AN ENVIRONMENTAL ASSESSMENT OF SENSOR-BASED VARIABLE-RATE NITROGEN MANAGEMENT IN CORN

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by
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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

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VARIABLE-RATE NITROGEN MANAGEMENT IN CORN

Presented by Darrin F. Roberts

A candidate for the degree of Master of Science

And hereby certify that in their opinion it is worthy of acceptance.

Dr. Newell Kitchen

Dr. Peter Scharf

Dr. Kenneth Sudduth

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ABSTRACT

Nitrogen (N) fertilizer use in agricultural production systems has increased dramatically over the past 50 years. N fertilizer unused by the crop is left to the fate of the processes of the N cycle, and can eventually lead to detrimental effects to the environment. As a result, an issue of increasing concern in the U.S. Midwest is nitrate contamination of surface and ground waters. A likely contributing factor to contamination is that crop N need varies spatially across whole fields. In order to address this problem, various methods have been used to try to account for spatial variability of N within agricultural fields. One approach to account for this variability and thereby reduce nitrate pollution is in-season site-specific N application according to economic optimal N rate (EONR). Active-light reflectance sensors have been successfully used for site-specific N applications in wheat. Recently, these sensors have been tested for mid-season, on-the-go N fertilizer application in corn. This 2004 and 2005 study was conducted on 12 Missouri producer corn fields to (1) evaluate the relationship between EONR and active-light reflectance sensor readings, and (2) evaluate the relationship between environmental measurements and EONR. N treatments were arranged in a randomized complete block design at rates of 0-235 kg N ha^{-1} at 34 kg N ha^{-1} increments. Measurements included EONR, crop N yield efficiency (YE), N fertilizer recovery efficiency (NFRE), and post-harvest soil inorganic N levels. A quadratic-plateau function was used to determine EONR for 68 different treatment sets obtained from the 12 fields. Crop response to N was significant (i.e. EONR was calculable) for nearly all treatment sets in 2004 because of very good growing conditions. Nearly the opposite was found in 2005 because of a droughty growing season. In 2004, EONR was significantly related to active-light sensor indices, but with regression model coefficients of determination (r^2) ≤ 0.35 for all sensor indices evaluated. However, including soil electrical conductivity (EC) in the regression model improved the r^2 to 0.47. Sensor measurements were found to be significantly related to delta yield. However, delta yield was not a good predictor of EONR ($r^2 = 0.34$). A relationship between EONR and the indices could not be established for 2005 data. In 2004, YE at EONR was not the same between fields, and ranged from 19-47 kg grain (kg N)$^{-1}$. As N rate approached EONR, both YE and NFRE declined, while post-harvest inorganic N levels increased. These preliminary results show promise for using active-light reflectance sensors to achieve EONR and reduce N loss off fields.

CHAPTER 1

INTRODUCTION

Nitrogen (N) is a major component in cereal crop production. In 2002, world N fertilizer application topped 84 million Mt (FAO, 2006). With this tremendous global consumption, a growing concern has developed about low crop use efficiency. N use efficiency has been measured to be 30-60%, depending on crop type, management practices, and climatic factors. Unused N that is left in the soil can be denitrified or leached into groundwater, eventually contaminating surface water.

For many years farmers have uniformly applied N fertilizer across whole fields. Although this method is fast and easy, it fails to consider spatial variability in crop N need within fields (Scharf et al., 2005). Great strides have been made to develop methods and equipment to variably apply N. Many of these methods rely on plant color or reflectance characteristics as an indication of N need. For example, a handheld SPAD chlorophyll meter has been found to give a good indication of a crop's N status (Blackmer and Schepers, 1995) and to correct N deficiency during the growing season (Varvel et al., 1997). Preliminary results show satellite imagery to be useful in detecting N stress (Han et al., 2002), although research in this area is limited. Aerial photography has been shown to be useful in predicting side-dress N need (Scharf and Lory, 2002). Although these methods are very innovative in determining crop N need, their use has primarily been in research settings. Production agriculture has not adopted these methods because of cost of implementation, application accuracy, inconvenience, added risk with side-dressing, and limited commercial availability.

Within-season N application based on EONR is one practice that seeks to improve N use efficiency and decrease the detrimental effects of excess N application. One technology that is being tested to determine its ability to calculate EONR is active-light reflectance sensors. In the past 15 years, studies have been conducted using ground-based active-light reflectance sensors to help develop an on-the-go fertilizer application system (Raun et al., 2002; Shanahan et al., 2003). Preliminary results from using these sensors have shown this to be an effective system to variably apply N in wheat grown on producers' fields (Raun et al., 2005). Recently, these sensors have been tested for within-season, on-the-go N application in corn based on EONR. Many questions concerning this N application technology remain to be answered: Can sensor measurements be used to determine EONR? Can the use of active-light reflectance sensors improve the environment by increasing N use efficiency and/or decreasing profile inorganic N as compared to uniform N applications? This research project sought to address these preliminary questions for using active-light reflectance sensors for variable-rate, within-season N application.

CHAPTER 2

REVIEW OF LITERATURE

The Nitrogen Cycle

For hundreds of years, man has been amending the soil to increase crop productivity. One nutrient that dramatically influences crop productivity is Nitrogen (N). Over the past century much has been learned about the transformations N goes through in the environment. Because of differences in availability and temporally-variant transformations in soils, N availability for plant uptake in crop production systems varies widely. N is removed from a crop production system or made unavailable for plant uptake through ammonia volatilization, immobilization, denitrification, leaching, and N removal with crop residue. Ammonia volatilization results in N being lost to the atmosphere as NH_3. Immobilization is the conversion of inorganic N ions to organic forms, making N unavailable for crop uptake. Denitrification is the reduction of NO_3^- by soil organisms to NO_2, N_2O, and N_2 gas. Leaching is the washing of N through the soil and past the crop root zone. All of these processes result in N being removed from the crop production system (Figure 2.1).

Other processes and transformations add N to the soil, from which some is readily available for crop uptake. These processes include industrial N fixation, nitrification, mineralization, and biological N fixation. Industrial N fixation occurs when N_2 gas from the atmosphere is used to make N fertilizers for application in crop production systems. Nitrification is a process in which Nitrosomonas and Nitrobacter soil bacteria help to oxidate NH_4^+ to NO_3^-. Mineralization of residues in soil converts an element from an organic form to an inorganic form, a form usually available for crop uptake. Biological

N fixation occurs in the soil and results in atmospheric N_2 being fixed into organic N forms through symbiotic and nonsymbiotic organisms. All of these transformations lead to N becoming available for crop uptake.

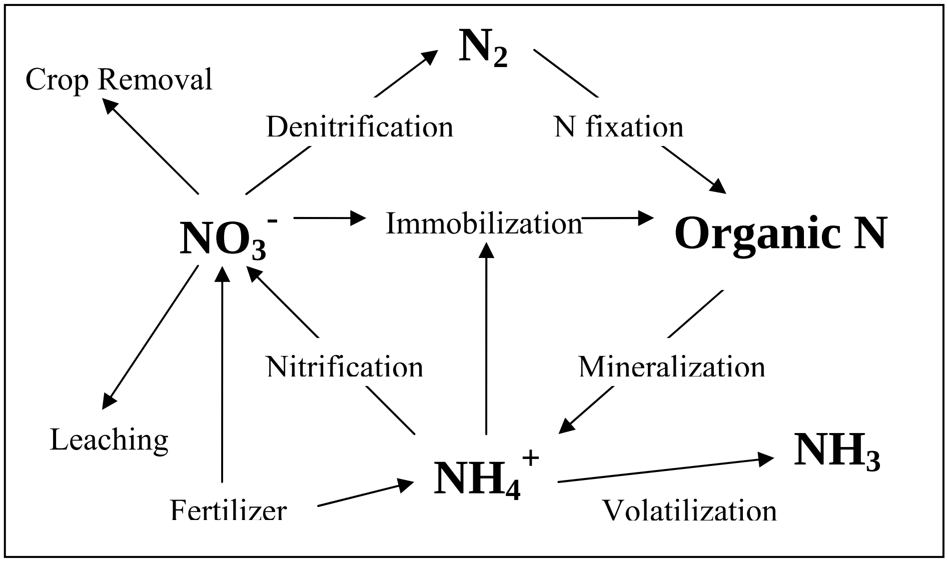


Figure 2.1: The N Cycle.

For an in-depth discussion of the various pathways of the N cycle see Follett (2001). Because the magnitude and control of these pathways vary from point to point, N levels within a field are different from year to year and within the same year. Accurate and timely prediction of spatial N need within crop production systems is the focus of current research.

The Need for Improved N Management for Crop Production

Environmental Factors

N has increasingly become a major component in cereal crop production. N application grew dramatically from the 1960s to the 1970s, and then leveled off during the 1980s and 1990s. In 2002, world N fertilizer application topped 84 million Mt (FAO, 2006). A growing concern has developed about the potential environmental hazards of increasing N applications. Agriculture point- and nonpoint-source N pollution has been linked to detrimental effects to both environment and human health. Over-application of N for a growing season causes excess N to be left to the fate of the processes of the N cycle. The processes of greatest environmental concern are leaching and runoff losses of N from crop fields into groundwater, lakes, and waterways.

Groundwater. In the United States, groundwater is the source of domestic water for almost 90% of the rural population and about 50% for the total population. Groundwater is the main domestic water source in the Midwest, and provides 75-80% of irrigation water in the United States (Power and Schepers, 1989). As a result of this reliance on groundwater use, maintaining quality groundwater has become a major interest. Excess NO_3^- in the soil from agriculture practices can be leached through the soil profile and into groundwater.

High levels of NO_3^- in wells have been linked to certain health risks, mainly in infants. Comly (1945) first linked methemoglobinemia in infants to high NO_3^- concentrations in private wells. Methemoglobinemia, or blue-baby syndrome, is a potentially fatal condition which develops from low O_2 in the blood (Knobeloch et al., 2000). Upon ingestion, NO_3^- is reduced to NO_2^- in the digestive tract causing excessive amounts of NO_2^- that can interfere with O_2 transport in the blood. As a result of this correlation, the U.S. Environmental Protection Agency (EPA) established a maximum contaminant level (MCL) for NO_3^- in drinking water. Although acute toxicity is generally associated with levels exceeding 50 mg/L NO_3^--N, the MCL was set at 10 mg/L. Uncontaminated groundwater usually contains less than 3 mg/L NO_3^--N; wells having between 3 and 10 mg/L NO_3^--N are suspected of being influenced by human activity (Power and Schepers, 1989). In a survey conducted by the United States Geological Service, 124,000 analyses were performed on well water samples from locations throughout the United States. Twenty percent of these samples contained more than 3 mg/L NO_3^--N level (Power and Schepers, 1989). Although this appears to be a small fraction of total wells, heavy reliance on groundwater should warrant protection against further NO_3^- contamination.

Although prior research suggests a link between NO_3^- and health risks, Spalding and Exner (1993) concluded that additional research would be necessary to confirm a relationship between NO_3^- in drinking water and health effects such as hypertension, central nervous system birth defects, certain cancers, and non-Hodgkin's lymphoma. Spalding and Exner (1993) went on to state that health effects of NO_3^-, whether carcinogenic or noncarcinogenic, have not been proven conclusively, are based on only weak correlations, and should not be used to establish a cause-and-effect relationship. Barrett et al. (1998) concluded there was no relationship between NO_3^- concentrations in drinking water and stomach or esophageal cancers and that further research is needed to determine if a relationship exists between NO_3^- and other cancers. Addiscott and Benjamin (2004) argued that NO_3^- does not threaten human health and can actually preserve it. They also suggested that MCLs could be increased significantly to reduce drinking water regulation costs, without endangering human health. Because of limitations with present technologies for removing NO_3^- from drinking water, small communities are faced with economic hardships to bring their water supply into compliance with the EPA MCL or with finding new sources of drinking water (Spalding and Exner, 1993).

Surface water. Excess N in crop production systems not only poses a threat to groundwater quality, but to surface water quality also. In the Midwest, subsurface drainage is a common management practice to relieve seasonally perched water tables or shallow groundwater. This practice increases crop productivity, reduces risk, and improves economic returns to crop producers (Randall and Goss, 2001). However, subsurface drains can also contribute to NO_3^- contamination of surface water.

Dinnes et al. (2002) explained how artificial subsurface drainage had significant effects on the Midwest ecosystem. Midwestern soils developed in a subhumid climate with poor surface drainage and high levels of organic matter. With the installation of artificial drainage lines, the wet conditions of these soils were modified, which led to an increased potential for N mineralization from the abundant organic matter reserves in the soil. This mineralized N can contaminate surface water when it flows into subsurface drains and is subsequently discharged into streams and lakes.

High levels of NO_3^- in surface water have been linked to eutrophication and hypoxia. Eutrophication is the stimulated growth of aquatic plants as a result of nutrient enrichment. As organic matter is produced, then subsequently dies after eutrophication, O_2 necessary to sustain fish life is depleted. Hypoxia occurs when O_2 concentrations become less than 2 mg/L (Burkhart and James, 1999). If water column stratification occurs, isolating the bottom water from exchange with oxygen-rich surface water, the complete absence of oxygen, or anoxia, may occur (Diaz, 2001). The three largest hypoxic zones in the world are found on coastal areas of the Baltic Sea, the northern Gulf of Mexico, and the northwestern shelf of the Black Sea (Rabalais et al., 2002).

Anthropogenic activities have been linked to declining O_2 levels in coastal waters around the world (Diaz, 2001). N inputs into the Gulf of Mexico from the Mississippi and Atchafalaya Rivers are of particular concern. These two rivers have been estimated to account for 91% of the total N load into the northern Gulf of Mexico (Rabalais et al, 2002). As a result, numerous studies have tried to assess N input levels into the Gulf of Mexico from these rivers (Goolsby et al., 2001; Burkart and James, 1999; Rowe, 2001; Turner and Rabalais, 1991). In 2001, the mid-summer Gulf of Mexico hypoxia, or dead-zone, was estimated to be 20,700 km^2. This hypoxic area most likely began to develop around the turn of the last century and became more severe since the 1950s as Mississippi River NO_3^- levels increased (Rabalais et al., 2002). Turner and Rabalais (1991) stated that water quality problems in lakes, rivers, and continental shelves are often related to eutrophication from fertilizer use. They also concluded that eutrophication will not likely be reduced without a reduction in fertilizer use. Without efforts to curtail NO_3^- loading, water quality in the northern Gulf of Mexico, and other water bodies of the world, will continue to decline.

Economic Factors

Agricultural producers constantly balance the competing needs of environmental stewardship and maximizing economic profit. Currently, many producers apply uniform, whole-field N rates. Although this method is relatively fast and easy, it also has many problems. Because of a variety of factors, soil N levels and crop N needs vary between fields (Bundy and Andraski, 1995; Mamo et al., 2003; Schmitt and Randall, 1994) and within the same field (Malzer et al., 1996; Scharf et al., 2005). As a result of spatial and temporal variability of N supply and need, uniform application rates inevitably lead to under-fertilization of some areas of a field, while others receive a wasteful overabundance of N. This situation is accentuated in drier than average years when overall productivity is reduced and less N is taken up by plants.

Economic optimum N rate (EONR) is the point at which the amount of N applied barely pays for itself in the yield which it produces. Areas of a field where N is applied at less than EONR are unable to reach yield potential, and profitability is lost. Conversely, areas of a field with N applied in excess of EONR reach yield potential but economic and environmental losses are incurred as a result of unused N in the soil. Producers generally perceive an economic incentive for over- rather than under-applying N. Although some have argued against the economics of "insurance N" applications (Bock and Hergert, 1991), many still see the reduced yield of under-application as outweighing the costs of unused applied N (Scharf et al., 2005). Profitability for the producer will increase and environmental concerns will be minimized as fertilizer use efficiency increases (Malzer et al., 1996). The goal of variable-rate N application is to match inputs with crop needs site-specifically and thus increase N use efficiency.

N Use Efficiency

"N use efficiency" (NUE) is a general phrase relating yield and N and can be calculated in a variety of ways. Calculations can be based on the relationship between yield and N rate (yield efficiency), yield and N recovered by the plant (physiological efficiency), or N recovered by the plant and N rate (N fertilizer recovery efficiency or NFRE). Yield efficiency is the average yield increase per unit of applied N. Physiological efficiency compares yield increases with increasing amounts of recovered

N. NFRE is the percent of N fertilizer recovered in the aboveground plant parts. These three methods for determining NUE are calculated by the following equations:

$$\text{Yield Efficiency (kg corn/kg N)} = (Y_i - Y_{\text{check plot}})/N_i \qquad [1]$$

$$\text{Physiological Efficiency (kg corn/kg N)} = (Y_i - Y_{\text{check plot}})/(NR_i - NR_{\text{check plot}}) \qquad [2]$$

$$\text{Recovery Efficiency (NFRE, \%)} = [(NR_i - NR_{\text{check plot}})/N_i]100 \qquad [3]$$

where Y=Yield (kg corn), N=N rate (kg N), NR=N recovered (kg N), and i=current plot. For an in-depth explanation of methods to calculate NUE see Bock (1984).

NUE is an important factor in determining N application rates. NFRE has been estimated to be between 30-60% for most crop production systems, based on plot research (Kitchen and Goulding, 2001); however, world average cereal grain NFRE has been estimated to be as low as 33% (Raun and Johnson, 1999). Low NFRE indicates inefficiency in N application and results in N being lost from the plant/soil system through the processes of the N cycle.

What Causes Low NFRE?

As aforementioned, NFRE typically varies between 30-60% (Kitchen and Goulding, 2001), but the world NFRE averages about 33% (Raun and Johnson, 1999). Low NFRE results from a variety of factors, some of which are controllable. Various adjustments can be made to these controllable factors to increase NFRE and reduce the potential for N loss. These adjustments could include reducing fertilizer rates to match EONR, proper fertilizer placement to minimize losses, proper timing of application, using more efficient fertilizer N sources, and using nitrification inhibitors. NFRE could possibly be increased 10-30% by altering one or more of these practices (Power and Schepers, 1989). In general, NFRE will be influenced by four major factors: (1) timing of N application, (2) inability to accurately predict climate effect on crop N need, (3) predictability of N supplied from soil mineralization or N supplied from manure application, and (4) spatial variability.

Timing

Improper timing of N fertilizer application contributes to low NFRE. N applications can occur in fall, spring, or at side-dress. Fall N application was encouraged for many years in order to increase efficiency of storage, transportation, and N application facilities (Aldrich, 1984). However, with concerns over NO_3^- contamination of water, increasing attention has been given to the time of N fertilizer application. The general conclusion of research is that N should be applied according to crop need (Aldrich, 1984; Fox et al., 1986; Olson and Kurtz, 1982; Randall et al., 2003). For corn production, the time of greatest N need occurs starting at about 6-8 weeks after planting and continues through the end of vegetative growth. Depending on climate zone, fall N applications are 75-90% as effective as spring N applications (Aldrich, 1984). Welch et al. (1971) determined that spring N applications were more effective than fall applications, and side-dress applications were more effective than spring applications. Blackmer and Schepers (1995) found it possible to monitor crop N status on a weekly basis and “spoon-feed” N to the crop through fertigation when needed. However, this method is not feasible for large-scale dryland agriculture. Russelle et al. (1983) pointed out that if N applications are delayed too long, both yield and fertilizer N recovery can decrease.

Attempts have been made to reduce NO_3^- loss through the use of nitrification inhibitors (Dinnes et al., 2002; Randall et al., 2003). Nitrification inhibitors limit the activity and population of Nitrosomonas bacteria that convert NH_4^+ to NO_3^-. In the Midwest, these inhibitors are mainly used to slow the conversion of fall-applied anhydrous ammonia to leachable NO_3^- (Dinnes et al., 2002). This helps to reduce N loss before it can be taken up by the crop during the following growing season. Results have been mixed using nitrification inhibitors, mainly due to soil type and climate effects. Some studies indicate that use of inhibitors could lead to increased NFRE, especially when used with fall-applied N (Dinnes et al., 2002). Other studies have concluded that there is no significant economic advantage of using nitrification inhibitors (Blackmer and Sanchez, 1988).

Climate Effect on Crop N Need

Inability to accurately predict climate effect on crop N need also contributes to low NFRE. Rainfall and temperature greatly influence crop N need and the amount of plant available N in the soil. Crop N need during a wet year varies considerably from crop N need during a dry year. Nutrient availability in the soil, plant uptake, and their effect upon crop yield are all greatly influenced by temperature and rainfall during the growing season (Asghari and Hanson, 1984a). The pathways of the N cycle can remove N or make it unavailable for crop uptake to varying degrees depending on climatic conditions. Asghari and Hanson (1984b) found that climatic conditions during the growing season did have a significant effect on leaf N and grain N levels. They suggested that the quantification of these conditions into precipitation and heat units could be beneficial in diagnosing N need. They also stated that they might have concluded N was a limiting factor in maximizing corn grain yield if July precipitation rates had not been taken into account. In order to establish an N fertilization program, Hollinger and Hoeft (1986) attempted to quantify weather effects on NH_3^+ fertilization in corn through the use of a climate forecast design. They concluded that this design was effective when used to remove the weather effects on experimental plots. These studies illustrate attempts that are being made to predict climate effects on crop N need in order to increase NFRE.

Uncertainty in N Mineralization

In order to calculate the correct N fertilizer rate, and thereby increase NFRE, it is helpful to correctly estimate N that will be made available to the plant through N mineralization. The amount of N supplied by the soil through mineralization can vary widely due to environmental factors such as temperature, soil moisture, or organic matter quality. N mineralization can vary both spatially and temporally within and between growing seasons. One means for increasing NFRE is by developing methods to better predict N that will mineralize through the growing season. Stanford and Smith (1972) discussed an incubation method to determine a soil's N mineralization potential. Results using this method have been mixed; some studies have shown it to be fairly accurate, while others have shown it to overpredict the amount of mineralizable N, as discussed by Cabrera and Kissel (1988). Fox and Piekielek (1984) stated that while laboratory incubation tests were correlated with greenhouse results, they were not highly correlated with N availability in the field. This was due to unpredictable factors in the field, such as temperature and soil moisture. Fox and Piekielek (1978) found two N availability tests that were highly correlated with the N-supplying capability of the soil under field conditions. However, they pointed out that these methods were still time consuming, expensive, and impractical.

Predicting mineralizable N has shown to be a difficult process. Recently, the Illinois Soil Nitrogen Test has been shown to detect soils where corn is nonresponsive to N fertilization (Khan et al., 2001; Ruffo et al., 2005). This test measures soil amino sugar N levels, which have been shown to be related to soil responsiveness to N fertilization. From a study of 12 nonresponsive and 13 responsive soils, Khan et al. (2001) found a high correlation between soil-test N and amino sugar N ($r^2 = 0.82$). This shows promise for being a convenient and inexpensive soil N test for predicting potentially mineralizable soil N.

Measuring N levels and predicting mineralizable N from soil with manure application is also a challenge. Manure application is based on rough estimates of manure N content. Davis et al. (2002) studied the number of samples that must be taken from manure in order to accurately determine N content. They concluded that for solid manures 25 sub-samples were necessary to determine total N, P, and K levels, and 100 sub-samples were needed to form a representative sample when determining NH_4-N and NO_3-N concentrations. Decay constants are also commonly used in order to determine the amount of N that becomes available each year from the time the manure was applied. Decay constants are discussed in greater detail in Smith and Peterson (1982), Schepers and Fox (1989), and Schepers and Mosier (1991). Although decay constants provide estimates of potential available N over time, they are still only rough estimates, and actual mineralizable N can vary widely depending on environmental conditions.

Spatial Variability

With all the factors that influence N in the environment, it is not surprising that N varies spatially in crop production fields. Spatial variability of soil mineralizable N, crop

N need, and N losses all contribute to an uncertain EONR, and to historically low NFRE. Research on the spatial variability of N mineralization of agricultural soils is limited (Goovaerts and Chiang, 1993; Cambardella et al., 1994; Mahmoudjafari et al., 1997). Cabrera and Kissel (1988) concluded that estimating the parameters used to determine N mineralization according to the method discussed by Stanford and Smith (1972) provided accurate estimates of actual N mineralized in the field. Through the use of geostatistics, kriging techniques, mapping procedures, and cluster and regression analyses, Selles et al. (1999) were able to identify areas of a field with differing N supplying capacities.

From an agricultural producer's standpoint, it is helpful to estimate EONR in order to optimize farm profitability. Past studies have shown N fertilizer need to be spatially variable across fields (Malzer et al., 1996; Mamo et al., 2003; Scharf et al., 2005). When comparing conventional uniform N-rate recommendations to site-specific N-rate management, Malzer et al. (1996) found that the potential benefit of site-specific application ranged from \$11-72 ha^{-1}. They also pointed out that achieving the maximum profitability would depend on accurate spatially variable N rate predictions. During two years of their study, Mamo et al. (2003) found that variable-rate N applications at EONR resulted in savings of 69 and 75 kg N ha^{-1} with a benefit of \$8 and \$23 (N fertilizer cost of \$0.44 kg^{-1}) when compared to uniform N application, respectively. In eight field-scale experiments, Scharf et al. (2005) concluded that variable-rate N application systems have potential to provide economic and environmental benefits because of high within-field EONR variability. Because economics are the inescapable bottom line for agriculture producers, an area of research with a high potential for economic returns and environmental benefits is N application according to spatially-variable EONR.

Estimating Spatially Variable Crop N Need

Traditionally, producers have applied N uniformly across fields. However, with ever-increasing advances in technology, there are a variety of methods for estimating spatially variable crop N need. These methods can be divided into three major categories: soil based, yield based, and plant based.

Soil Based

Soil based methods for estimating spatially variable crop N need include using soil surveys, soil sensors, and soil samples to establish N management zones within a field. Carr et al. (1991) discussed a concept of "farming soils, not fields." As a result of different nutrient supplying capabilities between soil types (Carr et al., 1991; Rennie and Clayton, 1960), varying N application according to soil type has possible economic advantages. Carr et al. (1991) found that the potential benefits of soil type N application ranged widely, from \$5.09 to \$58.07 ha^{-1}. However, they concluded that applying fertilizer based on soil type has the potential to increase the economic returns of N fertilizer application.

Franzen et al. (2002) explained the delineation of N management zones using soil surveys and how they might be used in agriculture. Soil surveys are divided into different orders (i.e. Order 1, 2) depending on their spatial scale and intended use. Order 1 soil surveys are generally used to provide very detailed soils information, but have only been done on a few fields in the U.S. In a study to determine soil survey value for creating N management zones in site-specific N application, Franzen et al. (2002) determined Order 1 soil surveys were related to soil NO_3^- levels. However, it was pointed out that they should only be used as one of several layers of information to establish N management zones. At the same time, it was concluded that the high cost of Order 1 soil surveys was a likely limitation in using them to conduct variable-rate N applications.

Topography is another type of soil classification used to establish N management zones. Malo and Worcester (1975) determined that soil properties and soil types were closely related to landscape position. They concluded that using landscape position to identify soil types could help with fertilizer management.

