received previous applications of animal manure and were managed by the producers using their normal practices. The objective of these studies were to i) determine what information attainable in late-spring was most useful in evaluating N sufficiency in manured cornfields, ii) characterize relationships between soil nitrate concentrations in late-spring, prices of corn and fertilizer, and optimal rates of N fertilization in manured cornfields, and iii) develop quantitative guidelines for use of the end-of-season test for cornstalk nitrate in manured cornfields.

Dissertation Organization

This dissertation is presented as a series of three papers intended for publication. All three papers will be submitted to Agronomy Journal. The papers are preceded by a General Introduction and succeeded by a General Conclusion. References cited in the General Introduction and General Conclusions are listed in the Literature Cited section.
ESTIMATING NITROGEN SUFFICIENCY LEVELS IN CORNFIELDS TREATED WITH ANIMAL MANURE

A paper prepared for submission to Agronomy Journal

D.J. Hansen, A.M. Blackmer, A.P. Mallarino, and M.E. Wuebker

Abstract

Efficient management of N in agricultural soils requires reasonable ability to estimate the sufficiency of N in soil (i.e., supply relative to need) before crops are grown. The objective of this study is to compare the ability various types of information to estimate the sufficiency of N for corn growth following application of animal manure. Focus was on information potentially available to producers who are considering the application of more N when plants are about 30 cm tall. Data were collected in 205 trials on soils that had been treated with animal manure by farmers using their normal practices. Grain yield responses to additional N provided the basis for defining N-sufficiency levels. Amount of manure-N applied, method of application, time of application, and yield level did not provide useful estimates of N sufficiency levels. However, soil nitrate concentrations in the surface 60-cm layer of soil explained 37% of the variability in observed yield response. All other types of information explained less than 10% of this variability in response.

Introduction

Animal manures can provide N needed for corn production, but there is often great uncertainty in amounts of plant-available N supplied by a given application of animal manure (Bouldin et al. 1984; Bouldin and Klausner, 1998; Sharpley et al., 1998; Klausner et al., 1994). In a recent review Schepers and Fox (1989) attributed this uncertainty to inaccurate
and vague estimates by the farmer concerning amounts of manure applied, extreme variability
in the N concentration of similar types of manure, variable amounts of N lost by ammonia
(NH₃) volatilization following unincorporated surface applications, uncertainty concerning
the proportion of the manure N that will become available for plant uptake, and the
possibility that manure additions will increase N losses due to denitrification in some soils.
This uncertainty makes it difficult to decide how much commercially prepared N fertilizer
should be applied in fields already treated with animal manure.

Commonly used methods for assessing N fertilizer needs on manured soils involve
several steps (Midwest Planning Service, 1985; Bock and Hegert, 1991; Killorn, 1995;
Schmidt et al., 1997). These steps usually include estimating amounts of N expected to be
removed by the crop and the amount of plant-available N supplied by the manure. Amounts
of N expected to be removed by the crop are estimated from expected yield or yield potential
of the soil. Amounts of plant-available N are assessed by analyzing the manure, adjusting for
expected losses of N soon after application, and adjusting for expected amounts of N to be
mineralized from the present and previous applications of manure. Such adjustments often
are presented as absolute values intended to represent an average across many conditions.
Although it is recognized that there is great variability from site to site, little attention has
been given to the amount or the importance of the variability. A better understanding of this
variability is needed to evaluate the potential benefits of site-specific management of N.

The objective of this study was to determine what information attainable in late-
spring was most useful in evaluating N sufficiency in manured cornfields. The evaluations
focus on information the farmer could reasonably obtain before fertilizers are applied. In
addition to information usually used to select N rates, information provided by soil nitrate testing in late spring will also be considered. Numerous studies have shown that concentrations of soil nitrate when corn plants are 15 to 30 cm tall can be used to assess amounts of plant-available N (Magdoff et al., 1984; Blackmer et al., 1989; Fox et al., 1989; Magdoff et al., 1990; Binford et al., 1992). Hansen and Blackmer (1999a) address how N fertilizer needs can be predicted by soil nitrate testing.

Materials and Methods

Trials evaluating the response of corn to commercially prepared N fertilizer were conducted in 205 cornfields that had been manured by farmers using their normal practices. The trials were distributed across 28 counties in Iowa, with approximately equal numbers each year from 1992 through 1997. Sites were selected to include variety with respect to soil type, manure type, rate of application, method of application, and time of application. Soil and crop management practices (except N fertilization) were those normally used by each farmer.

The manure came from beef cows at 22 sites, dairy cows at nine sites, swine at 149 sites, and poultry at nine sites. Sixteen sites received two or more forms of animal manure. Approximately equal numbers of sites were manured in the fall, winter, and spring before planting. Some sites had not received applications of animal manure since harvest of the previous crop, but these sites had received at least two applications of manure in the previous four years. Information concerning amounts, type, and time of manure application was provided by farmers. At about one-third of the sites the information provided by the farmer included manure analyses. At the remainder of the sites N content of the manure was

Each trial consisted of 16 plots arranged in a randomized complete-block design with 4 replications. Plots were 12.2-m long and six rows wide for 76-cm spacings or four rows wide for 91-97 cm spacings. Soil samples were collected from each block within each site. Each sample was derived from a composite of 32 soil cores. The soils were air-dried and subsequently analyzed for inorganic nitrogen by the Lachat flow-injection procedure (Lachat Instruments, Milwaukee, WI; Method 12-107-4-1-B). Composite samples from each site were used for determination of (Bray and Kurtz P-1) phosphorus (P), exchangeable potassium (K), soil organic matter content, and pH as described in by the Missouri Agricultural Experimental Station (1998). Rainfall amounts were obtained from the National Climatic Data Center, Asheville, North Carolina (1998).

Soon after soil samples were collected, four rates of N (0, 33, 67, and 100 kg N/ha) were broadcast on the soil surface. In 1992, 1993, and 1994, N was applied as ammonium nitrate (NH$_4$NO$_3$); in 1995, 1996, and 1997 N was applied as urea ((NH$_2$)$_2$CO). Grain was hand-harvested from 7.6-m sections of the center two rows of each plot. Yields were adjusted to 15.5% moisture content. Yield responses to N fertilization were calculated by subtracting the mean yield of the nonfertilized plots from the mean yield of the fertilized plots for each site. Only yield responses to 100 kg N/ha are used in this paper.

Statistical analyses of yield response were performed by using a curvilinear function described by Nelson and Anderson (1977) or linear functions. The protected least significant difference (LSD) value for yield responses for pooled data were calculated after Snedecor and Cochran (1980). The treatment effect required by this method was determined by standard
analysis of variance (ANOVA) techniques. All statistical analyses (α = 0.05) were conducted using the regression (REG), means (MEANS), or nonlinear regression (NLIN) procedures of the SAS package (SAS Institute, 1988).

Results and Discussion

The mean yield without addition of fertilizer N across all sites was 9.13 Mg/ha, and the mean yield with 100 kg added N/ha was 9.68 Mg/ha. This relatively small response to fertilizer N is consistent with other studies on manured soils (Roth and Fox, 1990; Sims et al., 1995) and can be explained by manure supplying significant amounts of plant-available N. Concentrations of nitrate in cornstalks at the end of the season indicated that 100 kg of fertilizer N/ha was adequate to alleviate N deficiencies at 96% of the sites (Hansen and Blackmer, 1999b).

Analyses of the pooled data from all sites indicated that application of fertilizer N at a rate of 100 kg/ha resulted in statistically significant (α = 0.05) yield increases at 118 sites, significant yield decreases at 43 sites, and no significant effects at 44 sites. The change in yield needed to attain statistical significance (LSD) was 0.23 Mg/ha. These observations illustrate the great need of methods that can distinguish between responsive and non-responsive sites before fertilizers are applied.

It should be noted that it would not have been profitable to apply fertilizer at many of the sites that showed statistically significant yield increases. If, for example, application costs the equivalent of 0.11 Mg/ha of grain (Edwards and Vontalge, 1998) and the cost of 100 kg of N were 0.50 Mg grain, then application of 100 kg N/ha would not be profitable unless a yield response greater than 0.61 Mg occurred. Assuming these costs fertilization
would have been profitable at only 37% of the sites in this study. Because fertilizers are applied to increase profits, there is need to focus on identifying sites where fertilization was profitable rather than sites where statistically significant responses occurred.

Rate of manure-N application was not a useful predictor of yield responses to fertilizer N (Fig. 1A). Significant relationships also could not be attained by considering only the most common type of manure (liquid swine) and the most common method of application (injection) (Fig 1B). Analyses (not presented) showed that these relationships were not improved by considering only sites where the manure was analyzed or by adjusting rates of application for expected losses by using published guidelines (Killorn, 1995). This lack of improvement is undoubtedly caused in part by uncertainty in amounts of manure-N applied. However, because mean yield response was essentially the same at the highest and lowest rates of manure application, it is unlikely that uncertainty in amounts of manure applied is the major factor responsible for the poor relationships. Manure analyses were available for approximately 60% of these sites.

Concentrations of nitrate-N and nitrate- plus ammonium-N in the surface 60-cm layer of soil showed a statistically significant linear trend to increase with increasing rates of manure-N application (Figs 2A and 2B). These relationships are not very important, however, because they explained only 4% of the variability in inorganic-N concentrations. The concentrations of nitrate were much greater than those usually found in nonfertilized fields in Iowa (Blackmer, 1986; Binford et al., 1992; Morris et al., 1993; Karlen and Colvin, 1992) and therefore reflect some effects of the added manure.

