EVALUATION OF NITROGEN RECOMMENDATIONS FOR CORN BASED ON SOIL ANALYSIS AND REMOTELY SENSED DATA

THESIS

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ABSTRACT

Nitrogen (N) fertilizer is applied to corn (*Zea mays* L.) annually to compensate for losses in grain removal and to the environment. It is important to identify optimum N fertilizer requirements to obtain maximum economic return, while reducing environmental impact. The presidedress soil nitrate test (PSNT) may be used to predict if a grain yield response to additional N fertilizer is likely. The normalized difference vegetation index (NDVI), based on remote sensing measurements derived from canopy reflectance of near-infrared and red light, and existing sensor-based algorithms may aid in improving N fertilizer recommendations. The objectives of this study were to identify optimum sidedress N fertilizer rates obtained using sensor-based algorithms and evaluate the PSNT in corn that received preplant manure applications. The relationships between remotely sensed information, ear-leaf N concentration, and soil NO_3-N concentration were also determined.

The study was conducted at the Western Research Station of the Ohio Agricultural Research and Development Center (OARDC) near South Charleston, Ohio, in 2007 on Crosby silt loam (a fine mixed, active, mesic Aeric Epiaqualf) and on Kokomo silty clay loam (a fine, mixed superactive, mesic Typic Argiaquoll) in 2008. An additional site was located at the OARDC East Badger Farm near Wooster, Ohio, on

Canfield silt loam (a fine-loamy, mixed active, mesic Aquic Fragiudalf). A split-plot, randomized complete block design was used at all three sites. Three manure preplant application rates were used as main plots, and five sidedress N application rates were used as subplots. The 15 treatments were replicated four times. Soil samples for PSNT evaluation and remote sensing measurements were collected between the V6-V8 growth stages. Ear-leaf samples for total N analysis were collected at initial silking (R1 growth stage). The critical value for the PSNT was identified using three types of segmented models. Remote sensing measurements were used in existing algorithms to predict sidedress N recommendations.

When compared to empirical evidence, the sensor-based algorithms under-predicted sidedress N recommendations. The sensor was only able to distinguish NDVI measurements among preplant treatment rates at the 2008 Western Branch OARDC site. Collection of remote sensor measurements needs to be researched further to improve the sensor's ability to distinguish between preplant treatment rates. The presidedress soil nitrate test critical value for all sites combined was 13-22 $\mu g\ g^{-1}$, depending on the model. This indicated that a grain yield response to N fertilizer was unlikely at a soil test NO_3-N value > 22 $\mu g\ g^{-1}$. There was no relationship between NDVI and PSNT or between NDVI and ear-leaf N concentration. However, at the 2008 Western OARDC site, ear-leaf N increased linearly with soil NO_3-N conentration.

Dedicated to my parents.

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PUBLICATIONS

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FIELDS OF STUDY

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CHAPTER 1

INTRODUCTION

Nitrogen (N) is an essential plant nutrient. It is a constituent of many molecules, including proteins, nucleic acids, certain hormones, and chlorophyll. Significant soil N loss from year to year requires annual application of N fertilizer to corn (*Zea mays* L.), making it important to identify optimum N fertilizer rates to obtain maximum economic return, while minimizing environmental impact.

Various methods to identify optimum N fertilizer rates for grain production have been proposed and used. Traditional methods are based on cropping history and potential yield goals (Pesek and Heady, 1958). Yield goals may be based on previous years' yields, but are often times just speculation. This may not be a practical approach to determine N rates because of failure to address spatial variations and in-season N loss (Scharf et al., 2006), among sites and among years at a site (Sawyer and Nafziger, 2005).

In some cases, soil N tests can also be used to predict plant response to additional N fertilizer. The preplant nitrogen test (PPNT) can be used to determine N fertilizer response in semi-arid regions of the United States, but is not calibrated in more humid regions of the United States (Bundy et al., 1999), including Ohio. The presidedress soil nitrate test (PSNT) measures the concentration of nitrate-nitrogen (NO_3-N) in the surface

30 cm of soil when corn is 30-45 cm tall (Magdoff, 1991). This test is often successful in identifying sites that will respond to an additional N fertilizer application at time of sidedressing, but fails to provide guidance in making N rate recommendations (Magdoff et al., 1984; Fox et al., 1989; Meisinger et al., 1992; Heckman et al., 1996).

In addition to yield goals and soil N tests, vegetation indices calculated from remotely sensed data can be used to estimate plant health and may aid in making sidedress N recommendations. One such index is the normalized difference vegetation index (NDVI), which is based on red and near-infrared light reflectance from the crop canopy. Many winter wheat (*Triticum aestivum* L.) studies in Oklahoma have successfully used NDVI to determine the responsiveness of a crop to additional N fertilization (Lukina et al., 200l; Raun et al., 2001, 2005; Mullen et al., 2003). Additionally, NDVI has been successful in predicting corn biomass and grain yield in Oklahoma (Teal et al., 2006; Freeman et al., 2007; Martin et al., 2007).

Previous studies have developed algorithms that determine N application rates using sensor measurements collected between Feekes 4-9 growth stages for winter wheat receiving commercial forms of N fertilizer (Lukina et al., 2001; Raun et al., 2001, 2002, 2005; Teal et al., 2006). Previous corn studies that predicted yield potential also used commercial forms of N fertilizer (Shanahan et al., 2001). However, in this study, corn received either preplant liquid hog or dairy cow manure applications. In-season soil N tests and vegetation indices that aid in making N fertilizer recommendations are important to manure management because of the uncertainties associated with N mineralization from manure sources (Saint-Fort et al., 1990; Ma et al., 1999; Raun et al., 2008).

The objectives of this study were to identify optimum sidedress N fertilizer rates and to evaluate sensor-based algorithms and the PSNT for making sidedress N recommendations for corn receiving preplant manure applications. The relationships between the NDVI, ear-leaf total N concentration, and PSNT performance were also determined.

CHAPTER 2

LITERATURE REVIEW

2.1 Nitrogen

Nitrogen (N) is one of the 17 nutrients required for plant growth and development. It is a constituent of many molecules, including proteins, nucleic acids, certain hormones, and chlorophyll. It is essential for carbohydrate utilization, root development and activity, and supportive to the uptake of other nutrients (Olson and Kurtz, 1982). Nitrogen gas (N_2) accounts for approximately 78 percent of the gas in the atmosphere, but must be in the form of nitrate (NO_3^-) or ammonium (NH_4^+) for plants to use. Nitrogen fertilizer is often annually applied in corn production because N losses to the surrounding environment.

2.1.1 Soil nitrogen additions

Nitrogen can be added to the soil system through the application of organic fertilizers, such as manure, or commercial fertilizers, such as urea, ammonium-nitrate, and anhydrous ammonia. Fertilizers can be applied before planting (preplant), at the time of planting, or later in the growing season after the crop has been established (sidedress or topdress).

There are several possible non-fertilizer additions to the plant available (NH_4^+ and NO_3^-) soil N pool. The biological conversion of atmospheric N_2 to NH_4^+ or NO_3^- can supply N to leguminous plants through a symbiotic relationship with N-fixing microorganisms. Lightning can also convert atmospheric N_2 into plant available forms. One addition to the soil mineral N pool that is difficult to predict is the conversion of organic N to NH_4^+ by microorganisms through the process of mineralization.

The mineralization of organic-N to plant available forms of N is difficult to predict because it is driven by environmental factors, such as soil temperature (Saint-Fort et al., 1990) and moisture (Agehara and Warncke, 2005), and management practices, such as tillage (Rice and Havlin, 1994; Mikha et al., 2006). Several field methods using buried polyethylene bags have been developed to estimate N mineralization (Eno, 1960; Smith et al., 1977; Westerman and Crothers, 1980). In addition to field methods, laboratory techniques have been developed to estimate N mineralization. There is a standard 7-day incubation technique to determine the potential of soil to mineralize N (Bundy and Meisinger, 1994). Due to soil variability in physical, chemical, and biological properties and time constraints, these field and laboratory measurements of N mineralization are often impractical for producers. Quick, in-season estimates of N availability using soil NO_3-N tests or remote sensing measurements may be more useful for producers to adjust sidedress N fertilizer rates because they reflect the current season's growing conditions and can be done more timely.

Nitrogen mineralization estimates are important when manure is used. In Ohio, the number of cattle and swine from 1977 to 2009 is shown in Figure 2.2 (National Agricultural Statistics Service, 2009a). The number of cattle in Ohio has decreased since

1977 and steadied in 1999. Swine in Ohio decreased from 1977-2002, but has since increased. In 2007, approximately 326,100 ha of Ohio cropland and pasture, ranking 8th in the US, was treated with manure applications (National Agricultural Statistics Service, 2009b) The total N produced is difficult to estimate due to differences in animal type, diet, and manure storage. However, using the Ohio Livestock Manure Management Guide (Randall et al., 2006) and number of cattle and swine, total N produced by cattle and swine in Ohio can be estimated between 82,000-188,000 Mg N ha^{-1} in 2009. Due to uncertainty in N mineralization from organic sources (Agehara and Warncke, 2005) and the widespread use of manure in Ohio, soil tests and reflectance measurements are needed to estimate the in-season N fertilizer needs.

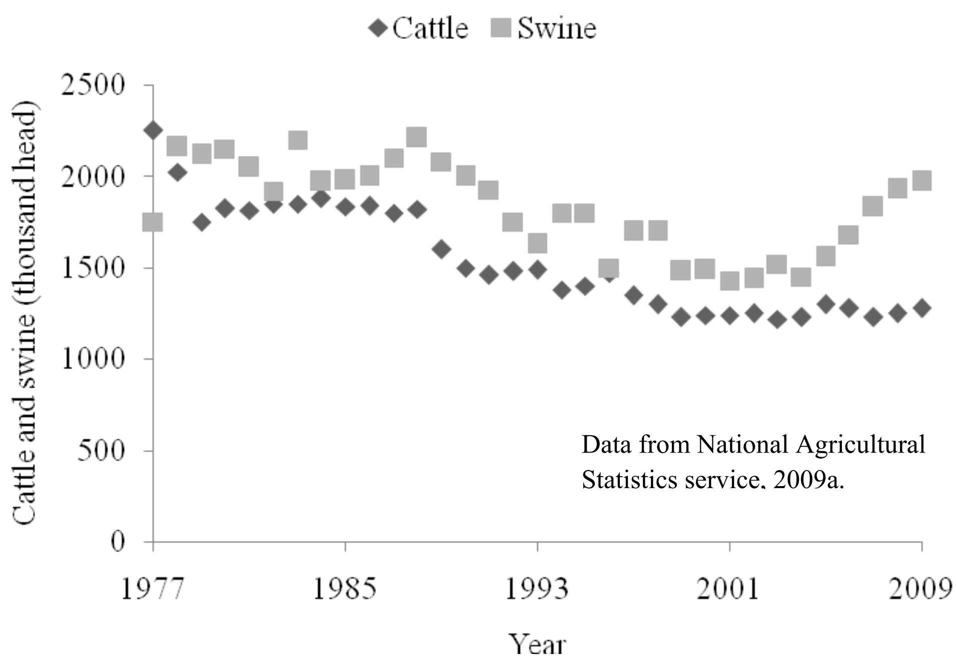

Figure 2.1: Number of cattle and swine in Ohio from 1977-2009.

2.1.2 Soil nitrogen losses

Environmental conditions can cause N to be lost from the soil. The three primary ways N is lost to the environment include denitrification, volatilization, and leaching. Denitrification occurs when fields are waterlogged. Under anaerobic conditions, NO_3^- serves as the electron acceptor for microorganisms and is reduced to gaseous N_2 forms. Ammonia volatilization is another process in which N is lost in a gaseous form. Volatilization occurs primarily when urea-based fertilizers or animal manures are not incorporated into the soil. Under warm, moist conditions, ammonia is lost along with water vapor from the soil surface (Nelson, 1982). Leaching occurs when NO_3^-, which is water soluble, moves through the soil profile with rainfall or through subsurface drainage. Ammonium may leach from sandy soils (Stevenson, 1982).

Denitrification, volatilization, and leaching are all controlled in part by weather conditions encountered during the growing season, making N losses often unpredictable. Estimates of crop N requirements need to be assessed in-season due to this variability.

2.2 Effects of nitrogen loss

Nitrogen loss should be avoided to reduce contamination to the surrounding environment. Nitrate is very water soluble and may contaminant surface or ground water, causing environmental and human health problems. Additionally, due to the rise of N fertilizer costs, it is important to optimize N use to minimize economic losses.

2.2.1 Environmental implications

Some researchers contend that agriculture is a major contributor to non-point pollution of surface waters in the Midwestern United States (Bernot et al., 2006). While N fertilizer is often applied to most non-leguminous crops, it is often over applied due to uncertainty by the producers for what the optimum N rate should be. When inorganic N exceeds crop uptake or is lost from the soil by leaching or through subsurface drainage, excess N may enter surface and/or groundwater, which may have detrimental environmental effects.

Productivity in Louisiana shelf waters is enhanced by dissolved inorganic N (Lohrenz et al., 2008). Increased productivity or eutrophication can lead to reduced dissolved oxygen levels and hypoxic conditions (dissolved oxygen levels < 2 ml l^{-1}). According to Dybas (2005), there are 146 coastal dead zones (coastal waters too low in oxygen to sustain life) worldwide. The Gulf of Mexico hypoxic zone was recorded at 20,700 km^2 in 2001 (Robalais et al., 2002) and at 22,000 km^2 in 2007 (Justic et al., 2007).

In 2000, there was no decrease in the $2.8 billion fishing industry (Earles, 2000), which may have been a result of the ability of some marine organisms to detect and avoid hypoxic zones (Pihl et al., 1991). However, researchers argue that there may be an impact if the zone continues to grow (Greenlaugh and Sauer, 2003), due to a decrease in species diversity and richness (Diaz and Rosenberg, 1995).

Although, N fertilizer from agriculture is thought to contribute significantly to the hypoxic zone in the Gulf of Mexico, other factors such as hydrological changes to the landscape, atmospheric deposition of NO_3^-, runoff and domestic wastewater discharges, and point discharges from feedlots may also contribute to the problem (Mitsch, 2001).

This indicates that even if fertilizer N that enters groundwater and surface water sources is reduced, hypoxia in the Gulf of Mexico may persist.

2.2.2 Health implications

Nitrate contamination of well water, can cause methemoglobinemia, or "blue baby" syndrome, in infants. Methemoglobinemia occurs when hemoglobin in red blood cells is oxidized to methemoglobin, which is unable to transport oxygen. If not treated, babies with methemoglobinemia may die. In two case studies that examined babies affected by methmoglobinemia in Wisconsin, well water used to make baby formula contained 22.9 and 27.4 mg L^{-1} NO_3-N (Knobeloch et al., 2000). Potential sources of NO_3-N in the well water included barnyard runoff, septic tank effluent, and agricultural fertilizers. Nitrate contamination is a concern for well water because it is not regulated by the Safe Drinking Water Act (1974). For government-regulated drinking water, methmoglobinemia is less of a concern.