Soil sampling has been used to determine spatially variable crop N need. Numerous studies have been conducted to determine the proper grid size for soil sampling (Franzen and Peck, 1995; Lenz, 1996; Franzen et al., 1998). Franzen and Peck (1995) discussed the different grid size recommendations that have been used since the 1920s. These include grid sizes ranging from 11 samples per 16 hectares to sampling every 61 m (2.7 samples per hectare). Cost of sampling and sample analysis is an important limitation in deciding the density of the sampling grid (Sawyer, 1994). He further pointed out that a required soil sampling intensity is not clearly defined, and may vary by soil test, different fields, or different geographic region.

In a study comparing topography soil sampling with grid sampling, Franzen et al. (1998) concluded that topography sampling more closely related to NO_3^- levels than did grid sampling. However, based on this study and previous research, they also gave guidelines to determine whether fields are better suited for topography sampling or grid sampling.

In addition to determining the number of soil samples to take, deciding when to sample may be just as crucial. Schmitt and Randall (1994) discussed determining N fertilizer recommendations based on a preplant N test. The use of a preplant N test can provide a soil N credit which can be subtracted from the initial N recommendation. Magdoff et al. (1984) developed a side-dress N test which helped measure soil N levels closer to the time of N application when the corn plant begins its period of rapid N uptake. This test may reduce excess N application, thus reducing the amount of unused N remaining in the soil subject to loss to the environment. Scharf (2001) concluded, however, that the side-dress N test reduced N rate recommendations but did not have a significant impact on profitability.

In addition to soil surveys and soil sampling, other soil based properties have been studied in order to establish N management zones within a field. Soil electrical conductivity (EC) is one soil property that has been researched (Kitchen et al., 1999; Kitchen et al., 2000; Fridgen et al., 2000). Kitchen et al. (1999) concluded that using EC for variable-rate applications of N fertilizer has potential and deserved further research. In addition, on-the-go soil N sensors have also been evaluated for their use in precision agriculture (Adamchuk et al., 2004). Many of these soil based methods provide a means of estimating spatial crop N need. However, without the use of automated sensors these methods are usually time consuming and impractical for use on the production scale.

Yield Based

Estimating spatially variable crop N need can also be accomplished through yield based methods. This can be done with yield goal predictions prior to planting, or through the use of yield monitoring and mapping.

One method discussed by Stanford (1973) and Meisinger (1984) to calculate yield based N fertilizer recommendations is the mass balance approach. Through a variety of

N credits and debits, the mass balance approach determines how much N will be available in the soil for crop uptake, and how much will be removed with the crop. This calculation arrives at an N application rate for a specified area. One of the important inputs to the mass balance approach is appropriate crop yield prediction for the specified year. Vanotti and Bundy (1994) listed a few of the problems of the yield goal N recommendation method. These included unrealistic yield goals, lack of consensus on how yield goals should be determined, and poor relationships between actual economic optimum N rates and yield-based N recommendations. Using the yield goal based N recommendation, Vanotti and Bundy (1994) estimated N application exceeded EONR by 101 kg ha^{-1}. Studies have also shown that yield goal does not correlate well with EONR (Fox and Piekielek, 1995; Kachanoski et al., 1996; Bundy, 2000; Lory and Scharf, 2003). Unrealistic yield goals result in N being applied in excess of EONR.

Delta yield is an alternative approach to using yield goal in N-rate recommendations. Delta yield is the yield increase when fertilizer is applied compared to yield without fertilization. Lory and Scharf (2003) provided a rationale for using delta yield to determine side-dress N rates. Although delta yield was more related to EONR than yield, they found that delta yield could explain no more than 50% of the variation in EONR. For this reason, they concluded that N fertilizer recommendations incorporating yield prediction methods should use delta yield, but not rely on it alone.

In addition to yield goal predictions, yield monitoring and mapping are tools that have become increasingly used by farmers in the USA. From 1996 through 2002, 16-37% of corn, 13-29% of soybean, and 6-9% of wheat acres in the USA were harvested with yield monitor recording data (USDA-ERS, 2004). Yield-based management zones offer the advantage of being the only source of data that is a direct measure of how soil fertility affects yield (Flowers et al., 2005). In order to examine the temporal relationship between yield maps and soil fertility, they combined multiyear yield data into a yield region map. When compared to soil sampling strategies to determine management zones, the yield region map was found to be as effective at capturing nutrient recommendation variability as a 98-m grid cell soil sampling method. From these results, they concluded that soil fertility management zones derived from multiyear yield data provided an effective method to estimate nutrient variability.

Davis et al. (1996) conducted a study to characterize the spatial relationship of yield variability and variable-rate N application. They found that check plot (zero N) yields were more accurate at predicting spatial N patterns than were well-fertilized plots. Because most corn producers apply adequate amounts of N, spatial N patterns would be difficult to discern. Davis et al. (1996) concluded that yield maps from well-fertilized soils would most likely not accurately characterize spatial soil N, and should therefore not be used alone to determine areas of a field with different N requirements. Similarly, from a study conducted over eight different fields, Scharf et al. (in review) found that yield level explained an average of only 15% of the variability in EONR. Therefore, if yield maps are used to calculate EONR and establish N management zones within a field, they should be used in conjunction with other spatial data to increase accuracy.

Plant Based

Many of the soil- and yield-based methods of estimating crop N need occur before or after the growing season. In contrast, plant based methods have the benefit of assessing crop N need by monitoring the crop during the growing season. By doing this, an in-season variable rate N application is calculated and applied according to crop N status for the conditions of the specific growing season in question. This has the potential to reduce many of the detrimental effects associated with N recommendations made before the crop is planted. Rather than estimating N credits and predicting how much N will be required before the growing season begins, the plant itself is used as the indicator of N health and fertilizer need. Within season assessment of crop N has been an emphasis area of precision agriculture over the past 15 years. Plant based methods that will be discussed here are: tissue tests, chlorophyll meter, aerial and satellite imagery, and active-light reflectance sensors.

Tissue tests. Tissue tests are based on the relationship between N concentrations in a plant and the sufficiency of N for plant growth (Binford et al., 1990). Tissue tests can be conducted throughout the growing season at different crop growth stages. Early-season test results could be used to help correct N deficiencies that may exist in a crop; late-season tests could be valuable for diagnostic assessment of season-long N availability. Tissue tests are influenced by a variety of factors, such as portion of the plant that is tested, stage of growth at which sampling occurs, and time of day or shading effects on the plant. Compared with other methods of measuring crop N need, tissue tests provide a means to directly measure plant N levels.

Specific to corn, N content has been shown to vary depending on the part of the plant that is tested and the time of sampling. Hanway and Englehorn (1958) determined that when there is abundant N available in the soil, NO_3^- tends to accumulate in the lower portion of mature corn stalks. Binford et al. (1990) found that stalk NO_3^- tests at maturity were an easy test that could be performed by farmers, had a sufficiently long sampling window, and provided a good measure of the N status of corn. Fox et al. (2001) found that sampling for the stalk NO_3^- test could occur from the kernel milk stage (R3) until a few weeks after black layer formation (R6). This long sample window is a major advantage for the stalk NO_3^- test. Because the test is conducted at the end of the season, it would not help to correct N levels for the current crop. However, test results could be used to calculate N rates for subsequent crops.

In contrast to sampling at the end of the growing season, tissue tests have also been conducted a few weeks after corn emergence (Rauschkolb et al., 1974; Iversen et al., 1985b; McClenahan and Killorn, 1988). Hanway (1962) concluded that when tissue tests were conducted early in the growing season, the percentage of NO_3^- in the leaves, leaf sheaths, or stalks provided a better estimate of the N status of the plant than the percentage of total N in any other plant part. Although tissue N concentrations at the V4/V5 growth stage had only a weak relationship to optimum N rate, Scharf (2001) found tissue N concentrations at the V6 growth stage to be a good predictor of optimum N-rate. Iversen et al. (1985b) found that the basal portion of corn stalks sampled around 30 days after planting was well correlated with soil N availability to corn. Due to the correlation between tissue NO_3^- concentrations and corn yield, Rauschkolb et al. (1974) proposed a critical stalk NO_3^- concentration of 4-6 g NO_3^- kg^{-1} at 35 days after emergence to maintain maximum crop yield. Sampling at this time was late enough for N-sufficient and N-deficiencies to be detected, and early enough in the season to apply N at side-dress if necessary.

Although tissue tests are useful tools to assess crop N need, they are not without drawbacks. One concern is the high site-to-site variation in stem NO_3^- content at identical levels of yield. Plant N requirements to attain maximum yield were found to vary according to soil parent material (McClenahan and Killorn, 1988). In greenhouse experiments, Iversen et al. (1985a) found that stem NO_3^- content exhibited a diurnal cycle in which it peaked at 8AM, and was lowest at 2PM. Plants shaded for only one or two days were also observed to have higher stalk NO_3^- levels than plants that were not shaded. Fox et al. (1989) stated that when stalk NO_3^- tests were used over a range of weather, crop management, and soil conditions, it was not an accurate predictor of soil N availability. In part, this was attributed to stalk NO_3^- concentrations being sensitive to solar radiation and soil moisture availability in the days preceding sampling. Disadvantages of early season tissue testing identified by Scharf (2001) were the narrow side-dress N application window, slow turnaround time to send tissue samples to a lab and receive results for making fertilization decisions, and rapidly changing tissue N concentrations at this corn growth stage.

Chlorophyll meter. The hand-held chlorophyll meter (Minolta SPAD-502) is another tool to measure crop N need. Previous research has shown a strong relationship between leaf N concentration and leaf chlorophyll content (Girardin et al., 1985; Zelitch, 1982; Schepers et al., 1992). To operate the meter, it is clamped onto a single leaf to block out interference from outside light. The meter measures leaf transmittance centered at 650 nm (red) and 940 nm (NIR) wavelengths. The 650 nm source is sensitive to chlorophyll concentration while transmittance at 940 nm factors in leaf moisture content and thickness. Together the wavelengths produce an accurate standardized reading (Blackmer and Schepers, 1995). Meter readings have been shown to be correlated with leaf N concentration in corn (Wolfe et al., 1988; Blackmer and Schepers,

1995) and a variety of other crops (Kitchen and Goulding, 2001). The SPAD has been shown to be an effective tool for correcting N deficiencies in irrigated corn (Varvel et al., 1997). However, results under rain-fed conditions have not been as effective (Bullock and Anderson, 1998).

Much research has been conducted to use the SPAD meter as a tool to correct mid-season N deficiencies with side-dress N applications (Piekielek and Fox, 1992; Scharf, 2001). Piekielek and Fox (1992) studied whether or not chlorophyll meter readings at the six-leaf growth stage would be useful in determining side-dress N recommendations. They concluded that the correlation between SPAD readings and the N supplying capability for each site was probably too low to determine side-dress N rates. Similar conclusions were made by Bullock and Anderson (1998). Rather than being an N management tool in corn, they suggested that the meter could be more useful as a diagnostic aid in detecting N deficiencies.

Others have successfully used SPAD readings for N fertilization. Varvel et al. (1997) proposed a sufficiency index to identify N deficiencies. This is calculated by dividing SPAD readings from unfertilized plants by SPAD readings from fertilized plants, and multiplying by 100. Whenever the sufficiency index falls below 95%, they recommended N be applied. They also found that maximum yields were achieved when early season N levels were adequate to maintain sufficiency indexes between 90-100% at the V8 growth stage. By using a chlorophyll meter and the sufficiency index approach, in-season N applications based on crop need resulted in less N being applied.

While the chlorophyll meter is portable, makes rapid assessment of mid-season corn N status possible, and has been shown to be a useful tool in N management, it still has disadvantages. Chlorophyll content has been shown to be affected by water stress (Sanchez et al., 1983). For this reason, calibration may be difficult, and results may be confounded by crop water status (Schepers et al., 1992). The meter also does not show a difference in chlorophyll content when N is adequate. Because differences in high N rates are not detectable with the chlorophyll meter, N applications are based on N deficiencies. In order to detect N deficiencies, a sufficient-N reference is typically recommended in each field as a basis for comparison. By measuring crop greenness relative to greenness of a well-fertilized portion of a field, side-dress rates can be calculated and the crop can be spoon-fed N when it is needed (Power et al., 2000). Fox et al. (2001) pointed out that reluctance to establish these high-N strips is one reason why farmers have not adopted the use of chlorophyll meters. Perhaps most importantly, use of a SPAD meter on a production scale is not practical for most producers because of the difficulty in obtaining numerous readings for a representative sample in a given area. Also, as a point measurement, it is a poor tool when spatial variability of crop N need exists.

Aerial and satellite imagery. Remote sensing is the science of obtaining information about an object without being in direct physical contact with the object. Remote sensing information can be obtained from a variety of platforms, including ground-based booms, aircraft, or satellites. Two sources of remote sensing which have shown potential for determining spatially variable crop N need over a large area in a short amount of time are aerial and satellite imagery.

The use of aerial and satellite imagery to detect differences in N levels relates to chlorophyll content and crop color. Al-Abbas et al. (1974) determined that the chlorophyll content of a leaf affects the amount of light absorbed or reflected by that leaf. Chlorophyll content influences the green color of plants and is positively correlated with plant N concentration (Wolfe et al., 1988). N deficient leaves tend to reflect more light over the visible spectrum (400-700 nm) and reflect less NIR (near infrared, 700-1000 nm) radiation than N sufficient leaves. Walburg et al. (1982) and Blackmer et al. (1996) showed that canopy reflectance in these portions of the electromagnetic spectrum can be used to detect N deficiency in corn. Although a variety of factors can influence the reflectance of a crop canopy, images can be an efficient means of detecting N deficiency when calibrated with high-N reference strip images within a field (Blackmer et al., 1996).

Aerial and satellite imagery have several advantages over other methods of measuring spatial variability of crop N need. High resolution images can be used to monitor whole fields and allow identification of potential problem areas within a field (Blackmer and Schepers, 1996). With the added benefits of GPS technology, these areas can also be located and treated. Aerial and satellite imagery is cheaper than using tissue tests to assess N status (Blackmer and Schepers, 1996), is more spatially detailed, and potentially cheaper than collecting information with a chlorophyll meter (Scharf and Lory, 2002). Aerial imagery can be used as an effective method to determine side-dress N rates (Scharf and Lory, 2002), or for directing rescue N applications during years with substantial in-season N loss (Scharf and Lory, 2000). Because of these advantages, aerial and satellite imagery are more practical than previously discussed methods to determine spatial variability of crop N need.

Despite the advantages, there are drawbacks to this technology also. For instance, data collection and resolution could be limited by weather conditions and the distance from the crop surface. Although these methods have proven useful in predicting side-dress N rates, there is still a lag time between time of data collection and N application to the crop. Scharf et al. (2002) listed the barriers to adoption of aerial or satellite imagery for crop management decisions as image availability, timeliness, spatial resolution, susceptibility to weather conditions, and limited knowledge of how to use the images to make management decisions. However, it was also pointed out that these barriers are slowly being overcome as additional infrastructure and means for transmitting and interpreting images becomes available. Soil color in images also creates problems with assessing crop reflectance, although Scharf and Lory (2002) found that digitally removing the soil pixels substantially increased the correlation between crop color and optimum N rate. Although aerial and satellite imagery have shown to be useful tools in N management, there are still concerns that need to be addressed before they can be widely used in production agriculture.

Active-light reflectance sensors. Active-light sensing is a ground-based form of remote sensing. Active-light reflectance sensors use an LED (light emitting diode) light source to generate two wavelengths of light, one in the visible portion of the electromagnetic spectrum and one in the NIR. These wavelengths of light are then reflected off the crop and measured by a photodiode on the sensor. Passive reflectance sensors that rely on ambient sunlight are affected by environmental conditions such as clouds or sun angle. These changing conditions have minimal impact on the active-light sensors. Recently, studies have been conducted using active-light reflectance sensors to help develop an on-the-go fertilizer application system (Raun et al., 2002; Shanahan et al., 2003). Active-light reflectance technology is based on reflectance measurements discriminating plants with different color and/or biomass, relative to varying levels of N in the plant.

As with aerial and satellite imagery and the chlorophyll meter, reflectance readings are typically compared to measurements from an N-rich reference area in order to create a sufficiency index from which an N fertilization rate can be made. Prior research identified an appropriate algorithm for N application in wheat (Raun et al., 2002; Raun et al., 2005). The reflectance information has also been used to calculate vegetative indices which can then be incorporated into an N-rate algorithm. Normalized difference vegetative index (NDVI) is a commonly used index that helps measure plant health and vigor by using reflectance values from the red and NIR wavelengths. Current research is underway to determine efficient algorithms that incorporate reflectance measurements to calculate side-dress N application rates in corn.

Active-light reflectance sensors offer many advantages. Unlike many of the other methods of estimating spatially variable crop N need, active-light reflectance sensor measurements can be taken at the same time as N application. Reflectance readings are taken by the sensors mounted on the front of a fertilizer applicator, processed by an onboard computer to determine an N rate, and instructions are sent to the controller for delivery amounts. Unlike aerial and satellite imagery which require fields to be divided into representative pixels, crop N need can be assessed on a small segment of row (~1-2 m) because sensor measurements can be taken many times per second. The sensors are usually operated close to the crop canopy (~0.6 m above canopy).

Active-light sensors also have disadvantages. These include N application during the narrow side-dress application window, uncertainty of proper N rate algorithm based on geographic region, and cost of technology adoption.

Research Objectives

A variety of innovative methods for determining spatially variable crop N need and fertilization have been discussed. Implementation on production-scale fields, distance from the crop canopy, and turnaround time are all concerns associated with these methods. These concerns are less of an issue for active-light reflectance sensors. However, much research is needed on these sensors. First, the science and engineering of active-light reflectance sensing needs to be examined and potentially expanded. Second, agronomic knowledge is needed for how to best collect and convert the information from these sensors into N rate applications. Third, economic and environmental implications of applying N using these sensors needs to be explored. Questions of consideration for this thesis include the following: Can sensor measurements be used to determine EONR? Compared to uniform N application, is NFRE increased through the use of active-light reflectance sensors? Using this technology, are post-harvest soil inorganic N levels reduced compared to uniform N application?

The goal of this thesis was to provide an assessment of the environmental effects of using active-light reflectance sensors on producers' cornfields in Missouri. Specifically, the major objectives of this research were to assess within and between field EONR variability, relate active-light reflectance sensor indices to EONR, and relate EONR to environmental measurements of N application.

CHAPTER 3

MATERIALS AND METHODS

Research Locations

Research was conducted during the 2004 and 2005 growing seasons on eight producer corn fields in 2004 and five fields in 2005. Field locations were primarily in central Missouri (Figure 3.1), and were selected from three major corn-production soils of Missouri (river bottom, loess hills, and claypan). Specific locations are described in Tables 3.1-3.2. Fields CI04, CII04, D04, and D05 were located in the Missouri River flood plain; fields P04, G05, and L05 were located in loess hill areas; fields B04, H04, S04, W04, and S05 were claypan soils.

Fields CI04 and CII04 were located in different areas of the same producer corn field. The only difference between these two was CII04 received the urease inhibitor Agrotain (n-butyl thiophosphoric triamide) (Agrotain Int. LLC, St. Louis, MO) at the time of N application, while CI04 did not. For purposes of this study, results for these two experimental areas are reported as separate producer fields. See Tables 3.1-3.3 for detailed field descriptions, soil classifications, and monthly and seasonal precipitation totals.

Because research was conducted on producer fields, cooperating producers selected the planting date, hybrid, planting population, and prepared and planted each field with their own equipment. See Table 3.4 for detailed field cropping information. Fields were in rainfed production areas, except for B04, which received supplemental pivot irrigation when needed (Table 3.3). Rainfall amounts in 2004 were favorable for corn production. In 2005, however, extreme drought stress began shortly after side-dress

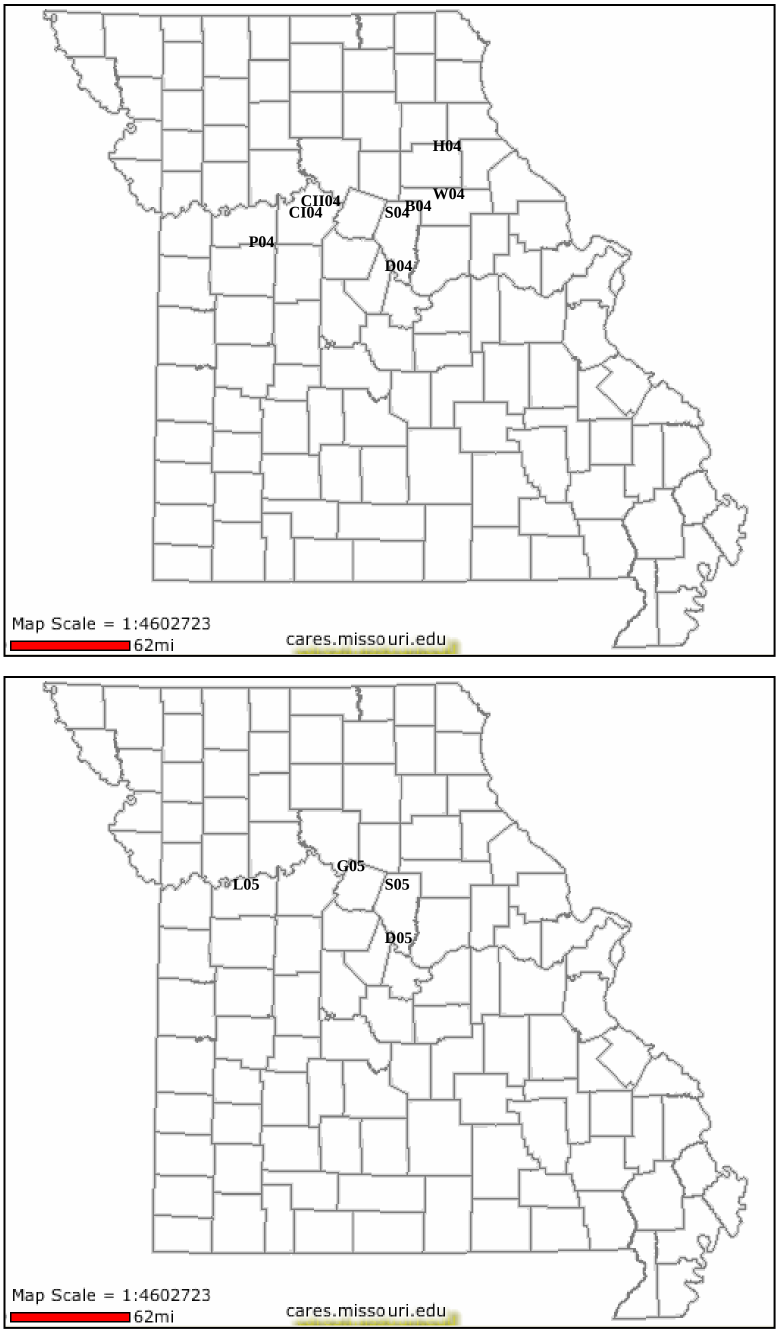


Figure 3.1: Missouri state maps with locations of producer corn fields for 2004 (top) and 2005 (bottom). See Table 3.1 for field ID explanation. (Map Source: cares.missouri.edu)

Table 3.1: Detailed location information for 2004 fields.

Field	County	Northing†	Easting	Site Length	Number of N Treatment Sets	Soil EC		Soil Series	Soil Taxonomic Classification
						mean	median		
		m	m	m		mS/m	mS/m		
B04	Boone	4343450	576400	655	11	20.1	19.8	Adco Silt Loam	Fine, smectitic, mesic Vertic Albaqualfs
								Armstrong Loam	Fine, smectitic, mesic Aquertic Hapludalfs
								Mexico Silt Loam	Fine, smectitic, mesic Aeric Vertic Epiaqualfs
								Putnam Silt Loam	Fine, smectitic, mesic Vertic Albaqualfs
CI04	Saline	4349200	477100	305	5	55.4	53.8	Aholt Clay	Very-fine, smectitic, calcareous, mesic Vertic Endoaquolls
								Levasy Silty Clay	Clayey over loamy, smectitic, calcareous, mesic Fluvaquentic Endoaquolls
								Moville Silt Loam	Coarse-silty over clayey, mixed, superactive, calcareous, mesic Aquic Udifluvents
CII04	Saline	4349350	477100	305	5	63.7	61.4	Aholt Clay	Very-fine, smectitic, calcareous, mesic Vertic Endoaquolls
								Levasy Silty Clay	Clayey over loamy, smectitic, calcareous, mesic Fluvaquentic Endoaquolls
								Moville Silt Loam	Coarse-silty over clayey, mixed, superactive, calcareous, mesic Aquic Udifluvents
D04	Boone	4289700	553650	351	6	43.8	44.4	Blake Silt Loam	Fine-silty, mixed, superactive, calcareous, mesic Aquic Udifluvents
								Haynie Loam	Coarse, silty, mixed, superactive, calcareous, mesic Mollic Udifluvents
								Leta Silty Clay	Clayey over loamy, smectitic, mesic Fluvaquentic Hapludolls
								Sandover Sand	Sandy over loamy, mixed, superactive, nonacid, mesic Aquic Udifluvents
H04	Monroe	4387850	605220	366	6	11.0	10.4	Mexico Silt Loam	Fine, smectitic, mesic Aeric Vertic Epiaqualfs
								Putnam Silt Loam	Fine, smectitic, mesic Vertic Albaqualfs
P04	Lafayette	4310450	454200	183	3	14.3	14.5	Macksburg Silt Loam	Fine, smectitic, mesic Aquic Argiudolls
S04	Boone	4340980	566750	366	6	13.4	12.7	Mexico Silt Loam	Fine, smectitic, mesic Aeric Vertic Epiaqualfs
W04	Audrain	4351950	586900	366	6	17.1	15.6	Armstrong Loam	Fine, smectitic, mesic Aquertic Hapludalfs
								Leonard Silty Clay Loam	Fine, smectitic, mesic Vertic Epiaqualfs
								Mexico Silty Clay Loam	Fine, smectitic, mesic, Aeric Vertic Epiaqualfs

† All fields were located within UTM NAD 83, Zone 15.

Table 3.2: Detailed location information for 2005 fields.

Field	County	Northing†	Easting	Site Length	Number of N Treatment Sets	Soil Series	Soil Taxonomic Classification
		m					
D05	Boone	4289100	554200	487	8	Darwin Silty Clay Loam	Fince, smectitic, mesic Fluvaquentic Vertic Endoaquolls
						Haynie Loam	Coarse-silty, mixed, superactive, calcareous, mesic Mollic Udifluvents
						Leta Silty Clay	Clayey over loamy, smectitic, mesic Fluvaquentic Hapludolls
G05	Chariton	4352100	514200	365	6	Speed Silt Loam	Fine-silty, mixed, superactive, mesic Argiaquic Argialbolls
L05	Lafayette	4335350	430260	182	3	Blackoar Silt Loam	Fine-silty, mixed, superactive, mesic Fluvaquentic Endoaquolls
						Otter Silt Loam	Fine-silty, mixed, superactive, mesic Cumulic Endoaquolls
S05	Boone	4339850	568800	365	6	Adco Silt Loam	Fine, smectitic, mesic Vertic Albaqualfs
						Mexico Silt Loam	Fine, smectitic, mesic, Aeric Vertic Epiaqualfs

† All fields were located within UTM NAD 83, Zone 15.

Table 3.3: Precipitation at 2004 and 2005 fields.