Figures 2A and 2B show that there was no useful relationship between soil nitrate
Fig 1. Relationship between A) quantity of manure-N applied and yield response to 100 kg added N/ha, and B) quantity of manure-N applied as injected liquid swine manure and corn yield response to 100 kg add N/ha.
Fig. 2. Relationship between quantity of manure-N applied and A) soil nitrate-N concentrations to 60 cm depth, and B) soil nitrate-N plus ammonium-N to 60 cm depth.
concentrations and rates of liquid swine manure-N injected into the soil. It seems unlikely that this lack of relationship can be explained by variability in amounts or composition of the manure or percentages of manure-N mineralized before the soil was sampled. This lack of relationship, however, could be explained if increasing rates of manure injection resulted in greater percentages of manure-N denitrified. Comfort et al. (1990) showed that denitrification is likely under such conditions.

Concentrations of nitrate in the surface 30 cm of soil explained 26% of the variability in yield response (Fig 3A). This is consistent with previous reports that found good relationships between soil nitrate concentrations before fertilization and yield response to added N (Blackmer et al., 1989; Magdoff, 1984; Sims et al., 1995). Detailed analyses of critical concentrations are presented by Hansen and Blackmer (1999). These concentrations were generally similar to those found by others (Magdoff et al., 1984; Blackmer et al., 1989; Fox et al., 1989; Magdoff et al., 1990; Binford et al., 1992).

Concentrations of nitrate in the surface 60 cm of soil explained 34% of the variability in yield response (Fig 3B). Concentrations of nitrate in the 30- to 60-cm layer of soil (not shown) explained 22% of the variability in yield response. The observed advantage of deeper sampling was slightly greater than previously observed by Binford et al. (1992) who studied non-manured fields that were fertilized shortly before planting. A possible explanation is that, in this study, much of the manure was applied in the fall and nitrate had a greater opportunity to move lower in the soil profile. Dou et al. (1995) reported evidence that such downward movement occurs.

Concentrations of exchangeable ammonium in the surface 30-cm layer were not
Fig. 3. Relationships between A) concentrations of soil nitrate-N to 30 cm depth, B) concentrations of soil nitrate-N to 60 cm depth, C) concentrations of exchangeable ammonium-N to 30 cm depth, D) concentrations of soil nitrate-N plus ammonium-N to 60 cm depth and corn yield response to 100 kg added N/ha.
useful for predicting responsive sites (Fig 3C). Exchangeable ammonium-N plus nitrate-N in the 0-30 cm layer explained 22% of the variability in yield response, which is less than the variability explained by nitrate-N alone. Exchangeable ammonium-N plus nitrate-N in the 0-60 cm layer explained 33% of the variability in yield response (Fig 3D), which is slightly less than the variability explained by nitrate-N alone. These findings are consistent with other studies (Binford et al., 1992; Sims et al., 1995) who found that considering exchangeable ammonium did not significantly improve the ability of the soil test to predict yield responses.

Analyses (not shown) revealed no significant relationship between rainfall during March through May or May and yield responses to added N. Rainfall during these periods, however, explained 17% and 11% of the variability in yields on fertilized plots. Although this information would not be available before fertilizers are applied, rainfall during the growing season (April through September) explained 28% of the variability in yields observed on fertilized plots, but was not significantly related to yield response. These findings suggest that weather was an important factor influencing yields, but was not an important factor influencing yield responses.

More rainfall during May had a significant tendency to reduce concentrations of nitrate in the surface 30-cm layer of soil, but this relationship explained only 8% of the variability in these concentrations. May rainfall did not influence nitrate concentrations in the surface 60-cm layer of soil (Fig 4), but it explained 11% of the variability in differences in soil nitrate concentrations between the 0-30 cm and 30-60 cm layers of soil. Nitrate concentrations in the surface 30-cm layer of soil were linearly correlated (slope=0.31; $r^2=0.34$) with those between 30 and 60-cm. These observations suggest that May rainfall had
Fig. 4. Relationship between May rainfall and A) soil nitrate-N concentration to 30 cm, B) soil nitrate-N concentration to 60 cm, C) soil exchangeable ammonium-N to 30 cm, and D) soil nitrate-N and exchangeable ammonium-N to 60 cm.
a tendency to move nitrate from the surface to the lower layer of soil.

Published yield potentials of the soils showed no useful relationship to yield response to added N (Fig 5). Yields observed on fertilized plots were significantly related to yield responses (Fig 6), but this relationship explained only 5% of the variability in yield response. Lack of good relationships in Fig 5 and Fig 6 should be expected because N from manure would obscure relationships that might be expected without the addition of manure. Published yield potentials showed statistically significant linear relationships with yields observed on the fertilized plots, but this relationship explained only 2% of the variability in yields. Weather and other factors obscured any expected relationship between yield potential and observed yields within any given field and year.

Soil organic matter concentrations showed no significant relationship to yields or yield responses to applied N (Fig 7). Organic matter concentrations were linearly related to published yield values and yields observed on fertilized plots, but these relationships explained only 5% and 2% of the respective variability. Although yield potential is influenced by soil organic matter content (Follet et al, 1987), Doran and Smith (1987) noted that N availability from soil organic matter is often difficult to predict.

Soil test values for phosphorus (P) and potassium (K) were significantly related to yield responses (Fig. 8A and 8B), but they explained only 6% and 7% of the variability in yield response. The greatest responses tended to occur at the lowest soil test values. A likely explanation for this relationship is that the higher P and K soil test values resulted from previous applications of animal manure and that these applications increased mineralization rates in the soil. Evidence to support this possibility is provided by a statistically significant
Fig. 5. Relationship between published yield potential of the soils and corn yield response to 100 kg added N/ha.
Fig. 6. Relationship between yields observed with 100 kg added N/ha and corn yield response to 100 kg added N/ha.

\[ y = 0.1158(x) - 0.572 \]

\[ r^2 = 0.05 \]
Fig. 7. Relationship between soil organic matter concentration and corn yield response to 100
Fig. 8. Relationship between A) soil test phosphorus, B) soil test potassium, and corn yield response to 100 kg added N/ha.

A. Bray-1 extractable P

\[ y = 0.16 + (1.072 \times e^{-0.0295 \times P}) \]

\[ r^2 = 0.06 \]

B. Ammonium acetate-extractable K

\[ y = -1.53 + (2.7236 \times e^{-0.0014 \times K}) \]

\[ r^2 = 0.07 \]
Fig. 9. Relationship between A) soil test phosphorus, B) soil test potassium, and soil nitrate-N concentration to 30 cm.
tendency for soil nitrate-N concentrations to increase with soil test values for P and K (Fig 9A and 9B). The relatively high soil test values observed in this study undoubtedly reflect previous application of manure at relatively high rates. Soil test P and soil test K showed a significant linear relationship (Fig 10) with an $r^2$ of 0.56. However, neither P nor K was significantly correlated with manure-N applied for the years studied.

Soil pH was significantly related to yield response (Fig 11). The greatest responses tended to occur at the highest pH values. This relationship explained 7% of the variability in response. A possible explanation for this general trend observed in Fig. 11 is greater volatilization of ammonia soon after application to soils having relatively high pH values. Al-Kanani et al. (1992) observed a relationship between soil pH and rates of ammonia volatilization.

Concluding Comments

Of the factors considered, soil nitrate concentration provided the most reliable distinction between responsive and non-responsive sites. This can be explained because the reliability of the soil test is not affected by uncertainty in amounts of manure-N applied, percentages of manure-N lost soon after application, or amounts of N mineralized from previous applications of manure. Detailed analyses presented by Hansen and Blackmer (1999) show how the soil test can be used to select optimal rates of fertilization on manured soils.

The finding that soil nitrate concentrations showed good relationships with yield responses to added N but poor relationships with amount of manure-N applied deserves attention. It seems unlikely that uncertainty in amounts of manure-N applied or amounts
Fig. 10. Relationship between soil test phosphorus and soil test potassium.

\[ y = 1.65x + 121.061 \]

\[ r^2 = 0.56 \]
Fig. 11. Relationship between soil pH and corn yield response to 100 kg added N/ha.
mineralized could be responsible for the lack of relationship between rate of manure-N application and soil nitrate concentrations. However, unpredictable variability in percentage losses of manure-N that tend to increase with rate of application could be the major factor. If the uncertainty is largely caused by losses of manure-N soon after application, then testing soils for nitrate concentrations in late spring may be an effective way to compare percentages of manure-N lost by various application methods. Soil testing for nitrate should be more reliable for this purpose than measuring yield response because yield response is greatly affected by factors other than N loss. For this reason soil testing to evaluate manure application techniques may provide benefits that are independent of assessing N fertilizer needs.

This study was not conducted with a high degree of certainty concerning amounts of manure applied or composition of the manure. However, current methods of manure application and variability in manure composition make it difficult to attain certainty in amounts of manure-N applied in controlled studies. It is unrealistic, therefore, to expect a high degree of certainty concerning amounts of manure-N applied in production agriculture. Moreover, this knowledge is of little value unless the percentage of manure-N lost soon after application is known. For these reasons, the finding that we could not identify significant relationships in our study means that they should not normally be expected in production agriculture.