2.2.3 Economic implications

The cost of N fertilizer has increased significantly since 2002. The rise in fertilizer N prices can be attributed to the rise in cost of natural gas, which is used to produce to N fertilizers. Additionally, the strong world demands for fertilizers, high transportation costs, and weak US dollar have influenced N fertilizer prices (Ward, 2008). Prices received for corn grain have also increased (National Agricultural Statistics Service, 2008), but at a much slower rate. Due to the widening gap between N fertilizer cost and corn price (Figure 2.1), it is increasingly important to identify N rates that are optimum for plant growth to maximize economic return.

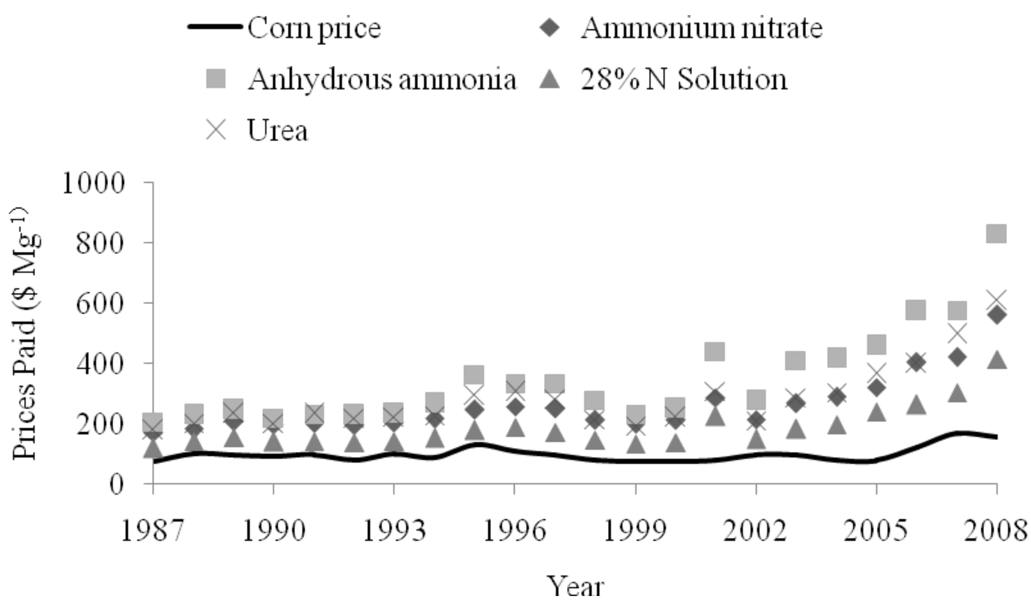

Figure 2.2: Prices paid for N fertilizer and received for corn grain from 1987 through 2008.

2.4 Nitrogen use efficiency

Nitrogen use efficiency (NUE), defined as the ratio of N removed from the soil by cereal production to N fertilizer applied to cereals, is estimated at 33% for worldwide cereal grain production (Raun and Johnson, 1999). This indicates significant N loss due to immobilization or loss to the surrounding environment.

One practice that has been proposed to improve NUE on sandy soils (where leaching is a concern) and on poorly drained soils (where denitrification may occur) is a split application of N fertilizer (Vitosh et al., 1995). A split application of N fertilizer involves applying a small portion of preplant N fertilizer combined with a large portion of N at sidedress after the crop has been established (Welch et al., 1971; Ma et al., 2005). However, a study conducted in southern Minnesota observed higher amounts of residual NO_3^- at the end of the growing season when a split-application (at preplant and V8 stage) of N fertilizer was used, indicating that N may have been lost from the profile or immobilized under the conditions of their study (Jokela and Randall, 1989).

Sidedressed N fertilizer may achieve comparable yields to preplant N fertilizer (Jokela and Randall, 1989; Eckert and Martin, 1994) because the greatest amount of N is taken up by the plant between V9-VT (tasseling) growth stages (Mengel, 1995), as displayed in Figure 2.3. Producers have more time to implement in-season soil and sensor reflectance measurements when sidedress N is applied to identify fields where there may be an N deficiency.

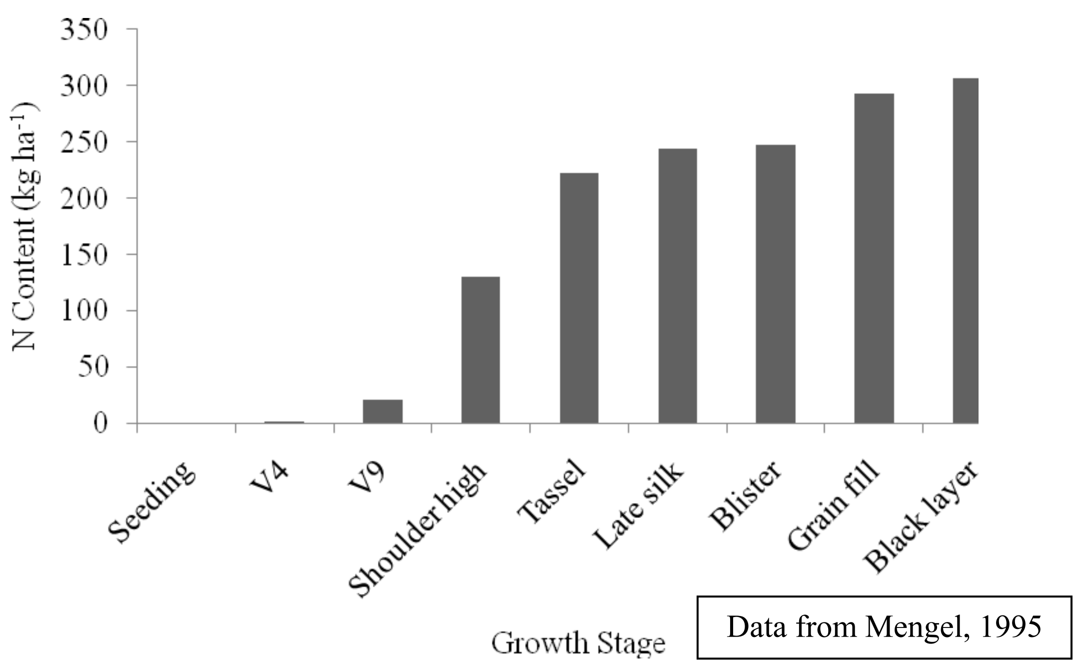

Figure 2.3: Nitrogen content of corn plant according to growth stage.

2.5 Nitrogen recommendations

In the 1930s when commercial fertilizers were being introduced in the United States, researchers understood that there would be a high demand for these fertilizers, and research was needed to know how much to apply (Brown, 1936). In the 1950s, yield response curves to increasing N application rates were examined to develop N recommendations (Pesek and Heady, 1958). However, researchers realized that year to year yield fluctuations made precise response predictions difficult (Heady and Shrader, 1953). Beginning in 1968, Purdue University agronomists made N recommendations for corn based on cropping history and yield goals (Phillips and Lessman, 1968). Currently, in Ohio, Michigan, and Indiana, cropping history and yield goal algorithms are still being used to make N recommendations for corn (Vitosh et al., 1995).

Yield goal estimates may not always be realistic and fail to address in-season variations that may affect crop production. Using the average maximum yield over 10 years, one study found that recommendations were over-predicted by 61 kg N ha^{-1} when yield goal based rates were compared to rates based on empirical data (Varvel et al., 2007). This method of making N recommendations may underestimate the soil N supply or may not recognize in-season N loss (Scharf et al., 2006).

2.5.1 Soil tests

During the early 1940s, soil testing programs developed as a result of a sufficient database of crop-fertilizer response, instrumentation, and the increased need for crop production brought on by World War II (Peck, 1990). Soil NO_3-N concentrations may be evaluated before the crop is planted or prior to sidedressing N to aid in making N fertilizer decisions.

The preplant soil nitrate test (PPNT) is used to measure residual or carryover NO_3-N from N use in previous years (Bundy et al., 1999). For Wisconsin soils, using PPNT as an aid to adjust N fertilizer rates, 89% of sites received correct N application rates for corn and excessive N application was reduced by 67% (Bundy and Andraski, 1995). However, this test has only been implemented in arid regions of the United States and is not yet effective in the Midwest, due to weather variations which affect the probability of NO_3-N losses, soil N mineralization, and crop N demand (Bundy et al., 1999). Data from a study conducted in Ontario, Canada, suggest that caution should be taken when deciding the rate of sidedress N based on the PPNT, especially under more humid conditions (Ma and Wu, 2008).

The presidedress soil nitrate test (PSNT), developed by Magdoff (1991), measures the concentration of NO_3-N in the surface 30 cm of soil, accounting for plant-available N and may be used to predict if there will be a grain yield response to additional N fertilizer (Bundy et al., 1999). This is under the assumption that the amount of NO_3-N present at sampling is directly related to the N supplying capability of the soil during the entire growing season (Magdoff et al., 1984). Soil samples for PSNT analysis are generally collected when the corn height is 15-45 cm. Researchers in many states over several years found the PSNT critical level, where yield response to additional N fertilizer is unlikely, to be between 17-26 NO_3-N $\mu g\ g^{-1}$ of soil (Magdoff et al., 1990; Binford et al., 1992; Meisinger et al., 1992; Bundy and Andraski, 1995; Heckman et al., 1996). Results of these studies are shown is Table 2.1. Although PSNT critical levels may be useful in determining the probability that additional N fertilizer will produce a yield response, it is not widely used to determine N sidedress rates.

Table 2.1: Presidedress soil nitrate test critical levels by location and corn height at time of soil collection.

Location	Corn Height (cm)	Critical Level ($\mu g\ g^{-1}$)	Source
Northeast USA	20-25	20-30	Magdoff et al., 1990
Iowa	15-30	23-26	Binford et al., 1992
Maryland	15-30	22	Meisinger et al., 1992
Wisconsin	15-30	21	Bundy and Andraski, 1995
New Jersey	30-45	22	Heckman et al., 1996

Delaying soil N testing prior to sidedress N application may improve economic return by supplying N to the plant when it is most needed, reducing the chance of N loss to the environment (Bundy et al., 1999). However, too long of a delay may cause irreversible yield loss from N stress. One study found that delaying N application to the V6 stage resulted in loss of maximum grain yield when N deficiency was severe (Binder et al., 2000). However, another study reported no irreversible yield loss when N applications were delayed as late as the V11 stage (Scharf, et al., 2002).

2.5.2 Plant tissue tests

Plant tissue tests provide another method of evaluating the N status of corn plants. Tissue tests have the additional benefit of easier sampling and better integration of factors that influence N availability when compared to soil N tests (Binford et al., 1992). Plant tissue samples may be collected in the late spring, during initial silking, or at the end of the growing season.

There are conflicting results in the relationship between grain yield and stem NO_3^- concentrations for tissue samples collected in the late spring. Iverson et al. (1985) found a significant relationship between relative yields and basal stem NO_3^- concentrations at approximately 30 days after emergence. However, another study indicated that the late spring tissue test was not a reliable indicator of N status when used over a range of weather, crop management, and soil conditions (Fox et al., 1989).

Ear leaves may also be collected at initial silking or tasseling and analyzed for total N to evaluate the N status of the plant. Studies have found that N deficiencies in corn are most apparent in leaves and leaf sheaths near silking time (Hanway, 1962), and N applications significantly increase the percent of N in corn ear leaves (Bennett et al., 1953). Total N of 2.90-3.50 percent in ear leaves collected at initial silking are considered within the N sufficiency range, while total N of 2.44-2.89 percent is considered marginal (Vitosh et al., 1995). However, if an N deficiency is identified at initial silking, irreversible N stress may have occurred (Binder et al., 2000; Scharf et al., 2002). Even if irreversible damage does not occur, it is difficult for producers to apply N fertilizer without high-clearance equipment. Additionally, weather may prohibit field work and further delay sidedress N applications.

The lower portion of the cornstalk at physiological maturity can be used as an indicator of corn N status (Binford et al., 1990). At N rates less than required to attain near-maximum yields, additions of N tend to increase plant growth without changing stalk NO_3^- concentrations, but at higher rates of fertilization, stalk NO_3^- tends to increase linearly with increases in the rate of fertilization (Binford et al., 1992). This tissue test can identify excessive amounts of N fertilization whereas the late spring tissue tests may not. It is suggested that producers who grow corn on manured soils or after alfalfa should use this test since N supply tends to be underestimated in these systems (Blackmer and Mallarino, 1996). End of the year tissue tests, however, can only be integrated into the N management for the following year. This may be useful to correct situations in which N fertilizer is routinely over-applied.

2.5.3 Remote sensors

Remote sensors can be used to measure the amount of reflected light from plant canopies, as an estimation of plant health. The spongy mesophyll of a healthy plant will reflect near-infrared light, as a function of plant biomass. Near-infrared light has a longer wavelength and less energy than red light; therefore, near-infrared light is not used in photosynthesis. Chlorophyll absorbs red light for use in photosynthesis; therefore, little red light should be reflected from a healthy plant. As leaf area index increases, red (600-700 nm) reflectance decreases and near infrared (800-110 nm) reflectance increases (Daughtry et al., 1980) as a result of the crop canopy. The strong absorption (low reflectance) of red light by chlorophyll and low absorption (high reflectance and transmittance) in the near infrared region by green leaves (Avery and Berlin, 1992) is the basis of many vegetation indices.

The usefulness of remote sensing in plant studies became apparent when infrared aerial photography was able to detect loss of vigor from disease in wheat (*Triticum aestivum* L.) and other small grains (Colwell, 1956). In a study conducted by Vina et al.

(2004), remote sensing was used to identify stress-induced abnormalities in corn throughout the growing season. Sensors may aid in identifying abnormalities or nutrient deficiencies in the crop early in the growing season when corrective measures may still be considered.

Remote sensors may also aid in variable N application. Uniform N application within a field may result in parts of the field being over- or under-fertilizer as a result of spatial and temporal variations (Mamo et al., 2003). Schmidt et al. (2002) suggested that precision agriculture technologies may improve N management for corn by taking in-field variability into account. Sensors may be able to separate areas that may be responsive to additional N fertilizer from areas that may be unresponsive.

2.5.4 Vegetation indices

Remotely sensed data collected from plant canopies can be used to formulate vegetation indices that may give an indication of plant health. Several vegetation indices have been developed including, normalized difference vegetation index (NDVI), green normalized vegetation index (Penuelas et al., 1995), and infrared to red reflectance ratio or simple ratio (SR) (Sapp, 1981). In a study that evaluated several vegetation indices, NDVI consistently differentiated 0 N control and N treatments from the V6 to V8 growth stage in corn (Ma et al., 2005).

The amount of near-infrared (840-880 nm) reflectance and red (620-670 nm) reflectance from the plant canopy is used to calculate NDVI. The equation for NDVI (Rouse et al., 1973; Tucker, 1979) is:

$$NDVI = (\rho NIR - \rho Red)/(\rho NIR + \rho Red) \quad (1)$$

Where,
NDVI is the normalized difference vegetation index.
ρNIR is the near infrared reflectance in the range of 840 to 880 nm.
ρRed is the red light reflectance in the range of 620 to 670 nm.