Field	May	June	July	August	September	Seasonal Total
	cm					
B04†	15.4	3.8	13.4	14.3	2.3	49.2
CI04	12.3	11.4	12.8	22.0	4.0	62.5
CII04	12.3	11.4	12.8	22.0	4.0	62.5
D04	15.4	3.8	13.4	14.3	2.3	49.2
H04	7.5	3.2	7.5	23.1	2.7	44.0
P04	12.3	11.4	12.8	22.0	4.0	62.5
S04	15.4	3.8	13.4	14.3	2.3	49.2
W04	12.6	4.1	12.1	16.1	6.4	51.3
D05	7.9	10.5	1.3	23.0	12.5	55.2
G05	9.7	15.2	4.5	19.1	8.1	56.6
L05	9.7	15.2	4.5	19.1	8.1	56.6
S05	7.9	10.5	1.3	23.0	12.5	55.2

† Also received 1.8 cm of water through pivot irrigation on June 24, June 29, July 15, and July 23.

Table 3.4: Detailed cropping information for 2004 and 2005 fields.

Field	Planting Date	Seeding Rate	Hybrid	Pre-study N	Producer N Rate at Planting
		seeds ha^{-1}		kg ha^{-1}	kg ha^{-1}
B04	27 April	74100	Pion 33P67	MAP, 33	202
CI04	15 April	74100	Pion 33D31		168
CII04	15 April	74100	Pion 33D31		168
D04	16 April	69160	Asgrow RX752YG		202
H04†	29 April	70148	Pion 34B23 Pion 34B24BT	DAP, 30	168
P04	7 April	74100	DKC 60-215		202
S04	9 April	61750	Pion 33G28 LibertyLink	VR MAP, 28-45	168
W04	14 April	66690	Pion 34M95	DAP, 45	134
D05	15,16 April	69160	Pion 31N28		202
G05	8 April	71630	Asgrow RX715RR2		202
L05	9 April	70395	NK N67T4		202
S05	9 April	69160	Pion 34M94	DAP, 30	168

† No visible differences due to two hybrids were observed.

N application and continued until late in the growing season. Data was not reported for one additional field in 2005 which was abandoned due to drought stress.

Experimental Design and Treatments

Producer fields varied from 0.4 to 0.8 km in length. Research plots for each treatment set were arranged in a randomized complete block design (RCBD). Each treatment set consisted of eight different N treatments. These varied from 0 to 235 kg N ha^{-1} on 34 kg N ha^{-1} increments. Experimental plot dimensions differed between the two years (Figure 3.2). In 2004, each research plot within a treatment set was 6 rows wide (4.5 m on 76 cm corn row spacing) by 15.2 m long. Treatment sets were two plots wide by four plots long. In 2005, research plots were 12 rows wide (9.1 m on 76 cm corn row spacing) by 30.5 m long. Treatment sets were four plots wide by two plots long. The number of treatment sets per field varied from 3 to 11, depending on the length of the field. N-rich reference areas were located on both sides of the treatment sets. These areas were six corn rows wide and extended the full length of each field. N was applied to these areas at the time of crop emergence. In both years, the experiment was located adjacent to other N research conducted at each field.

Fertilizer Application

An AGCO Spra-Coupe (AGCO Corp., Duluth, GA) high-clearance applicator outfitted with reflectance sensors was used to apply N treatments. N treatments were applied at side-dress, which varied between V7 to V9 growth stage depending on the field. See Table 3.5 for detailed side-dress application information for each field.
N was applied in the form of UAN (32% N), with an appropriate amount of urease inhibitor Agrotain, at rates of 0, 34, 67, 101, 134, 168, 202, and 235 kg N ha^{-1}. To

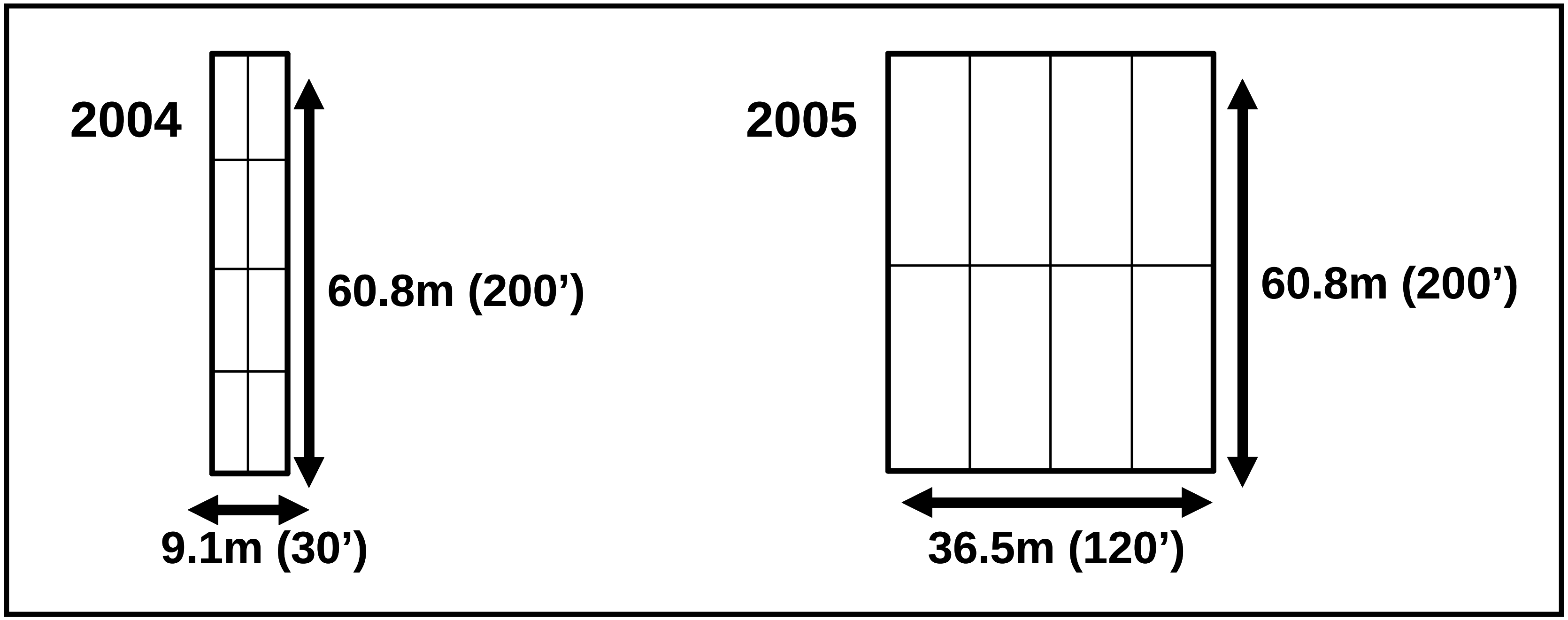


Figure 3.2: Treatment layout for 2004 and 2005.

Table 3.5: Detailed side-dress application information for 2004 and 2005 fields.

Field	N-rich Reference Application Date	Days from Planting	Days to ∑ = 2cm+ Rainfall after N-rich Application†	Side-dress Application Date	Days from Planting to Side-dress	Response Plot Height at Side-dress	N reference Corn Height at Side-dress	Days to ∑ = 2cm+ Rainfall after Side-dress N Application†
						——— cm ———		
B04	17 May	20	2	16 June	50	na	na	16
CI04	6 May	21	12	3 June	49	55	86	7
CII04	6 May	21	12	3 June	49	55	86	7
D04	6 May	20	7	4 June	49	88	86	11
H04	17 May	18	7	21 June	53	na	na	10
P04	19 April	12	1	4 June	58	108	109	6
S04	17 May	38	2	7 June	59	88	94	5
W04	12 May	28	6	8 June	55	56	91	1
D05	10 May	24	1	19 June	64	na	na	54
G05	5 May	27	6	17 June	70	na	na	16
L05	9 May	30	2	17 June	69	na	na	16
S05	6 May	27	5	20 June	72	na	na	53

† Precipitation data source: //agebb.missouri.edu/weather/stations/.

achieve these rates, the Spra-Coupe was outfitted with three drop nozzles fitted with varying orifice plates to obtain 1x, 2x, and 4x (1x = 34 kg N ha^{-1}) flow volume. Combinations of these three nozzles being turned on accomplished the different rates. In 2004, drop nozzles were installed between rows 1 and 2, 3 and 4, and 5 and 6. In 2005, drop nozzles were installed in-between each row. Fertilizer was not incorporated. The Spra-Coupe was also equipped with a three-way valve system allowing N to re-circulate to the tank when it wasn't being applied to the corn. N rate changes occurred within ~1.0 m of the desired location.

EONR Measurements and Calculation

In 2004, the research plots were hand-harvested from 6 m of the middle two rows of each plot and ears were placed in burlap bags. These bags were transferred to a research shed for shelling and weighing. Stalk counts from the harvested area were taken to calculate plant population. In 2005, eight of the 12 rows of each plot were harvested with a Gleaner R42 combine (AGCO Corp., Duluth, GA) with a four row corn header. Plant population was collected with mechanical sensors on the combine header, as discussed by Sudduth et al. (2004). Yield data was collected with an Ag Leader Yield Monitor 2000 (Ag Leader Technology, Ames, IA) and data was cleaned using Yield Editor 1.02 (USDA-ARS, Columbia, MO). The center 18 m of each plot was used to calculate yield. Individual yield points that were questionable were removed so that the resulting yield represented the actual yield as closely as possible. As outlined by Drummond and Sudduth (2004), yield data points were removed for reasons such as GPS positional error, abrupt combine speed changes, significant ramping of grain flow during entering or leaving the crop, and other outlying values.

Statistical analysis was conducted with SAS 9.1 software (SAS Inst., Cary, NC). For all fields, a regression *F*-test ($\alpha = 0.05$) was first performed to determine the influence of N rate on field plant population. For all fields, there was no relationship found between N rate and plant population. A regression *F*-test ($\alpha = 0.05$) was also used to assess whether plant population significantly affected yield. In 2004 there was no relationship found between plant population and yield. For 2005, plant population did have a significant influence on yield at fields D05, G05, and S05. A population correction based on each field's mean population was used to adjust individual plot yield, according to the formula:

$$\text{Adjusted Yield} = \text{plot yield} - a(b - c) \quad [4]$$

where a was the SAS-estimated population parameter, b was an individual plot's plant population, and c was the average plant population for the field. The effect of plant population on yield could not be assessed for field L05 because plant population was not collected for this field.

Once yield data had been cleaned and adjusted for population, a yield response model was selected. Based on work by Cerrato and Blackmer (1990) and Scharf et al. (2005), a quadratic plateau function was determined to most accurately describe corn yield response to N rate. Therefore, the quadratic plateau function was the only yield response model used to characterize the data in this experiment. Using Proc NLIN in SAS (SAS Inst., 2000), a quadratic plateau model was fitted to data for each research field, and for each treatment set within each field. Models of data sets with an *F*-test $p \leq 0.10$ were judged to be significant. To evaluate goodness of fit for each model, r^2 values were calculated. Parameters b and c from the quadratic plateau models were then used to calculate EONR in Microsoft Excel (Microsoft Corp., Redmond, WA). EONR was determined based on a corn grain price of \$0.08 kg^{-1} (\$2 bu^{-1}) and N fertilizer cost of \$0.66 kg^{-1} (\$0.30 lb^{-1}). EONR was calculated based on the equation:

$$EONR = [b - (\$0.66/\$0.08)]/2c \quad [5]$$

where b and c were the linear and quadratic coefficients of the quadratic plateau response function, and where $b > 0$ and $c < 0$. EONR was constrained to never exceed 235 kg N ha^{-1}, the highest N application rate.

Reflectance by Sensors

Active-light reflectance sensor measurements were taken from treatment sets and N-rich reference areas on the same day N was applied to the treatment sets. The sensors used were the Holland Scientific Crop Circle (ACS-210), (Holland Scientific, Inc., Lincoln, NE). Emission bands from the sensors were focused at 590 and 880 nm. Two sensors were mounted on the front of the applicator ~53 cm above rows 2 and 5 of a 6-row corn strip. Depending on crop canopy height, sensor height could be adjusted with an electrical motor to maintain the sensors at ~53 cm above the crop canopy.

The N-rich reference areas were adjacent to both sides of the research area. These areas spanned the length of each field and were also part of an adjacent N experiment at each field. Sufficient amounts of N were applied to the N-rich areas shortly after corn emergence. As the Spra-Coupe drove over each N-rich area at side-dress time, visible and NIR sensor readings, along with GPS coordinates, were recorded on a laptop in the Spra-Coupe cab. These readings were then used to create an N-rich reference map for the entire experimental area using nearest neighbor interpolation. Sensor readings were also taken as the applicator traveled over the N rate response plots, at the same time the fertilizer treatment sets were being applied.

Although N treatments in this study were set application rates and sensor readings were not used to apply N, sensor readings from the N-rich strips and treatment sets were critical for data analysis of this research. Average reflectance values for each treatment set were compared to reflectance values from the adjacent N-rich reference area. This comparison was accomplished using vegetation indices. Three indices evaluated in this project were the relative chlorophyll index ratio (RCI_{ratio}), the visible relative to near-infrared ratio (Vis/NIR_{ratio}), and the normalized difference vegetation index ratio ($NDVI_{ratio}$). These indices related reflectance measurements from the N-rich reference area to reflectance measurements from the plot (or target) area through the following formulas:

$$RCI_{ratio} = [(NIR/Vis)_{target} - 1] / [(NIR/Vis)_{Nref} - 1] \quad [6]$$

$$Vis/NIR_{ratio} = [(Vis/NIR)_{Nref}] / [(Vis/NIR)_{target}] \quad [7]$$

$$NDVI_{ratio} = [(NDVI)_{target}] / [(NDVI)_{Nref}] \quad [8]$$

where “target” was the N rate treatment set area and “Nref” was the adjacent N-rich reference area. These calculations resulted in three indices which ranged from 0.4 to 1.0. As index values approached 1.0, the plot area reflectance measurements resembled reflectance measurements from the N-rich reference area. Index values for each treatment set were then related to EONR. An analysis of variance *F*-test was performed ($\alpha = 0.05$) and an r^2 value was calculated to evaluate the relationship between each index and EONR.

The relationship of soil EC and these index ratios to EONR was evaluated for 2004 fields. Table 3.1 contains mean and median soil EC values for each field. Previous research in Missouri explored the use of EC for precision agriculture (Kitchen et al., 2005; Sudduth et al., 2005). EC data for each field was collected prior to crop establishment using one of two Veris soil EC mapping systems (Veris Technologies Inc., Salina, KS). The Veris 2000XA was used to collect soil EC data from B04, H04, P04, S04, and W04, while the Veris 3100 collected data from CI04, CII04, and D04. Data analysis from the Veris 3100 was based on the "deep" EC soil reading. Average treatment set EC was determined using ArcGIS 9 ArcMap 9.1 (ESRI, Inc., Redlands, CA). Although EC measurements were taken at different dates and one of two different sampling instruments were used, data was pooled across all fields and a stepwise regression *F*-test ($\alpha = 0.05$) was performed to determine the best-fit model. Data was graphed using TableCurve 3D 3.0 (Systat Software Inc., Point Richmond, CA).

The relationship between sensor measurements, delta yield, and EONR was also explored. Previous research has shown yield to be a poor predictor of EONR (Vanotti and Bundy, 1994). However, Lory and Scharf (2003) concluded that delta yield was a much better predictor of EONR and that further research with delta yield was needed before incorporating it into fertilizer N recommendations. Delta yield was calculated:

$$\text{Delta yield} = Y_{\text{max}} - Y_{\text{check plot}} \qquad [9]$$

where Y_{max} was grain yield at EONR (kg ha^{-1}) and $Y_{\text{check plot}}$ was yield of a plot that did not receive N fertilizer (kg ha^{-1}). These yield calculations were related to sensor measurements through $\text{RCI}_{\text{ratio}}$, $\text{Vis/NIR}_{\text{ratio}}$, and $\text{NDVI}_{\text{ratio}}$.

Environmental Measurements

Three environmental measurements were used to account for N fertilizer that was applied to each plot. These included yield efficiency (YE), N fertilizer recovery efficiency (NFRE), and post-harvest soil profile inorganic N. Each were measured on N rate treatments and related to EONR.

Yield Efficiency (YE)

YE was calculated based on yield data collected from each plot as follows:

$$YE = (Y_i - Y_{\text{check plot}}) / N_i \qquad [10]$$

where Y_i was plot yield (kg ha^{-1}), $Y_{\text{check plot}}$ was yield of a plot that did not receive N fertilizer (kg ha^{-1}), and N_i was the N rate of the plot (kg ha^{-1}). Results from this calculation produced YE in kg grain (kg N)$^{-1}$, and related to the difference from EONR. As a result of the lack of significance for much of the EONR data for 2005 fields, YE for 2005 fields was also related to N rate.

N Fertilizer Recovery Efficiency (NFRE)

After physiological maturity, six plants were removed from N rate treatments of selected fields. These included fields B04, D04, S04, D05, G05, and S05. In 2004, the samples were collected from an area near the center of the research plot, but outside of the area that was later hand-harvested for yield (three samples came from each end of the yield area). Corn ears were removed and processed separately. Corn stalks were cut at ground level, folded 1-2 times, and tied with twine to prevent significant leaf loss. For 2005 fields, six plants were randomly selected from the center of each research plot. The samples were then bundled according to the procedure for 2004. Corn stalks and bags of corn ears were then transferred to a storage shed for further preparation for laboratory analysis. During storage, fans were used to further dry the samples.

Corn stalks were weighed and ground with a small stationary flail chopper. Each sample was mixed, and a subsample weighed, then dried for 24 hours at 41°C. Samples were again weighed, ground through a Wiley Mill with a 1 mm sieve (Thomas Scientific, Swedesboro, N.J.), and a subsample transferred to an 8.9 by 16.5 cm coin envelope. These subsamples were further ground with a cyclone mill (UD Corp., Boulder, CO) and sent to a lab for total N analysis.

The six-ear grain samples were weighed and shelled with a stationary, spinning plate corn sheller. Cobs were weighed and grain subsamples were collected. Moisture content of grain samples was determined using a GAC 2000 DICKEY-john moisture tester (DICKEY-john Corp., Auburn, IL). Grain subsamples were transferred to 8.9 by 16.5 cm coin envelopes and dried for 72 hours at 41°C. Samples were then ground through a Wiley Mill with a 1 mm sieve, further ground with a cyclone mill, and sent to a lab for total N analysis.

In 2004, grain and stover total N analysis was conducted at Harris Lab in Lincoln, NE using the total Keldahl N procedure. In 2005, due to time constraints, grain and stover N analysis was conducted with a LECO FP-428 machine (LECO Corp., St. Joseph, MI) through the Soil and Plant Testing Laboratory at the University of Missouri-Columbia. Based on laboratory results, NFRE was calculated according to the equation:

$$\mathrm{NFRE} = [(\mathrm{NR}_i - \mathrm{NR}_{\text{check plot}}) / \mathrm{N}_i]100 \qquad [11]$$

where NR_i was the N recovered from the plot (kg ha^{-1}), $\mathrm{NR}_{\text{check plot}}$ was the N recovered from a plot the did not receive N fertilizer (kg ha^{-1}), and N_i was the N rate of the plot (kg ha^{-1}). This calculation produced a percent NFRE, and related to the difference from EONR. As a result of the lack of significance for much of the EONR data for 2005 fields, NFRE for these fields was also related to N rate.

Soil Inorganic N

For both years, post-harvest soil samples were collected from three different fields in order to calculate residual soil N levels. These fields were representative of the three major agriculture production soils in Missouri: fields D04 and D05 (flood plain); fields P04 and G05 (deep loess); and fields S04 and S05 (claypan). Soil samples were collected with a John Deere Gator-mounted Giddings Soil Coring Machine (Giddings Machine Co., Windsor, CO).

Soil samples were taken from selected N treatment sets at varying distances throughout each field. Sampled treatment sets were as follows: D04-treatment sets 2,4, and 6; P04-treatment sets 1 and 2; S04-treatment sets 2 and 4; D05-treatment sets 1, 4, and 7; G05-treatment sets 1, 3, and 6; S05-treatment sets 1,3, and 5.

Sample cores were 3.8 cm in diameter and taken to a depth of 120 cm. Four cores were extracted from the center of each plot, and were spaced at various distances between corn rows to avoid biasing data as a result of location of fertilizer placement between rows. Each core was divided into 5 depths, consisting of 0-15 cm, 15-30 cm, 30-60 cm, 60-90 cm, and 90-120 cm. Samples from each depth for each plot were transferred to gallon-sized re-sealable bags, labeled, and stored in a refrigeration unit at 4°C. Cores were then sieved at field-moisture conditions through a 6-mm screen and mixed to create a homogeneous sample. To reduce microbial activity, samples were then stored in a freezer at -17°C until laboratory analysis. For both years, inorganic N analysis (NO_3^- and

NH_4^+) was conducted at the Soil and Plant Testing Laboratory at the University of Missouri-Columbia using 2 M KCl extraction and analyzed with a Lachat flow injection system (Lachat Instruments, Milwaukee, WI). In order to measure NO_3^- and NH_4^+ with minimal transformations, soil samples were analyzed as wet samples (Scharf, personal communication, 2005). Results were used to calculate residual soil profile inorganic N in kg N ha^{-1}, and related to the difference from EONR. As a result of the lack of significance for much of the EONR data for 2005 fields, profile inorganic N for these fields was also related to N rate.

CHAPTER 4

RESULTS AND DISCUSSION

EONR Measurements and Calculation

Yield response models varied widely between each of the research fields in 2004 (Figure 4.1). Corn production conditions were favorable in 2004 and resulted in high yields, each with significant ($\alpha = 0.05$) yield response models. Almost the opposite was true in 2005 (Figure 4.2). Yield response models for the four 2005 fields correspond to the level of precipitation at each field (Table 3.3). No significant yield response was found for fields with severe drought (D05 and S05). Stress was less for G05 and L05 and yield response to N application was significant.

Tables 4.1 and 4.2 contain the quadratic model information for each field and for each N treatment set for the two growing seasons. In 2004, the field average r^2 value for the yield response models was 0.70. The r^2 value for the four 2005 fields varied from 0 to 0.59. This wide range of r^2 variability for 2005 fields was attributed to extremely dry conditions at essential times during the growing season. Drought stress resulted in poor growth and grain production, and an inability of plants to respond to differences between N treatments. Field L05 ($r^2 = 0.59$) was located in the least drought stressed area of the 2005 fields. It received 10 cm more rainfall during the months of May, June, and July than the other fields (Table 3.3), resulting in a significant yield response model.

Yield response models also varied widely within each field. In 2004, yield significantly ($\alpha = 0.05$) responded to N in 41 of the 45 treatment sets (Table 4.1). Two additional treatment set yield response models were significant at $\alpha = 0.10$ level. Significant yield response models could be calculated for all 2004 fields and most

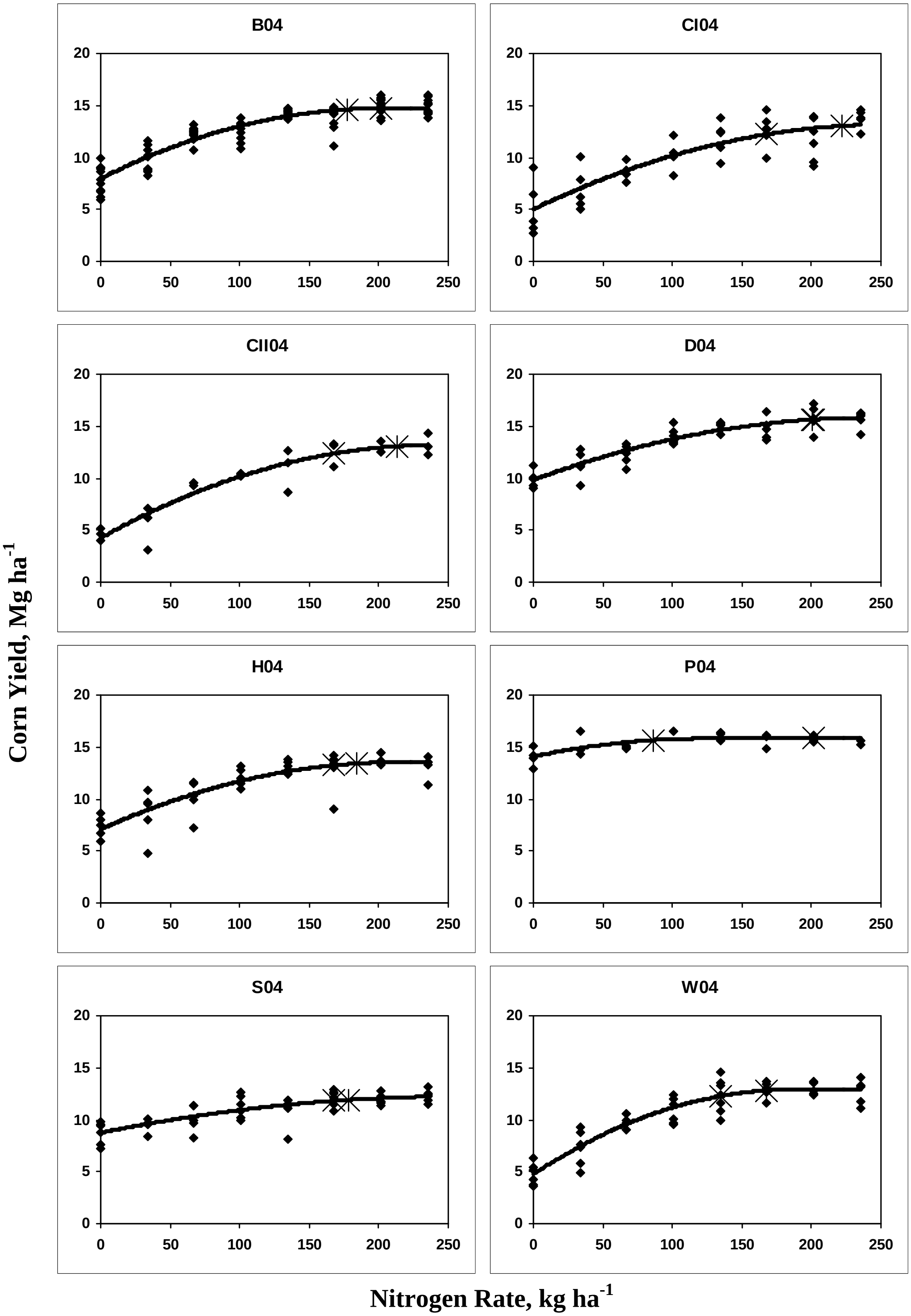


Figure 4.1: Yield as a function (quadratic-plateau model) of N rate by field for the 2004 growing season. (⋇: EONR; X: producer N rate)

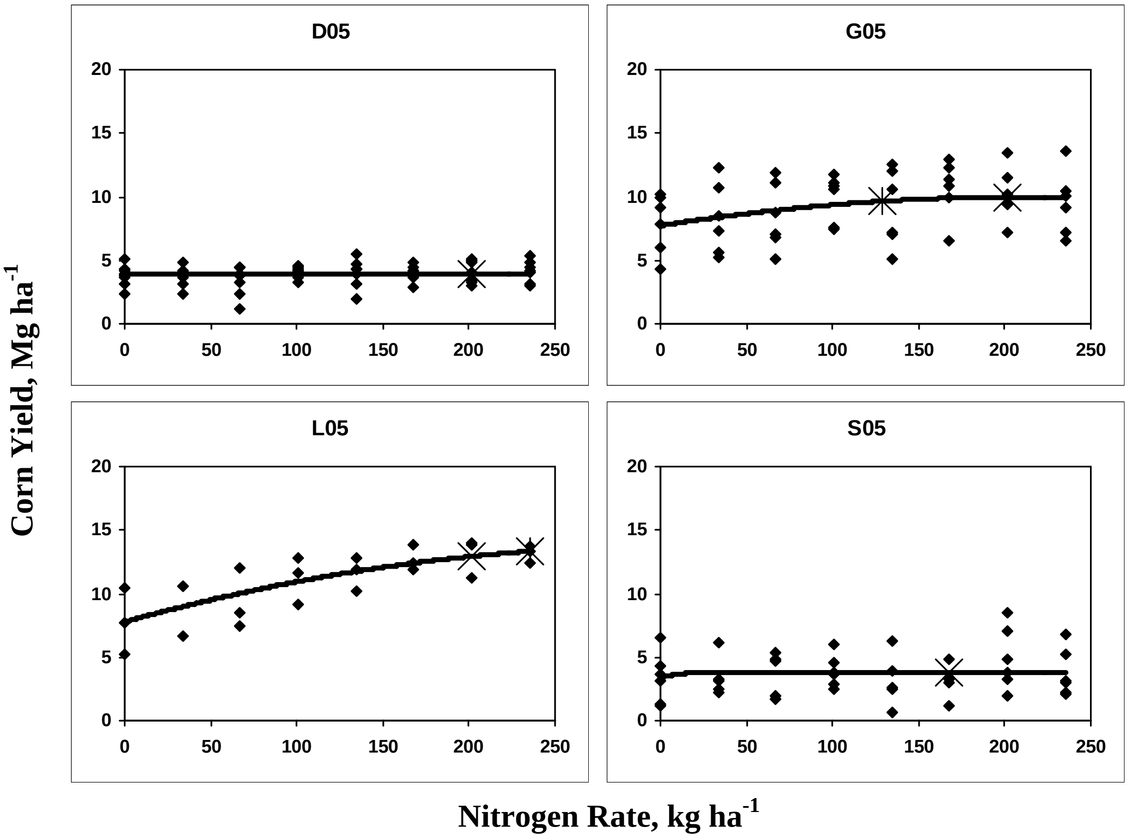


Figure 4.2: Yield as a function (quadratic-plateau model) of N rate by field for the 2005 growing season. (⋇: EONR; X: producer N rate)

Table 4.1: Quadratic model and EONR for each field and treatment set within each field in 2004.