SOIL NITRATE TEST CALIBRATIONS BASED ON PROBABILITY OF RESPONSE AND NET RETURNS TO FERTILIZATION

A paper prepared for submission to Agronomy Journal

D.J. Hansen and A.M. Blackmer

Abstract

Soil tests based on nitrate concentrations in the surface 30 cm of soil when corn (Zea mays L.) plants are approximately 30 cm tall have been shown to reduce uncertainty concerning amounts of plant-available N supplied by applications of animal manures. The extent to which this potential is utilized, however, depends on the quality of the N fertilizer recommendations used with the soil test. Nitrogen response trials with four rates of N (0, 33, 67, and 100 kg N/ha) were conducted at 205 sites in Iowa that were manured and managed by corn producers using their normal practices. Soil nitrate concentrations before fertilization and price ratios for corn and fertilizer N common in the Corn Belt were used to develop recommendations that allow site-specific adjustments of N rates based on maximizing net returns to fertilizer N. Use of these recommendations across the range of prices considered would have increased mean net returns to fertilization from 0.18 to 0.64 Mg/corn when compared to a constant rate of 100 kg N/ha. Mean rates of N fertilization would have decreased from 48% to 73%. Results suggest that use of these recommendations can help producers increase mean net returns to fertilization while decreasing mean rates of fertilizer N on manured cornfields.

Introduction

Concentrations of nitrate in the surface 30-cm layer of soil in late spring can be used to assess whether soils have adequate nitrogen for growth of corn (Magdoff et al., 1984; Blackmer
et al., 1989; Fox et al., 1989; Magdoff et al., 1990; Binford et al., 1992). Studies across a wide range of conditions show remarkable agreement that the critical concentration of soil nitrate-N (i.e., the concentration that distinguishes soils that should be fertilized from those that should not) occurs between 20 and 25 mg N/kg (Magdoff, 1990; Sims et al., 1995). There is widespread agreement that additional N should not be applied to soils testing above the critical concentration (Fox et al., 1989; Meisinger et al., 1992; Schepers and Meisinger, 1994; Lory et al., 1995). However, the ability of soil nitrate tests to predict optimal rates of N fertilization at low-testing sites has not been established.

The need for assessing the ability of late-spring tests for soil nitrate to predict N fertilizer needs on cornfields recently treated with animal manure was illustrated in a study reported by Hansen et al. (1999). This study involved measuring yield responses to commercial N fertilizer at 205 sites where manure had been applied by producers using normal practices. The results showed that soil nitrate concentrations were more reliable predictors of yield responses than any other information likely to be available to producers at the time of fertilization. Variability in percentages of manure-N lost between manure application and late spring seemed to make rates of manure application a poor predictor of yield responses to the commercial N fertilizer.

There is no generally accepted single method for experimentally establishing amounts of fertilizer N needed for given soil-test values that are below established critical concentrations. The problem is especially severe on soils treated with animal manure because yield responses may not occur at many sites and they are often small at most sites. A possible solution to this problem is offered by profit-maximizing techniques used by Binford et al.
(1992), Morris et al., (1993) and Mallarino and Blackmer, (1994). This method essentially involves measuring yield responses at many sites where fertilizer N is added and using the results to develop recommendations that would have maximized mean net returns to fertilization across all these sites in relevant price ratios. It is well established that relative prices of grain and fertilizer influence optimal rates of fertilization (Oberle and Keeney, 1990; Bock and Hegert, 1991; Mallarino and Blackmer, 1994).

The objective of this study was to calibrate the late-spring test for soil nitrate in terms of probabilities of response to additional fertilizer and expected net returns to fertilization in cornfields that have already received applications of animal manure. The term "calibration" is used to denote experimental determination of appropriate critical concentrations and amounts of fertilizer that should be applied for any given concentration of soil nitrate in any given price ratio. Probability of response is often discussed as a basis for interpreting the results of soil tests (Fitts, 1955; Dahnke and Olson, 1990). Blackmer and White (1998) concluded that estimates of the probability of a yield response to fertilization offer promise for making fertilizer recommendations that address spatial and temporal variability in fertilizer needs within and among fields.

Materials and Methods

Trials evaluating the response of corn to commercially prepared N fertilizer were conducted in 205 cornfields that had been manured by farmers using their normal practices. The trials were distributed across 28 counties in Iowa, with approximately equal numbers each year from 1992 through 1997. Sites were selected to include variety with respect to soils, manure type, rate of application, method of application, and time of application. Soil and crop
management practices (except N fertilization) were those normally used by each farmer.

The manure came from beef cows at 22 sites, dairy cows at nine sites, swine at 149 sites, and poultry at nine sites. Sixteen sites received two or more forms of animal manure. Approximately equal numbers of sites were manured in the fall, winter, and spring before planting. Some sites had not received applications of animal manure since harvest of the previous crop, but these sites had received at least two applications of manure in the previous four years. Information concerning amounts, type, and time of manure application was provided by farmers.

Each trial consisted of 16 plots arranged in a randomized complete-block design with 4 replications. Plots were 12.2-m long and six rows wide for 76-cm spacings or four rows wide for 91-97 cm spacings. Soil samples were collected from each block within each site. Each sample was derived from a composite of 32 soil cores. The soils were air-dried and subsequently analyzed for inorganic nitrogen by the Lachat flow-injection procedure (Lachat Instruments, Milwaukee, WI; Method 12-107-4-1-B). Rainfall amounts for the nine regions within Iowa were obtained from the National Climatic Data Center, Asheville, North Carolina (1998).

Soon after soil samples were collected four rates of N (0, 33, 67, and 100 kg N/ha) were broadcast on the soil surface. In 1992, 1993, and 1994, N was applied as ammonium nitrate (NH₄NO₃); in 1995, 1996, and 1997 N was applied as urea ((NH₂)₂CO). Grain was hand-harvested from 7.6-m sections of the center two rows of each plot. Yields were adjusted to 15.5% moisture content.

Yield responses to N fertilization were calculated by subtracting the mean yield of the
nonfertilized plots from the mean yield of the fertilized plots for each site. Mean net returns (Mg/ha) to N fertilization for various price ratios were calculated by subtracting the cost of fertilizer and fertilizer application, expressed as a quantity of grain, from the mean yield responses by site and treatment. Price ratios were selected to include the range of prices found in Iowa (N.A.S.S., 1998). We assumed an application cost equal to 0.1 Mg/ha of grain after Edwards and Vontalge (1998).

Statistical analysis of yields response and mean net returns were performed by using a linear response-plateau model (Waugh et al., 1973). Protected least significant difference (LSD) values for yield responses for pooled data were calculated after Snedecor and Cochran (1980). The treatment effect required by this method was determined by standard analysis of variance (ANOVA) techniques. An alpha of 0.05 was used for all analyses (SAS Institute, 1988).

Results

Mean yields for the various N treatments within years are shown in Table 1. It is noteworthy that yields were low in 1993 due to poor weather conditions (i.e., unusually wet and cloudy) during the growing season. The low yields cannot be attributed to N deficiencies, however, because cornstalk nitrate concentrations indicated that 95% of the sites had sufficient quantities of N (Hansen and Blackmer, 1999). Data from these trials were retained in the analyses because yield responses to applied N were not extraordinarily different than those observed in other years.

Figure 1 shows the relationship between relative yields of grain and concentrations of nitrate found in the surface 30-cm of soil when corn plants are 15 to 30-cm tall (i.e., before
Table 1. Mean yields of corn at 4 different N rates observed in 205 trials on manured cornfields.

<table>
<thead>
<tr>
<th>Year</th>
<th>0 kg N/ha</th>
<th>33 kg N/ha</th>
<th>67 kg N/ha</th>
<th>100 kg N/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>10.04 (0.29)</td>
<td>10.45 (0.26)</td>
<td>10.74 (0.27)</td>
<td>10.75 (0.26)</td>
</tr>
<tr>
<td>1993</td>
<td>6.11 (0.18)</td>
<td>6.23 (0.17)</td>
<td>6.27 (0.18)</td>
<td>6.30 (0.18)</td>
</tr>
<tr>
<td>1994</td>
<td>9.84 (0.33)</td>
<td>10.31 (0.30)</td>
<td>10.52 (0.28)</td>
<td>10.67 (0.30)</td>
</tr>
<tr>
<td>1995</td>
<td>9.09 (0.24)</td>
<td>9.23 (0.23)</td>
<td>9.39 (0.21)</td>
<td>9.39 (0.20)</td>
</tr>
<tr>
<td>1996</td>
<td>10.49 (0.37)</td>
<td>10.85 (0.34)</td>
<td>11.15 (0.28)</td>
<td>11.26 (0.28)</td>
</tr>
<tr>
<td>1997</td>
<td>9.48 (0.21)</td>
<td>9.58 (0.21)</td>
<td>9.78 (0.20)</td>
<td>9.94 (0.18)</td>
</tr>
</tbody>
</table>

*Numbers in parenthesis are standard error of the mean.*

application of commercial fertilizers). Such relationships are a measure of yield response to fertilizer N and have been used to establish critical concentrations of soil nitrate (Magdoff et al., 1984; Blackmer et al., 1989; Fox et al., 1989). The Cate-Nelson two-population split identified 13 mg N/kg as the critical concentration of nitrate.

As noted by Black (1993) relationships of the type presented in Fig. 1 do not permit economic analyses, which are critical to the objectives of this paper. In our analyses we also found a problem associated with situations where the addition of fertilizer N decreased yields. These yield decreases often resulted in unrealistically high relative yields at relatively low soil nitrate concentrations. For these reasons all analyses elsewhere in this paper are based on observed yield responses to added fertilizer N as recommended by Nelson and Anderson (1977).

Figure 2 shows relationships between yield responses to commercial fertilizer and
Fig. 1. Relationship between soil nitrate-N concentration to 30 cm depth and relative yield of corn.
Fig. 2. Relationship between soil nitrate-N concentration to 30 cm depth and corn yield response to A) 33 kg, B) 67 kg, and C) 100 kg added N/ha.
concentrations of nitrate in the soil before fertilizers were added. Models presented indicate that soil nitrate concentrations explained from 24 to 37% of the variability in yield response. Percentages of the variability explained tended to increase with increasing rate of fertilization. This observation is reasonable because the higher rates of fertilization produced greater yield responses at low soil nitrate concentrations without increasing variability in yields at high soil test values. Inflection point of the models occurred between 17 and 26 mg N/kg soil. Although these inflection points could be considered critical concentrations, we are not using them as critical concentrations because they do not consider profitability of fertilization.