According to several years of data collected in Oklahoma, NDVI values <0.25 were recorded on bare soil (Raun et al., 2005), although soil reflectance has been found to decrease with decreasing clay content (Al-Abbas et al., 1972). Martin et al. (2007) found that the average NDVI was the lowest at the V3 growth stage for corn due to soil reflectance, and NDVI was proportional to the level of vegetation coverage between the V3 and V10 stages. There was only a small change in NDVI values in corn between V10-VT (tasseling) growth stages, where the maximum NDVI was reached (Martin et al., 2007). After corn tassels fully emerged, NDVI values decreased due to the yellowing of the mature tassels and continued to decrease as the plants entered the reproduction stages and senescence occurred, which gave NDVI readings as low as 0.30 (Martin et al., 2007).

Near infrared reflectance tends to increase with leaf area index (Daughtry et al., 1980). At the V3-V5 growth stages biomass yields were poorly related with NDVI (Martin et al., 2007). In a three year study at three locations in Oklahoma, there was a weak relationship between NDVI and plant biomass for data collected from corn growth stages V8 to V10 (Freeman et al., 2007).

Chlorophyll absorbs red light (Daughtry et al., 1980). At the V8-V10 and V11-R1 growth stage of corn, NDVI and N uptake was related ($P < 0.001$) (Freeman et al., 2007). Freeman et al. (2007) explained the strong relationship between NDVI and N uptake by the ability of NDVI to detect differences in red absorption and variation in chlorophyll content.

Growth stage is a major factor in predicting yield potential. At the V3-V5 growth stages of corn, grain yields were poorly related with NDVI, but increased between the V6-V7 growth stages (Shanahan et al., 2001; Martin et al., 2007). However, Teal et al. (2006) reported a poor exponential relationship between NDVI from sensor measurements taken at the V6-V7 leaf stage and grain yield. This was attributed to yield potential still developing after NDVI measurements were taken. At the V8-V10 growth stage of corn, yield was accurately predicted using NDVI (Freeman et al., 2007; Martin et al., 2007). After tasseling and into senescence, the relationship between NDVI and grain yield decreased (Shanahan et al., 2001). The results of these studies indicate that NDVI may be a useful index of plant health and may be used in a series of equations to aid in predicting optimum sidedress N fertilizer rates.

2.6 Sensor-based algorithm components

Sidedress N recommendations can be made using an algorithm, a series of equations, which implement a yield prediction model and an in-season prediction of N response model. These models were originally developed at Oklahoma State University to make sidedress N recommendations for winter wheat (Raun et al., 2005), but similar concepts have been applied to the Ohio State algorithm for corn (Mullen et al., 2007).

The algorithms use NDVI measurements collected from control plots (0 N applied), target plots (small amount of preplant N applied), and reference plots (non-N limiting).

<u>2.6.1 Yield prediction model for winter wheat</u>

The yield prediction model is used to make an in-season estimate of yield (INSEY) potential based on NDVI measurements and is an estimate of winter wheat biomass produced per day on the specific date when sensor readings were collected (Raun et al., 2005). Raun et al. (2001) hypothesized that once the potential yield is determined, topdress N rates could be adjusted to reflect the INSEY. This measure of INSEY takes into account a wide range of growing conditions, planting times, and sensing dates (Raun et al., 2001) because measurements are collected in-season and reflect the current growing conditions. The in-season estimate of yield equation for winter wheat is:

$$\text{INSEY} = \text{NDVI}/\text{DAP} \qquad (2)$$

Where,
INSEY is the in-season estimate of yield.
NDVI is the normalized difference vegetation index of the crop canopy.
DAP is days after planting to sensing, where only growing degree days [maximum temperature in °C + minimum temperature in °C)/2-4.4°C] > 0 are considered.

A study conducted in Oklahoma examined the ability of INSEY to predict grain yield of winter wheat (Raun et al., 2001). This study found a strong, exponential relationship between measured grain yield and estimated yield, predicted using NDVI measurements, when only sites with optimum growing conditions were considered.

When all sites were considered, the exponential relationship was not as strong. One standard deviation above this exponential relationship between empirical grain yield data and INSEY is used in the algorithm to capture the uppermost INSEY values and predict yield potential with no additional N fertilizer (YP_0). The equation for the YP_0 model is (Raun et al., 2005):

$$YP_0 = 0.359e^{324.4\mathrm{INSEY}} \quad (3)$$

Where,
YP_0 is the predicted yield potential without additional N.
INSEY is the in-season estimate of yield (Equation 2) calculated by dividing NDVI in-season measurements by days after planting.

2.6.2 In-season prediction of nitrogen response model

The predicted YP_0 does not translate directly into an N recommendation. It must be used in conjunction with the in-season prediction of N response model. Crop response to additional N fertilizer can be estimated using in-season sensor measurements of a crop treated with a normal field N rate and an excessive N rate (Mullen et al., 2007), as to make N a non-limiting factor in grain yield. Response index used in the algorithm was developed by determining the RI at harvest. The equation to calculate RI at harvest is defined as (Johnson and Raun, 2003):

$$RI_{Harvest} = Yld_{Reference}/Yld_{Target} \quad (4)$$

Where,
$RI_{Harvest}$ is the fertilizer response index for a harvested crop.
$Yld_{Reference}$ is the grain yield from a reference strip with an adequate supply of N (non-limiting).
Yld_{Target} is the grain yield from an adjacent area at the normal field N application rate.

Due to the relationship between $RI_{Harvest}$ and the grain yield for the target and reference strip, an in-season RI is considered to determine the extent to which the crop will respond to additional N fertilizer (Raun et al., 2005). An in-season RI can also be calculated by the equation (Johnson and Raun, 2003):

$$RI_{NDVI} = NDVI_{NRich}/NDVI_{FieldRate} \quad (5)$$

Where,
RI_{NDVI} is the response index using NDVI.
$NDVI_{NRich}$ is NDVI of an area within the non-N limiting reference strip.
$NDVI_{FieldRate}$ is NDVI of an adjacent area treated at the normal N rate.

Studies indicate there is a strong relationship between the RI at harvest ($RI_{Harvest}$) and RI_{NDVI} in winter wheat (Hodgen et al., 2005; Raun et al., 2005). Due to this strong relationship, RI is used in the algorithm to predict grain yield response to additional N fertilizer. Mullen et al. (2003), found a relationship ($P < 0.001$) between RI_{NDVI} and $RI_{Harvest}$ in winter wheat Feekes 5 growth stage. Relationships were also found at Feekes 9-10 growth stages (Mullen et al., 2003). Identifying N response early in-season, such as Feekes 5 for winter wheat, allows time for to apply additional N fertilizer, if needed. However, one study conducted in Oklahoma found the linear relationship between $RI_{Harvest}$ and RI_{NDVI} to be poor for winter wheat, which suggested that yield response could not be reliably predicted to added N mid-season (Arnall et al., 2006).

Although RI_{NDVI} has been mostly successful in predicting nitrogen response for winter wheat (Hodgen et al., 2005), RI_{NDVI} has not been as successful in predicting N response for corn. Preplant fertilizer may mask the N response at the time of sensing, which is a possible explanation for this difference. At the time of sensing, the corn plant may not yet display signs of N deficiency since rapid N uptake occurs after the V9 growth stage (Mengel, 1995). In winter wheat, rapid N uptake occurs at Feekes 4-5 growth stage (Baethgen and Alley, 1989) during stem elongation (Nelson et al., 1988). Sensor measurements are collected from the winter wheat canopy between Feekes 4-6 growth stage (Lukina et al., 2001; Hodgen et al., 2005). The time of sensing in winter wheat may correspond better with rapid N uptake than in corn.

2.6.3 Nitrogen recommendation

The two main components of the sensor-based algorithm, the yield prediction model and in-season prediction of N model based on NDVI measurements, are both used to make topdress N recommendations for winter wheat. The predicted yield potential with additional N fertilizer (YP_N) is calculated according to the equation (Raun et al., 2005):

$$YP_N = YP_0 * RI_{NDVI} \qquad (6)$$

Where,
YP_N is the predicted yield potential (in Mg ha^{-1}) with additional N fertilizer.
YP_0 is the predicted yield potential (in Mg ha^{-1}) from Equation 4without additional N fertilizer.
RI_{NDVI} is the response index (Equation 6) calculated using NDVI measurements.

The topdress N requirement (R) is then calculated using the predicted yield potential with additional N fertilizer and without additional N fertilizer and 23.9 as the decimal percentage of N by weight contained in wheat grain. The equation to calculate topdress recommendations is (Raun et al., 2005):

$$R = 23.9((YP_N\text{-}YP_0)/\eta) \qquad (7)$$

Where,
R is the topdress N rate (in Mg ha^{-1}).
YP_N is the predicted yield potential (Mg ha^{-1}) from Equation 7 with additional N fertilizer.
YP_0 is the predicted yield potential (in Mg ha^{-1}) from equation 4 without additional N fertilizer.
ŋ is a conversion constant ($0.5 \geq ŋ \leq 0.7$).

This algorithm is used to estimate topdress N requirements for winter wheat and have been developed in Oklahoma. Similar equations and procedures are used to estimate sidedress N requirements in corn (Mullen et al., 2007), which were evaluated in this study.

2.7 Significance

Nitrogen fertilizer management is becoming increasingly important due to the rise of N fertilizer prices and growing environmental concerns. To reduce N loss to the environment, optimum N fertilizer rates need to be identified. Traditionally, yield goals have been used to adjust N fertilizer rates. Now, soil N tests and vegetation indices based on optically sensed data may aid in improving recommendations. This project will contribute to soil science by adding to the existing studies concerning optical sensing algorithms to identify optimum N fertilizer rates and expand the knowledge base to include corn grain crops treated with manure instead of the traditional inorganic fertilizer used in previous studies. Additionally, if existing algorithms do not fit this project, new algorithms may need to be developed.

CHAPTER 3

METHODS

3.1 Locations and site descriptions

This study was conducted in 2007 and 2008 at the Western Research Station (39.8633°N, 83.6721°W) of the Ohio Agricultural Research and Development Center (OARDC) near South Charleston, Ohio. The 2007 study was primarily located on the Crosby silt loam soil series, a fine, mixed Aeric Epiaqualf. The 2008 study at the Western OARDC was located on Kokomo silty clay loam, a fine, mixed, superactive, mesic Typic Argiaquoll. In 2008, there was an additional site at the OARDC (40.7787°N, 81.9308°W) located near Wooster, Ohio. The primary soil series at this site was Canfield silt loam, a fine-loamy, mixed active, mesic Aquic Fragiudalf.

3.2 Experimental design

A split-plot, randomized complete block design was used at all three sites. The main plots consisted of three preplant manure rates (0, 37, and 75 kl ha^{-1}), representing the three types NDVI measurements were collected from and used in the algorithm, control (no N applied), target (small, preplant N rate), and reference (non-N limiting). Raw liquid hog manure and liquid dairy cow manure were used at the Western and Wooster locations, respectively. It was estimated that 75 percent of the total NH_4-N and

33 percent of the organic-N would become plant available nitrogen (Randall et al., 2006). Potentially plant available nitrogen (PAN) differed among the sites (Table 3.1) due to differences in animal species and management, manure storage, and handling system. Plots were designated as control (no N applied), target (plot that sidedress N recommendation is being made), and reference (non-N limiting). Target plots consisted of plots that received no preplant N and plots that received a small amount of preplant N.

Table 3.1: Location, manure type, NH_4-N and Org-N in manure, potentially plant available N, application rate, and predicted N application rate.

Site	Manure	NH_4-N (kg N kL^{-1})	Org-N (kg N kL^{-1})	PAN (kg N kL^{-1})	Preplant manure rate (kL ha^{-1})	Preplant manure estimate N rate (kg ha^{-1})	Plot type
Western 2007	Hog	3.5	1.4	3.1	0	0	Control
					37	117	Target
					75	233	Reference
Western 2008	Hog	2.1	2.9	2.5	0	0	Control
					37	94	Target
					75	188	Reference
Wooster 2008	Dairy cow	1.5	1.9	1.7	0	0	Control
					37	63	Target
					75	126	Reference

The subplots consisted of five 28% urea ammonium-nitrate (UAN) sidedress N rates, which were 0, 57, 113, 170, and 227 kg ha^{-1} at all three sites. There were a total of fifteen treatments, each replicated four times. Plots were 3.05 m by 12.19 m, with four rows of corn per plot spaced 38 cm apart.

3.3 Field methods

Date of fertilizer application, planting, sampling, stand counts, and harvest are shown in Table 3.2. Tissue samples were not collected at the Western OARDC site in 2007. Herbicides and insecticides used are shown in Table 3.3.

Table 3.2: Dates of fertilizer application, planting, sample collection, stand counts, and harvest.

	2007	2008	
Field Operation	Western	Western	Wooster
Preplant manure	18-Apr	24-Apr	6-7 May
Planting	1-May	25-Apr	21-May
Sensor measurements	14-Jun	17-Jun	9-Jul
PSNT samples	14-Jun	17-Jun	7-Jul
Sidedress N	15-Jun	11-Jun	7-Jul
Ear leaf samples	None	23-July	4-Aug
Initial stand count	23-Jun	11-Jun	26-Jun
Final stand count	28-Oct	20-Oct	23-Oct
Harvest	31-Oct	21-Oct	6-Nov

Table 3.3: Pesticides used and application rates at all three sites.

Site/year	Type	Application	Commercial name	Rate (l ha^{-1})
Western 2007	Herbicide	4-May	Bicep Magnum II	4.7
			Callisto	0.2
Western 2008	Herbicide	30-Apr	Brawl	4.7
			Buccaneer	2.3
			Callisto	0.2
Wooster 2008	Insecticide	Seed treatment	Roundup Yield Guard	---
			Poncho 250	---
	Herbicide	29-May	Lexar	7.0
			Roundup Original Max	3.5

3.3.1 Cultural practices

The cultural practices for this study are displayed in Table 3.4. A seeding rate of 79,100 seeds ha^{-1} and planting depth of 3.8 cm was used at all sites. Tillage at the Western OARDC site in 2007 consisted of fall chisel plow followed by a spring field cultivator pass. In 2008, the sites were not tilled. All manure treatments were surface applied. Urea ammonium-nitrate (UAN) solution was coulter-injected at the sidedress application time.

Table 3.4: Cultural practices, including hybrid, tillage, previous crop, and sidedress N fertilizer type for all three sites.

Cultural Practice	2007	2008	
	Western	Western	Wooster
Hybrid	Seed Consultants 11L05	Seed Consultants 11RR28	Pioneer 36B11
Tillage	Fall chisel; spring cultivator	No till	No till
Previous crop	Soybean	Corn	Soybean
Preplant manure	Hog	Hog	Dairy cow
Sidedress N	28% Urea ammonium-nitrate	28% Urea ammonium-nitrate	28% Urea ammonium-nitrate

3.3.2 Plant density

Initial and final stand counts were recorded at each site five to seven weeks after planting and just prior to harvest, respectively, to calculate plant density. In 2007, all plants in the middle two rows of the plot (rows 2 and 3) were counted and total plot length was recorded. In 2008, the plants in the western row at the Western Branch OARDC and the northern row at the Wooster OARDC of each plot were counted along a 5.3 m pole or tape measure. Plants density for each plot was calculated according to the plot length or along the 5.3 m and 0.38 m row spacing.