Field	Treatment Set	Quadratic Model a	 b	 c	Max Yield	N rate at Max Yield‡	EONR†‡	Yield at EONR	N rate at Max Yield - EONR	F-test P>F	r^2
					kg ha^{-1}						
B04	Field	8000	75.27	-0.20	14700	201	176	14600	25	<0.01	0.855
	1	7900	72.82	-0.18	15100	219	191	14900	28	0.02	0.936
	2	6800	91.26	-0.24	15400	211	189	15300	22	<0.01	0.965
	3	6800	63.58	-0.15	13500	235	202	13400	34	0.01	0.866
	4	6900	98.51	-0.33	14100	163	147	14000	16	0.01	0.833
	5	9800	46.36	-0.08	15900	235	235	15900	0	<0.01	0.982
	6	8700	74.46	-0.22	14900	185	162	14800	23	<0.01	0.957
	7	8800	69.75	-0.20	14700	189	164	14600	26	<0.01	0.951
	8	7900	94.48	-0.33	14500	158	142	14500	16	<0.01	0.940
	9	9200	73.38	-0.23	15000	178	155	14900	23	<0.01	0.970
	10	7600	72.60	-0.18	14900	224	195	14700	29	<0.01	0.966
	11	6300	122.69	-0.49	13900	140	129	13900	11	<0.01	0.934
CI04	Field	5000	71.66	-0.15	13100	235	222	13000	14	<0.01	0.728
	1	8800	54.71	-0.13	14400	230	191	14300	40	0.02	0.968
	2	6500	56.72	-0.12	12900	235	213	12800	22	0.74	0.683
	3	3800	93.58	-0.21	13800	235	217	13700	18	<0.01	0.990
	4	3000	96.20	-0.22	13400	235	220	13300	16	<0.01	0.985
	5	3300	66.67	-0.13	11400	235	235	11400	0	0.01	0.937
CII04	Field	4200	83.45	-0.19	13200	235	213	13100	23	<0.01	0.875
	1	4000	91.90	-0.24	12600	209	187	12500	21	<0.01	0.959
	2	4600	96.86	-0.27	13000	195	176	12900	19	<0.01	0.980
	3	4100	63.29	-0.07	14100	235	235	14100	0	0.02	0.813
D04	Field	9800	55.41	-0.12	15800	235	201	15600	34	<0.01	0.843
	1	9700	48.41	-0.07	16400	235	235	16400	0	0.01	0.959
	2	9700	69.93	-0.18	16200	210	181	16100	28	<0.01	0.919
	3	11200	44.90	-0.09	16200	235	199	16000	36	<0.01	0.907
	4	9700	58.95	-0.13	16300	235	212	16100	23	<0.01	0.969

Table 4.1 (Continued).

		Quadratic Model									
Field	Treatment Set	a	b	c	Max Yield	N rate at Max Yield‡	EONR†‡	Yield at EONR	N rate at Max Yield - EONR	F-test P>F	r^2
					kg ha^{-1}						
	5	9900	37.53	-0.05	15200	235	235	15200	0	0.01	0.882
	6	8700	71.28	-0.20	14800	192	167	14700	25	<0.01	0.870
H04	Field	7000	68.03	-0.17	13500	214	184	13400	30	<0.01	0.732
	1	7500	71.59	-0.20	13700	195	169	13600	26	<0.01	0.972
	2	7000	35.34	.	.	.	235	.	.	0.13	0.561
	3	7300	71.51	-0.19	14000	208	181	13900	27	<0.01	0.919
	4	7100	61.28	-0.14	13400	231	195	13200	35	<0.01	0.967
	5	6400	115.36	-0.48	13200	133	122	13200	11	0.01	0.822
P04	Field	14100	31.71	-0.14	15800	123	86	15700	36	<0.01	0.506
	1	12900	47.73	-0.21	15600	125	101	15500	25	0.02	0.849
	2	14100	28.47	-0.12	15800	132	89	15600	44	0.06	0.666
	3	14500	105.82	-1.86	16000	32	29	16000	3	0.01	0.611
S04	Field	8700	30.57	-0.06	12200	235	178	11900	57	<0.01	0.617
	1	8400	24.32	-0.03	12100	235	235	12100	0	0.04	0.714
	2	7900	40.40	-0.08	12700	235	210	12600	25	<0.01	0.906
	3	9400	27.11	-0.06	12100	220	144	11800	76	<0.01	0.889
	4	9500	43.71	-0.18	12100	133	104	12000	29	0.04	0.735
	5	9200	46.09	-0.19	11900	134	106	11800	27	0.07	0.653
	6	7500	27.29	-0.02	12300	235	235	12300	0	0.05	0.689
W04	Field	4800	97.94	-0.29	12900	186	168	12800	18	<0.01	0.868
	1	3300	113.12	-0.43	10700	147	135	10600	12	0.03	0.904
	2	3400	99.62	-0.27	12500	203	184	12400	19	<0.01	0.953
	3	5600	70.88	-0.17	12900	231	200	12800	31	<0.01	0.966
	4	4400	104.95	-0.33	12700	177	161	12700	16	<0.01	0.985
	5	6300	98.44	-0.32	13700	167	151	13600	16	<0.01	0.957
	6	5300	116.96	-0.41	13500	156	144	13400	13	<0.01	0.995

† Based on corn grain price of \$0.08 kg^{-1} and N fertilizer cost of \$0.66 kg^{-1}.

‡ N rate at maximum yield and EONR were constrained to maximum N rate (235 kg ha^{-1}) when calculated EONR exceeded the maximum N rate.

Table 4.2: Quadratic model and EONR for each field and treatment set within each field in 2005.

Field	Treatment Set	Quadratic Model a	Quadratic Model b	Quadratic Model c	Max Yield	N rate at Max Yield	EONR	Yield at EONR	N rate at Max Yield - EONR	F-test P>F	r^2
					kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}		
D05	Field	3800	25.95	-1.25	3900	12	7	3900	4	0.67	0.003
	1	4700	-9.80	-1.25	4700	0	0	4700	0	.	0.000
	2	3900	42.03	-1.25	4300	19	15	4200	4	0.40	0.119
	3	3900	-17.26	-1.25	3900	0	0	3900	0	.	0.000
	4	3800	10.49	-1.25	3900	5	0	3800	4	0.96	0.000
	5	4300	24.51	-1.25	4400	11	7	4400	4	0.85	0.006
	6	3700	59.40	-1.25	4400	27	22	4300	4	0.13	0.336
	7	2300	44.66	-1.25	2700	20	16	2700	4	0.64	0.038
	8	3200	29.56	-1.25	3300	13	9	3300	4	0.88	0.004
G05	Field	7700	24.24	-0.06	10000	210	129	9600	82	0.09	0.103
	1	10200	13.05	.	.	.	235	.	.	0.08	0.640
	2	10200	29.69	-1.25	10400	13	9	10400	4	0.95	0.000
	3	8200	51.66	-0.24	11000	120	98	10900	22	0.35	0.345
	4	7900	46.00	-1.25	8300	21	16	8300	4	0.86	0.006
	5	4400	20.77	-0.01	8300	235	235	8300	0	0.17	0.512
	6	6000	112.09	-0.96	9200	65	60	9200	5	0.44	0.282
L05	Field	7800	42.00	-0.07	13300	235	235	13300	0	<0.01	0.591
	1	5200	55.65	-0.10	12300	235	235	12300	0	<0.01	0.977
	2	7700	106.80	-0.54	13000	110	100	12900	10	<0.01	0.888
	3	10000	20.93	.	.	.	235	.	.	0.16	0.513
S05	Field	3300	45.69	-1.25	3800	20	16	3700	4	0.60	0.006
	1	4300	108.43	-1.25	6600	48	44	6600	4	0.06	0.887
	2	5900	-3.65	-1.25	5900	0	0	5900	0	.	0.000
	3	3100	61.69	-1.25	3900	28	23	3900	4	0.36	0.141
	4	1300	53.61	-0.48	2800	62	51	2800	11	0.19	0.488
	5	1200	56.47	-1.25	1800	25	21	1800	4	0.40	0.118
	6	3300	-3.18	-1.25	3300	0	0	3300	0	.	0.000

treatment sets within each field due to favorable corn production conditions during this growing season. In the ten years prior to 2004, Missouri state corn production averaged 7300 kg grain ha^{-1}. Favorable 2004 growing conditions resulted in a new state record for average corn yield being set at 10200 kg grain ha^{-1} (MASS, 2006). Precipitation played a key role in the difference in ability to calculate EONR each year. In 2005, yield responded to N for only 2 of 23 treatment sets at $\alpha = 0.05$ level and one additional treatment set at $\alpha = 0.10$ level (Table 4.2). Again, the lack of model significance for many of the 2005 treatment sets was attributed to the droughty conditions which severely limited a yield response to N application, although fields D05 and S05 were more impacted than fields L05 and G05.

Yield response model results were incorporated into the EONR calculation. Between-field EONR calculations varied widely (Tables 4.1 and 4.2). EONR for the eight 2004 fields ranged from 86 to 222 kg N ha^{-1}. Low EONR for field P04 was attributed to the field being managed in pasture prior to 2002. N mineralization from the soils on this field was undoubtedly high, which allowed the plants to receive most of their N requirement from the soil, giving a low EONR. Further, this field produced the highest yield at EONR of all the 2004 fields. Field-average EONR between the other seven 2004 fields still ranged 54 kg N ha^{-1}, with an average EONR of 192 kg N ha^{-1}. Favorable corn production weather in 2004 increased crop N need and resulted in record-setting yields.

In contrast to 2004 production weather, lack of precipitation in 2005 severely limited corn production in many areas of Missouri. Lack of precipitation resulted in an inability to show N treatment differences and, therefore, a lack of significance for many of the 2005 yield response models. Because of the lack of significance of the yield response model for fields D05 and S05, further EONR data analysis for 2005 fields only involved fields G05 and L05. These two fields had significant EONR values possibly due to higher precipitation levels at these fields and because of their good water-holding capacity soils, which were able to support plant growth during the droughty conditions of 2005. Increased plant growth led to increased crop N need which allowed N treatment differences to be established and yield response models to be calculated. The greatest yield response to N application occurred at field L05. As before mentioned, this field was located towards the western border of Missouri, which was not as drought stressed as mid-Missouri where the other fields were located (Table 3.3).

EONR varied widely between treatment sets within each field as well (Tables 4.1 and 4.2). Variability of EONR within fields found here was similar to findings by Mamo et al. (2003) and Scharf et al. (2005). The range of EONR for 2004 fields was as narrow as 44 kg N ha^{-1} (CI04), and as wide as 131 kg N ha^{-1} (S04). For the two 2005 fields with significant yield response models, within-field EONR varied as much, if not more, than in 2004 fields. Ranges of within-field EONR for fields G05 and L05 were 226 and 135 kg N ha^{-1}, respectively.

Of 23 treatment sets in 2005, the only treatment sets with a significant ($\alpha = 0.10$) EONR value were field G05-treatment set 1, field L05-treatment sets 1 and 2, and field S05-treatment set 1. However, due to lost yield data from 4 of 8 plots from S05-treatment set 1, no additional results are reported for this treatment set. Treatment set 1 of G05 was located in a part of the field with uniform landscape and minimal spatial variability. Treatment sets 2-6 had high and low areas in the soil landscape where water could runoff or pool easily. Treatment set 5 also had a severe cocklebur infestation.

These factors increased the spatial variability in treatment sets 2-6 of G05 and likely resulted in areas with varying problems such as drought stress, denitrification, and competition for nutrients, ultimately leading to extreme variability within treatment sets unrelated to N rate.

A similar response was observed at L05. Treatment sets 1 and 2 had significant yield response models while treatment set 3 was not significant. There are two possible explanations for this: Treatment sets 1 and 2 were located at the bottom of a hill where the landscape was flat. Treatment set 3 was located where the soil was less uniform and corn rows curved around a terrace. These conditions possibly led to less plant available water in treatment set 3 which reduced the yield response to N in this area. Reduced yield might also have been related to some plants being driven over by the fertilizer applicator at the time of N application. As a result, reduced plant population in this area could have contributed to a lower yield response to N for this treatment set.

Soil type seemed to be a factor impacting EONR for 2004 fields. Fields located in river bottom soils (CI04, CII04, D04) all had EONR > 200 kg N ha^{-1}. Fields located in claypan soils (B04, H04, S04, W04) all had EONR < 200 kg N ha^{-1}. These results could be attributed to a few reasons: River bottom soils likely had a higher N need possibly due to their lower water-holding capacity and propensity for leaching NO_3-N below the root zone. On the other hand, fields located in claypan soil regions had lower EONR, possibly associated with a better water-holding capacity soil with the ability to better retain soluble nutrients such as NO_3-N. Perhaps more importantly, river bottom soils are more agriculturally productive than claypan soils. For example, average corn yield in Chariton County (high percentage of river bottom soils) for the period 1996-2005 was

7800 kg ha^{-1}, while corn yield in Audrain County (predominantly claypan soils) was only 6800 kg ha^{-1} (MASS, 2006). Higher corn productivity on river bottom soils than claypan soils would lead to a higher plant N requirement in river bottom areas. Claypan soils have also been shown to severely limit crop root growth (Myers, 2005), which would decrease plant growth and crop N need.

Producer N rate and EONR for each field are indicated on each graph in Figures 4.1 and 4.2. For both years, there was a wide range of variability between EONR and producer N rate. For six fields (CI04, CII04, H04, S04, W04, L05), producers did not apply enough N at planting. On the other hand, producers over-applied N at fields B04, P04, and G05. The producer N rate at field D04 roughly matched EONR (202 and 201 kg ha^{-1}, respectively), and a comparison could not be made for two additional fields (D05 and S05). These results indicate that most producers are losing profitability by under- or over-applying N. If the amount of N producers apply could better match EONR, profitability could increase, and for the case of over-application, less N would be lost to the environment.

Reflectance by Sensors

Once EONR was determined for each field and treatment set within each field, active-light reflectance sensor measurements were then related to EONR through the use of three vegetation indices: relative chlorophyll index ratio (RCI_{ratio}), visible relative to near-infrared ratio (Vis/NIR_{ratio}), and normalized difference vegetation index ratio ($NDVI_{ratio}$).

Figure 4.3 contains results for each of the vegetation indices for 2004 fields. Results from a regression *F*-test ($\alpha = 0.05$) showed that for some fields EONR was

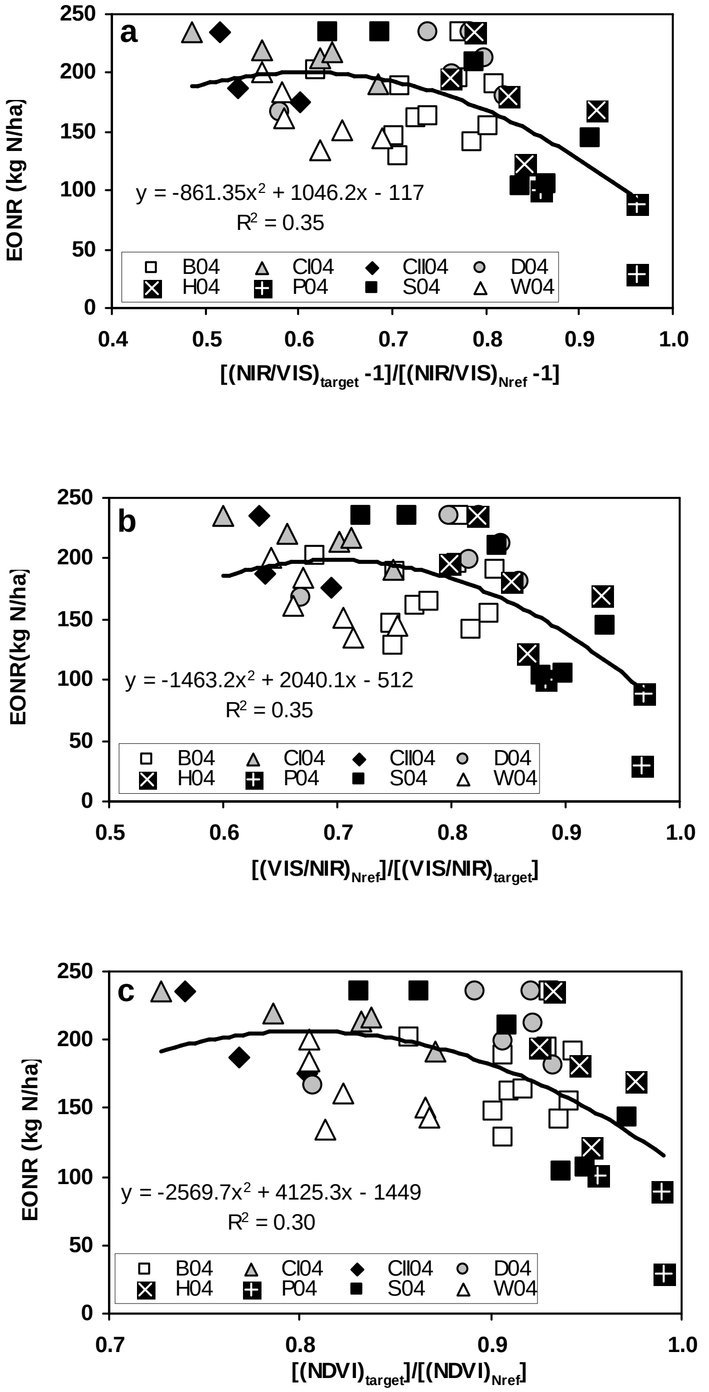


Figure 4.3: EONR related to active-light reflectance sensor indices for 2004 data: (a) RCI_{ratio}, (b) Vis/NIR_{ratio}, and (c) $NDVI_{ratio}$.

significantly related to the indices, while it was nonsignificant for others. However, since the ultimate goal is to have a universal relationship (not just a field-specific calibration), the fields were pooled together. Pooled there was a significant relationship between EONR and the indices. The eight different symbol types on each graph correspond to the eight producer fields in 2004. The number of dots for each symbol type corresponds to the number of treatment sets within that particular field. Therefore, EONR for a particular dot is the calculated EONR for one treatment set. The index ratio value associated with that dot consists of the average of all sensor measurements over that treatment set and the average sensor measurements for that treatment set's adjacent N-rich reference area.

In 2004, data for all three indices was fitted with a second-order significant ($\alpha = 0.05$) polynomial. The $\mathrm{RCI}_{\mathrm{ratio}}$ and $\mathrm{Vis/NIR}_{\mathrm{ratio}}$ provided a better relationship for predicting EONR ($r^2 = 0.35$) than did $\mathrm{NDVI}_{\mathrm{ratio}}$ ($r^2 = 0.30$). The $\mathrm{RCI}_{\mathrm{ratio}}$ (Figure 4.3a) had the widest range (0.4-1.0) of the three indices evaluated. This wider range was useful in spreading out the data to show slightly different index values for varying levels of EONR. This was perhaps best illustrated in field S04, which had the widest range of index values (0.63-0.91) and also the widest range of within field EONR variability (104-235 kg N ha^{-1}). This same pattern was also observed for fields with lower index values. Although field CI04 had the narrowest range of EONR of any of the 2004 fields (191-235 kg N ha^{-1}), the indices separated the treatment sets into a broad range of index values.

Index values did not seem to vary according to the three different soil types represented by these fields. They were better able to distinguish extremes in soil variability within the same field. For example, treatment sets 1-5 of D04 were located in a gentle sloping area of the field, with relatively uniform soil landscape characteristics. EONR for these five treatment sets averaged 212 kg N ha^{-1} with a standard deviation of 23 kg N ha^{-1}. Treatment set 6 of D04 had a severe infestation of shattercane, a higher sand content in the soil compared to the other treatment sets, and was located where the landscape position dropped off rapidly into a water-accumulating area of the field. EONR for this treatment set was only 167 kg N ha^{-1}. The sensors were able to distinguish between these two areas of the field. RCI_{ratio} values for treatment sets 1-5 averaged 0.78, while the index value for treatment set 6 was 0.58. A similar but less pronounced pattern was observed in index values from Vis/NIR_{ratio} and $NDVI_{ratio}$.

The RCI_{ratio} and Vis/NIR_{ratio} were more closely related to EONR than $NDVI_{ratio}$ (Figure 4.3). Generally, these indices were able to grossly identify corn that needed less N (> 0.80 RCI_{ratio}). For this year of ideal growing conditions, sensor readings at side-dress growth stage were not sensitive to variation in EONR for lower ratio values (e.g. < 0.80 RCI_{ratio}). For RCI_{ratio} values between 0.80 and 1.0, the regression-predicted EONR decreased from about 160 to 90 kg ha^{-1}, respectively. For those fields with points on Figure 4.3a > 0.80, the average producer N rate was 185 kg ha^{-1}. Because the indices are able to roughly distinguish between areas of a field which required high amounts of N from areas of a field which require less N, the RCI_{ratio} and Vis/NIR_{ratio} might be useful tools for determining N management zones within fields based on sensor measurements. Such an N management strategy would likely reduce NO_3-N leaching potential, as discussed by Delgado et al. (2005).

In 2005, only three treatment sets had significant EONR values (Figure 4.4). Each of the indices was able to separate between the high and low EONR for the two

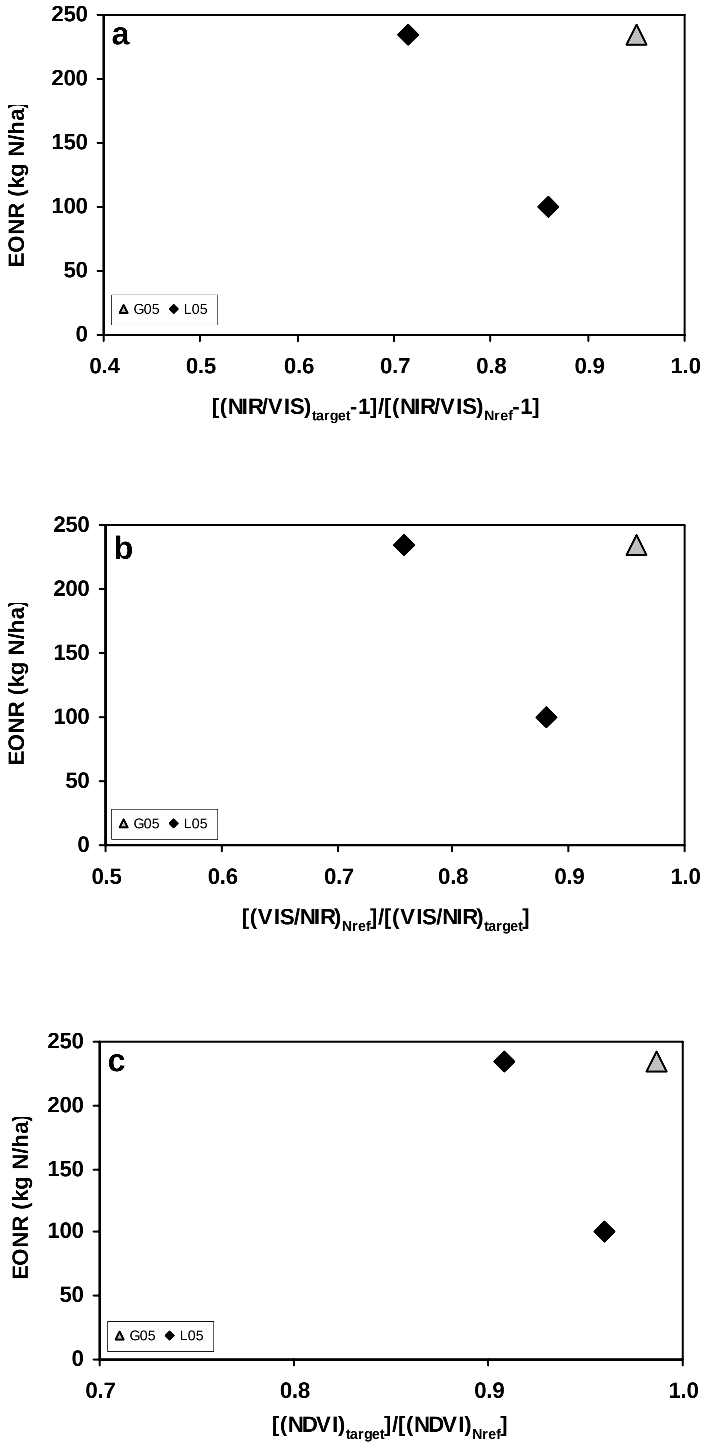


Figure 4.4: EONR related to active-light reflectance sensor indices for 2005 data: (a) RCI$_{ratio}$, (b) Vis/NIR$_{ratio}$, and (c) NDVI$_{ratio}$.

treatment sets from L05. However, due to a limited number of 2005 treatment sets where EONR could be found, a meaningful relationship could not be established between EONR and the vegetation indices. Also, because response was so limited in 2005, I chose not to combine the two growing seasons.