Table 2 shows mean yield responses for various categories formed by soil nitrate concentrations and rates of N application. These categories are used to facilitate interpretation of soil nitrate concentrations and the rationale for selecting break points between categories is explained in the discussion section. Mean yield responses to added N ranged from -0.08 to 1.97 Mg/ha for the various categories. The greatest range in yield responses occurred within the highest rate of N application. Additions of N resulted in mean decreases in yields when 67 or 100 kg N/ha was applied to sites having soil nitrate concentrations greater than 25 mg N/kg. The reason for these yield decreases is not known. The mean yield responses observed in this study provide an estimate of yield responses that could be expected in other situations where soil nitrate concentrations are known.

Percentages of sites showing positive yield responses within various categories formed by soil nitrate concentrations and rates of N application ranged from 26 to 100% (Table 3). The greatest range in percentage among soil nitrate categories was observed at the highest rate of N application; this indicates that the highest rate was sometimes needed to maximize yields.
Table 2. Mean yield response of corn to 3 different N rates observed in 205 trials when sites are grouped by soil nitrate concentration before fertilization.

<table>
<thead>
<tr>
<th>Soil N Category</th>
<th>Mean yield response to added N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>33 kg N/ha</td>
</tr>
<tr>
<td>&lt; 10 mg N/kg</td>
<td>1.01 (0.13)</td>
</tr>
<tr>
<td>10 to 14 mg N/kg</td>
<td>0.47 (0.11)</td>
</tr>
<tr>
<td>15 to 19 mg N/kg</td>
<td>0.32 (0.10)</td>
</tr>
<tr>
<td>20 to 24 mg N/kg</td>
<td>0.14 (0.12)</td>
</tr>
<tr>
<td>≥ 25 mg N/kg</td>
<td>0.01 (0.06)</td>
</tr>
</tbody>
</table>

*Numbers in parenthesis are standard error of the mean.

Results show that addition of N to sites having soil nitrate concentrations greater than 25 mg N/kg before fertilization were more likely to decrease yields than to increase yields. The percentage of positive responses in this study provides an estimate of the probability of response that could be expected at other sites. These probabilities clearly indicate that substantial uncertainty accompanies any recommendation.

Table 3. Percentage of sites showing statistically significant yield responses to N treatments in 205 trials when sites are grouped by soil nitrate concentration before fertilization.

<table>
<thead>
<tr>
<th>Soil N Category</th>
<th>Percent of sites showing significant yield response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>33 kg N/ha</td>
</tr>
<tr>
<td>&lt; 10 mg N/kg</td>
<td>95 (5)</td>
</tr>
<tr>
<td>10 to 14 mg N/kg</td>
<td>67 (30)</td>
</tr>
<tr>
<td>15 to 19 mg N/kg</td>
<td>67 (17)</td>
</tr>
<tr>
<td>20 to 24 mg N/kg</td>
<td>50 (33)</td>
</tr>
<tr>
<td>≥ 25 mg N/kg</td>
<td>39 (35)</td>
</tr>
</tbody>
</table>

*Numbers in parenthesis are percent of sites with a significant negative yield response to added N.
Data concerning the profitability of fertilization are presented in Table 4, which shows mean net returns to fertilization within the various categories formed by soil nitrate concentrations and rates of N application under various price conditions. Mean net returns were positive for all combinations of price ratio and rates of fertilization when soils tested less than 15 mg N/kg. Mean net returns were negative for all combinations of price ratio and rates of fertilization when soils tested greater than 20 mg N/kg. Mean net returns to fertilization changed from negative to positive with increasing price ratio for soils testing between 15 and 20 mg N/kg.

The rates of fertilization that would have provided the greatest mean net returns to fertilization for the various soil nitrate-price ratio categories are underlined in Table 4. The 33-kg N/ha rate was best in no category. Two different rates of fertilization often resulted in essentially the same net returns. Such results should be expected when added fertilizer increases yields only enough to pay for the fertilizer and associated application costs. Such effects tend to decrease the importance of selecting an exact optimal rate of fertilization at any given site.

Across the range of price ratios considered, the economic cost of having too little fertilizer in the low-testing soil nitrate category was not always higher than the economic cost of having too much fertilizer in the high-testing soil nitrate category. At the lowest price ratio the losses associated with applying too much N were greater than the benefits of applying the optimal rate of N. At the highest price ratio the greatest losses from fertilization were about one-fourth of the greatest net returns to fertilization. At a price ratio of 200 the greatest losses
Table 4. Mean net returns to added N calculated for 5 price scenarios in 205 trials when sites are grouped by soil nitrate concentration before fertilization.

<table>
<thead>
<tr>
<th>Soil N Category</th>
<th>N rate</th>
<th>Mean net returns at various price ratios&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg N/kg Kg/ha</td>
<td>100</td>
</tr>
<tr>
<td>&lt; 10</td>
<td>33</td>
<td>0.58&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.86</td>
</tr>
<tr>
<td>10 to 14</td>
<td>33</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-0.04</td>
</tr>
<tr>
<td>15 to 19</td>
<td>33</td>
<td>-0.12</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>-0.13</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-0.46</td>
</tr>
<tr>
<td>20 to 24</td>
<td>33</td>
<td>-0.30</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>-0.38</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-0.72</td>
</tr>
<tr>
<td>≥ 25</td>
<td>33</td>
<td>-0.43</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>-0.85</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-1.17</td>
</tr>
</tbody>
</table>

<sup>a</sup> Price ratio is equal to the corn price in $/Mg divided by the cost of N in $/kg.

<sup>b</sup> Underlined values identify rates that produced the highest mean net returns.
were about one-half of the greatest net returns.

The percentages of sites showing statistically significant positive (and negative) net returns to added N in various price ratios are shown in Table 5. As should be expected, the percentage of sites having a positive net return to added N increased as price ratio increased for all rates of N. The percentage of sites having significant negative net returns to added N was greater than or equal to the percentage of sites having significant positive net returns for all rates of fertilization and all price ratios when soil nitrate concentrations were greater than 20 mg N/kg.

The finding that net returns to fertilization changed from negative to positive as price ratios increased within the 15 to 20 mg N/kg soil nitrate category (Table 4) means that critical concentrations of soil nitrate must also vary with price conditions. To establish critical concentrations based on net returns to fertilization, figures analogous to Fig 2 were constructed with net returns to fertilization rather than yield responses. Different figures were constructed for each price ratio. Models describing these points were superimposed as shown in Fig 3. The soil nitrate concentrations at which 67 and 100 kg N/ha provided the same net returns was identified. The soil nitrate concentrations at which 0 and 67 kg N/ha provided the same net returns was also identified. These points and points for other price ratios were plotted as shown in Fig 4. Data for the 33 kg N/ha rate are not presented because they never provided maximum net returns. The lines in Fig 4 indicate soil nitrate concentrations where net returns to fertilization are the same for two different rates of fertilization.
Table 5. Percentage of sites having statistically significant mean net returns to added N for 5 price scenarios in 205 trials when sites are grouped by soil nitrate concentration before fertilization.

<table>
<thead>
<tr>
<th>Soil N mg N/kg</th>
<th>N rate Kg/ha</th>
<th>100</th>
<th>140</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>%b</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10</td>
<td>33</td>
<td>76(5)</td>
<td>81(5)</td>
<td>95(5)</td>
<td>95(5)</td>
<td>95(05)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>71(24)</td>
<td>71(19)</td>
<td>76(10)</td>
<td>76(5)</td>
<td>81(05)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>71(24)</td>
<td>76(14)</td>
<td>76(14)</td>
<td>86(00)</td>
<td>86(0)</td>
<td></td>
</tr>
<tr>
<td>10 to 14</td>
<td>33</td>
<td>37(43)</td>
<td>43(33)</td>
<td>50(30)</td>
<td>53(30)</td>
<td>57(30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>43(43)</td>
<td>53(37)</td>
<td>57(27)</td>
<td>57(20)</td>
<td>63(20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>33(53)</td>
<td>43(40)</td>
<td>47(33)</td>
<td>53(27)</td>
<td>60(27)</td>
<td></td>
</tr>
<tr>
<td>15 to 19</td>
<td>33</td>
<td>33(47)</td>
<td>44(36)</td>
<td>47(31)</td>
<td>50(31)</td>
<td>50(31)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>39(42)</td>
<td>42(33)</td>
<td>50(31)</td>
<td>61(25)</td>
<td>61(22)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>17(56)</td>
<td>31(50)</td>
<td>44(36)</td>
<td>50(28)</td>
<td>50(22)</td>
<td></td>
</tr>
<tr>
<td>20 to 24</td>
<td>33</td>
<td>21(63)</td>
<td>21(54)</td>
<td>21(50)</td>
<td>33(46)</td>
<td>33(38)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>25(63)</td>
<td>29(54)</td>
<td>38(46)</td>
<td>42(46)</td>
<td>42(42)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>13(71)</td>
<td>21(63)</td>
<td>33(54)</td>
<td>38(46)</td>
<td>38(42)</td>
<td></td>
</tr>
<tr>
<td>≥ 25</td>
<td>33</td>
<td>5(70)</td>
<td>11(65)</td>
<td>18(56)</td>
<td>18(51)</td>
<td>23(49)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>2(93)</td>
<td>4(86)</td>
<td>7(72)</td>
<td>7(61)</td>
<td>12(58)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0(100)</td>
<td>0(93)</td>
<td>2(82)</td>
<td>4(70)</td>
<td>7(60)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>33</td>
<td>28(51)</td>
<td>34(44)</td>
<td>40(39)</td>
<td>43(36)</td>
<td>45(35)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>29(60)</td>
<td>33(53)</td>
<td>38(43)</td>
<td>41(37)</td>
<td>45(35)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>20(68)</td>
<td>27(60)</td>
<td>33(51)</td>
<td>38(41)</td>
<td>40(36)</td>
<td></td>
</tr>
</tbody>
</table>

a Price ratio is equal to the corn price in $/Mg divided by the cost of N in $/kg.
b Numbers in parenthesis are percent significant negative net returns.
Fig. 3. Relationship between soil nitrate-N concentrations at 30 cm depth and net returns to added N calculated at price ratios of A) 100, B) 200, and C) 400 (kg N per Mg corn).
Data presented in Table 4 show that the critical concentration of soil nitrate (i.e., the concentration above which fertilization would not be profitable) varies with price ratio. Data presented also show that the soil nitrate concentration at which it was profitable to change from 67 to 100 kg N/ha varied with price ratio. For these reasons price ratio changed critical soil nitrate concentrations and optimal rates of fertilization simultaneously. However, the optimal combination of N rates and critical levels can be easily read from Fig 4.