3.4 Sensor measurements

A GreenSeeker^{TM} optical sensor (NTech Industries, Inc., Ukiah, CA) unit was used to measure red and near infrared reflectance from the crop canopy between the V6-V8 growth stages (Ritchie et al., 2005). The sensor contained a light-emitting diode in the red (650 nm) and near-infrared (770 nm) light bands. Red and near-infrared light reflection from the crop canopy was measured with a photodiode, recording 10 readings per second. The sensor was mounted on a bicycle approximately 0.91 m above the crop canopy, which was pushed through the plots. The normalized difference vegetation index was measured for the center two rows (rows 2 and 3). The average NDVI reading per plot was used to calculate N recommendations using the optical sensor algorithm. Normalized difference vegetation was calculated by the sensor according to the equation:

$$NDVI = (\rho NIR - \rho Red)/(\rho NIR + \rho Red) \quad (1)$$

Where:
NDVI is the normalized difference vegetation index.
ρ_{NIR} is the near infrared reflectance in the range of 840 to 880 nm.
ρ_{red} is the red light reflectance in the range of 620 to 670 nm.

3.5 Soil nitrate-nitrogen concentration

Soil samples for the presidedress soil nitrate test (PSNT) were collected prior to sidedressing. Soil samples were collected to a depth of 30 cm. These samples were air-dried and ground to pass a 2 mm sieve. Soil NO_3-N was extracted using a 2M KCl and concentration determined by ion chromatography (Mulvaney, 1996; Gelderman and Beegle, 1998).

3.6 Ear-leaf nitrogen concentration

Six ear-leaf samples per plot were collected in 2008 at both sites during initial silking. The leaf directly below the uppermost ear was collected. Ear-leaf samples were oven-dried at 60°C. The dry samples were cut into approximately 2.5 cm strips and ground using a Cyclone Sample Mill (Udy Co., Fort Collins, CO). Samples were homogenized by plot and approximately 5 mg was used for total N analysis, measured with a Carbon-nitrogen Combustion Analyzer (AOAC, 1989).

3.7 Agronomic optimum nitrogen rate

Before the algorithms were evaluated, the agronomic optimum sidedress N rate (AONR), defined as sidedress N rate at which highest grain yield was achieved, was calculated using empirical data. For each site and each manure rate, a quadratic model was fit to mean grain yield and the five sidedress N rates. The first derivative of the quadratic model was computed, and the equation was set to equal zero. The equation was solved for N sidedress rate. This value approximated the AONR and was compared to the recommended sidedress N rates calculated by the sensor-based algorithms.

3.8 Algorithm model evaluation

Two existing algorithms based on research conducted in 2004 through 2006 in several states, Canada, Mexico, and Argentina were evaluated (Mullen et al., 2007). The algorithms consisted of a series of equations used to make an in-season prediction of grain yield, response to N fertilizer, and sidedress N recommendation. Normalized difference vegetation index measurements and days after planting (DAP) to sensing were used in the algorithms to calculate sidedress N rates. These values for the target, control, and reference plots are given in Table 3.5.

Table 3.5: Normalized difference vegetation index measurements and days after planting to sensing used in the algorithm.

	NDVI					
Site/year	Targets Evaluated			Reference	Control	DAP
Western 2007	0.5798	0.5434	n/a†	0.5684	0.5798	45
Western 2008	0.5095	0.5900	n/a	0.6457	0.5095	53
Wooster 2008	0.6916	0.7082	0.7385	0.7385	0.6916	49

† Only two targets were evaluated at the 2007 and 2008 Western OARDC sites.

Normalized difference vegetation index values (from Table 3.5) for the control, target, and reference plots were entered into the algorithm to calculate the SR for each. Simple ratio was used because it tended to delineate response to N fertilizer better than NDVI (Mullen et al., 2007). Simple ratio is calculated by the equation:

$$SR = (1 - NDVI)/(1 + NDVI) \qquad (2)$$

Where,
SR is the simple ratio, based on the NDVI of the control, target or reference plot (from Table 3.5.
NDVI is the normalized difference vegetation index (Equation 1).

The yield prediction model component of the algorithms used the SR from the target plot and number of DAP to sensing to estimate the grain yield potential with no additional N fertilizer. The yield prediction equation was developed according to the relationship between the target SR, DAP, and empirical grain yield from previous studies (Mullen et al., 2007).

The grain yield potential with no additional fertilizer is:

$$YP_0 = 20.216e^{-0.0647 * \text{TargetSR} * \text{DAP}} \tag{3}$$

Where,
YP_0 is the yield potential (in Mg ha^{-1}) with no additional N fertilizer.
Target SR is the simple ratio of the target plot (plot which the sidedress N recommendation is being made) from Equation 2.
DAP is number of days after planting to sensing.

The second component of the algorithm was the in-season prediction of N response model calculated using a response index (RI) to additional N fertilizer. The response index was calculated two ways. One way utilized the target SR (RI_{Target}) and the other way used the check plot SR (RI_{Check}). If the RI > 1, 1 was used as the RI. This ensured that a sidedress N rate > 0 kg ha^{-1} was recommended. The equation to calculate RI using the target SR is:

$$\text{RITarget} = \text{ReferenceSR}/\text{TargetSR} \tag{4}$$

Where,
RI is the response index, using the target SR.
Reference SR is the simple ratio of the reference strip (non-N limiting strip) from Equation 2.
Target SR is the simple ratio of the check plot (plot which the sidedress N recommendation is being made) from Equation 2.

The equation calculate RI using the check plot SR is:

$$RICheck = ReferenceSR/CheckSR \quad (5)$$

Where,
RI is the response index, using the check SR.
Reference SR is the simple ratio of the reference strip (non-N limiting strip) from Equation 2.
Check SR is the simple ratio of the check plots (plot with no N applied) from Equation 2.

The response index was transformed due to a linear relationship between $RI_{Harvest}$ and RI_{SR} from previous studies (Mullen et al., 2007). There are two ways the transformed RI was calculated, depending if RI_{Target} or RI_{Check} was used to determine RI (Equations 4 or 5). The transformed RI_{Target} is calculated according to the equation:

$$TransformedRI_{Target} = -1.969 * RI + 3.1744 \quad (6)$$

Where,
Transformed RI_{Target} is the linearly transformed response index.
RI is the response index of RI_{Target} from Equation 4.

The transformed RICheck is calculated according to the equation:

$$TransformedRI_{Check} = -1.6778 * RI + 2.7734 \quad (7)$$

Where,
Transformed RI_{Check} is the linearly transformed response index.
RI is the response index of RI_{Check} from Equation 5.

The estimated yield potential with additional N fertilizer (YP_N) was calculated using the transformed RI and YP_0 from the yield prediction model, according to the equation:

$$YP_N = (\text{Transfomed RI}) * YP_0 \quad (8)$$

Where,
YP_N is the yield potential (in Mg ha^{-1}) with additional N fertilizer.
Transformed RI is the linearly transformed response index (Equation 6 or 7).
YP_0 is the yield potential (in Mg ha^{-1}) with no N fertilizer (Equation 3).

The final step in the algorithm was to make a sidedress N recommendation. This was accomplished by determining the N uptake in YP_0 and YP_N, assuming 1.3% N in grain. The equation used to calculate grain N uptake when no additional fertilizer was applied is defined as:

$$\text{N uptake } YP_0 = YP_0 * 0.013 \quad (9)$$

Where,
N uptake YP_0 is the amount of N in grain (in Mg ha^{-1}) where no N fertilizer was applied.
YP_0 is the predicted yield potential with no N fertilizer (Equation 3).

The equation used to calculate grain N uptake when additional N fertilizer is applied is:

$$\text{N uptake } YP_N = YP_N * 0.013 \quad (10)$$

Where,
N uptake YP_N is the amount of N (in Mg ha^{-1}) in the grain in plots where additional N fertilizer was applied.
YP_N is the predicted yield potential (in Mg ha^{-1}) with additional N fertilizer (Equation 8).

To make a sidedress N recommendation, the difference in N uptake in YP_N and YP_0 was calculated, assuming 60% efficiency. This sidedress N recommendation equation is:

$$\text{Recommendation} = ((\text{N uptake } YP_N - \text{N uptake } YP_0)/0.60) * 1000 \qquad (11)$$

Where,
Recommendation is the amount of sidedressed N fertilizer needed to maximize yield (kg ha^{-1}).
N uptake YP_N is the amount of N in the grain in plots where additional N fertilizer was applied (Equation 10).
N uptake YP_0 is the amount of N in grain where no N fertilizer was applied (Equation 9).

3.9 Presidedress soil nitrate test evaluation

Soil collected at the V6-V8 growth stage and analyzed for NO_3-N concentration was used for PSNT evaluation. Relative yield (RY) was calculated by dividing individual control plot grain yields by the highest yield achieved among the sidedressed plots. Linear-plateau, quadratic-plateau, and quadratic plus plateau models (plateau begins where first derivation of quadratic model is equal to 0) were constructed to fit the RY versus soil NO_3-N concentration. The soil NO_3-N value where the two models joined was considered the PSNT critical value. Soil NO_3-N concentration was also correlated with the empirical optimum N rate.

3.10 Statistical procedures

The General Linear Model (Proc GLM) was used to detect if there were differences in means between treatments. Least Significant Difference (LSD) at $\alpha = 0.05$ was used to indicate which treatment means differed. Critical values used in PSNT evaluation were found using Segmented Model (Proc NLIN). All statistical procedures were conducted using SAS 9.1 (SAS Institute, 2003).

3.11 Weather data

Temperature and precipitation information were collected from the Western Branch and Wooster OARDC weather systems. The cumulative growing degree days (GDD) from plant date to the time of sensor measurements, soil sampling for PSNT, sidedress N, stand counts, and harvest were calculated. For any temperature above 30° C, 30° C was used as the maximum temperature, and for temperature below 10° C, 10° C was used as the minimum temperature to reflect the maximum and minimum temperatures for growth of corn (Cross and Zuber, 1972). Growing degree days were calculated according to the equation (Wang, 1960):

$$GDD = ((T_{Max} + T_{Min})/2) - 10 \tag{12}$$

Where,
GDD is growing degree days.
T_{Max} is the maximum temperature (if > 30°C, use 30), recorded in Celsius.
T_{Min} is the minimum temperature (if <10°C, use 10) recorded in Celsius.

CHAPTER 4

RESULTS

4.1 Plant density

A seeding rate of 79,000 seeds ha^{-1} was used at all locations. Initial and final plant densities for all three sites are shown in Table 4.1. There was no statistically significant difference in the initial stand count among the preplant manure treatments at all three locations.

At the Western Research Station in 2007, the initial stand count, recorded in late June, showed no differences in plant density among the treatments. However, in October there was a reduction in plant density on plots where no preplant manure was applied ($P < 0.05$). At the Western and Wooster OARDC sites in 2008, there was no statistically significant difference in final stand count among N fertilizer treatments.

Table 4.1: Initial and final plant density recorded at all three sites.

Site/year	Preplant manure rate (kl ha^{-1})	Preplant manure estimate N (kg ha^{-1})	Plant density Intial (plants ha^{-1})	Plant density Final (plants ha^{-1})
Western 2007	0	0	73,400	66,100
	37	117	74,500	72,500
	75	233	74,000	72,400
$LSD_{0.05}$			2,900	4,300
CV (%)			3.7	7.1
Western 2008	0	0	74,300	57,000
	37	94	70,500	56,600
	75	188	73,600	49,200
$LSD_{0.05}$			6,700	11,700
CV (%)			9.7	25.1
Wooster 2008	0	0	71,800	70,200
	37	63	67,400	65,200
	75	126	67,300	64,600
$LSD_{0.05}$			6,500	7,200
CV (%)			10.9	12.2

At the Western OARDC in 2008, there was a 23%, 20%, and 33% reduction in erect plants from the time of the initial to final stand count at 0, 94, and 188 kg N ha^{-1} preplant manure treatments, respectively. Many plants were lodged due to a wind storm as a result of Hurricane Ike, where maximum wind speed recorded by the Western OARDC weather system was 53.4 km hr^{-1} on September 14, 2008. Although there was a large number of plants that were lodged between the initial to final stand count, grain yield was unaffected and were able to be harvested.

4.2 Normalized difference vegetation index and simple ratio

Normalized difference vegetation index (NDVI) and simple ratio (SR) measurements are displayed in Table 4.2. At the 2007 Western OARDC site and the 2008 Wooster OARDC site, there were no differences in NDVI and SR among the preplant manure treatments. At the 2008 Western OARDC site, NDVI increased and SR decreased with preplant manure estimate N rate ($P < 0.05$).

Table 4.2: NDVI and SR measurements recorded for each preplant manure treatment and site.

Site/year	Preplant manure estimate N (kl ha^{-1})	Preplant manure estimate N rate (kg ha^{-1})	NDVI	SR
Western 2007	0	0	0.58	0.273
	37	117	0.543	0.306
	75	233	0.568	0.284
$LSD_{0.05}$			0.091	0.078
CV (%)			10.6	18.0
Western 2008	0	0	0.51	0.333
	37	94	0.59	0.269
	75	188	0.646	0.223
$LSD_{0.05}$			0.043	0.036
CV (%)			20.8	35.7
Wooster 2008	0	0	0.692	0.187
	37	63	0.708	0.174
	75	126	0.739	0.146
$LSD_{0.05}$			0.072	0.055
CV (%)			9.7	28.6

4.3 Soil nitrate-nitrogen concentration

Soil NO_3-N concentrations used for PSNT evaluation are shown in Table 4.3. Soil NO_3-N concentrations increased with preplant manure estimate N rate at the 2007 Western OARDC site. At the 2008 Western OARDC site, there was a difference in soil NO_3-N concentrations at the lowest and highest application rate of preplant manure. The 2008 Wooster OARDC site, showed no differences in soil NO_3-N concentration between the three preplant manure treatments.

Table 4.3: Soil NO_3-N concentration at each preplant manure treatment rate and site.

Site/year	Preplant manure rate (kl ha^{-1})	Preplant manure estimate N rate (kg ha^{-1})	Soil NO_3-N concentration ($\mu g\ g^{-1}$)
Western 2007	0	0	7.9
	37	117	10.7
	75	233	15.1
$LSD_{0.05}$			2.2
CV (%)			30.1
Western 2008	0	0	8.9
	37	94	10.1
	75	188	16
$LSD_{0.05}$			6.8
CV (%)			46.7
Wooster 2008	0	0	9.5
	37	63	10.2
	75	126	9.8
$LSD_{0.05}$			3.4
CV			27.0

4.4 Ear-leaf N concentration

Ear-leaf N concentrations as influenced by preplant manure and sidedress N applications at the 2008 Western OARDC site are given in Table 4.4. There may have been an interaction between preplant manure rate and sidedress N rate (P = 0.058). As preplant manure rate increased, ear-leaf N concentration response to sidedress N decreased. When no preplant manure was applied, ear-leaf N concentration increased until 113 kg ha^{-1} sidedress N was applied. When 94 kg N ha^{-1} preplant manure was applied, there was only a difference in ear-leaf N concentration between the 0 kg ha^{-1} sidedress rate and the other four rates. There was no increase in ear-leaf N concentration within the 188 kg N ha^{-1} preplant manure estimate N rate. Between preplant N rates, there were only differences at the 0 and 57 kg ha^{-1} sidedress rates. There was no difference in earleaf N for sidedress N rates between preplant manure rates at the 57, 113, and 227 kg ha^{-1} sidedress N rates.