The relationship for predicting EONR using the indices and soil EC was evaluated for 2004 fields (Table 4.3). Although EC alone was not a significant variable, the interaction of each ratio and EC was significant ($\alpha = 0.05$). The addition of EC better explained EONR results in the field ($r^2 = 0.47$) compared to the relationship between index values and EONR alone ($r^2 \leq 0.35$). For a given index, EONR was less at lower soil EC values (Figure 4.5). The interaction between EC and the ratio is not entirely clear since there is not a full range of ratio and EC values. However, the ridge in the response function observed at ~0.80 $\text{Vis/NIR}_{\text{ratio}}$ helps to visualize the point at which EONR drops off rapidly as the index ratio increases. As shown in Figure 4.5, EC helped to separate corn with lower index values that looked very different from N-rich corn (< 0.80 for $\text{Vis/NIR}_{\text{ratio}}$) from corn with higher index values that more closely resembled N-rich corn (> 0.80 for $\text{Vis/NIR}_{\text{ratio}}$). These results suggest that soil EC measurements have potential for establishing N management zones within or between fields, similar to findings by Kitchen et al. (2005).

Delta yield was significantly ($\alpha = 0.05$) related to each of the indices (Figure 4.6). The relationships between $\text{Vis/NIR}_{\text{ratio}}$ and delta yield ($r^2 = 0.50$) suggests that sensor measurements have potential to predict delta yield, and could thereby be used as a basis to apply N in-season as suggested by Lory and Scharf (2003).

Table 4.3: Regression model for three indices pooled across all 2004 fields, relating EONR, Ratio, and soil EC.

Ratio	Regression Model				F-test P>F	r^2
	Intercept	Index	Index x EC	Index^2		
RCI	-265	1345.5412	1.4428	-1037.812	<0.01	0.467
Vis/NIR	-794	2632.7087	1.3174	-1798.747	<0.01	0.473
NDVI	-2397	6096.6628	1.2335	-3618.944	<0.01	0.411

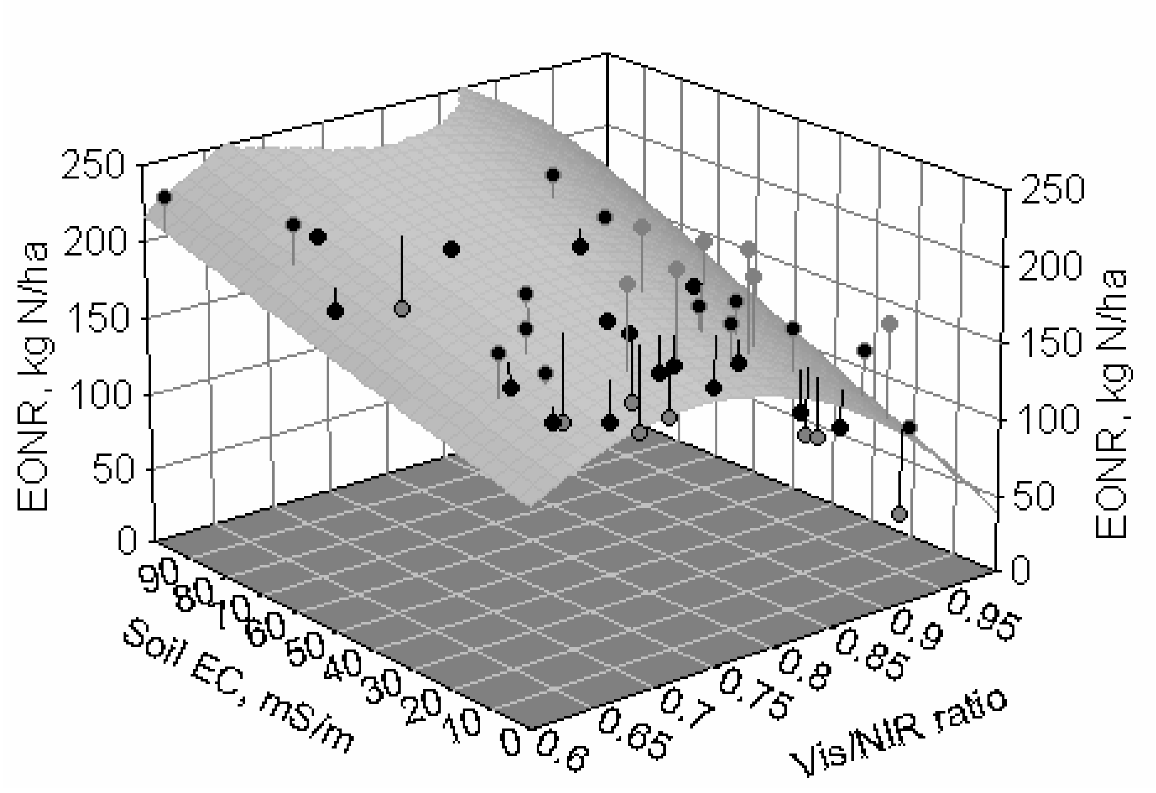


Figure 4.5: EONR relationship with soil EC and Vis/NIR$_{ratio}$, pooled across all 2004 fields. (black points: < 1 standard deviation; gray points: < 2 standard deviations)

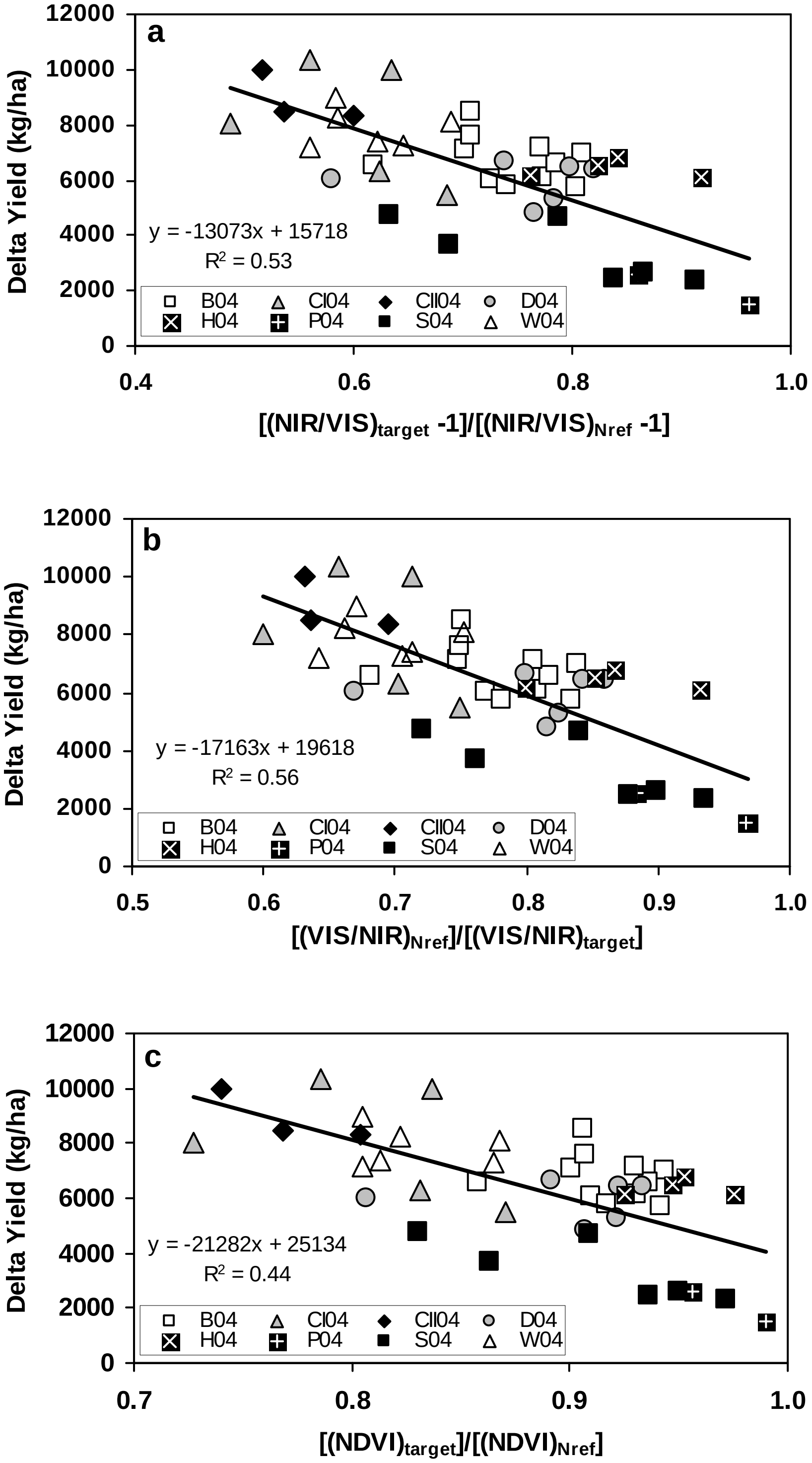


Figure 4.6: Delta yield related to active-light reflectance sensor indices for 2004 data: (a) RCI_{ratio}, (b) Vis/NIR_{ratio}, and (c) $NDVI_{ratio}$.

Despite the strong relationship between delta yield and sensor measurements, a weaker relationship was observed between delta yield and EONR ($r^2 = 0.34$) (Figure 4.7). This was in contrast to the results found by Lory and Scharf (2003) in which delta yield and EONR for Missouri data was highly correlated ($r^2 = 0.65$). However, the regression model intercept values (EONR as a function of delta yield) for this research project and their research were similar (39 and 55 kg ha^{-1}, respectively). Lory and Scharf (2003) determined to only use a linear model to fit the data because there was no indication of a curvilinear relationship between delta yield and EONR. Previously, Kachanoski et al. (1996) suggested a nonlinear model with a plateau N rate of ~175 kg ha^{-1} best fit the relationship between delta yield and EONR. In contrast to Lory and Scharf (2003) who observed a maximum delta yield of ~8000 kg ha^{-1}, Figure 4.7 of this research shows a nonlinear model with a delta yield above 8000 kg ha^{-1} with many data points. This wider range of delta yield is likely the reason for the curvilinear response, a result of greater plant response to applied fertilizer N due to the favorable 2004 growing conditions.

Environmental Measurements

Difference from EONR was related to each of three environmental measurements: yield efficiency (YE), N fertilizer recovery efficiency (NFRE), and post-harvest soil profile inorganic N. These three measurements are a means to account for N fertilizer that was applied at side-dress.

Yield Efficiency (YE)

Figure 4.8 shows the difference from EONR related to average YE for each of the eight 2004 fields. The points are the YE values for each N application rate, averaged

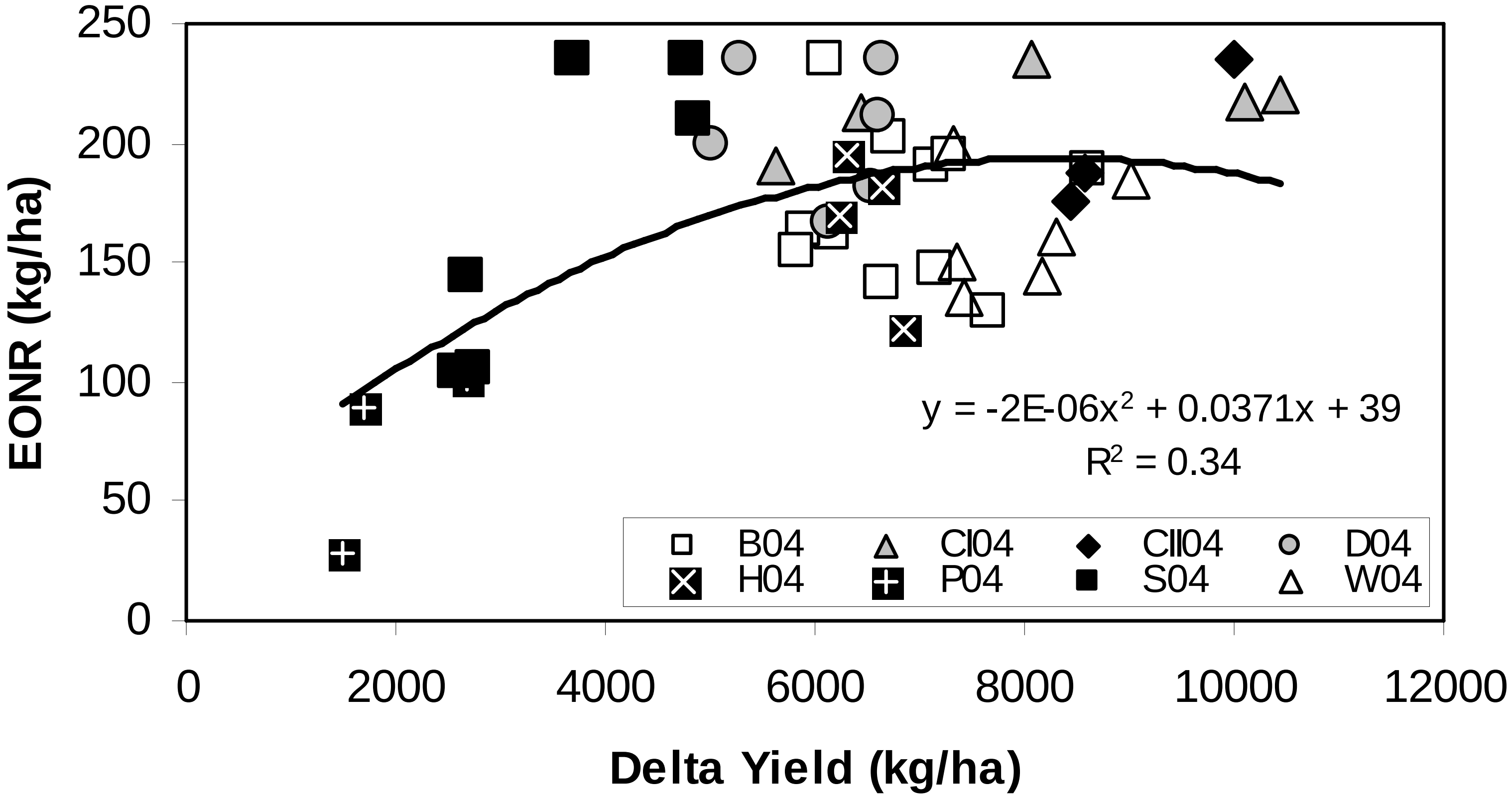
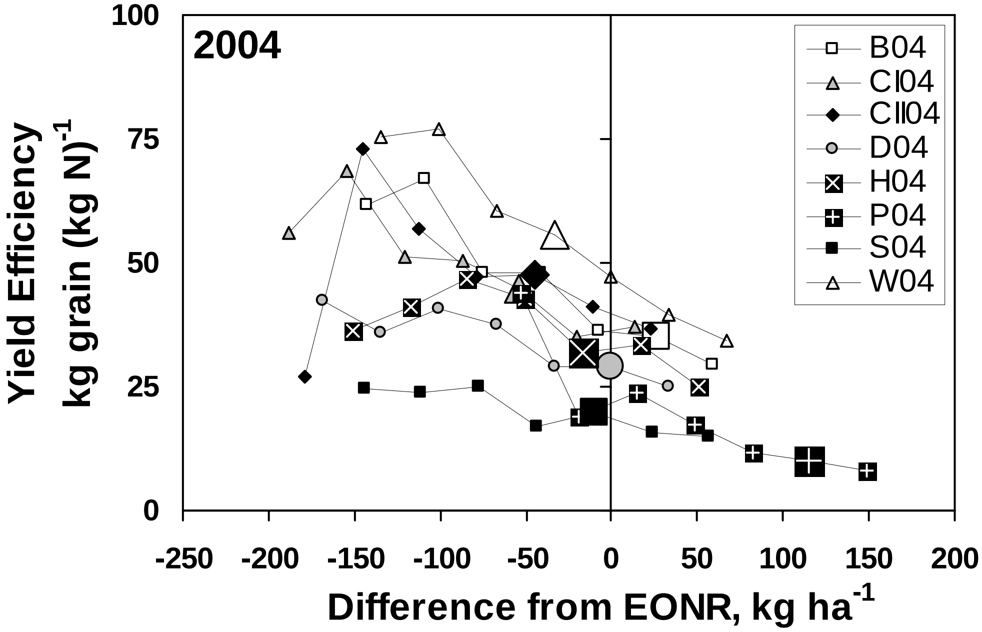


Figure 4.7: EONR related to delta yield for 2004 fields.



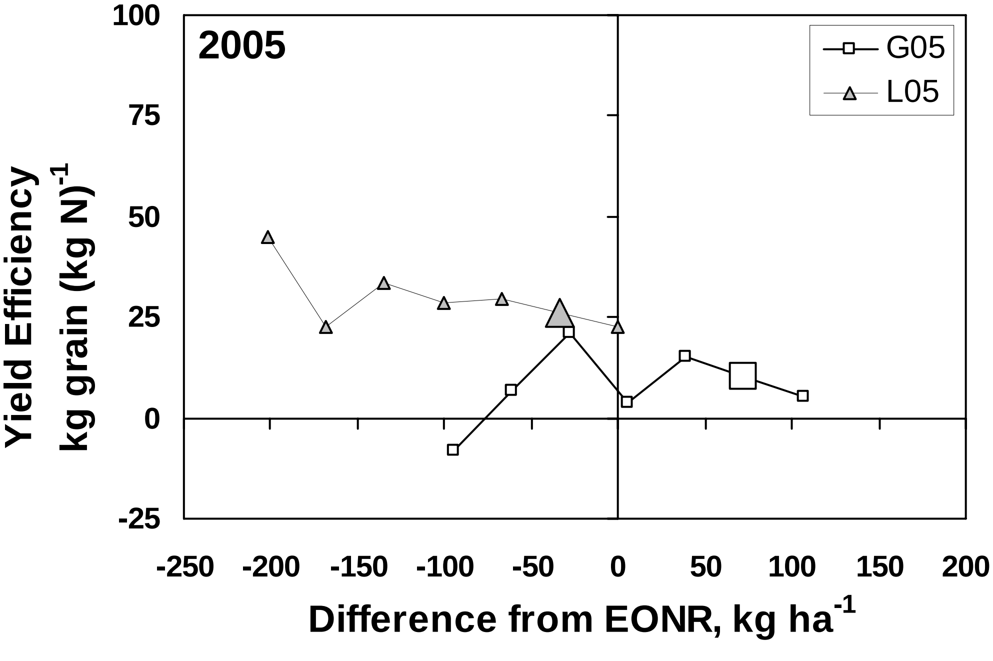


Figure 4.8: Yield efficiency field averages in relation to difference from EONR for 2004 and 2005 fields. Producer N rate at planting for each field indicated by enlarged symbol on each trendline.

over all treatment sets within a field. Zero N application rates are not included in the trendlines because YE is undefined with zero N. Therefore, each trendline contains seven points representative of the other seven N application rates within each treatment set. For these figures, values to the left of zero (negative on the x-axis) represent N rates that are below EONR. To the right of zero (positive) are N rates in excess of EONR. YE at EONR was not the same between fields in 2004, ranging from 19-47 kg grain (kg N)$^{-1}$. This wide range of variability in YE at EONR could possibly be linked to soil characteristics at each of the fields. However, even more importantly, producer management practices could have contributed to this observed variability through type of tillage used, selected corn hybrid, past N management practices, among other things.

In 2005 there were only two fields with determinable EONR for comparison with YE (Figure 4.8). Field G05 did not show any trend as N rate increased. Field L05 weakly showed a trend similar to 2004 fields, with decreasing YE as N rate approached EONR. At EONR, YE for fields G05 and L05 was 7 and 23 kg grain (kg N)$^{-1}$, considerably lower YE than in 2004. This difference could be attributed to the drier growing season, which limited yield in 2005.

The producer N rate at planting for each field is indicated by an enlarged symbol on each trendline (Figure 4.8). This shows that for most fields, producers were either under- or over-applying N compared to EONR.

YE also varied between treatment sets within each field. YE by each treatment set for 2004 fields are shown in Figure 4.9. As N rate increased, YE trended downward. Generally, once N rate matched EONR, YE decreased at a slower rate due to the plant having sufficient amounts of N to carry out its vegetative and reproductive needs. Most

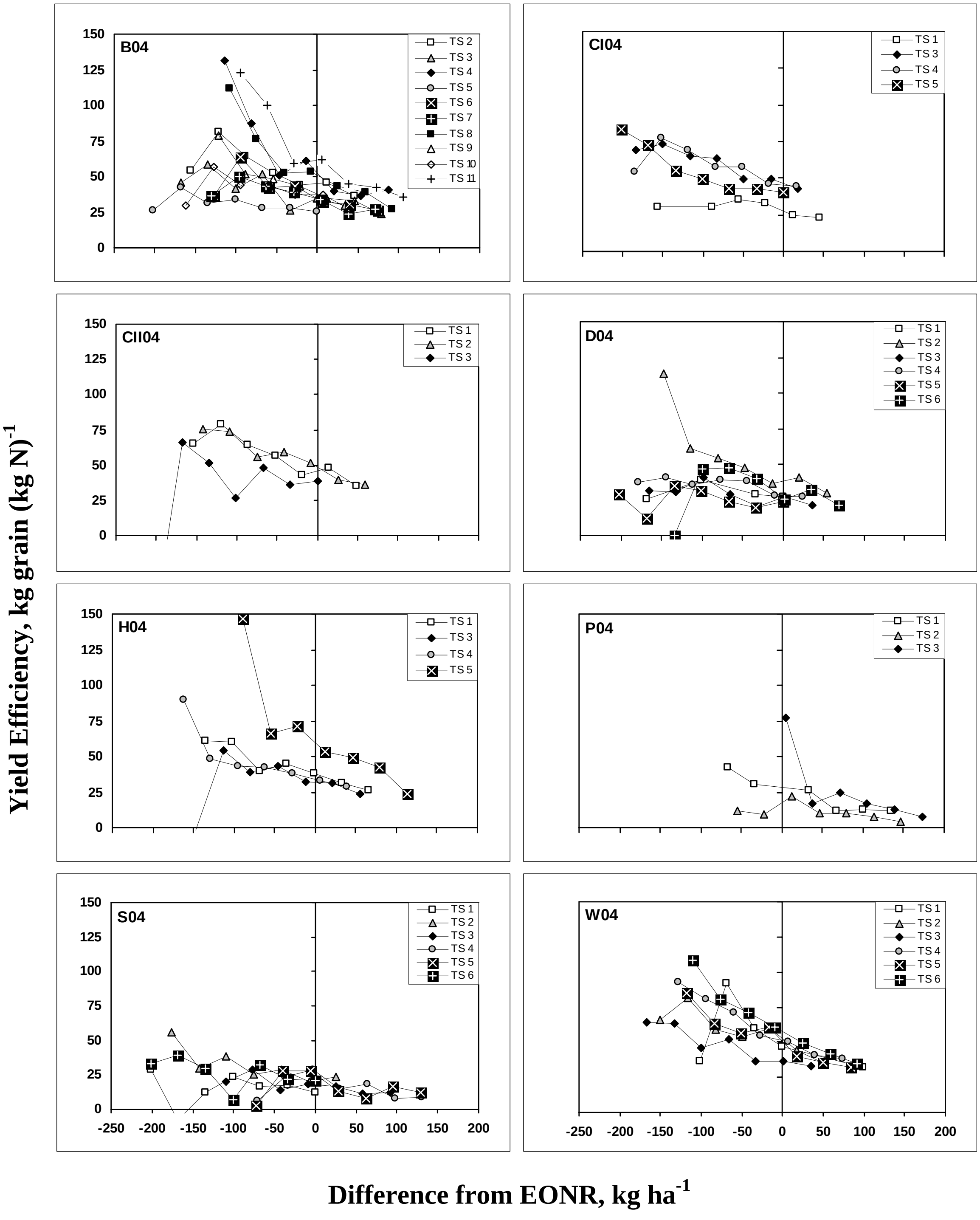


Figure 4.9: Within-field yield efficiency in relation to difference from EONR for 2004 fields.

all fields had at least one treatment set where YE increased between 34 and 68 kg N ha^{-1}, before a decreasing trend. For example, in B04 treatment sets 4, 8, 9, and 11 showed a decrease in YE with increasing N application rates. On the other hand, treatment sets 2, 3, 5, 6, 7, and 10 all had a YE which increased between 34 and 68 kg N ha^{-1}, and then began to decline with increasing N application rates. Also, YE was negative for some plots. These two observations of N application could be related to a "soil priming" effect with N fertilizer application (Leon et al., 1995). The soil priming effect is the theory that initial N applications are not taken up by the plant because of immobilization by soil microbes. For the cases where YE is less than zero, it suggests the crop is starved for N more with the first increment of N fertilizer than had no N been applied at all. For the cases where YE increases between 34 and 68 kg N ha^{-1}, it means that the magnitude of yield was greater with the second increment of N fertilizer than the first. In other words, the soil "fixed" the majority of the first increment of N fertilizer. As N application rate continued to increase and approach EONR, the plant was less starved for N and uptake decreased in proportion to incremental increases in fertilizer N. The result was a decrease in YE.

Within-field YE variability for significant EONR treatment sets of fields G05 and L05 are shown in Figure 4.10. At EONR, YE for treatment sets 1 and 2 of field L05 was 31 and 51 kg grain (kg N)$^{-1}$, respectively. Yield and YE was higher for the treatment sets at this field than for the treatment set in field G05 (YE = 15 kg grain (kg N)$^{-1}$), presumably due to slight precipitation differences between fields. Field L05 received higher amounts of precipitation that led to more vigorously growing plants and higher N requirements than at field G05.

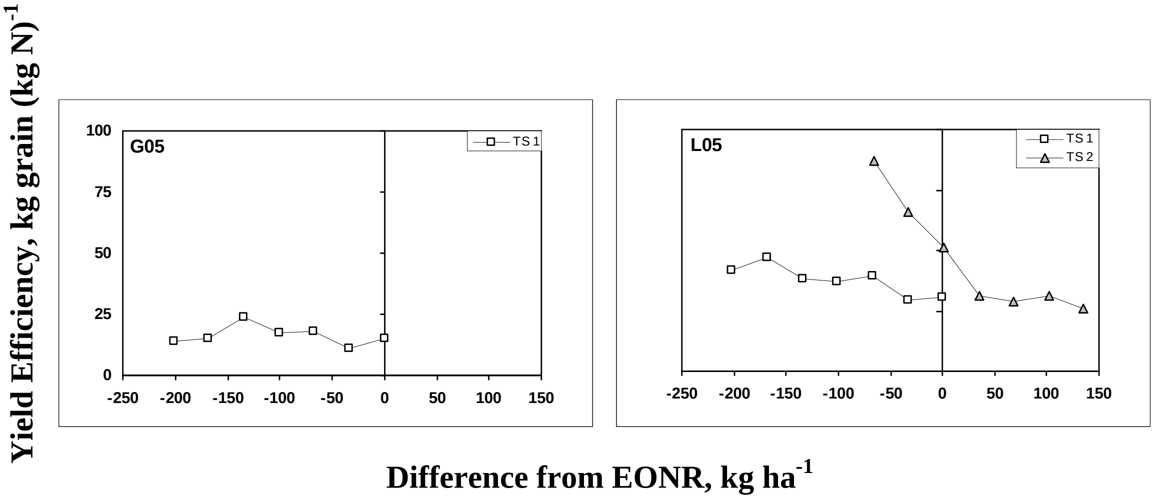


Figure 4.10: Within-field yield efficiency in relation to difference from EONR for 2005 fields.