Results (not presented) show that sampling to 60 cm resulted in essentially the same amounts of fertilizer applied and net returns to fertilization as did sampling to 30 cm (i.e., the underlined values in Table 4). It should be noted that the critical concentrations were lower for the deeper sampling. The appropriate critical levels for this depth are shown in Fig 5. The finding of no noteworthy benefits to deeper sampling is consistent with findings of Binford et al (1992) and Sims et al. (1997).

Discussion

The critical concentrations of nitrate shown in Fig 4 and 5 should be expected to differ from the Cate-Nelson critical levels (Fig.1) due to differences in objectives of the calculations involved. The Cate-Nelson critical concentrations are selected so as explain the greatest possible percentage of the variance in the relationship between soil nitrate concentrations and relative yields. The critical concentrations shown in Fig 4 and 5 were calculated so as to maximize net returns to fertilization. These can be denoted as profit-maximizing critical concentrations, and it should be expected that these vary with relative prices of fertilizer and grain. It is only fortuitous if the Cate-Nelson critical concentrations match the profit-maximizing concentrations in any given situation.
Fig. 4. Relationship between price ratio (kg N per Mg corn) and critical concentration of soil nitrate-N at 30 cm depth.

\[ y = -64.2068 + 27.2281 \ln x - 2.1460 (\ln x)^2 \]
\[ r^2 = 0.999 \]

\[ y = -104.6354 + 38.0418 \ln x - 3.0322 (\ln x)^2 \]
\[ r^2 = 0.999 \]
Fig. 5. Relationship between price ratio (kg N per Mg corn) and critical concentration of soil nitrate-N at 60 cm depth.
The tendency for profit-maximizing critical concentrations of nitrate to vary with price ratio makes it impossible to defend exact breakpoints between categories that describe soil nitrate. Our decision to break soil nitrate categories at concentrations of 10, 15, 20, and 25 mg N/kg, therefore, was based on the ease at which the breakpoints could be remembered. We reasoned that five categories were commonly used in soil testing and that five categories were adequate to capture most of the information the soil test provided amid uncertainties associated with sampling errors and effects of weather after the samples were collected.

Calibrating soil tests in terms of probability of obtaining a profitable response and expected net returns to fertilization gives an objective assessment of the uncertainty involved in any recommendation. Clear statements of uncertainty are important because, as noted by Melsted and Peck (1973), there has been considerable controversy associated with soil testing and much of this controversy can be traced to a lack of understanding of the meaning of soil tests and how they should be interpreted. Statements indicating probabilities of response or of profitable outcomes of fertilization clearly indicate that use of the recommendations are intended to maximize profits when used across many fields even though they cannot be expected to maximize profits in every field.

It is difficult to assess the benefits of using soil testing with profit-maximizing critical concentrations to guide N fertilization on manured cornfields because the benefits obtained depend both on amounts of plant-available N supplied by application of manure and reliability of the fertilizer recommendations currently used. Data presented in Tables 6 any 7 show that use of soil testing with profit-maximizing critical concentrations across the range of conditions included in this study would have increased net returns, decreased average rates
Table 6: Mean net returns to added N across 205 sites for five price ratios when different amounts of fertilizer N are added.

<table>
<thead>
<tr>
<th>Recommendation</th>
<th>Mean net returns to N (Mg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System</strong></td>
<td>100</td>
</tr>
<tr>
<td>33kg</td>
<td>-0.14</td>
</tr>
<tr>
<td>67kg</td>
<td>-0.24</td>
</tr>
<tr>
<td>100kg</td>
<td>-0.50</td>
</tr>
<tr>
<td>Soil Test</td>
<td>0.14(27)</td>
</tr>
</tbody>
</table>

*a* numbers in parenthesis are mean kg N/ha applied across all sites.

of fertilization, or both. It should be noted, however, that the range of field conditions included in this study was selected to be best for calibrating the soil test rather than to provide a survey of manure management practices.

It is impossible to assess the benefits of varying critical concentrations of soil nitrate to match price ratios from data collected in this study because we have not characterized variability in prices or farmer's ability to predict prices at the time of fertilization. Data in Table 7, however, show the costs of using inappropriate price ratios across the range of conditions included in this study. The question needs to be asked why any producer would elect to use a critical concentration selected without regard to price ratio when it costs no more to use a critical concentration selected for the specific price conditions expected.

The benefits of using soil testing to guide fertilization result from the grouping of soils so as to reduce amounts of unexplained variability in optimal rates of N fertilization. This grouping is based on amounts of plant-available N already in the soil. Reducing unexplained variability clearly improves ability to select rates that are optimal for individual sites, but it cannot be expected to alleviate all uncertainty. In fields where animal manure has
Table 7: Mean net returns added N across 205 sites when different critical soil nitrate concentrations are used.

<table>
<thead>
<tr>
<th>Fertilize Rate</th>
<th>Critical Value</th>
<th>Mean net returns to N</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/ha</td>
<td>mg N/kg</td>
<td>100</td>
</tr>
<tr>
<td>33 kg</td>
<td>10</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.01</td>
</tr>
<tr>
<td>67 kg</td>
<td>10</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.04</td>
</tr>
<tr>
<td>100 kg</td>
<td>10</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

been applied, however, adjusting rates of fertilization for amounts of plant-available N already in the soil seems to have great potential for improving N management. Analysis presented by Hansen et al. (1999) suggest that soil testing is the best available method of making such adjustments for manured cornfields.

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QUANTITATIVE INTERPRETATIONS FOR THE END-OF-SEASON TEST FOR CORNSTALK NITRATE

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Abstract

The end-of-season test for cornstalk nitrate has been used to evaluate and improve nitrogen management during corn (Zea mays L.) production. Use of the test, however, is limited by guidelines that are more qualitative than quantitative. Nitrogen response trials with four rates of N (0, 33, 67, and 100 kg N/ha) were conducted at 205 sites in Iowa that were manured and managed by corn producers using their normal practices. Guidelines were developed that define end-of-season cornstalk nitrate categories in terms of mean net returns and probabilities of a profitable yield response to fertilizer-N across the range of prices for corn and fertilizer commonly found in the Corn Belt. At the most favorable prices considered mean net returns to 100 kg added fertilizer N/ha ranged from 1.22 Mg corn when sites tested in the low cornstalk nitrate category to -0.40 Mg corn when sites tested in the above optimal category. These returns were associated with a probability of a significant ($\alpha = 0.05$) positive return to added N of 82% and 8%, and a probability of a significant negative net return of 7% and 56% respectively. Relationships also were developed that relate cornstalk nitrate concentrations to additional quantities of fertilizer N that should have been applied. Results show that use of the end-of-season test for cornstalk nitrate can be a useful tool to evaluate N management on manured cornfields.
Introduction

Concentrations of nitrate in cornstalks at the end of the season provide the basis for a tissue test that can be used to make after-the-fact assessments of N sufficiency for corn growth (Binford et al. 1990, 1992; Sims et al., 1995; Varvel et al., 1997). The test has been used in surveys to evaluate N management practices within a region (El-Hout and Blackmer, 1990). It has been used to help interpret results of N-response studies conducted on small plots (Binford et al., 1992; Morris et al., 1993). It has been used to give site-specific assessments of N sufficiency when characterizing spatial variability in N fertilizer needs within fields (Blackmer and White, 1998). Current guidelines for using this test in Iowa (Blackmer and Mallarino, 1996) recommend that all corn producers take a few samples from each of their fields to evaluate their N management and thereby obtain site-specific feedback that can be used to improve their management. This test is unique among tissue tests for corn in that it characterizes degrees of N excess as well as degrees of N deficiencies.

This test was calibrated by using pooled data from many response trials having 10 rates of fertilizer applied (Binford et al., 1992). The calibrations showed that commonly observed cornstalk nitrate concentrations ranged from <100 to >10,000 mg N/kg. Current Iowa guidelines for using the test divide cornstalk nitrate concentrations into four categories: low, 0 to 250 mg N/kg; marginal, 250 to 700 mg N/kg; optimal, 700 to 2000 mg N/kg; and above optimal, >2000 mg N/kg (Blackmer and Mallarino, 1996). Low concentrations indicate a high probability that greater availability of N would have resulted in higher yields. Marginal concentrations, while indicative of a high probability that N availability was in the range needed to maximize profits, are considered to be “too close” to low to serve as a target.
concentration. Optimal concentrations indicate high probability that N availability was in the range needed to maximize profits for producers. Above-optimal concentrations indicate high probably that N availability was greater than if fertilizer N had been applied at rates that maximized profits for producers. Although these qualitative definitions are useful when interpreting results of cornstalk testing, information that is more quantitative would be more useful.