Table 4.4: Ear-leaf N concentrations as influenced by preplant manure rate and sidedress N applications at the Western OARDC site in 2008.

Preplant manure rate (kl ha^{-1})	Preplant manure estimate N rate (kg ha^{-1})	Sidedress N rate (kg ha^{-1})					
		0	57	113	170	227	Mean
		---------------------------%---------------------------					
0	0	1.63	2.29	2.48	2.65	2.81	2.37
37	94	2.14	2.56	2.47	2.62	2.68	2.49
75	188	2.60	2.67	2.65	2.94	2.96	2.76
	Mean	2.12	2.51	2.53	2.74	2.82	

Sidedress N rate means within manure rates, $LSD_{0.05}$ - 0.36
Sidedress N rate means between manure rates, $LSD_{0.05}$ - 0.33
CV (%) - 15.2

Ear-leaf N concentrations as influenced by preplant manure and sidedress N applications at the 2008 Wooster OARDC site are given in Table 4.5. There was an interaction between manure and sidedress rate ($P < 0.05$). There was a response to sidedress N fertilizer within all preplant manure rates. When no preplant manure was applied, ear-leaf N concentration increased up to the 170 kg ha^{-1} sidedress N rate. Within the 63 and 126 kg N ha^{-1} preplant manure estimate N rates, ear-leaf N concentration increased up to the sidedress N rate of 113 kg N ha^{-1}. There was no significant difference in ear-leaf N within manure rates at the sidedress N rates of 113, 170, and 227 kg ha^{-1}. Between manure rates, there was only a significant difference in earleaf N at the 0 kg ha^{-1} sidedress rate between the preplant manure estimate N rates of 0 and 63 and 126 kg N ha^{-1}. There were no significant differences in ear-leaf N concentration between manure rates at any other sidedress N level.

Table 4.5: Ear-leaf N concentrations as influenced by preplant manure rate and sidedress N applications at the Wooster OARDC site in 2008.

Preplant manure rate (kl ha^{-1})	Preplant manure estimate N rate (kg ha^{-1})	Sidedress N rate (kg ha^{-1}) 0	57	113	170	227	Mean
		---------------------------%---------------------------					
0	0	1.81	2.38	2.94	3.05	3.05	2.65
37	63	2.28	2.49	2.75	2.9	2.96	2.68
75	126	2.18	2.55	2.86	3.01	2.93	2.71
	Mean	2.09	2.47	2.85	2.99	2.98	

Sidedress N rate means within manure rates, $LSD_{0.05}$ - 0.25
Sidedress N rate means between manure rates, $LSD_{0.05}$ - 0.24
CV (%) - 14.7

Overall, lower N concentrations in ear-leaf samples were associated with the lower rates of preplant manure and sidedress N applications. Previous studies have found that N deficiencies in corn are most apparent in leaves and leaf sheaths near silking time (Hanway, 1962), and N applications significantly increase the percent of N in the leaf (Bennett et al., 1953). Total N between 2.90-3.50% should be sufficient nitrogen concentration in the ear leaf when measured at initial silking, while between 2.44-2.89 is considered marginal (Vitosh et al., 1995). At both sites, lower levels of preplant N application resulted in corn that would be considered below the marginal range. With increasing sidedress N application, the N status of the plant became more sufficient. At the Western OARDC site in 2008, though, the N status of the corn remained marginal for the preplant manure estimate N rates of 0 and 94 kg ha^{-1}, even at the highest sidedress N rate.

4.5 Grain yields

The grain yield for each preplant manure and sidedress N combination at the 2007 Western OARDC site is displayed in Table 4.6. At this site, there was an interaction ($P < 0.05$) between preplant manure and sidedress N rate. Within the 0 and 117 kg N ha^{-1} preplant manure estimate N rates, there was a grain yield response to sidedress N fertilizer, with the greatest increase occurring between the 0 and 57 kg ha^{-1} sidedress N treatments. There was no grain yield response to sidedressed N fertilizer at the preplant manure estimate N rate of 233 kg N ha^{-1}.

Table 4.6: Grain yield as influenced by preplant manure rate and sidedress N applications at the Western OARDC Research Station in 2007.

Preplant manure rate	Preplant manure estimate N rate	Sidedress N rate ($kg\ ha^{-1}$)					
($kl\ ha^{-1}$)	($kg\ ha^{-1}$)	0	57	113	170	227	Mean
		------------------------Mg ha^{-1}------------------------					
0	0	7.32	10.2	10.82	12.34	10.57	10.25
37	117	10.51	12.46	13.96	12.24	13.03	12.44
75	223	10.26	11.55	11.35	11.34	11.62	11.22
	Mean	9.36	11.40	12.04	11.97	11.74	

Sidedress N rate means within manure rates, $LSD_{0.05}$ - 1.398
Sidedress N rate means between manure rates, $LSD_{0.05}$ - 3.353
CV (%) - 23.7

At the 2008 Western OARDC site, there may have been an interaction (P = 0.0753) between preplant manure N and sidedress N rate. Grain yield by preplant N and sidedress N rate is shown in Table 4.7. Within 0 kg N ha^{-1} preplant manure rate, grain yield increased with sidedress N rate until 113 kg ha^{-1} sidedress N rate. Within 94 kg N ha^{-1} preplant manure estimate N rate, grain yield increased to 170 kg ha^{-1} sidedress N rate. When 188 kg N ha^{-1} preplant manure estimate N was applied, there was no grain yield increase with sidedress N rate. There was an increase in grain yield between manure rates at the sidedress N rates of 0 and 57 kg ha^{-1}. There was no difference in grain yield between manure rates at sidedress rates of 79 kg ha^{-1} and greater. At this site, there was no need to sidedress N fertilizer with larger rates of preplant manure application.

Table 4.7: Grain yield as influenced by preplant manure rate and sidedress N applications at the Western OARDC Research Station in 2008.

Preplant manure rate	Preplant manure estimate N rate	Sidedress N rate (kg ha^{-1})					
(kl ha^{-1})	(kg ha^{-1})	0	57	113	170	227	Mean
		------------------------Mg ha^{-1}------------------------					
0	0	9.2	10.77	11.93	12.53	11.71	11.23
37	94	11.34	11.25	13.10	13.47	13.23	12.48
75	188	12.55	13.75	12.21	12.76	12.58	12.77
	Mean	11.03	11.92	12.41	12.92	12.51	

Sidedress N rate means within manure rates, $LSD_{0.05}$ - 1.837
Sidedress N rate means between manure rates, $LSD_{0.05}$ - 1.998
CV (%) - 19.1

Grain yield by preplant manure and sidedress N rate for the Wooster site is shown in Table 4.8. At this site, there may have been an interaction (P = 0.1995) between preplant manure and sidedress N treatments. Within the preplant manure estimate N rates of 0 and 63 kg N ha^{-1}, grain yield increased with sidedress N rates up to 170 kg ha^{-1} sidedress N. Within the 126 kg N ha^{-1} preplant manure estimate N rate, grain yield increased with sidedress N up to 227 kg ha^{-1}. There was no difference in grain yield between 0, 63, and 126 kg N ha^{-1} preplant manure estimate N rates when at least 113 kg ha^{-1} sidedress N was applied.

Table 4.8: Grain yield as influenced by preplant manure rate and sidedress N applications at the Wooster OARDC Research Station in 2008.

Preplant manure rate (kl ha^{-1})	Preplant manure estimate N rate (kg ha^{-1})	Sidedress N rate (kg ha^{-1}) 0	57	113	170	227	Mean
		-------------------------Mg ha^{-1}-------------------------					
0	0	5.24	6.99	8.11	8.42	8.7	7.49
37	63	6.13	7.37	8.43	8.94	8.8	7.93
75	126	6.47	8.03	8.59	8.5	8.84	8.09
	Mean	5.95	7.46	8.38	8.62	8.78	

Sidedress N rate means within manure rates, $LSD_{0.05}$ - 0.691
Sidedress N rate means between manure rates, $LSD_{0.05}$ - 0.803
CV (%) - 15.9

Grain yield for all treatments at the 2008 Wooster OARDC site was much less than both of the Western OARDC sites, ranging from 5.24 to 8.94 Mg ha^{-1} for all treatments. Varvel et al. (2007) noted that factors other than (or in addition to), the amount of available N determines fluctuations in maximum corn grain yields. One of the factors they noted included date of planting. The grain yield at the Wooster OARDC site was planted on May 21, 2008, which may be the cause of the overall reduced grain yields. The optimum planting date in northern Ohio is April 15-May 10 (Thomison, 2003). Delayed planting at the Wooster site in 2008, may explain the lack of difference in grain yield among the fertilizer N treatments and reduced grain yields. Planting after the optimum date can result in a grain yield reduction (Eckert and Martin, 1994; Lauer et al., 1999). Additionally, planting before or after the optimum date may cause a reduction in leaf area index (Swanson and Wilhelm, 1996), which may have also influenced the reflectance measurements collected from the crop canopy.

4.6 Algorithm evaluation

Existing sensor-based algorithms were evaluated by comparing empirical grain yield response to sidedress N fertilizer to optimum sidedress rates calculated using the algorithm models.

4.6.1 Agronomic optimum N rates

A quadratic model was fit to grain yield response to sidedress N fertilizer data for each site and preplant manure estimate N rate to estimate the agronomic optimum sidedress N rates. At the Western OARDC site in 2007, there was a quadratic relationship between grain yield and sidedress N rate at preplant manure estimate N rates of 0 and 117 kg N ha^{-1} (Figures 4.1 and 4.2). There was no effect of sidedressing additional N at the preplant manure estimate N rate of 233 kg ha^{-1} (data not shown).

0 kg N ha^{-1} preplant manure

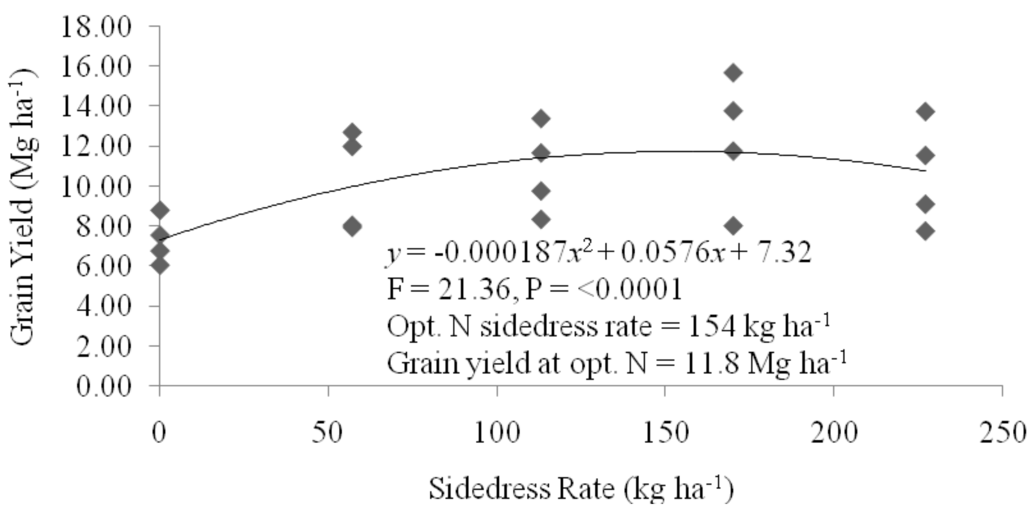

Figure 4.1: Grain yield for plots at the 2007 Western OARDC site that received no preplant manure applications as influenced by sidedress N applications.

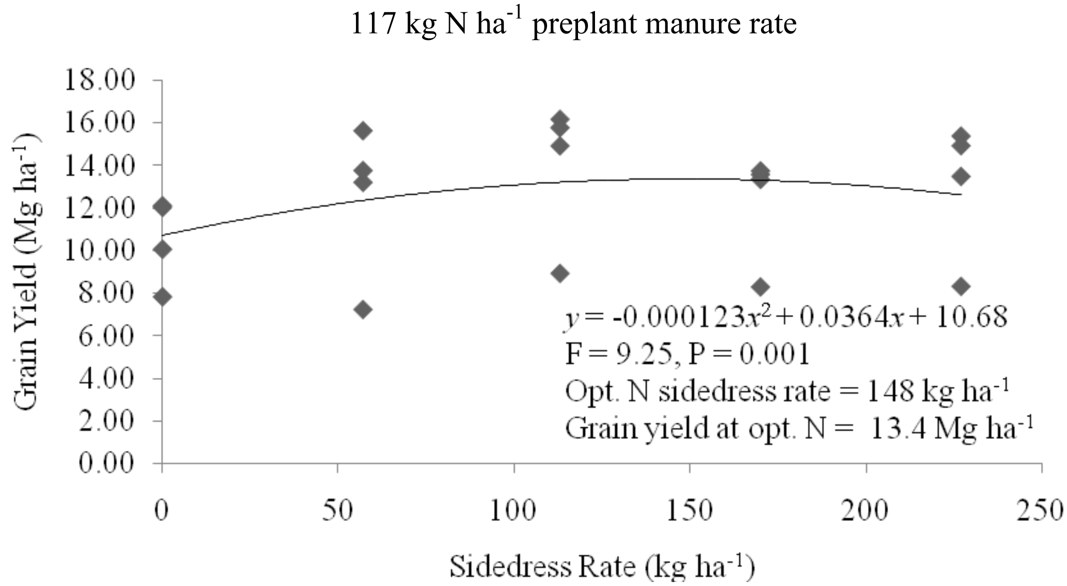

Figure 4.2: Grain yield for plots at the 2007 Western OARDC site that received 117 kg N ha^{-1} preplant manure application as influenced by sidedress N applications.

At the 2008 Western OARDC site, there was a quadratic relationship between grain yield and sidedress N rate when no preplant manure was applied (Figure 4.3). The quadratic model did not fit the other two preplant manure rates (data not shown); however, there was a linear correlation ($P < 0.05$) between grain yield and sidedress N rate at the 94 kg N ha^{-1} preplant manure estimate N rate (Figure 4.4).