Difference from EONR was only significant for 4 of 23 treatment sets in 2005. Therefore, in order to report results of all measurements taken, N rate was also related to YE for all of the 2005 fields and treatment sets. Figure 4.11 shows YE averaged across all treatment sets at each of the four 2005 fields. Fields with severe drought stress (D05 and S05) showed little N fertilizer response (Figure 4.12). Negative YE in many of the treatment sets was caused by individual plot yields being less than the check plot yield. G05 was moderately drought stressed, and showed some response to N application, while L05 was under the least amount of drought stress, and exhibited the most N fertilizer response. N application may have contributed to greater drought stress in these fields, as discussed by Eghball and Maranville (1991).

N Fertilizer Recovery Efficiency (NFRE)

Similar to YE, NFRE declined as N rate approached EONR. Figure 4.13 shows the NFRE results for the three selected fields of 2004, averaged across all treatment sets within each field. NFRE at EONR ranged from 35 to 46%. This value is higher than the estimate of the world average NFRE (33-37%) for cereal crops (Cassman et al., 2002; Raun et al., 2002). G05 was the only field sampled for NFRE that also had a significant EONR value. Averaged across all treatment sets, NFRE at EONR for this field was only 5%, with NFRE exhibiting no trend as N rate approached EONR. Due to the spatial variability between treatment sets in the same field, within-field NFRE at EONR was even more variable than between-field NFRE at EONR, ranging from 28 to 71% (Figure 4.14). G05 only had one treatment set with a significant EONR. This treatment set displayed no response in NFRE as N rate approached EONR.

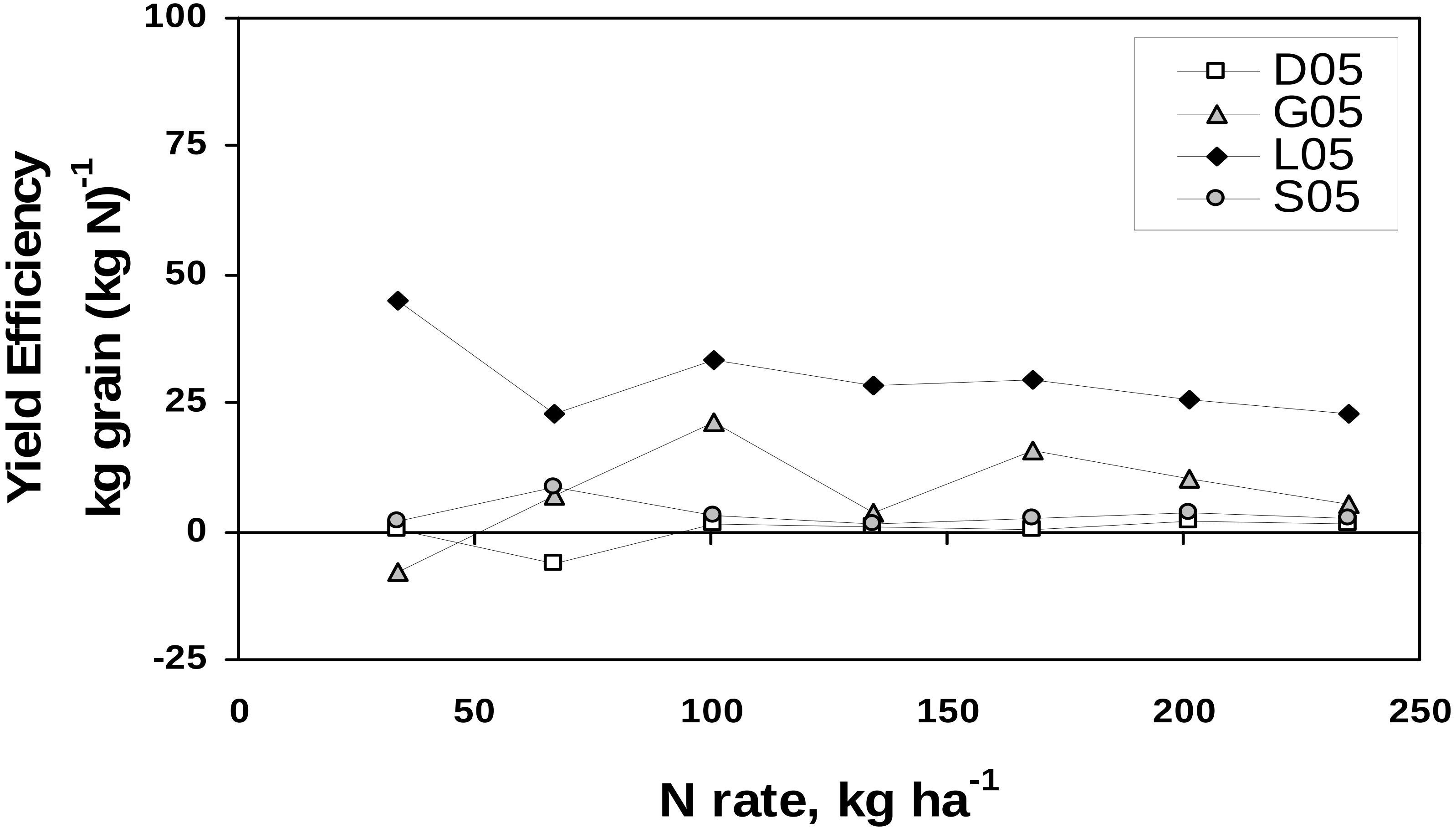


Figure 4.11: Yield efficiency field averages in relation to N rate for 2005 fields.

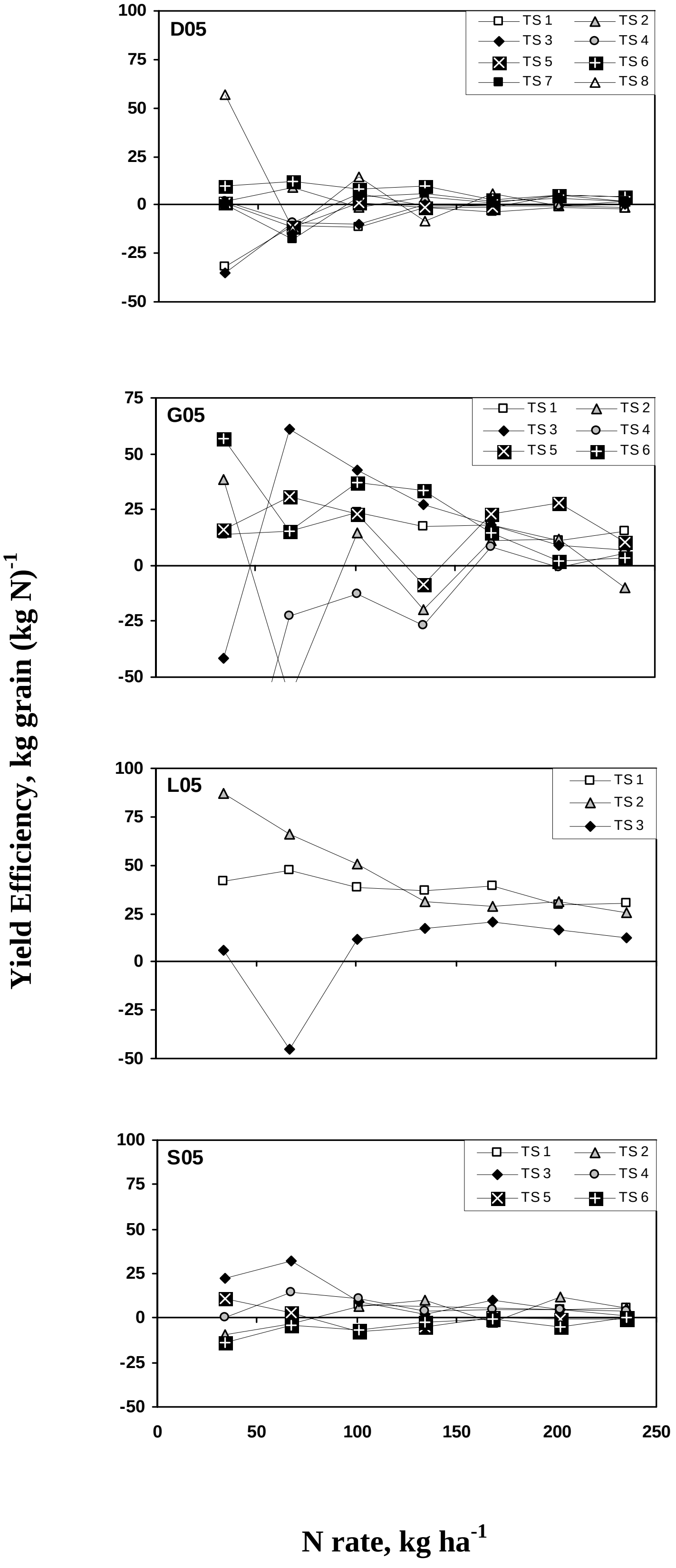
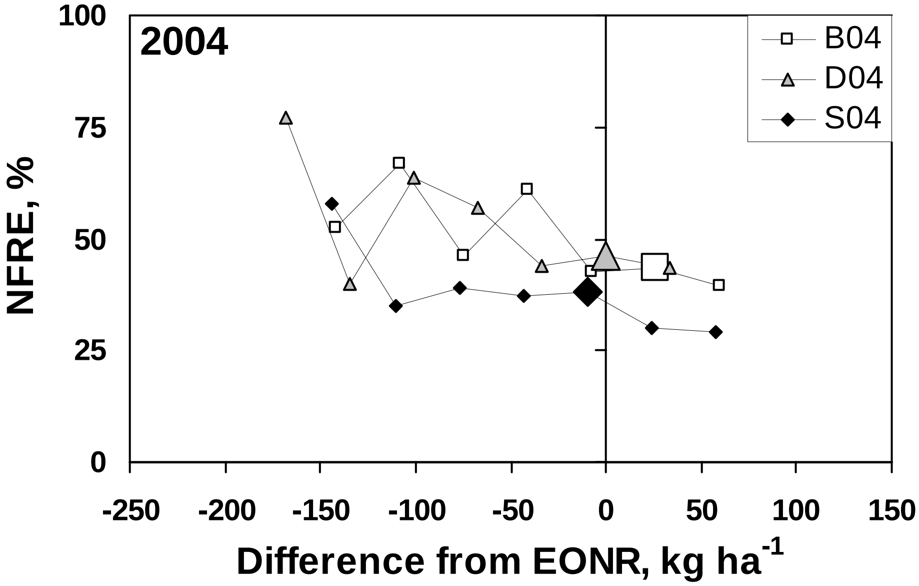


Figure 4.12: Yield efficiency in relation to N rate for 2005 fields.



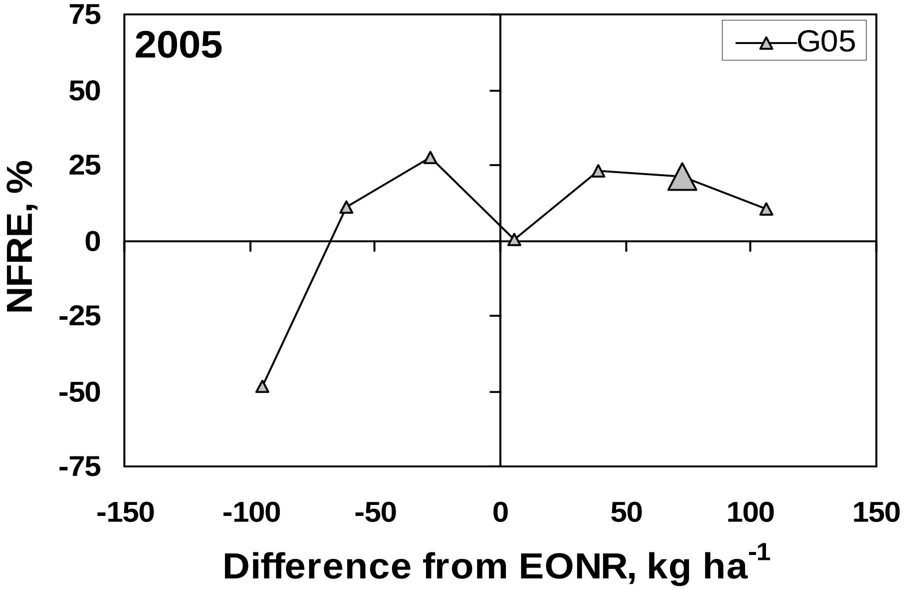


Figure 4.13: NFRE field averages in relation to difference from EONR for 2004 and 2005 fields. Producer N rate at planting for each field indicated by enlarged symbol on each trendline.

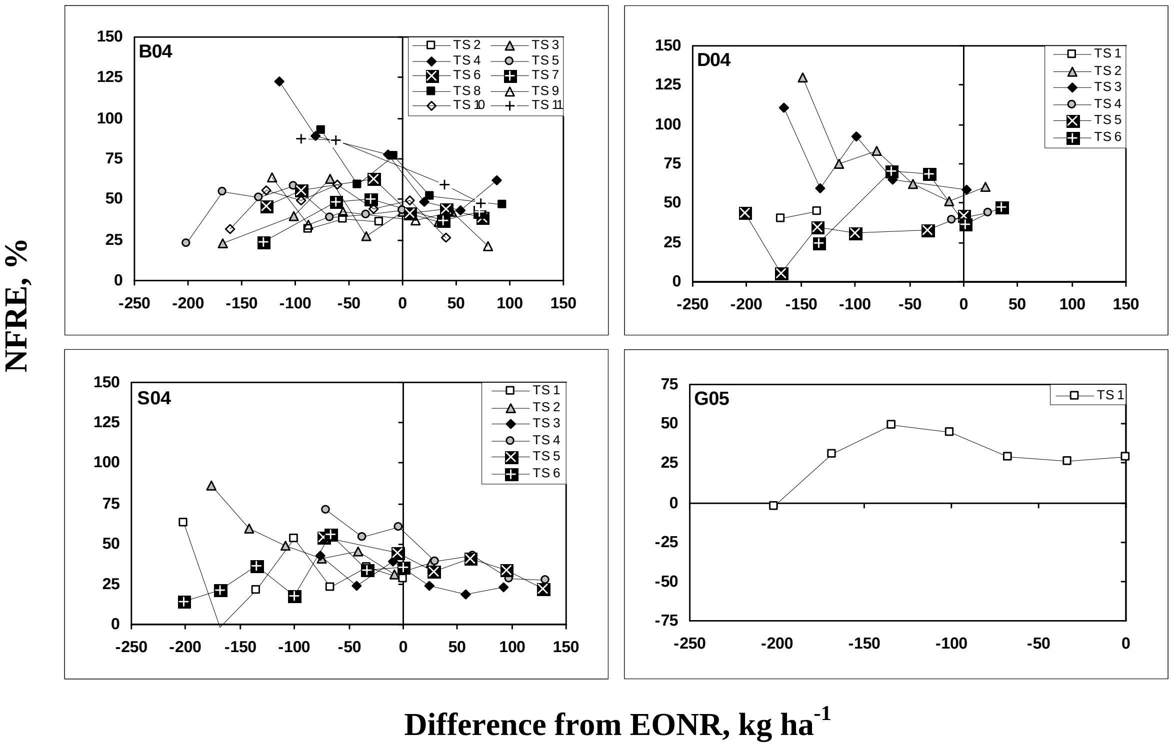


Figure 4.14: NFRE in relation to difference from EONR for 2004 and 2005 fields.

In order to report NFRE data collected for all three sampled 2005 fields, N rate was related to NFRE. Averaged across each field, NFRE changed little with increasing amounts of applied N (Figure 4.15; top). Again, droughty conditions best explain these results. Within-field NFRE variability ranged even more widely than between-field NFRE (Figure 4.15). The figures were constrained to -50-75% NFRE to better show average differences between treatment sets. Negative NFRE values resulted from more N being recovered from a check plot than from plots that received N fertilizer.

Soil Inorganic N

Difference from EONR was related to soil profile inorganic N. Profile inorganic N levels were not uniform between fields (Figure 4.16). Averaged across all treatment sets within a field, profile inorganic N at EONR ranged from 36 to 105 kg ha^{-1} for the three fields sampled in 2004. For D04 and S04, profile inorganic N tended to increase as N rate approached or exceeded EONR. For P04, levels of profile N were erratic above EONR, with some rates approximately the same as levels below EONR and some rates about 50 kg N ha^{-1} higher. Because this field had been managed as pasture for several previous decades, both the level of N (Carpenter-Boggs et al., 2000) and the spatial variability of N (Franzluebbers et al., 2000) might be expected to be higher for this field than the others. Field G05 was the only field sampled in 2005 for profile inorganic N which had a significant EONR. Averaged across all treatment sets in G05, profile inorganic N at EONR was 60 kg ha^{-1}.

Profile inorganic N levels were not always similar between treatment sets within fields. Figure 4.17 contains within-field profile inorganic N results for three 2004 fields and one 2005 field. Field S04 had the lowest profile inorganic N variability between

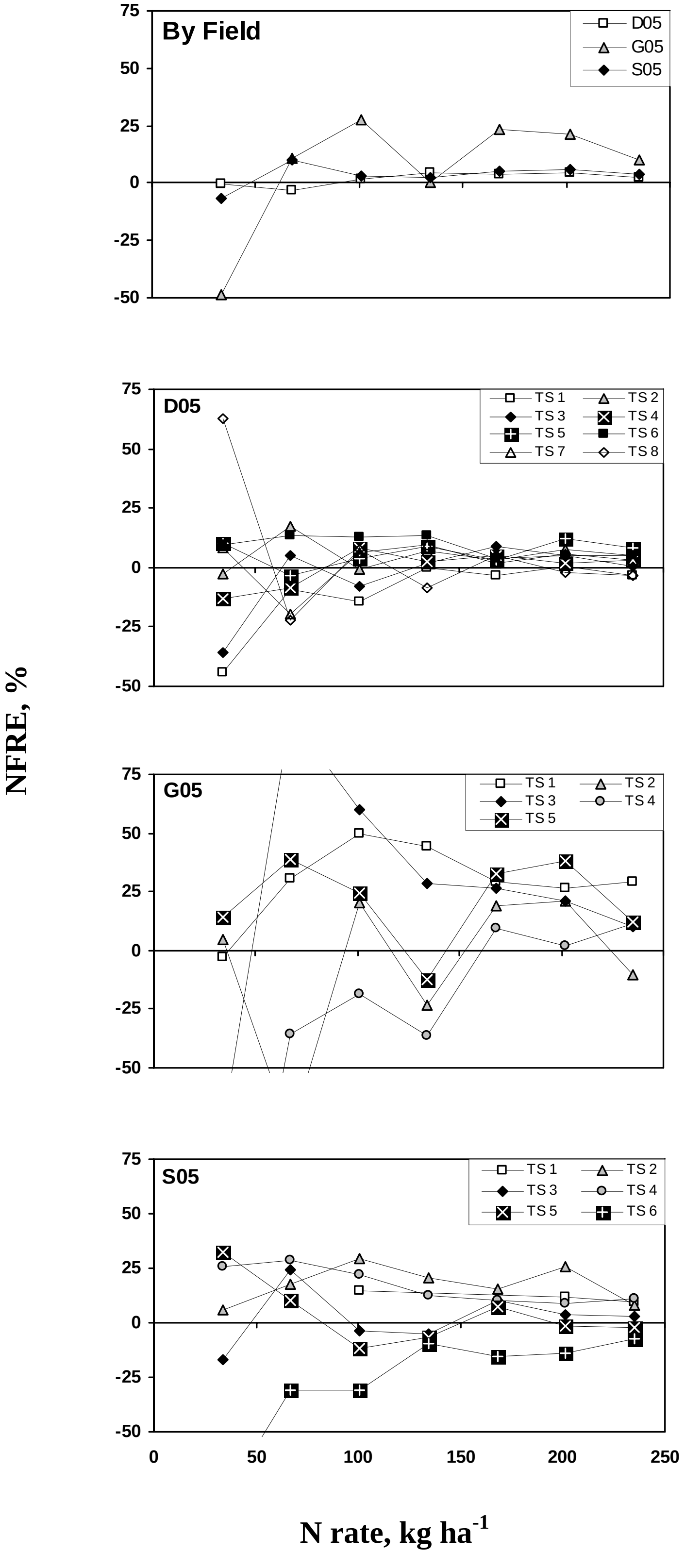
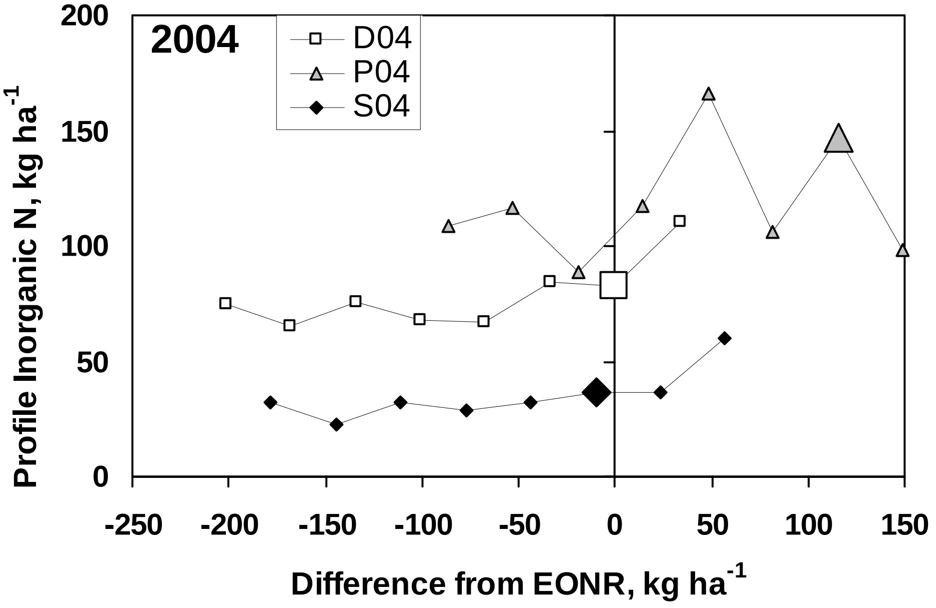


Figure 4.15: NFRE in relation to N rate for 2005 fields.



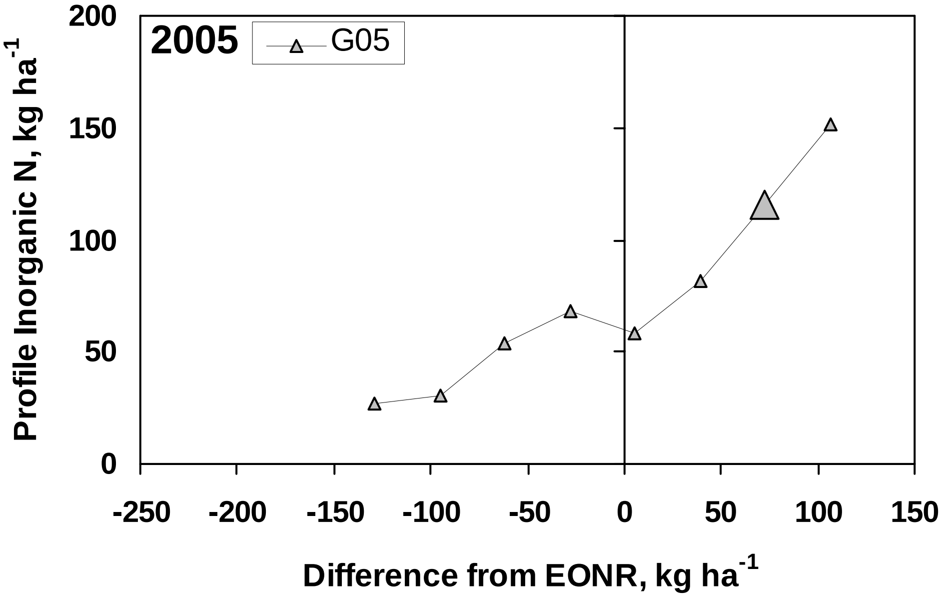


Figure 4.16: Profile inorganic N by field shown in relation to difference from EONR for 2004 and 2005 fields. Producer N rate at planting for the field indicated by enlarged symbol on trendline.

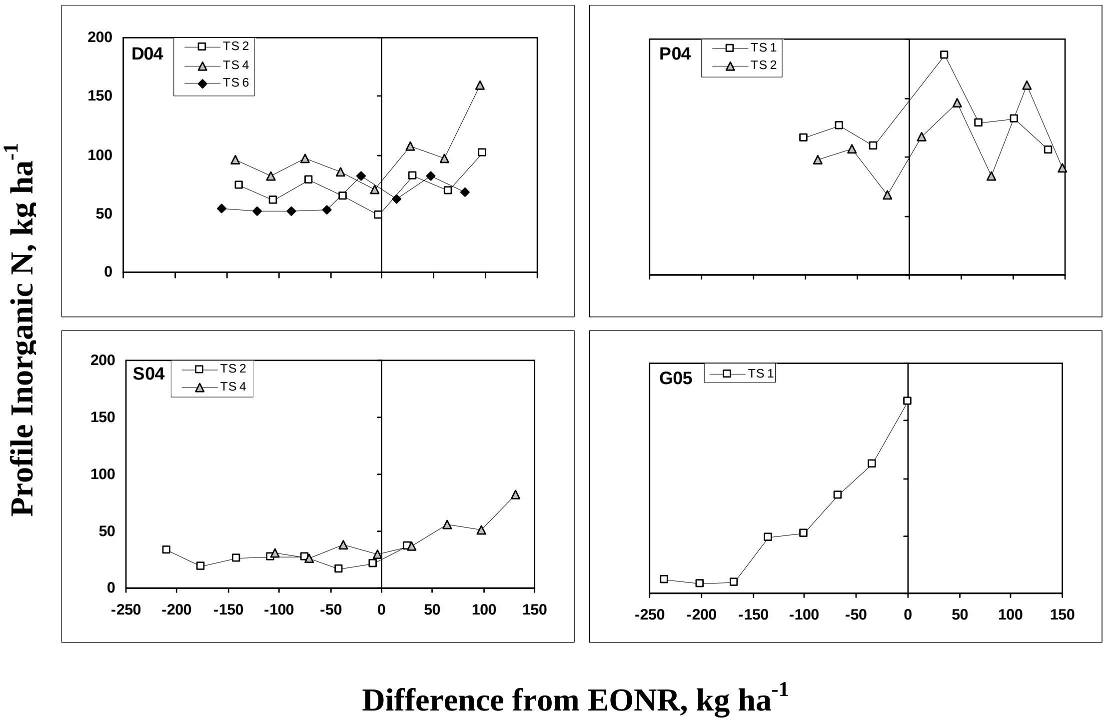


Figure 4.17: Profile inorganic N in relation to difference from EONR for 2004 and 2005 fields.

treatment sets at EONR (25-31 kg ha^{-1}), while P04 had the highest (100-148 kg ha^{-1}). The wide range of variability between treatment sets in P04 was due to residual soil N from previous pasture management. G05 only contained one treatment set with a significant EONR value. In this treatment set, profile inorganic N steadily increased as N rate approached EONR.