The objective of this study was to define end-of-season cornstalk nitrate concentrations more quantitatively in terms of expected effects of fertilizer N that could have been applied but was not applied. Fertilization effects considered are mean increase in yields, probability of a yield increase, mean expected returns to fertilization, and probability of a profitable yield increase. The design of the study assumes that the cornstalk test will most often be used to evaluate insufficiency in fields that were fertilized in accordance with normal production practices.

Materials and Methods

Trials evaluating the response of corn to commercially prepared N fertilizer were conducted in 205 cornfields that had been manured by farmers using their normal practices. The trials were distributed across 28 counties in Iowa, with approximately equal numbers each year from 1992 through 1997. Sites were selected to include variety with respect to common soil types, manure types, rates of application, methods of application, and times of application. Soil and crop management practices (except N fertilization) were those normally used by each farmer. Details concerning types and amounts of manure applied are given by Hansen et al. (1999). It was assumed that N supplied by manure gave a distribution of background levels of
plant-available N and that this distribution generally represents the range in N levels found after soils are fertilized by normal practices.

Fertilizer treatments were applied in a randomized complete-block design with four replications at each site. Plots were 12.2-m long and four rows wide for 76-cm spacings or six rows wide for 91-97 cm spacings. Four rates of N (0, 34, 67, and 100 kg N/ha) were broadcast on the soil surface in early June (i.e., when corn plants were approximately 30 cm tall). In 1992, 1993, and 1994, N was applied as ammonium nitrate (NH₄NO₃); in 1995, 1996, and 1997 N was applied as urea ((NH₂)₂CO). Grain was hand-harvested from 7.6-m sections of the center two rows of each plot. Yields were adjusted to 15.5% moisture content.

Cornstalk samples were collected from 7.6-m sections of the center two rows of each plot. Each sample consisted of sixteen 20-cm sections of the plant taken from 16 to 36-cm above the ground. Air-dried cornstalk samples are ground to pass a 1.0-mm sieve. A 0.5- to 1.0-g sample of the ground cornstalk is extracted with 50 ml of 0.025 M Al₂(SO₄)₃. The filtered extracts are treated with 1 ml of 2 (NH₄)₂SO₄ to each 50-ml extract to minimize differences in ionic strength. Nitrate determinations of the prepared extracts are performed using an Orion Model 93-07 nitrate specific electrode (Orion Research Inc., Boston MA).

Mean net returns (Mg/ha) to N fertilization for each site and N increment were calculated for various price ratios by subtracting the cost of fertilizer and fertilizer application, expressed as a quantity of grain, from the quantity of grain produced on fertilized plots compared with plots that did not receive the additional N. We assumed an application cost of 0.1 Mg of grain. The price scenarios were selected to include the range of prices found in Iowa (N.A.S.S., 1998).
Prior to some data analysis, cornstalk nitrate concentrations were transformed to YB Index values as described by Yang and Blackmer (1997). The transformation is given by the Equation [1].

\[ YB\ Index = 11.43 - 100 \times \log_{10}(\log_{10}(14,000/\text{stalk nitrate})) \]  

This transformation gives an index of nitrogen sufficiency that is linearly related to availability of N for corn growth. This index has negative values when availability of N is below optimal and positive values when availability of N is above optimal.

Statistical analyses of yield response were performed by using a exponential function described by Nelson and Anderson (1977). Cornstalk nitrate categories used are based on those presented by Blackmer and Mallarino (1996). Protected least significant difference (LSD) values for yield responses for pooled data were calculated after Snedecor and Cochran (1980). The treatment effect required by this method was determined by standard analysis of variance (ANOVA) techniques. An alpha of 0.05 was used for all analyses (SAS Institute, 1988).

Results

Statistically significant relationships were observed between yield responses to fertilizer N and stalk nitrate concentrations on non-fertilized plots at the same sites (Fig 1.). Within-site effects of fertilization are indicated by the magnitude of yield response, and these responses tended to be greatest at sites where stalk nitrate concentrations were below the optimal range. This trend should be expected because the stalk test is a measure of N.
Fig. 1. Relationship between concentration of nitrate-N in cornstalks and corn yield response to A) 33 kg, B) 67 kg, and C) 100 kg added N/ha.
sufficiency for corn growth; higher concentrations of stalk nitrate in the non-fertilized plots indicate that higher portions of the plant's N requirement were supplied by N derived from the soil or animal manure.

Figure 2 illustrates the effect of transforming stalk nitrate concentrations to YB index values. This transformation redistributes stalk nitrate data along the x-axis by placing more space between points at lower stalk nitrate concentrations and less space between points at higher stalk nitrate concentrations. The position of points on the y-axis is not changed. An advantage of this transformation is that the distance between points on the x-axis tends to be proportional to amounts of available N in soils and, therefore, trends are more clearly illustrated in the below- and near-optimal range. Although the transformation alters coefficients in models fit to the data, it has no effect on r-square values or the extent to which observations differ from the model.

An important point illustrated in Fig. 2 is that no obvious trend in yield response was observed among the data points within the low range for cornstalk values. The lack of trend within this range is consistent with the notion that nutrient concentrations in plant tissues have a "minimum percentage" as defined by Macy (1936). Unlike when higher concentrations are found, the magnitude of potential response to added nutrients cannot be estimated when concentrations of nutrients are at this minimum. An additional factor may be that stalk nitrate concentrations were determined with the idea that variations in concentrations below 100 mg N/kg were unimportant, so the measured variability in this range may not accurately indicate real variability in the plants. The lack of a trend within this category suggests that data collected in this study offer no practical reason to subdivide this
Fig. 2. Relationship between YB Index values and corn yield response to A) 33 kg, B) 67 kg, and C) 100 kg added N/ha.
Most of the variability in yield responses at the sites having above-optimal stalk nitrate concentrations should be attributed to within-site variability in yield for reasons that cannot be explained by measurements taken. Within-site variability, for example, can be caused by spatial variability in water availability or aeration due to locations of subsurface sand lenses, tile drains, or zones of compaction due to wheel tracks (Garcia et al, 1988). Because such variability is confounded with N availability, within-site variability in N availability cannot be distinguished from within-site variability due to other factors.

Greater variability in yield response was observed in categories where stalks on non-fertilized plots tested in the below-optimal category than when they tested in the optimal and above-optimal category. This difference should be expected because additional factors, including spatial variability in losses of fertilizer N, can cause within-site variability in magnitudes of yield response to applications of N. Furthermore, yield variability due to unintended within-site variability in N availability should tend to diminish as N availability increases because the physiological effects of excess N are relatively small.

Mean increases in yield ranged from -0.04 to 1.58 Mg/ha for various categories formed by stalk nitrate concentrations and rates of N application (Table 1). The greatest range occurred with highest rate of N application. Additions of N resulted in mean decreases in yields for the 67 and 100-kg N/ha treatments at sites where stalks on the non-fertilized plots had above-optimal concentrations of stalk nitrate. Analyses presented by Hansen and Blackmer (1999) indicate that responses to the 100-kg/ha rate were statistically significant at 58% of the sites. Similar analyses indicated that responses to the 33 and 67 kg/ha rates were
statistically significant at 60 and 59% of the sites.

The percentage of sites that showed statistically significant positive yield responses varied greatly among categories formed by considering rates of fertilization and stalk nitrate concentrations on non-fertilized plots (Table 2). Mean percentages for the various categories ranged from 36 to 91%. The greatest range occurred in the highest N treatment. It is noteworthy that significant yield decreases to added N ranged from 2 to 40% of the sites within the various categories. The percentage of sites showing a significant positive yield response to added N was approximately equal to the percent of sites showing a significant yield decrease to added N within the category formed by grouping all sites with cornstalk nitrate concentrations greater than 2000 mg N/kg.

Table 1. Mean yield response to 3 rates of added N observed in 205 trials when plots are grouped by nitrate concentration in cornstalks from nonfertilized plots.

<table>
<thead>
<tr>
<th>Stalk N Category</th>
<th>Mean yield response to various quantities of added N</th>
</tr>
</thead>
<tbody>
<tr>
<td>-mg N/kg-</td>
<td>33 kg N/ha</td>
</tr>
<tr>
<td>&lt; 250</td>
<td>0.70 (0.10) a</td>
</tr>
<tr>
<td>250-699</td>
<td>0.40 (0.09)</td>
</tr>
<tr>
<td>700-1999</td>
<td>0.11 (0.12)</td>
</tr>
<tr>
<td>&gt; 2000</td>
<td>0.01 (0.05)</td>
</tr>
</tbody>
</table>

a Numbers in parenthesis are standard error of the means.

The interpretations of stalk nitrate categories given in Tables 1 and 2 are based on yield responses whereas those previously given by Blackmer and Mallarino (1996) are based on expected profits. Data concerning the profitability of fertilization are presented in Table 3, which shows mean net returns to fertilization under various conditions. The price
conditions considered range from relatively unfavorable to relatively favorable for producers based on prices for grain and fertilizer found the Corn Belt during the past decade.

Ratios of prices for fertilizer and grain had significant effects on net returns to fertilization (Table 3). However, mean net returns to N fertilization were negative for all rates of fertilization and for all price scenarios for sites where stalks from the non-fertilized plots tested in the “optimal” or “above-optimal” categories. Mean net returns were positive for all rates of fertilization at sites where these stalks tested in the “low” category. Net returns varied from negative to positive with price conditions at sites where stalks tested in the “marginal” category.