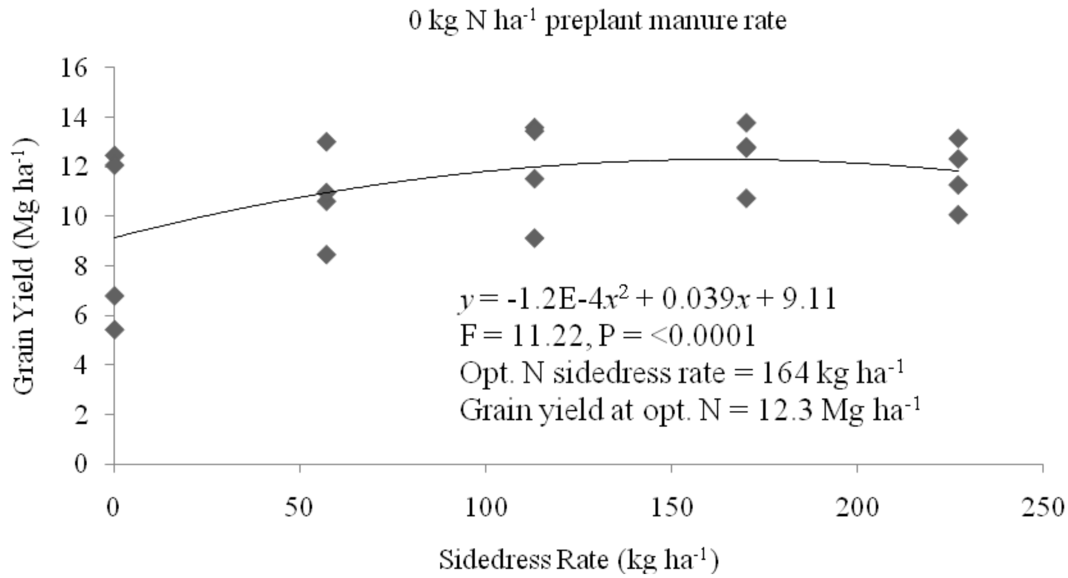

Figure 4.3: Grain yield for plots at the 2008 Western OARDC site that received no preplant manure application as influenced by sidedress N applications.

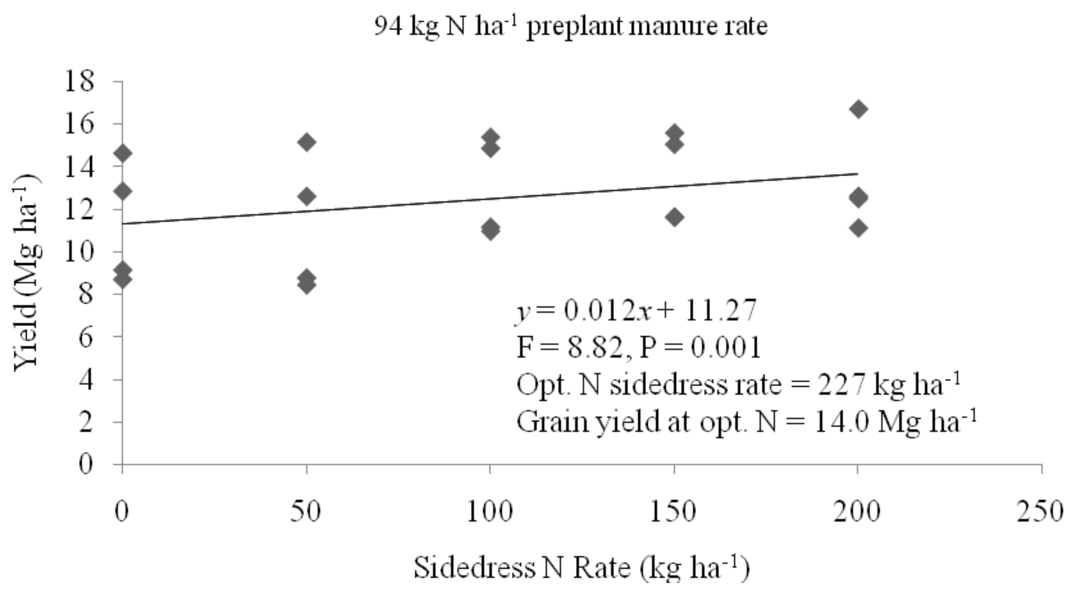

Figure 4.4: Grain yield for plots at the 2008 Western OARDC site that received 94 kg N ha^{-1} preplant manure application as influenced by sidedress N applications.

Grain yield response to sidedress N fertilizer for the 2008 Wooster OARDC site is shown in Figures 4.5, 4.6, and 4.7. Grain yield was highly responsive to sidedress N fertilizer at all three preplant manure rates. The response to sidedress N at all three preplant manure rates may be explained by loss of N in preplant manure applications, possibly due to denitrification.

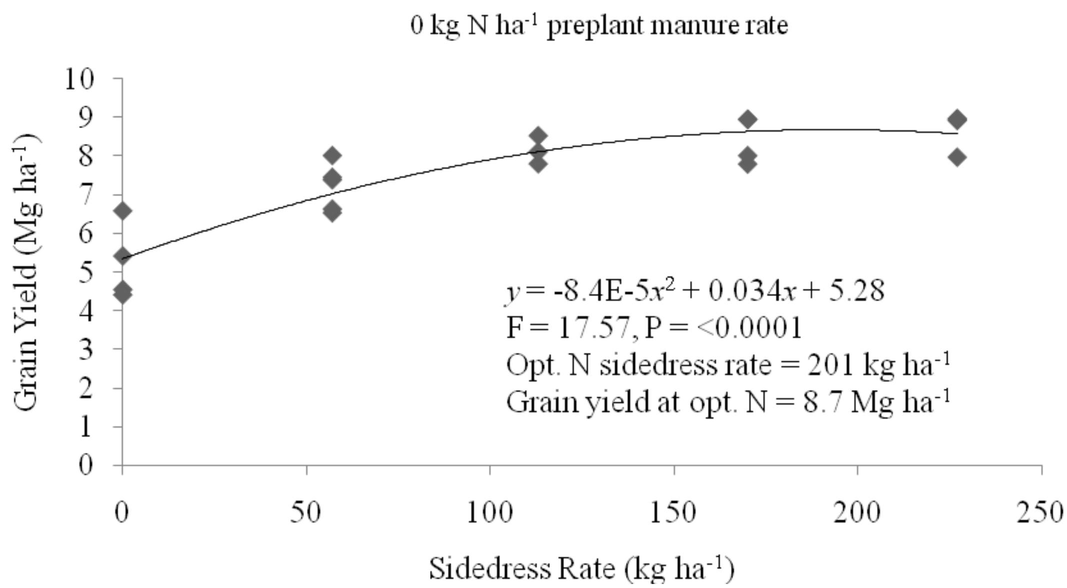

Figure 4.5: Grain yield for plots at the 2008 Wooster OARDC site that received no preplant manure application as influenced by sidedress N applications.

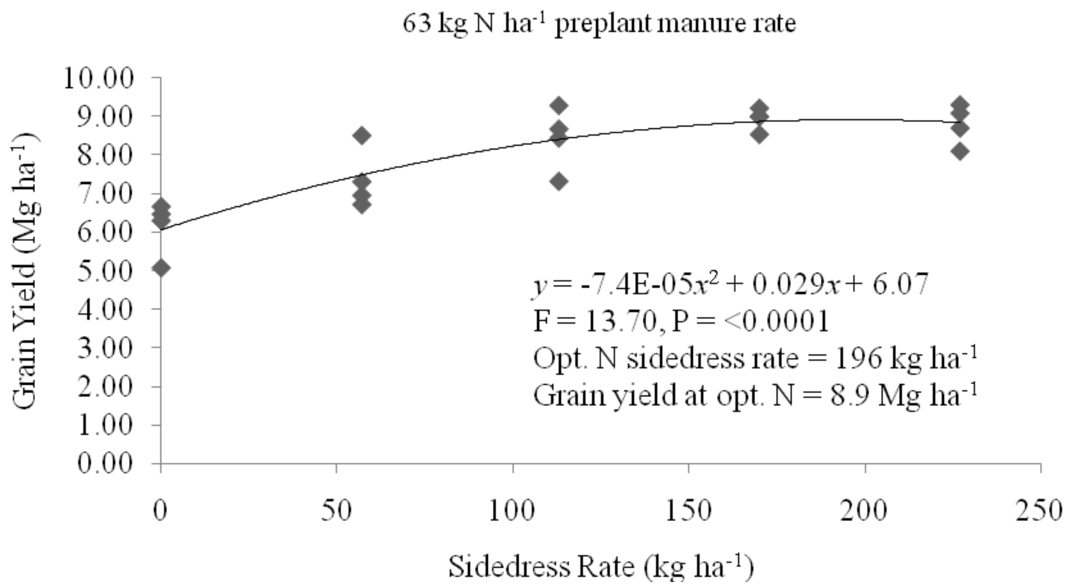

Figure 4.6: Grain yield for plots at the 2008 Wooster OARDC site that received 63 kg N ha^{-1} preplant manure application as influenced by sidedress N applications.

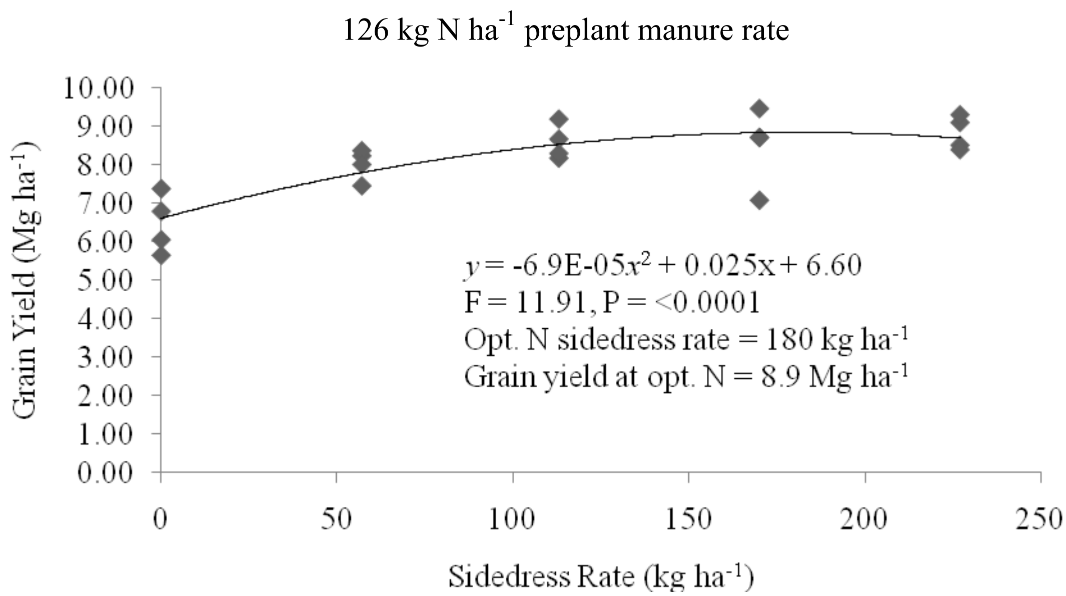

Figure 4.7: Grain yield for plots at the 2008 Wooster OARDC site that received 126 kg N ha^{-1} preplant manure application as influenced by sidedress N applications.

4.6.2 Algorithm sidedress N recommendations by site

Optimum sidedress N rates (sidedress N rates that produced highest grain yield) based on empirical data and the algorithm models are displayed in Table 4.9. When compared to the optimum sidedress N rates based on empirical data, the algorithms consistently underestimated sidedress N rates, regardless of which response index (RI) was used. Additionally, the economic optimum nitrogen rate (EONR) was also calculated, based on a corn grain price of \$157 Mg^{-1} and N cost of \$1.47 Mg^{-1}. Although the algorithm was not made to predict the EONR, the algorithm sidedress N rate calculations were close to the EONR at the 2008 Western OARDC site and 2008 Wooster OARDC site at the highest and lowest manure rates.

Table 4.9: The agronomic and economic optimum nitrogen sidedress rates based on empirical data and the optimum nitrogen sidedress rates based on the algorithm models.

			Optimum N sidedress rate (kg ha^{-1})			
	Preplant manure rate	Preplant manure estimate N rate	Empirical		Algorithm	
Site/year	(kl ha^{-1})	(kg ha^{-1})	Agronomic	Economic	RI_{Target}	RI_{Check}
Western 2007	0	0	154	131	44	21
	37	117	148	112	68	19
Western 2008	0	0	164	129	133	101
	37	94	227	133	102	127
Wooster 2008	0	0	201	147	144	102
	37	63	196	0	120	106
	75	126	180	59	59	113

At the 2008 Western OARDC site on plots where no preplant fertilizer was applied, the algorithm using RI_{Target} was the closest to predicting the optimum sidedress N rate, under-predicting the sidedress N rate by 31 kg ha^{-1}. This was the only site that the sensor was able to detect differences in reflectance due to preplant manure rate. However, the algorithm was unable to predict sidedress N recommendations at the same site when 94 kg N ha^{-1} preplant manure was applied.

4.6.3 Algorithm sidedress N recommendations by replication

The algorithm was also evaluated by separating mean NDVI by replication (Appendix A) because there was a replication effect at the Western and Wooster sites in 2008 ($P < 0.05$ for both sites). There was no replication effect at the Western OARDC site in 2007; therefore, algorithm sidedress N recommendations were not calculated by separating NDVI measurements by replication.

At the 2008 Western OARDC site, the algorithm under-predicted sidedress N rates for replications 3 and 4. The reference plot for replication 3 had a low NDVI calculation (0.5380), when compared to the other replications (0.7513, 0.6712, and 0.6224). The grain yield data did not fit the quadratic model for replication 4, giving a sidedress N rate of 250 kg ha^{-1}. For replication 1 and 2, the algorithm using RI_{Check} accurately predicted sidedress N rates within 3 kg ha^{-1}, based on empirical data. The check NDVI was less than reference NDVI for these two replications.

When separated by replication, the algorithm continued to under-predict sidedress N rates at the Wooster OARDC site in 2008, and there was no advantage at the site to separate the recommendations by replication.

4.7 Presidedress soil nitrate test evaluation

The presidedress soil nitrate test was evaluated using relative yield (RY), calculated by dividing individual control plot grain yields by the highest grain yield achieved among the sidedressed plots. Three models (linear-plateau, quadratic-plateau, and quadratic plus plateau) were fit to the RY and soil NO_3-N data. All three models fit the data significantly ($P < 0.05$). The soil NO_3-N value where the two functions joined was considered the PSNT critical value, which was 19 µg g^{-1} NO_3-N to achieve a RY of 95% for the linear- plateau model (Figure 4.8). The critical values were 13 (90% RY) and 22 (92% RY) µg g^{-1} NO_3-N for the quadratic-plateau and quadratic plus plateau models, respectively (Figures 4.9 and 4.10). There was one soil NO_3-N concentration that was much larger than the other measurements, which extended the plateau function of each model. When this potential outlier was removed, all three model types failed to fit the data (figures not shown). Other studies have found critical values that range from 21-30 µg g^{-1} NO_3-N (Magdoff et al., 1990; Binford et al., 1992; Meisinger et al., 1992; Bundy and Andraski, 1995; Heckman et al., 1996). From data collected in Ohio from 2004 to 2008, the critical value was found to be 30 µg g^{-1} (Mullen, 2009).