In order to report the data for all three fields sampled for profile inorganic N in 2005, N rate was also related to profile inorganic N for each field and treatment set within each field. Figure 4.18 contains field averages and within-field results for the three sampled fields in 2005. The wide range of variability in D05 treatment set 7 may be related to soil texture. Treatment sets 1 and 4 of D05 were similar in soil texture throughout the sampled profile. In treatment set 7, however, a sandy sub-soil layer in the profile was found at the lowest sampling depth (90-120 cm). This layer of sand could have contributed to the variability of the results in the treatment set through a lack of uniformity in nutrient holding capacity, allowing N already in the soil to be leached past this soil layer. Overall, profile inorganic N levels increased as N rate increased both within- and between-fields (Figures 4.18). These results suggest that fertilizing at EONR would potentially reduce N loss from crop production systems, thereby reducing detrimental effects of N fertilizer to the environment.

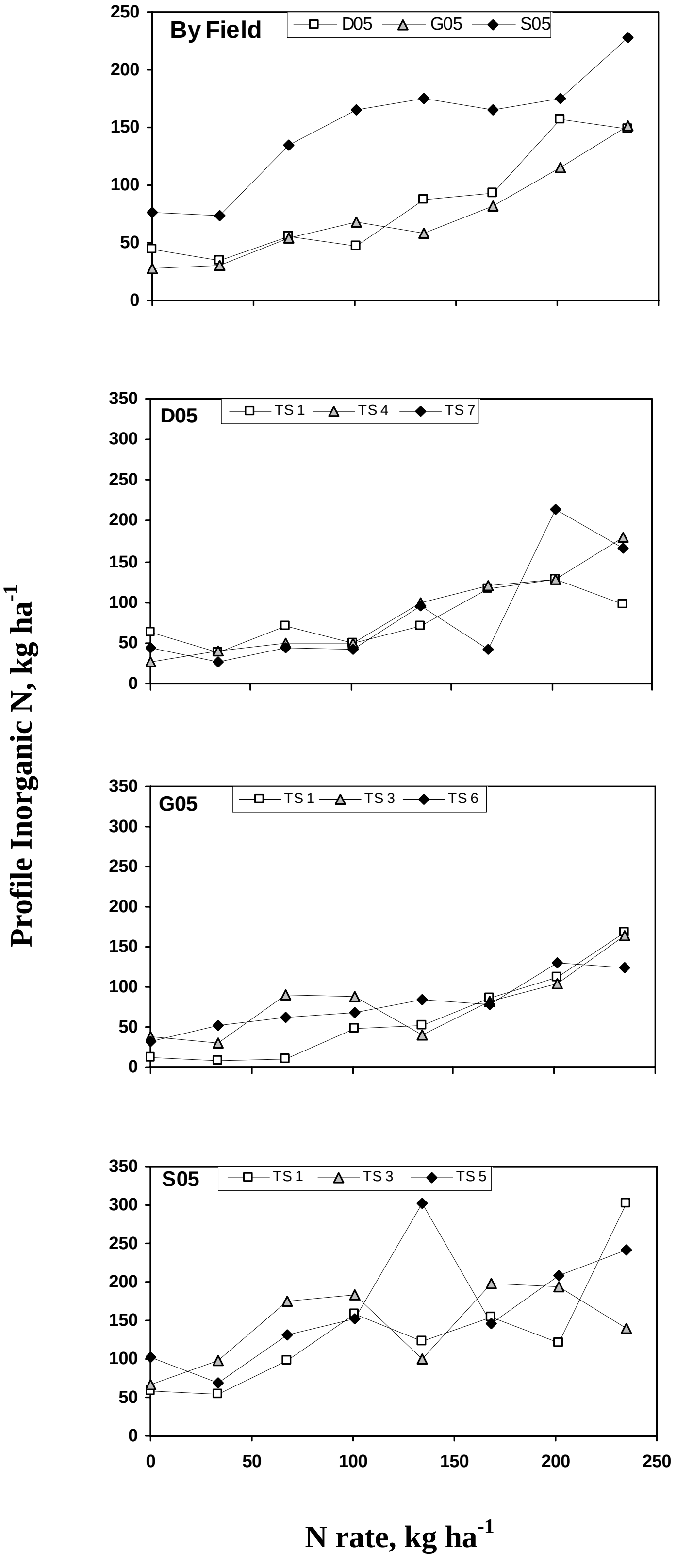


Figure 4.18: Profile inorganic N in relation to N rate for 2005 fields.

CHAPTER 5

CONCLUSIONS

The objectives of this thesis were to evaluate within- and between-field EONR variability, assess the relationship of active-light reflectance sensor indices to EONR, and relate EONR to YE, NFRE, and post-harvest soil inorganic N levels. EONR was at the center of this research project because it is the amount of N producers are trying to apply to achieve maximum profitability. Through the use of three indices, this research showed that EONR and active-light reflectance sensors are related. N application at EONR determined from active-light reflectance sensor measurements could reduce N loss to the environment. Three environmental measurements of N application that were evaluated in this thesis in their relationship to EONR were YE, NFRE, and post-harvest soil inorganic N levels.

The conclusions of this study were:

1. EONR was highly variable within and between corn fields.
2. EONR was greatly affected by yearly climate conditions. As a result of favorable growing conditions in 2004, EONR was calculated for all fields and nearly all treatment sets. In contrast, nearly the opposite was observed in 2005 due to droughty conditions.
3. Because sensor indices, in conjunction with soil EC, were able to separate low and high EONR values, further research might involve sensors in the development of N management zones within fields.
4. Continued research is needed to assess the relationship between sensor measurements and delta yield or EONR delta yield.

5. As a result of inconclusive data results from droughty conditions in 2005, continued research in this area would be beneficial to explore the relationship between EONR, soil EC, and sensor indices, and EONR and environmental measurements.
6. Active-light reflectance sensors show promise to achieve EONR, thereby increasing YE and NFRE, and reducing N loss off fields. N application at EONR would alter current producer N rates, resulting in increased profitability for producers, and an overall positive effect on the environment.

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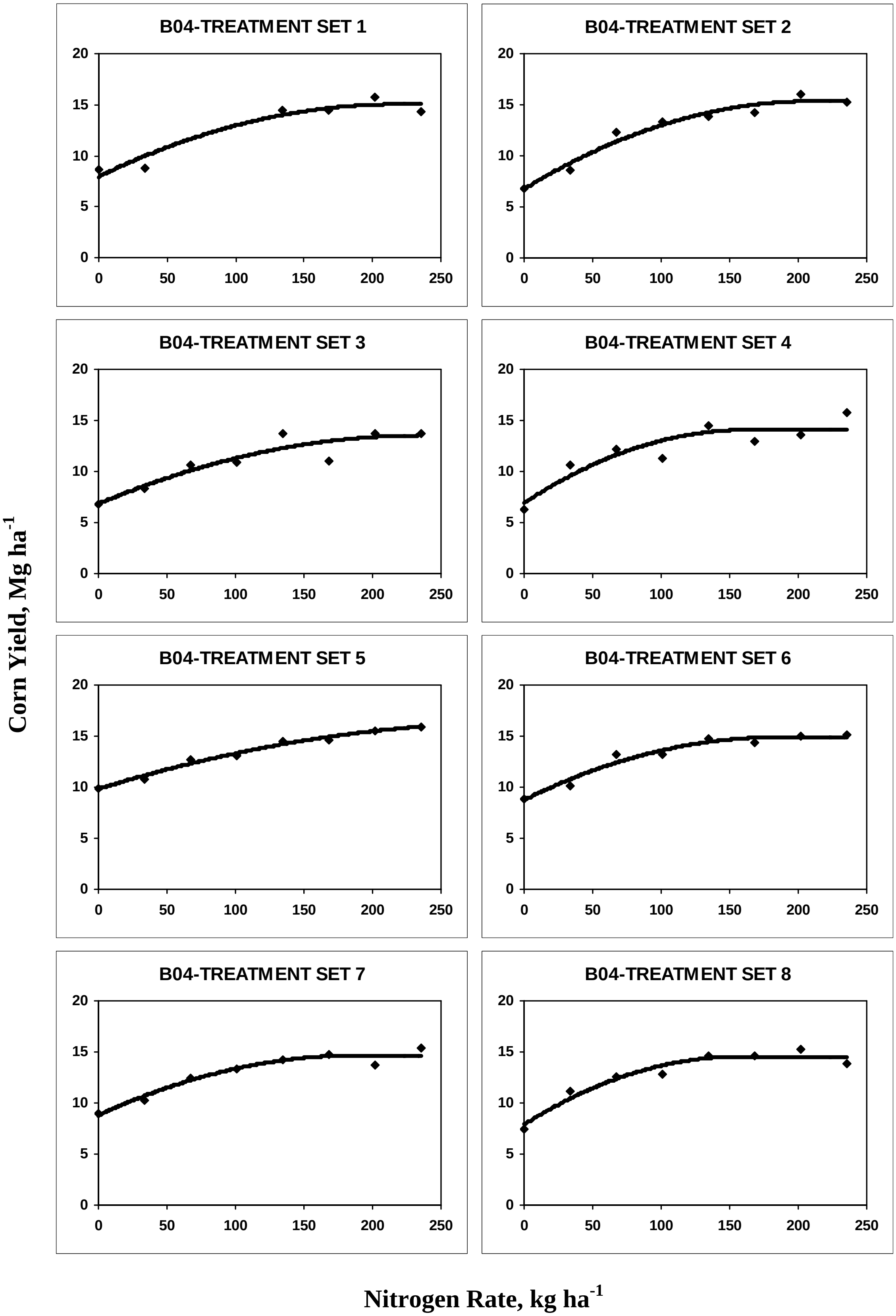
APPENDIX