Table 2. Percentage of sites having a statistically significant yield response to added N when plots are grouped by nitrate concentration in cornstalks from nonfertilized plots.

<table>
<thead>
<tr>
<th>Stalk N Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>mg N/kg-</td>
</tr>
<tr>
<td>&lt; 250</td>
</tr>
<tr>
<td>250 to 699</td>
</tr>
<tr>
<td>700 to 1999</td>
</tr>
<tr>
<td>≥ 2000</td>
</tr>
<tr>
<td>%</td>
</tr>
</tbody>
</table>

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of sites showing significant yield response</td>
</tr>
<tr>
<td>33 kg N/ha</td>
</tr>
<tr>
<td>%</td>
</tr>
<tr>
<td>85 (11)</td>
</tr>
<tr>
<td>68 (21)</td>
</tr>
<tr>
<td>55 (35)</td>
</tr>
<tr>
<td>44 (40)</td>
</tr>
</tbody>
</table>

a Numbers in parenthesis indicate the percentage of sites showing significant negative responses to added N.

Analyses presented in Table 3 indicate that, for all but the lowest price ratios, net returns would have been greatest if the 100-kg/ha rate had been applied to sites where stalks from the non-fertilized plots tested in the low category. The 67-kg N/ha rate would be best for sites where stalks from the non-fertilized plots tested in the marginal range and price.
conditions were represented by the four best ratios considered. Application of no fertilizer N was the best option for all remaining categories; application of fertilizer N at rates of 33 kg N was never indicated to be the best choice.

The rates of fertilization indicated in Table 3 are comparable to those identified as being optimal when the late-spring test for soil nitrate was used to group the soils (Hansen and Blackmer, 1999). The soil test data showed that the 33-kg N/ha rate was never the most profitable and it usually agreed where 0, 67, or 100 kg N/ha was optimal. Good agreement between the soil and cornstalk test was indicated by the finding that the soil test and the stalk test agreed when selecting the best rate of fertilization at 58% of the sites (at a price ratio of 200). Only at 5% of the sites did the tests disagree by more than 67 kg N/ha.

The finding that optimal rates of fertilization vary with price ratio means that economically optimal concentrations of stalk nitrate tend to vary with price conditions. The rate of this change is shown in Figure 3. The points indicate situations where the costs of fertilization are equal to the mean value of grain produced by the fertilization, so there is no net gain to fertilization. The best-fitting line indicates that the economically optimal critical stalk nitrate concentration ranges from about 370 to 950 mg N/kg for the range of price conditions considered. However, small errors in the concentration judged to be optimal would have resulted in relatively small effects on net returns to fertilization (Table 3).

Perhaps the most significant observation from data in Table 3 is that selection of the best rate of fertilization was not identified as an important factor affecting profits at sites that had near-optimal supplies of N without the added fertilizer. When averaged across many sites, within-category yield responses due to fertilization tended to be approximately equal to
Table 3. Mean net returns to added N calculated for 5 price ratios when sites are grouped by nitrate concentration in cornstalks from nonfertilized plots.

<table>
<thead>
<tr>
<th>Stalk N Category</th>
<th>N rate</th>
<th>Mean net returns to added N at various price ratios&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>mg N/kg</td>
<td>Kg/ha</td>
<td>0.27</td>
</tr>
<tr>
<td>&lt; 250</td>
<td>33</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-0.04</td>
</tr>
<tr>
<td>250 to 699</td>
<td>33</td>
<td>-0.13</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>-0.39</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-0.33</td>
</tr>
<tr>
<td>700 to 1999</td>
<td>33</td>
<td>-0.62</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>-0.93</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-0.43</td>
</tr>
<tr>
<td>≥ 2000</td>
<td>33</td>
<td>-1.15</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>-0.78</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-1.15</td>
</tr>
</tbody>
</table>

<sup>a</sup> Price ratio is equal to the corn price in $/Mg divided by the cost of N in $/kg.

the costs of fertilization. Similar results were observed when soil tests are used to select rates of N fertilization in late spring (Hansen and Blackmer, 1999).

Percentages of sites resulting in positive net returns to fertilization varied greatly, from 1 to 87%, among categories formed by considering N-sufficiency level of non-fertilized plots, rate of fertilization, and price conditions (Table 4). The chance of obtaining a profit was remarkably lower than chance of obtaining a positive yield responses when at sites where non-fertilized plots had optimal or above optimal concentrations of stalk nitrate. As recently pointed out by Blackmer and White (1998), observed probabilities of obtaining a profitable yield response to N fertilization provides a rational basis for selecting N fertilization rates in situations where optimal rates are influenced by many factors that interact in time and space.
Fig. 3. Relationship between price ratio (kg N per Mg corn) and critical concentration of cornstalk nitrate-N at A) 33 kg, B) 67 kg, and C) 100 kg added N/ha.
Table 4. Percentage of significant positive net returns to added N for various price ratios when plots are grouped by nitrate concentration in cornstalks from nonfertilized plots.

<table>
<thead>
<tr>
<th>Stalk N Category</th>
<th>N rate</th>
<th>Percentage of sites showing a positive net return</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg N/kg</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Kg/ha</td>
<td>%</td>
</tr>
<tr>
<td>&lt; 250</td>
<td>33</td>
<td>53 (25)</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>69 (22)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>51 (25)</td>
</tr>
<tr>
<td>250 to 699</td>
<td>33</td>
<td>32 (44)</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>32 (53)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>24 (65)</td>
</tr>
<tr>
<td>700 to 1999</td>
<td>33</td>
<td>23 (65)</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>13 (74)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>6 (84)</td>
</tr>
<tr>
<td>≥ 2000</td>
<td>33</td>
<td>8 (71)</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>4 (87)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0 (98)</td>
</tr>
</tbody>
</table>

Relationships between stalk nitrate concentrations on non-fertilized plots and those found following the addition of fertilizer N within the same trial are shown in Fig. 4. The solid line shows the best fitting models, which indicate that stalk nitrate concentrations were increased by an average of 413 mg/kg when 33 kg/ha fertilizer N was applied in trials where non-fertilized plots had stalk nitrate concentrations greater than 700 mg N/kg. The corresponding increases for the 67 and 100 kg/ha rates were 1209 and 2310 mg N/kg. Means of these values indicate that stalk nitrate concentrations tended to increase by an average of 19-mg N/kg for each kg of fertilizer N applied in excess of plant needs. Plots where non-fertilized plots had stalk nitrate concentrations less than 700 mg/kg are not included because
Fig. 4. Relationship between cornstalk nitrate-N concentrations on nonfertilized plots and cornstalk nitrate-N concentrations on plots that had received A) 33 kg, B) 67 kg, and C) 100 kg added N/ha.
such trials should not be expected to show linear relationships between rates of fertilization and stalk nitrate concentrations (Binford et al, 1992)

The dotted lines in Fig 4 indicate concentrations that would be expected on the fertilized plots if the applied fertilizer had no effect on availability of N to plants. Variability in vertical distance between points and the dotted line show variability in efficacy of the fertilizer N as revealed by the stalk nitrate test. Although some of the variability can undoubtedly be attributed to measurement errors and unaccounted for spatial variability in N availability within sites, the results suggest great variability in the efficacy of fertilizer N. This variability could be caused by losses of fertilizer N soon after application or to unavailability of this N due to position relative to roots. Such problems cannot be dismissed without serious consideration because the fertilizer N was broadcast without incorporation into the soil. Numerous studies have shown that much of this N can be lost soon after application (Hargrove, 1988; Weier, 1994; Bremner, 1995).

Relationships between YB index values on non-fertilized plots and those found following the addition of fertilizer N within the same trial are shown in Fig. 5. The solid line shows the best fitting models, which indicate that index values were increased by an average of 10 units for each additional increment of 33 kg N/ha. Such relationships are similar to those found in Fig 4. As noted earlier, when the YB Index is used trends are more clearly illustrated in the below- and near-optimal range.
Fig. 5. Relationship between YB Index values on nonfertilized plots and YB Index values on plots that had received A) 33 kg, B) 67 kg, and C) 100 kg added N/ha.
Discussion

This study documents outcomes of fertilization at specific sites in the past, but these outcomes provide the basis for more quantitative interpretations of stalk nitrate tests done at other times and locations. The meaning of the marginal category, for example, is more precisely defined by recognizing that application of 33 or 67 kg N/ha as a top dressing in late spring probably would have resulted in negligible economic benefit or loss. The meaning of test results in the optimal range is more precisely defined by recognizing that addition of more N probably would have reduced profits.

Interpretations of the cornstalk test based on averages over many trials clearly may not apply to all fields and years, so judgements concerning similarity of conditions must be included in interpretations. The need to make such judgements is not a serious problem because rates of fertilization must be selected without knowledge of weather and other factors that will influence plant growth and responses to fertilizer N in any given season. For this reason, mean results from many trials conducted under reasonably similar conditions may be the most appropriate basis for interpretations where the test is used to evaluate and improve N management practices in production agriculture.

It was initially expected that the results of this study could be used to more quantitatively assess how much rates of fertilization deviated from optimal within any area from which samples were taken. Although such assessments can be made, the finding of extreme variability in efficacy of fertilizer-N applied limits the value of such estimates. This extreme variability suggests that the optimal rates of fertilization were greatly influenced by efficacy of fertilization, which could be expected to vary substantially with time and method.
of fertilizer application. Only future work can reveal how much the interpretations reported here differ from those derived in studies involving other times and methods of fertilization.