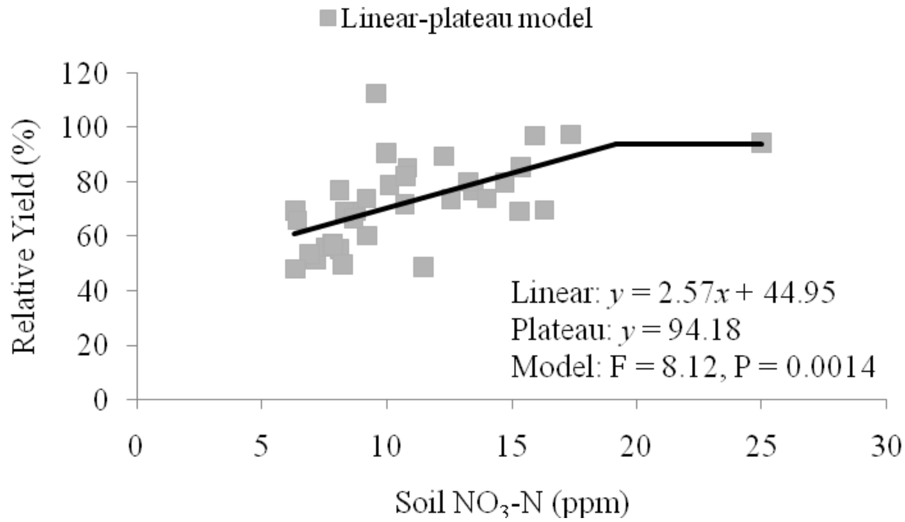

Figure 4.8: Relative yield as influenced by soil NO_3-N concentration for all three sites fit with a linear-plateau model.

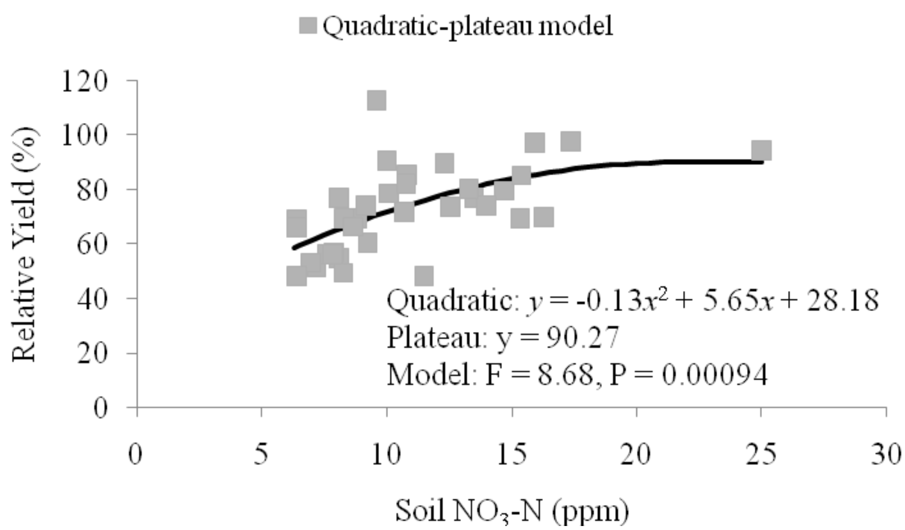

Figure 4.9: Relative yield as influenced by soil NO_3-N concentration for all three sites fit with a quadratic-plateau model.

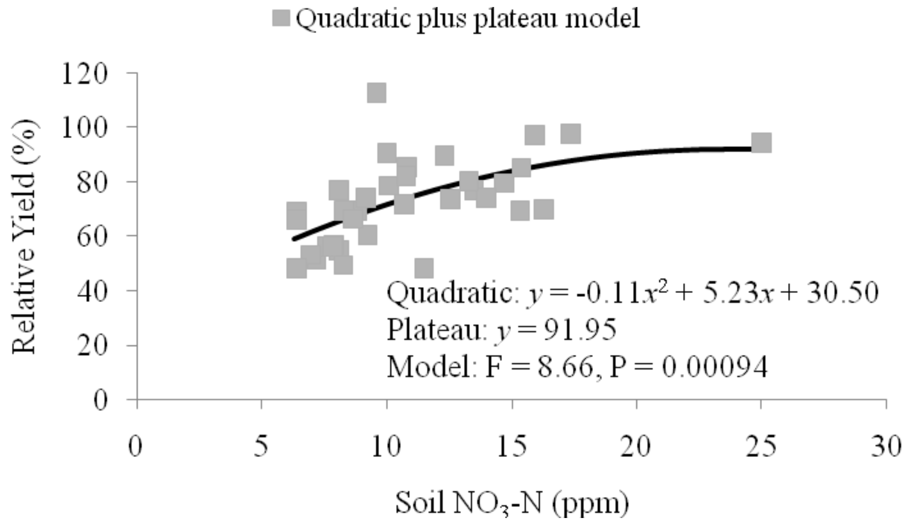

Figure 4.10: Relative yield as influenced by soil NO_3-N concentration for all three sites fit with a quadratic plus plateau model.

There was no relationship between optimum sidedress N rate and soil NO_3-N concentration; therefore, soil NO_3-N concentration may not be an appropriate indicator of optimum sidedress N rates. In Ohio, PSNT values are not used to make fertilizer recommendation rates (Mullen, 2009). This agrees with a study that concluded that a single calibration of sidedress N rate cannot exist for a field due to the non-linear relationship between yield response and soil test values (Kachanoski and Fairchild, 1996).

4.8 Ear-leaf nitrogen evaluation

There was a positive, linear correlation between grain yield and earleaf total N concentration during initial silking at both sites in 2008 (Figure 4.11). Sufficient N status for corn plants should be between 2.90 to 3.50% for eaf-leaf samples collected at initial silking (Vitosh et al., 1995). At ear-leaf N concentrations greater than 2.90%, the average RY achieved was 85%, athough RY at 2.90% N was as low as 68%.

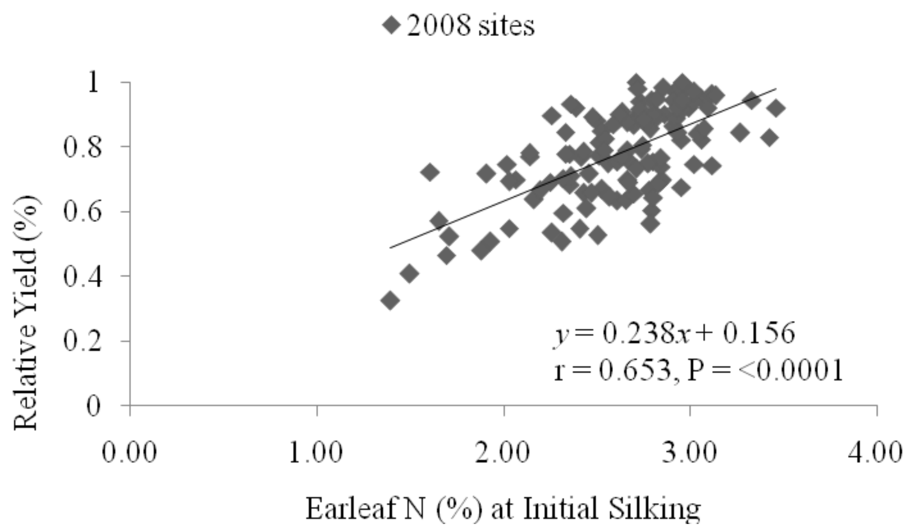

Figure 4.11: Relative yield as influenced by ear-leaf N concentration at initial silking for 2008 sites.

4.9 Relationship between NDVI, soil NO_3-N, and ear-leaf N concentrations

Soil NO_3-N concentrations and NDVI measurements collected at all three sites combined or separated by site (data not shown) were unrelated. This agreed with a study conducted in British Columbia, Canada, where leaf chlorophyll index at the V6 growth stage for silage corn was found to be a poor predictor of soil inorganic N supply (Zebarth et al., 2002). The correlation between NDVI and ear-leaf total N was also not significant (data not shown).

There was a linear correlation between ear-leaf N concentration and soil NO_3-N concentration at the 2008 Western OARDC site (Figure 4.12). There was no correlation between ear-leaf N concentration and soil NO_3-N concentration at the Wooster site in 2008 (data not shown). This indicates that there may have been a large amount of N loss between time of soil sampling and tissue sampling.

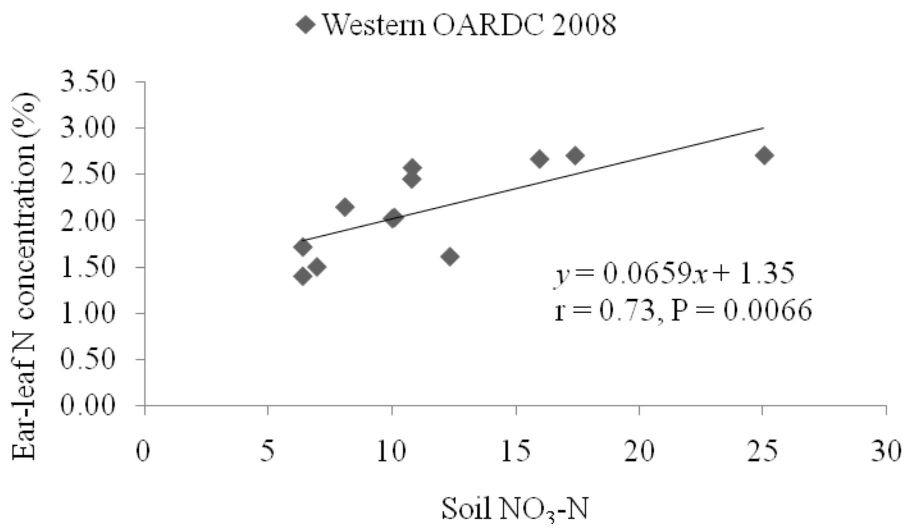

Figure 4.12: Ear-leaf N concentration at initial silking as influenced by soil NO_3-N concentration at the 2008 Western OARDC site.

<u>4.10 Weather conditions</u>

Weather conditions have a large effect on soil N, plant growth, and grain yield. In an incubation study, NO_3^- accumulation from the mineralization of dairy cow, poultry, and swine manure increased with temperature and could be predicted using GDD (Griffin and Honeycutt, 2000). Another incubation study conducted with soil collected from Michigan (sandy, mixed, mesic Typic Endoaquoll) found that the source of organic material had an effect on the amount of N mineralized, but concluded that mineralization increases with temperature from 10 to 25°C (Agehara and Warncke, 2005). A field study conducted in Ontario, Canada, found that the amount of N mineralized from manure linearly increased with air temperatures that ranged from 3.3 to 27°C throughout the growing season (Ma et al., 1999). Denitrification is also affected by weather conditions. Under waterlogged field conditions, NO_3^- is lost to the atmosphere as N_2 gas. Temperatures 25°C and above tend to speed up denitrification (Stevenson, 1982).

Temperature was close to the 26-year average at the Western and Wooster OARDC sites in 2007 and 2008 (Figures 4.13 and 4.14). The 26-year average precipitation compared to the 2007 and 2008 monthly precipitation accumulation at the Western OARDC site is shown in Figure 4.15. Precipitation at this site in 2007, was below average May through July. In 2008, precipitation was close to average every month except for June, where precipitation was approximately 20 cm above the average. At the Wooster OARDC site in 2008, precipitation was below average in April, May, August, and October and above average in March, June, and July (Figure 4.16).

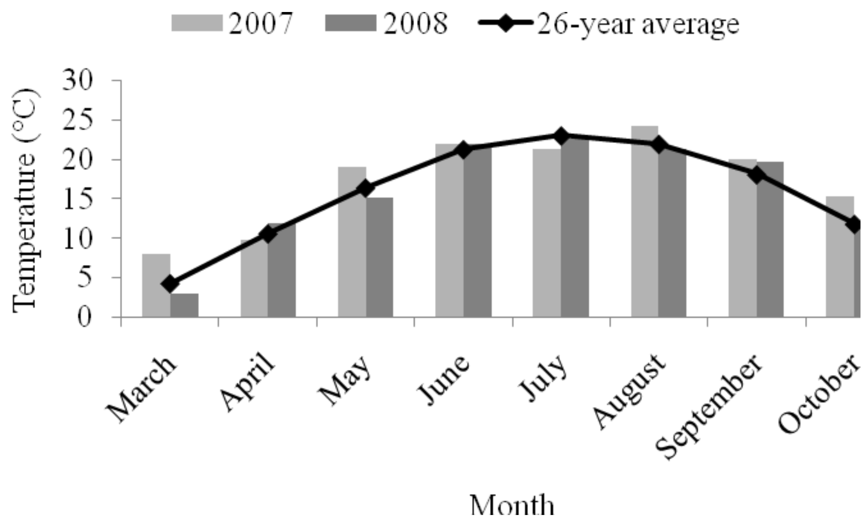

Figure 4.13: Monthly average air temperature in 2007 and 2008 compared to the 26-year average at the Western OARDC site. Data from Western OARDC weather station.

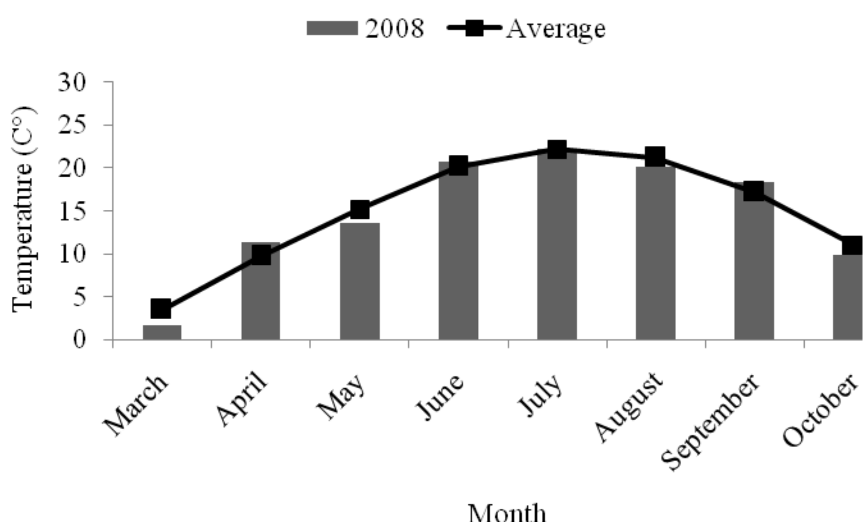

Figure 4.14: Monthly average air temperature in 2008 compared to the 26-year average at the Wooster OARDC site. Data from Wooster OARDC weather station.