Treatment set yield response models, including non-significant models.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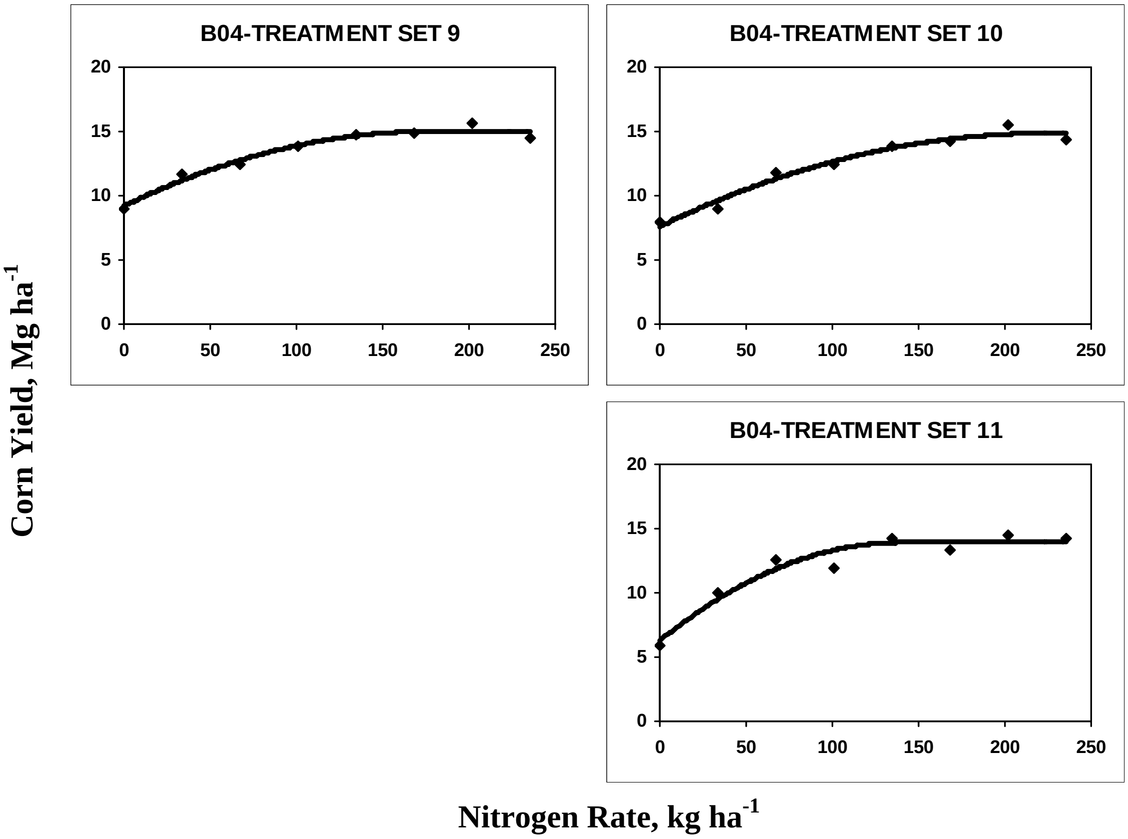
Corn Yield, Mg ha^{-1}
Nitrogen Rate, kg ha^{-1}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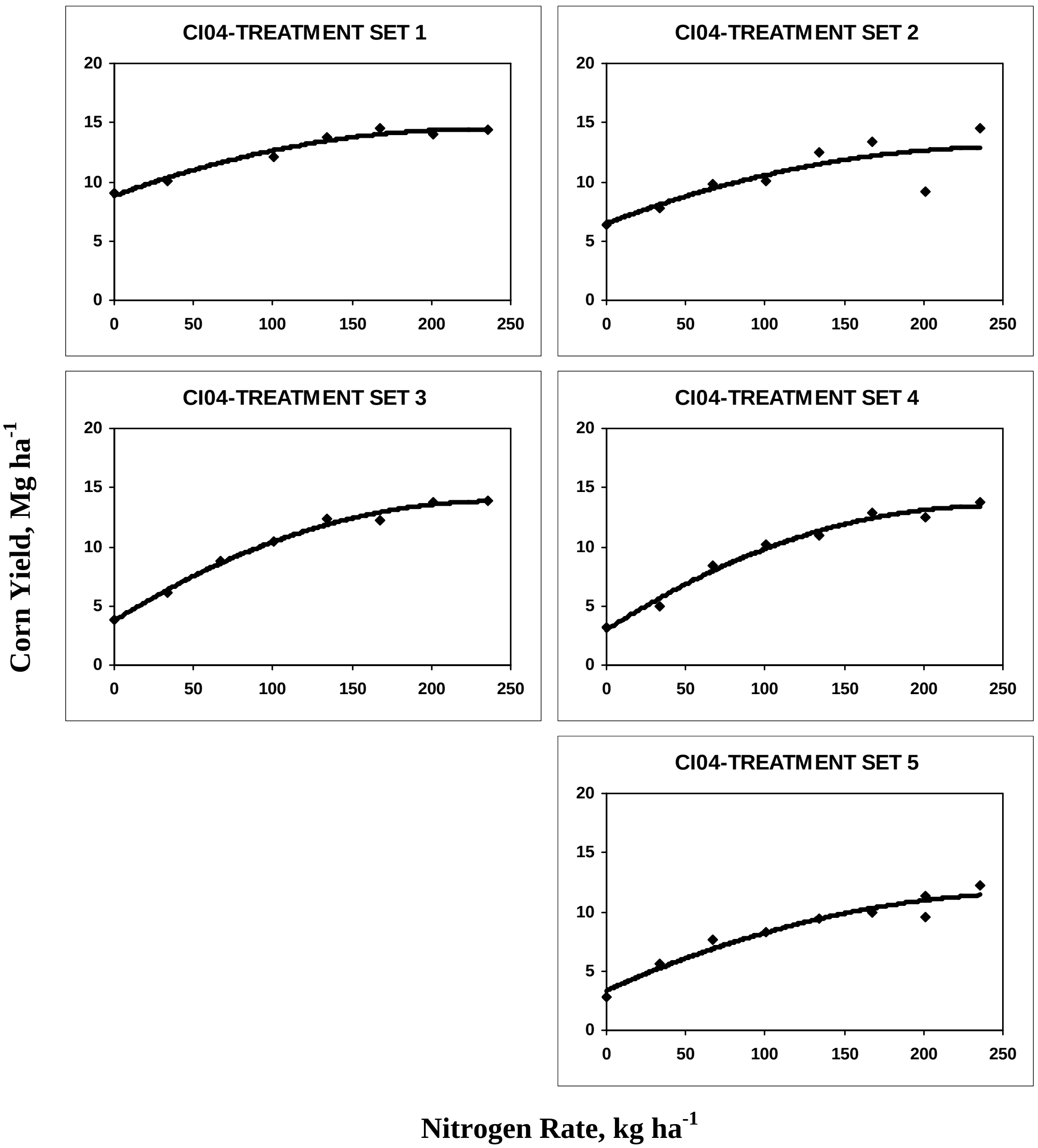
Corn Yield, Mg ha-1
Nitrogen Rate, kg ha-1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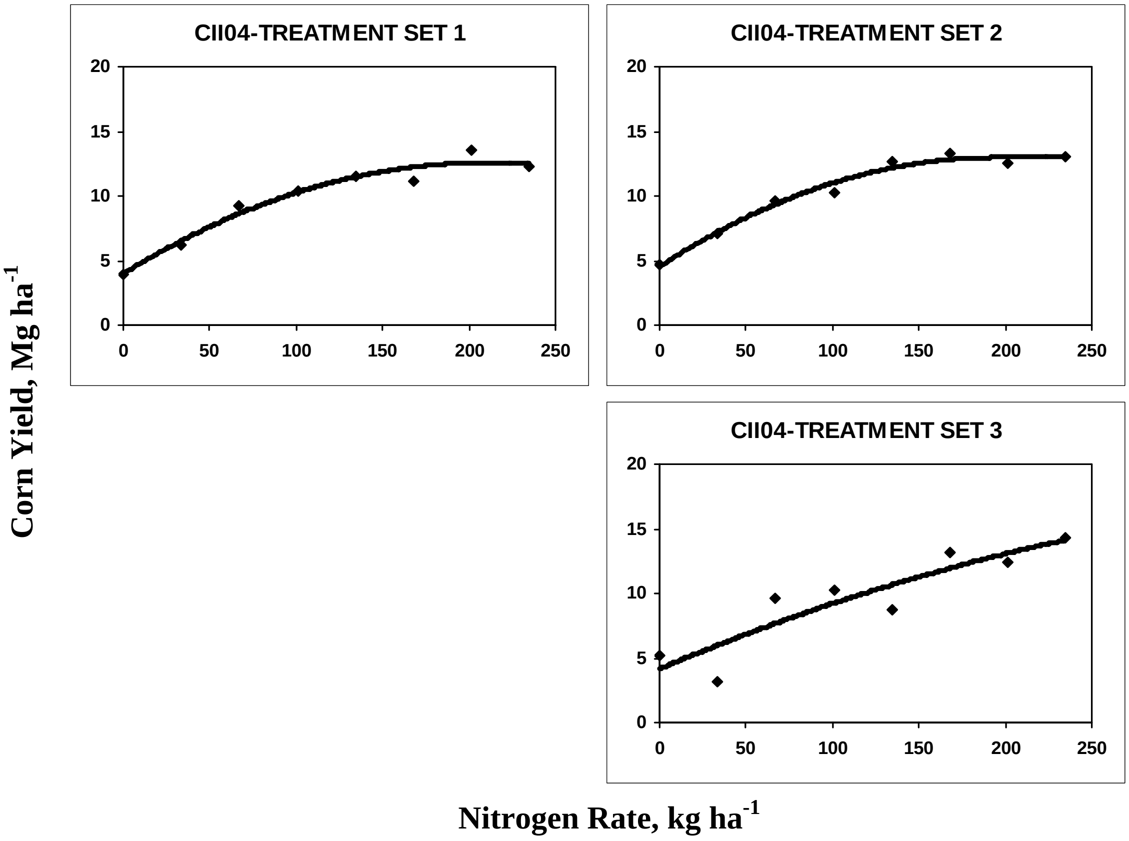
Nitrogen Rate, kg ha^{-1}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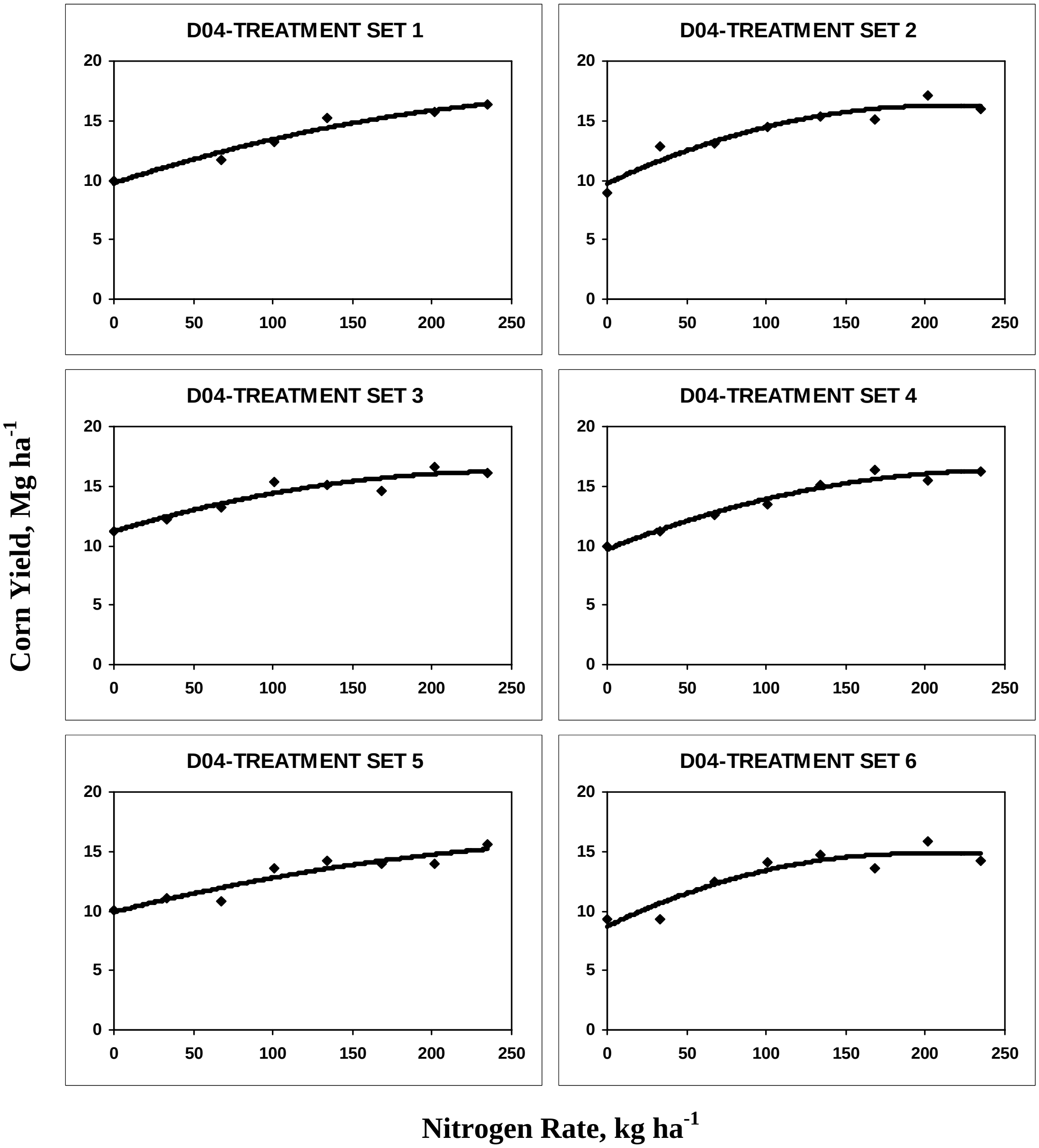
Corn Yield, Mg ha^{-1}
Nitrogen Rate, kg ha^{-1}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15
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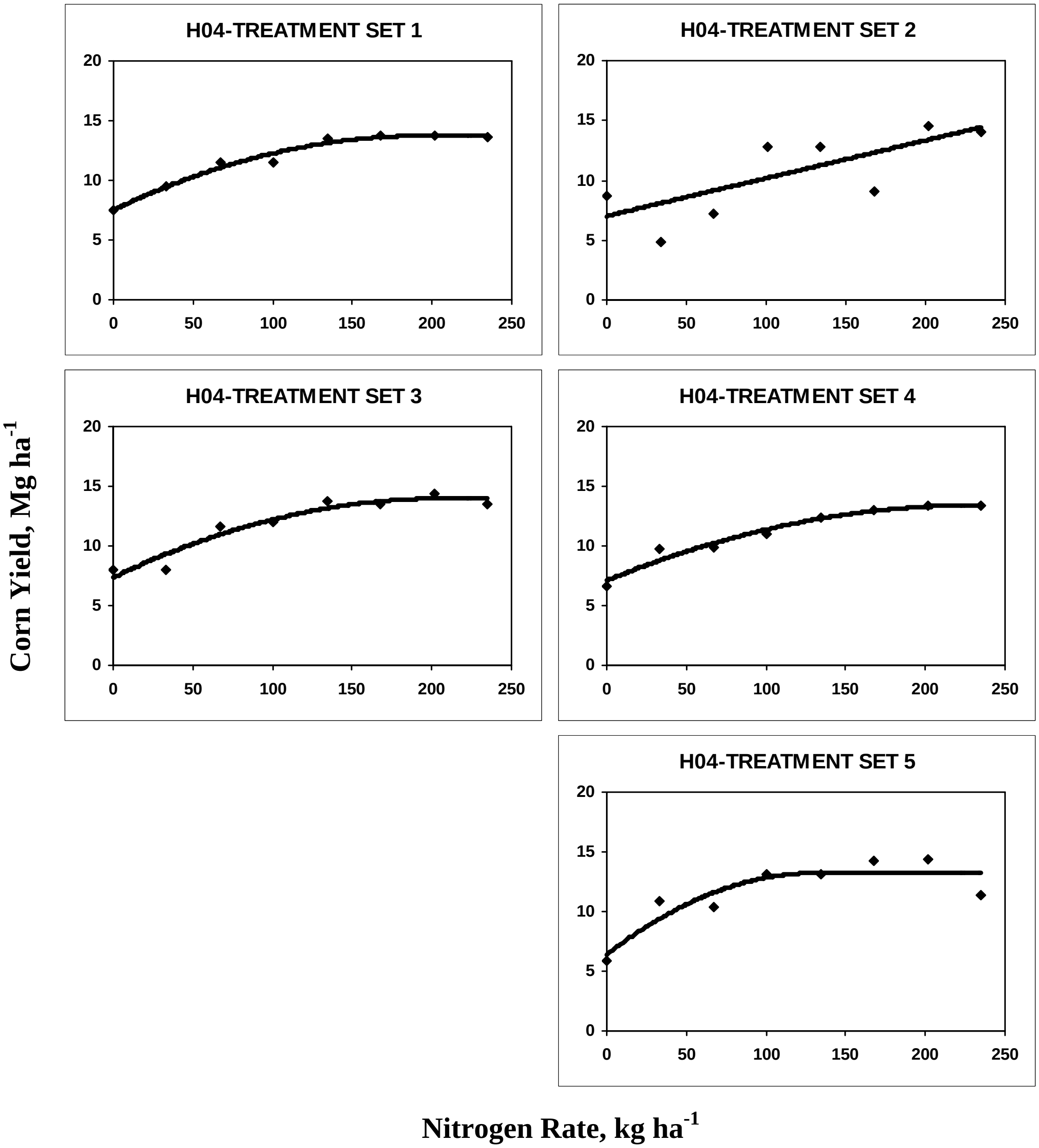
50
100
150
200
250
Corn Yield, Mg ha^{-1}
Nitrogen Rate, kg ha^{-1}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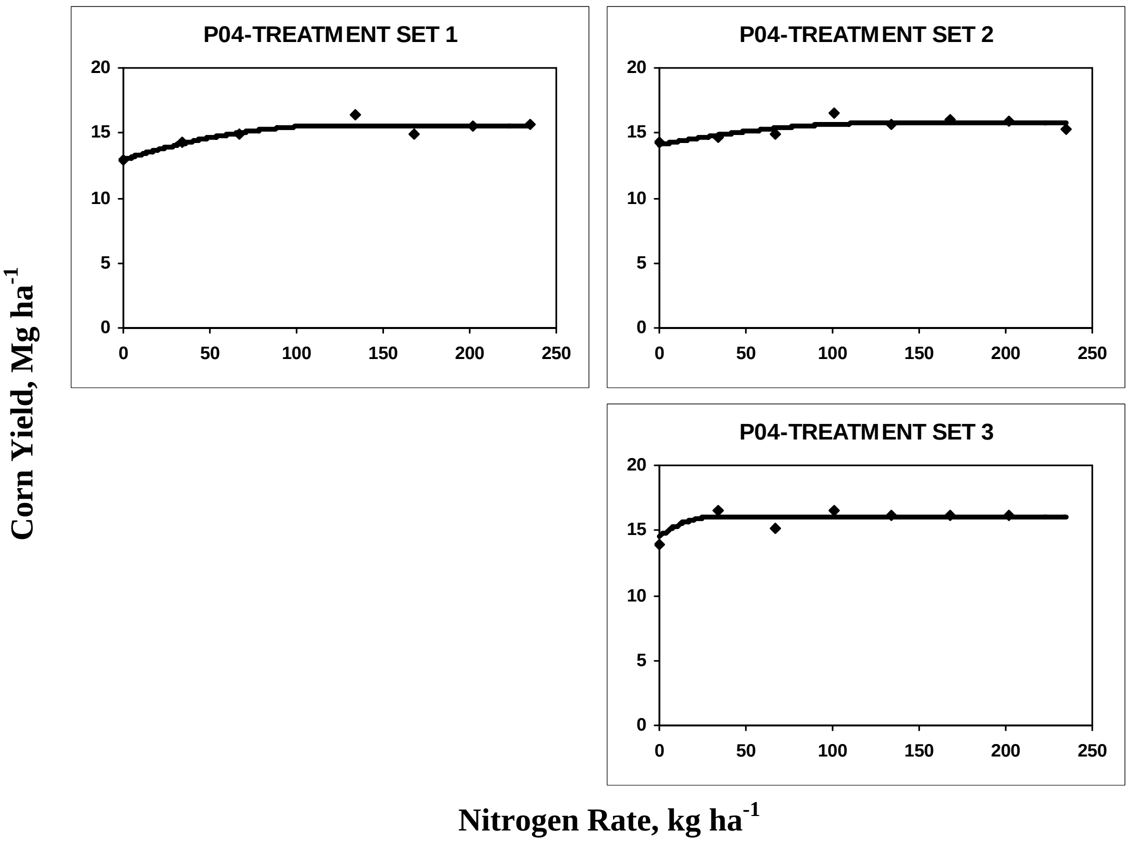
250
Corn Yield, Mg ha^{-1}
Nitrogen Rate, kg ha^{-1}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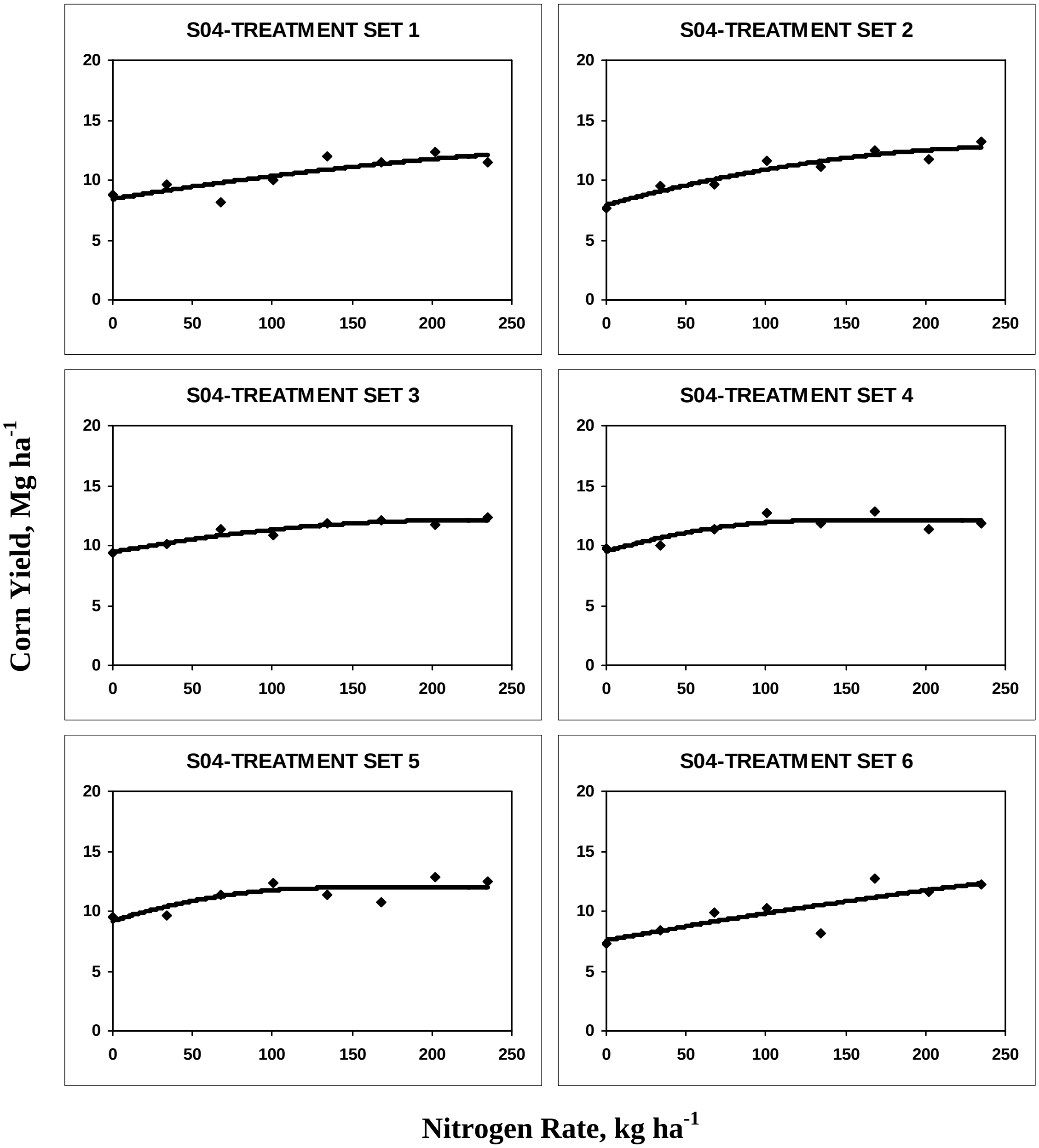
200
250
Corn Yield, Mg ha-1
Nitrogen Rate, kg ha-1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150
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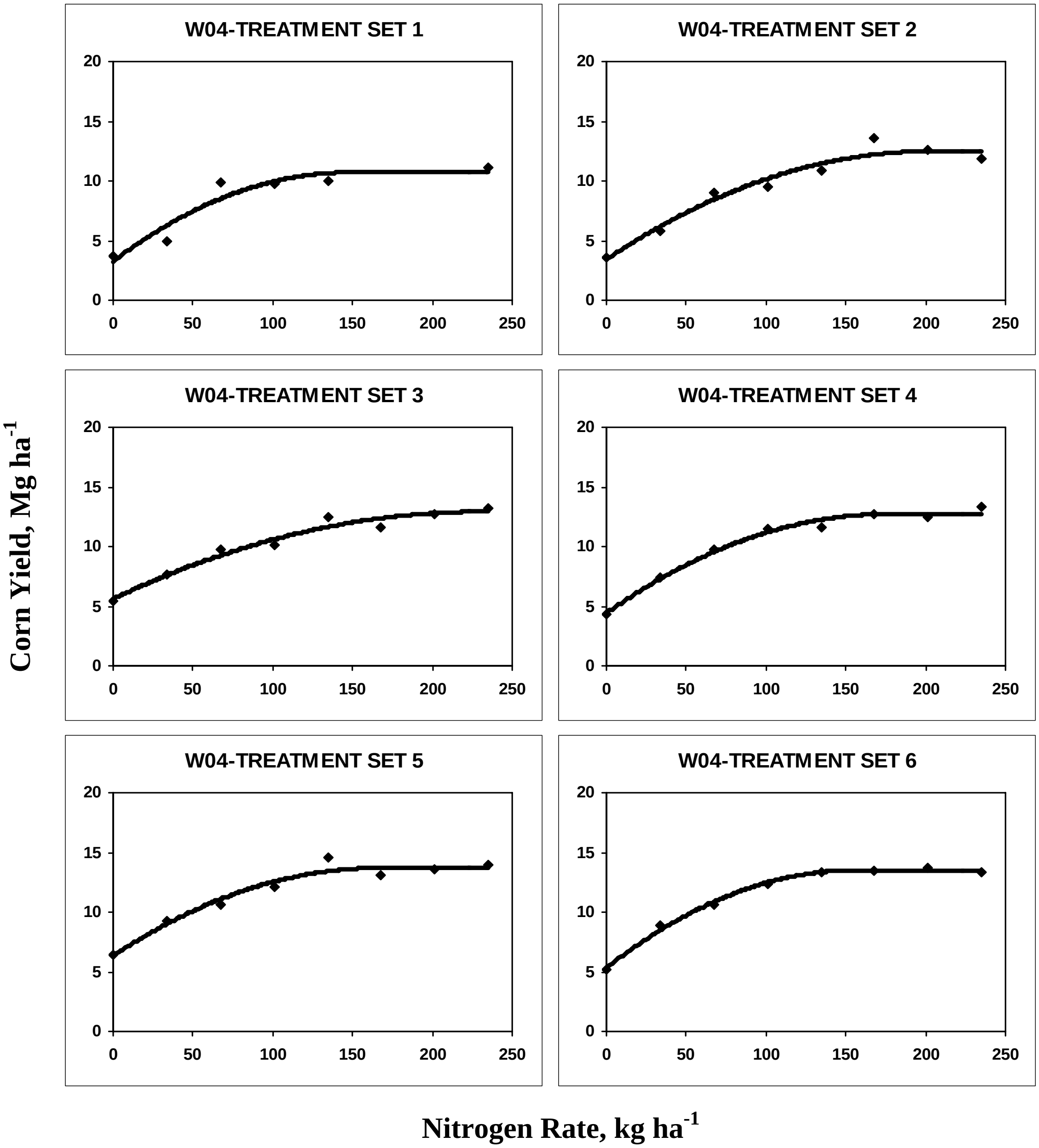
250
Corn Yield, Mg ha^{-1}
Nitrogen Rate, kg ha^{-1}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200
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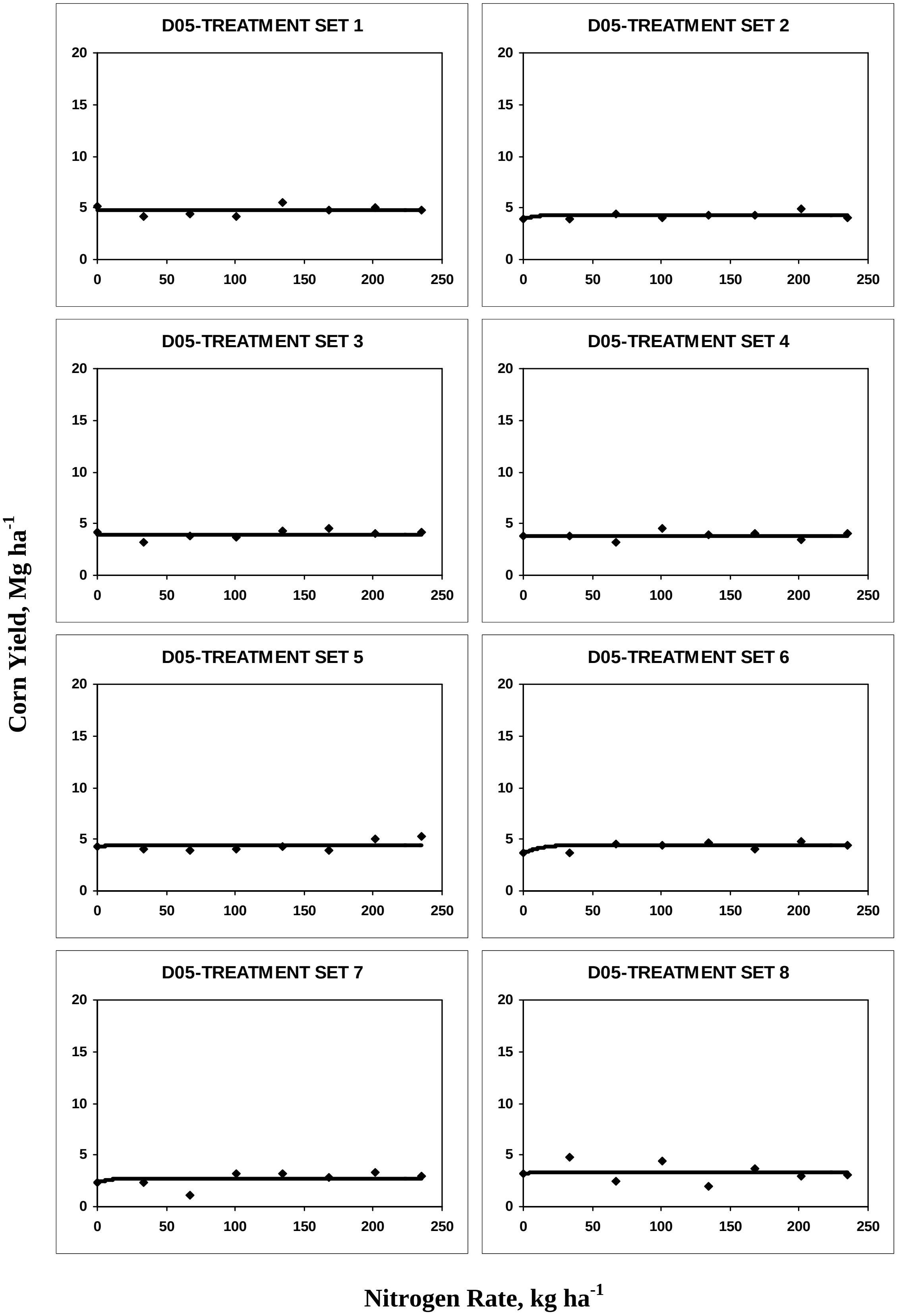
Corn Yield, Mg ha-1
Nitrogen Rate, kg ha-1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D05-TREATMENT SET 7
D05-TREATMENT SET 8
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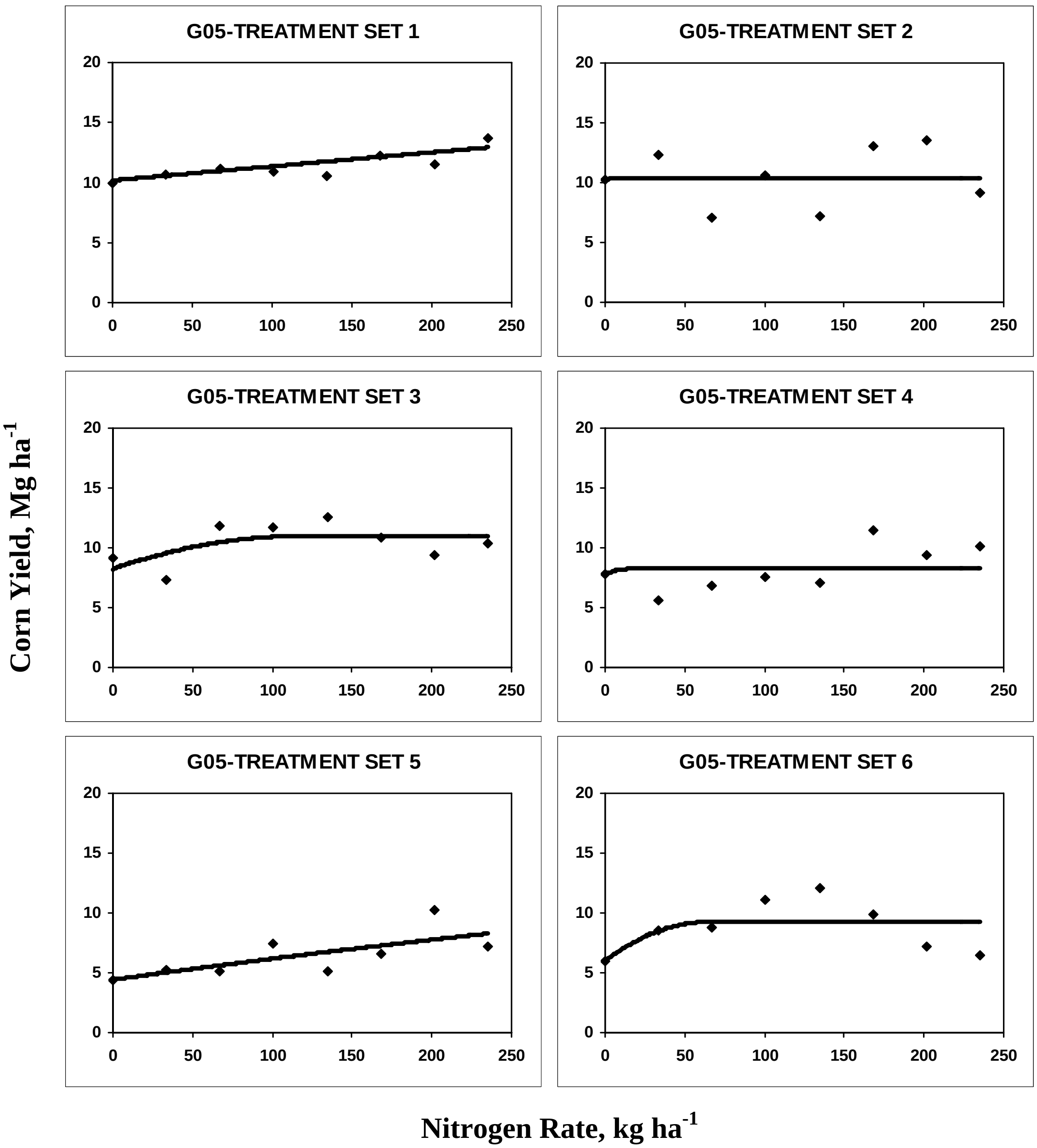
100
150
200
250
Corn Yield, Mg ha^{-1}
Nitrogen Rate, kg ha^{-1}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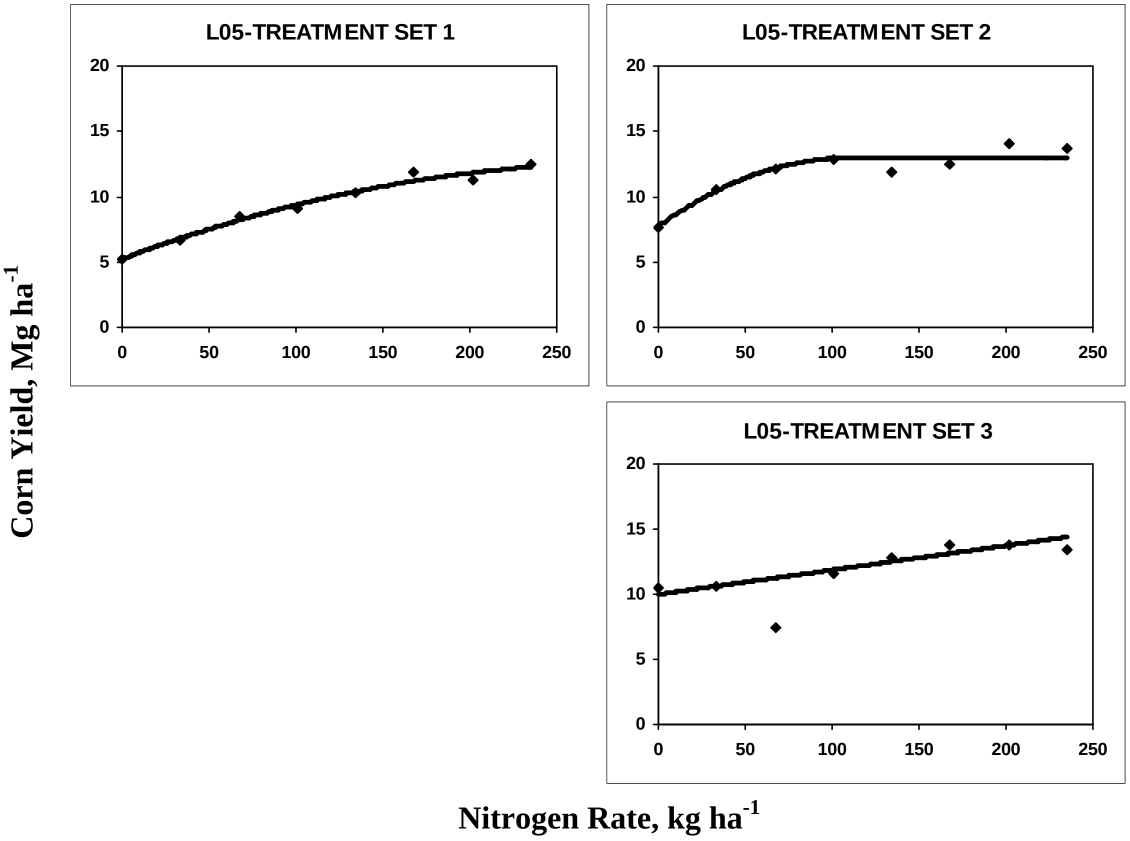
150
200
250
Corn Yield, Mg ha^{-1}
Nitrogen Rate, kg ha^{-1}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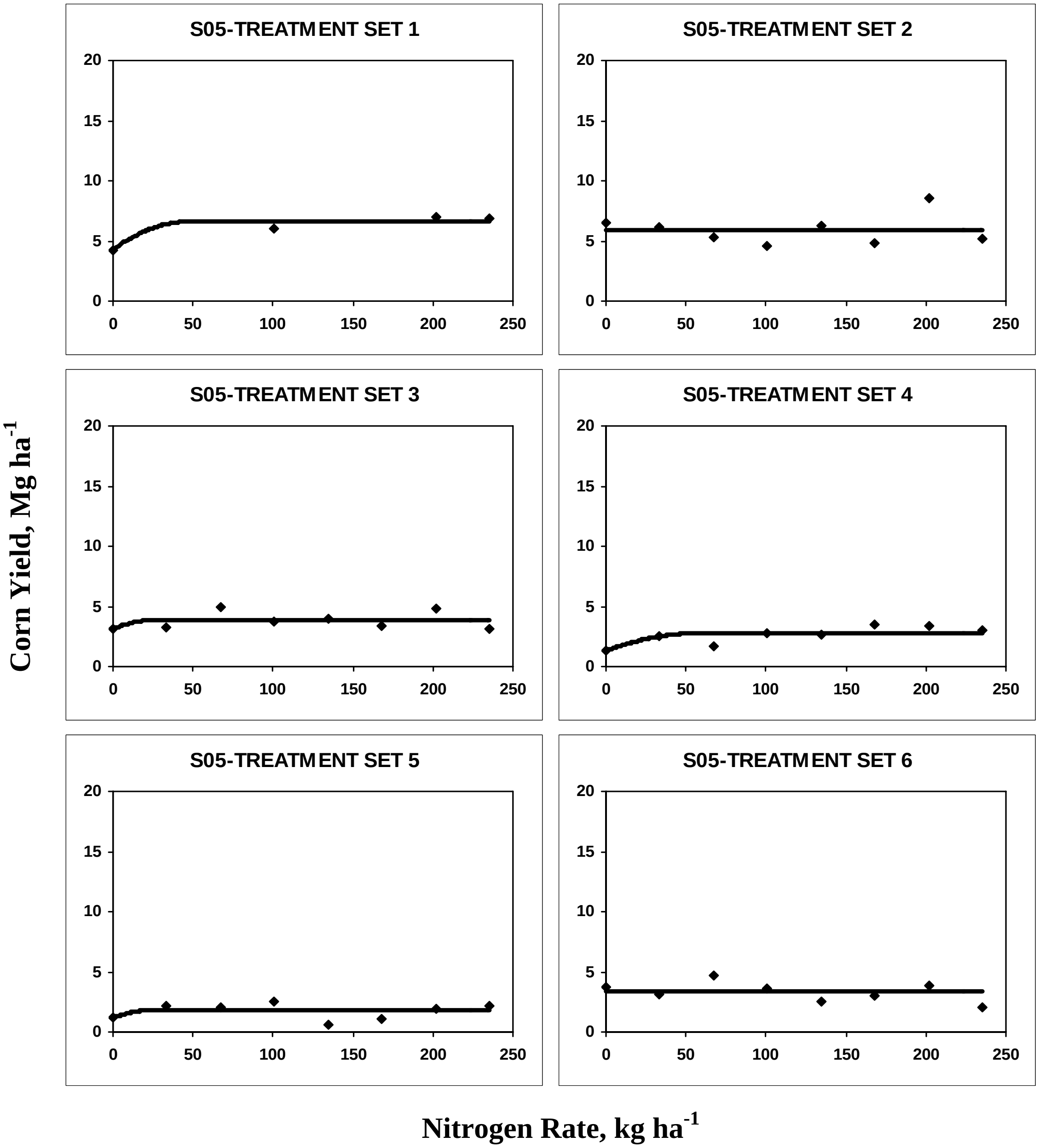
200
250
Corn Yield, Mg ha-1
Nitrogen Rate, kg ha-1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S05-TREATMENT SET 4
S05-TREATMENT SET 5
S05-TREATMENT SET 6
0
5
10
15
20
0
50
100
150
200
250
Corn Yield, Mg ha^{-1}
Nitrogen Rate, kg ha^{-1}