The results of this study show that the economically optimal concentrations of nitrate in cornstalks change relatively little with likely changes in ratios of prices for grain and fertilizer. This suggests that optimal concentrations of stalk nitrate should not be expected to vary greatly with reasonable differences in efficacy of fertilization. Results from this study show how much fertilizer N was needed compared to plots that did not receive fertilizer N, but they also can be used to estimate the extent to which any given rate of fertilization deviated from the rate needed to attain optimal stalk nitrate concentration. Limitations of the test when deficiencies are severe are not a problem when fine-tuning rates that already are near optimal. The fact that our fertilizer response trials had a relatively low frequency of extremely deficient sites makes the data set collected well-suited for calibrating the stalk test to estimate how much normally applied rates of N deviate from optimal rates.

Information provided by the stalk test suggests that there was marked variability in the effectiveness of the applied fertilizer in this study, and this observation supports the need for more quantitative interpretations of the stalk test. If the test is essentially correct, then the results suggest a need to focus more on selecting optimal time and method of fertilizer applications than on the rates at which fertilizer is applied. Comparison of stalk nitrate concentrations resulting from different times or methods of application seem to offer unique opportunity to compare the efficacy of fertilizer N applied by different methods at near-optimal rates. Quantitative interpretations of the stalk test, for example, would aid in studies comparing the effect immediate incorporation has on efficacy of the N applied at near
optimal rates, where yield responses are difficult to detect.

Future studies could easily show that results of this study offer reliable interpretations of stalk nitrate concentrations only for situations where fertilizer was surface applied in late spring without incorporation into the soil. The primary outcome of this paper, therefore, is an illustration of methods for developing more quantitative interpretations of the stalk test by using data collected over a restricted range of conditions. Only future studies conducted under different conditions can reveal how well the data analyzed here apply to other conditions, but these future studies must use more quantitative interpretations of the stalk test than has been used in the past.

Literature Cited


GENERAL CONCLUSION

Research was conducted from 1992 through 1997 on 205 sites in Iowa to calibrate the late-spring test for soil nitrate and the end-of-season test for cornstalk nitrate for use on manured cornfields. These calibrations can help producers evaluate and improve their N management by identifying fields that are likely to respond to additions of fertilizer N and by identifying management practices that most consistently result in optimal quantities of plant-available N.

The objective of these studies were to i) determine what information attainable in late-spring was most useful in evaluating N sufficiency in manured cornfields, ii) characterize relationships between soil nitrate concentrations in late-spring, prices of corn and fertilizer, and optimal rates of N fertilization in manured cornfields, and iii) develop quantitative guidelines for use of the end-of-season test for cornstalk nitrate in manured cornfields.

Results in Paper 1 show that, of the factors considered, soil nitrate concentration provided the most reliable distinction between responsive and non-responsive sites. This can be explained because the reliability of the soil test is not affected by uncertainty in amounts of manure-N applied, percentages of manure-N lost soon after application, or amounts of N mineralized from previous applications of manure.

The finding that soil nitrate concentrations showed good relationships with yield responses to added N but poor relationships with amount of manure-N applied deserves attention. It seems unlikely that uncertainty in amounts of manure-N applied or amounts mineralized could be responsible for the lack of relationship between rate of manure-N application and soil nitrate concentrations. However, unpredictable variability in percentage
losses of manure-N that tend to increase with rate of application could be the major factor. If the uncertainty is largely caused by losses of manure-N soon after application, then testing soils for nitrate concentrations in late spring may be an effective way to compare percentages of manure-N lost by various application methods. Soil testing for nitrate should be more reliable for this purpose than measuring yield response because yield response is greatly affected by factors other than N loss. For this reason soil testing to evaluate manure application techniques may provide benefits that are independent of assessing N fertilizer needs.

Paper 2 provides soil test calibrations intended to address the problem of N fertilizer needs amid marked variability in space and time. Mean yield responses to added N across many sites, percentages of sites that responded, and percentages of sites where the responses resulted in profit were all considered. This information can be used to predict mean responses across many sites, probability of response, and probability of a profitable response.

Soil test calibrations in this paper give an assessment of the uncertainty involved in any recommendation. Clear statements of uncertainty are important because, as noted by Melsted and Peck (1973), there has been considerable controversy associated with soil testing and much of this controversy can be traced to a lack of understanding of the meaning of soil tests and how they should be interpreted. Statements indicating probabilities of response or of profitable outcomes of fertilization clearly indicate that use of the recommendations are intended to maximize profits when used across many fields even though they cannot be expected to maximize profits in every field. Such statements emphasize that a soil test can only be used to determine the probability that a response will occur and the mean magnitude
of response expected across many sites.

Data presented show that use of soil testing with profit-maximizing critical concentrations across the range of conditions included in this study would have increased net returns, decreased average rates of fertilization, or both. It should be noted, however, that the range of field conditions included in this study was selected to be best for calibrating the soil test rather than to provide a survey current manure management practices. It is, therefore, difficult to predict the economic benefit of using these calibrations across all fields in Iowa.

Paper 3 documents outcomes of N fertilization on cornstalk nitrate concentrations in 205 response trials. These outcomes provide the basis for more quantitative interpretations of the end-of-season test for cornstalk nitrate. The meaning of the marginal category, for example, is more precisely defined by recognizing that application of 33 or 67 kg N/ha as a top dressing in late spring resulted in negligible economic benefit or loss when data from all sites are pooled. The meaning of test results in the optimal range is more precisely defined by recognizing that addition of more N reduced profits.

Interpretations of the cornstalk test based on averages over many trials may not apply when conditions differ greatly from those studied, so judgements concerning similarity of conditions must be included in interpretations. The need to make such judgements is not a serious problem because rates of fertilization must be selected without knowledge of weather and other factors that will influence plant growth and responses to fertilizer N in any given season. For this reason, mean results from many trials conducted under reasonably similar conditions may be the most appropriate basis for interpretations where the test is used to evaluate and improve N management practices in production agriculture.
It was initially expected that the results of this study could be used to more quantitatively assess how much rates of fertilization deviated from optimal within any area from which samples were taken. Although such assessments can be made, the finding of extreme variability in efficacy of fertilizer-N applied limits the value of such estimates. This extreme variability suggests that the optimal rates of fertilization were greatly influenced by efficacy of fertilization, which could be expected to vary substantially with time and method of fertilizer application. Only future work can reveal how much the interpretations reported here differ from those derived in studies involving other times and methods of fertilization.

Results presented in Paper 3 show that the economically optimal concentrations of nitrate in cornstalks change relatively little with likely changes in ratios of prices for grain and fertilizer. This suggests that optimal concentrations of stalk nitrate should not be expected to vary greatly with reasonable differences in efficacy of fertilization. Results from this study show how much fertilizer N was needed compared to plots that did not receive fertilizer N, but they also can be used to estimate the extent to which any given rate of fertilization deviated from the rate needed to attain optimal stalk nitrate concentration. Limitations of the test when deficiencies are severe are not a problem when fine-tuning rates that already are near optimal. The fact that our fertilizer response trials had a relatively low frequency of extremely deficient sites makes the data set collected well-suited for calibrating the stalk test to estimate how much normally applied rates of N deviate from optimal rates.

Information provided by the stalk test suggests that there was marked variability the effectiveness of the applied fertilizer in this study, and this observation supports the need for more quantitative interpretations of the stalk test. If the test is essentially correct, then the
results suggest a need to focus more on selecting optimal time and method of fertilizer (or manure) applications than on the rates of application. Comparison of cornstalk nitrate concentrations resulting from different times or methods of application seem to offer unique opportunity to compare the efficacy of fertilizer N applied by different methods at near-optimal rates. Quantitative interpretations of the stalk test, for example, would aid in studies comparing the effect immediate incorporation has on efficacy of the N applied at near optimal rates, where yield responses are difficult to detect.

Implications for Water Quality

In a recent review, Sharpley et al. (1998) reported that land applications of animal manures have been linked to both surface and groundwater contamination in many parts of the world. Nitrate-N is of particular concern because of the health problems associated with high levels of nitrate in drinking water, and because of potential environmental problems (i.e., hypoxia and eutrophication). Improvements in the management of manure-N should minimize the negative impacts of land applications of animal manures.

Results presented in this dissertation indicate that the late-spring soil test and end-of-season cornstalk test can be used to evaluate and improve N management on manured cornfields. The benefits of improving N management fall into two general categories; money and materials saved by avoiding unnecessary applications of fertilizer, and increased productivity where additional N is applied in situations where unexpected losses of manure-N have occurred. Each of these categories has unique and important implications for water quality.

The water quality implications of avoiding unnecessary applications of N are obvious.
Many studies have shown that ground and surface water contamination from agricultural sources is largely a factor of the degree to which N fertilizer is applied in excess of crop needs (Keeney, 1982; Aldrich, 1984; Power and Schepers, 1989). Calculations in this study suggest that significant improvements in N management are possible simply by indentifying sites that do not require additional N. Use of the soil test will also help producers identify and avoid management practices that consistently result in large losses of manure-N.

An important benefit of an increased ability to identify losses of manure-N that occur on a specific field in a specific year is that producers can increase productivity by supplementing their manure applications with commercial N. Although this seems to be more of an economic than an environmental benefit, an increased ability to identify situations where additional fertilizer is needed will allow producers to regard manure as a more reliable source of N. If producers have confidence in their assessments of the amounts of N supplied by manure they will be more likely to adjust rates of commercial N applications. Such adjustments should reduce applications of unneeded fertilizers, which will reduce amounts of N expected to move into groundwater and surface water supplies.

The late-spring soil test and end-of-season cornstalk test provide information that can be used to identify manure management practices that minimize losses of N from cornfields to water supplies. This information will allow producers to make site-specific improvements in N management that can result in increased profits and a decreased probability of environmental degradation.
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