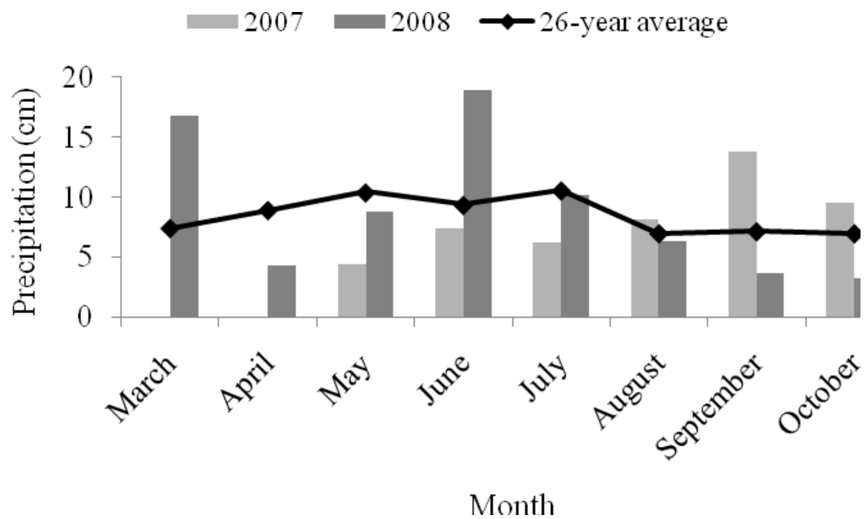

Figure 4.15: Monthly cummulative precipitation in 2007 and 2008 compared to the 26-year average at the Western OARDC. Data from Western OARDC weather station.

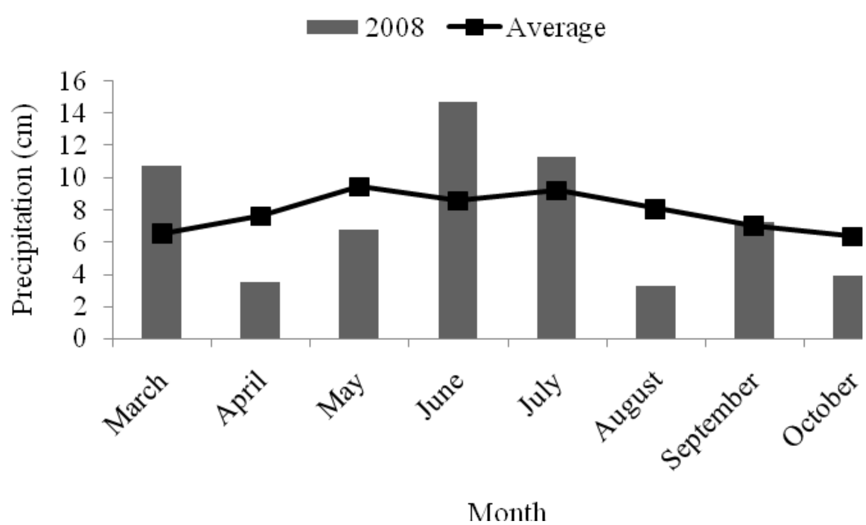

Figure 4.16: Monthly cummulative precipitation in 2008 compared to the 26-year average at the Wooster OARDC. Data from Wooster OARDC weather station.

CHAPTER 5

DISCUSSION

5.1 Evaluation of algorithm performance by site

The remote sensor-based algorithms were unsuccessful at predicting sidedress N rates when compared to optimum sidedress N rates determined by empirical grain yield data. For the algorithm to accurately predict optimum sidedress N rates, there needed to be differences in NDVI measurements among the control, target, and references plots, and N needed to be the main growth-limiting factor (Zillmann et al., 2006). At the 2007 Western and 2008 Wooster OARDC sites, there were no differences in NDVI among the preplant N treatments. There were differences in NDVI among preplant N treatments at the Western OARDC in 2008, which was also the site where the algorithm was the closest in predicting sidedress N rates.

5.1.1 2007 Western OARDC site

The algorithm under-predicted N sidedress rates for the preplant manure N estimate rates of 0 and 117 kg N ha^{-1}. There were no statistically significant differences in NDVI measurements among preplant manure N rates. However, there was a statistically significant difference in soil NO_3-N among the preplant N treatments. This indicates that there were differences in soil N among the preplant N rates, but the NDVI measurements collected from the plant canopy did not show these differences.

5.1.2. 2008 Western OARDC site

The 2008 Western OARDC site was the only site that the sensor was able to distinguish reflectance differences among the three preplant manure treatment rates. The algorithm using RI_{Target} under-predicted sidedress N rates where no preplant manure was applied by 31 kg ha^{-1} when compared to the optimum sidedress N rate using empirical data. High winds at this site caused severe lodging; therefore, the empirical data may not have been a good indicator of optimum sidedress N rate. The algorithm was designed to predict optimum sidedress N rates under ideal growing conditions, which did not occur at this site.

When 94 kg N ha^{-1} preplant manure estimate N was applied, there was a linear relationship between grain yield and sidedress N rate, indicating that at least 227 kg ha^{-1} sidedress N was needed to achieve maximum grain yield. At this preplant manure rate, the algorithm under-predicted sidedress N rates.

5.1.3 2008 Wooster OARDC site

The sensor did not detect any differences in NDVI measurements among the preplant treatment rates at the 2008 Wooster OARDC site. Soil samples collected two days prior to NDVI measurements also indicated that there was no significant difference in soil NO_3-N concentration among preplant treatment rates. Cool temperatures in May when the preplant manure was applied may have played a role in the lack of difference in

NDVI readings among preplant manure treatments. In no-till systems, the soil warms more slowly (Karlen et al., 1994). Mineralization of the organic-N in the preplant manure may have been slow as a result of the cooler temperatures (Ma et al., 1999; Griffin and Honeycutt, 2000).

In addition to slower mineralization rates, any mineralized N may have been lost through denitrification in June when precipitation was above average. No till fields have a higher number of denitrifying organisms 0 to 7.5 cm from the soil surface (Doran, 1980), which may have contributed to denitrification. Ear-leaf N concentration increased with July sidedress N applications. The plots that received no sidedress N applications were below the marginal concentration for ear-leaf N. Nitrogen loss through denitrification should be expressed through leaf tissue analysis (Schmidt et al., 2002). Grain yield was also highly responsive to sidedress N fertilizer, increasing among all preplant treatment rates.

5.2 Evaluation of presidedress soil nitrate test performance

The presidedress soil nitrate test critical value used in Ohio is 30 $\mu g\ g^{-1}$ soil NO_3-N (Mullen, 2008). At NO_3-N concentrations > 30 $\mu g\ g^{-1}$, it is unlikely that there will be a grain yield response to additional N fertilizer. At levels < 30 $\mu g\ g^{-1}$, it is difficult to predict whether or not there will be a grain yield response to additional N fertilizer. A wide range of relative yields can be attained at soil NO_3-N concentrations < 30 $\mu\ g^{-1}$.

In this study, all of the soil samples collected and analyzed contained < 30 $\mu g\ g^{-1}$ NO_3-N; therefore, grain yield response to additional N fertilizer was unpredictable. At the time of soil collection, soil NO_3-N levels may have been < 30 μg g^{-1} due to organic N from the manure not being mineralized or loss of N through denitrification.

At the 2007 and 2008 Western OARDC sites, the critical value of 30 μg g^{-1} correctly predicted that sidedress N was needed 67% of the time. The critical value indicated additional fertilizer was needed 33% of the time when grain yields indicated that it was not needed. At the Wooster OARDC site, soil NO_3-N levels were very low for all plots. The critical value of 30 μg g^{-1} was correct 100% in predicting grain yield response to additional N fertilizer. This site received heavy rainfall early and the growing season, and preplant N may have been lost through denitrification, which may explain why all plots were responsive to additional N fertilizer.

The presidedress soil nitrate test critical value for this study ranged from 13 to 22 μg g^{-1} soil NO_3-N, depending on which model was used. At PSNT levels between 9-13 μg g^{-1} soil NO_3-N concentration, there tended to be a lot of variability in relative yield. This indicated that even with lower PSNT values, high grain yields may still be achieved. Cool springs, when N mineralization is low (Ma et al., 1999; Griffin and Honeycutt, 2000; Agehara and Warncke, 2005), may be responsible for this variability. Instead of using the critical value as the “cut off” point where no additional fertilizer is required above the critical value, preplant manure application rate and form along with weather conditions need to also be taken into account.

5.3 Conclusions

The objectives of this study were to:

1.) Evaluate sensor-based algorithms in indentifying agronomic optimum sidedress N fertilizer rates.

The sensor-based algorithms greatly under-predicted sidedress N rates at the 2007 Western and 2008 Wooster OARDC sites. The sensor failed to detect differences in NDVI measurements among preplant treatment rates at these two locations. The algorithm under-predicted sidedress N rate at the 2008 Western OARDC site by 31 kg ha^{-1}. At this site, the sensor detected differences in NDVI among treatments.

The greatest amount of N is taken up by the plant between the V9-VT growth stages (Mengel, 1995). However, reflectance measurements are often collected earlier to allow time to sidedress N fertilizer. Reflectance measurements were between V6-V8 growth stages. At this time, however, the plants had only taken up approximately 7% of the total N (Mengel, 1995). This made distinguishing between N sufficient and deficient plants difficult this early in the growing season. Reflectance measurement collection needs to be researched further to improve the sensor's ability to distinguish between preplant treatment rates.

The cropping history may have also contributed to the inability of the sensor to detect NDVI differences among preplant manure rates. Soybean was the previous crop at the 2007 Western and 2008 Wooster OARDC sites. Sufficient N mineralization of the soybean residue early in the growing season may have masked any preplant manure treatment effects. Corn was the previous crop at the 2008 Western OARDC site. Less N mineralization due to a higher C:N ratio compared to soybean, may explain why the sensor was able to distinguish NDVI measurements recorded at this site early in the growing season.

Additionally, the sensor-based algorithms were calibrated to work under ideal growing conditions and are based on yield potential using response to N fertilizer. Ideal growing conditions were not achieved at the Western OARDC site in 2008 (wind damage) and the Wooster OARDC site in 2008, where rain may have contributed to N loss. Researchers have observed that yield potential may not be a good predictor of N needs (Varvel et al., 2007; Scharf et al., 2006), but the greatest source of variability in N requirements was observed with the annual effects of weather (Kahabka et al., 2004).

Although the sensor-based algorithm models were developed over several years and locations, they need to be evaluated over individual sites and years. New algorithms more specific to the growing conditions in Ohio may improve sensor-based sidedress N recommendations.

2.) Evaulate PSNT for making sidedress N recommendations.

Presidedress soil nitrate test critical values ranged from 13 to 22 $\mu g\ g^{-1}$, depending on model type. These values were lower than the 30 $\mu g\ g^{-1}$ critical value established for Ohio in previous studies. The presidedress soil nitrate test needs to be continually evaluated in Ohio over various soils, locations, and weather patterns.

3.) Determine the relationship between NDVI, ear leaf total N, and PSNT.

There was no relationship between NDVI and PSNT. This may indicate that there is a point in the growing season where PSNT is a more valuable tool than NDVI and vice versa. It also indicates that PSNT and NDVI may not be able to be used in conjunction because they are useful tools at different times in the growing season. Additionally, there was no significant relationship between NDVI and ear-leaf N concentrations.

At the 2008 Western OARDC site, ear-leaf N concentration increased linearly with soil NO_3-N conentration. There was no significant relationship between earleaf N and soil NO_3-N at the Wooster site in 2008.

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APPENDIX A

ALGORITHM INPUTS

Table A.1: NDVI measurements for each site, separated by replication and algorithm input.

		NDVI				
				Target		
Site	Rep	Check	Reference	#1	#2	#3
Western 2007	1	0.5711	0.5352	0.5711	0.5704	---
	2	0.5395	0.5254	0.5395	0.5188	---
	3	0.5852	0.6436	0.5852	0.4661	---
	4	0.6232	0.5695	0.6232	0.6181	---
Western 2008	1	0.6343	0.7513	0.6343	0.7395	---
	2	0.5434	0.6712	0.5434	0.6967	---
	3	0.4075	0.5380	0.4075	0.4774	---
	4	0.4400	0.6224	0.4400	0.5007	---
Wooster 2008	1	0.6436	0.6730	0.6436	0.5960	0.6730
	2	0.6389	0.7244	0.6389	0.7489	0.7244
	3	0.7431	0.7901	0.7431	0.6988	0.7901
	4	0.7406	0.7663	0.7406	0.7892	0.7663

Table A.2: Optimum N rate based on empirical data and optimum N rates based on algorithms, separated by site and replication.

			Optimum sidedress N rate		
				Algorithm	
	Preplant N rate		Empirical	RI_{Target}	RI_{Check}
Site/year	(kg ha^{-1})	Rep	-------------------kg ha^{-1}--------------------		
Western 2007	0	1	126	41	19
		2	179	38	18
		3	149	112	79
		4	164	46	21
	117	1	158	41	19
		2	188	42	18
		3	137	155	79
		4	158	46	21
Western 2008	0	1	144	187	143
		2	101	136	104
		3	173	79	59
		4	250	114	88
Wooster 2008	0	1	182	94	61
		2	212	173	129
		3	222	145	128
		4	207	124	82
	63	1	189	137	55
		2	198	61	141
		3	327	171	117
		4	157	66	91
	126	1	168	52	66
		2	232	58	156
		3	195	66	115
		4	144	63	87

APPENDIX B

ANOVA TABLES

Table B.1: Intial stand count ANOVA table for all three sites.

Site/year	Source	df	MSE	F-value	P-value
Western 2007	Manure	2	9,088,763	0.63	0.5633
	Rep	3	5,657,486	0.39	0.7623
	Manure*rep (error A)	6	14,367,296	---	---
	Sidedress	4	2,660,488	0.34	0.8511
	Manure*sidedress	8	16,059,622	1.15	0.3563
	Manure*sidedress*rep (error B)	36	7,716,118	---	---
Western 2008	Manure	2	81,813,274	1.11	0.3902
	Rep	3	34,265,470	0.46	0.7185
	Manure*rep (error)	6	74,012,119	---	---
Wooster 2008	Manure	2	127,208,734	1.78	0.2469
	Rep	3	52,827,100	0.74	0.5658
	Manure*rep (error)	6	71,388,882	---	---

Table B.2: Final stand count ANOVA table for all three sites.

Site	Source	df	MSE	F-value	P-value
Western 2007	Manure	2	200,556,774	11.03	0.0236
	Rep	2	198,494	0.01	0.9892
	Manure*rep (error A)	4	18,179,052	---	---
	Sidedress	4	7,338,811	0.38	0.8206
	Manure*sidedress	8	19,742,593	1.02	0.4463
	Manure*sidedress*rep (error B)	24	19,308,973	---	---
Western 2008	Manure	2	382,241,939	1.67	0.2646
	Rep	3	205,890,358	0.90	0.4936
	Manure*rep (error A)	6	228,496,693	---	---
	Sidedress	4	231,173,153	1.36	0.2655
	Manure*sidedress	8	146,425,874	0.86	0.5548
	Manure*sidedress*rep (error B)	36	169,425,955	---	---
Wooster 2008	Manure	2	192,780,246	2.19	0.1927
	Rep	3	164,231,419	1.87	0.2357
	Manure*rep (error A)	6	87,865,827	---	---
	Sidedress	4	69,203,165	1.48	0.2284
	Manure*sidedress	8	69,203,165	1.48	0.1986
	Manure*sidedress*rep (error B)	36	46,740,719	---	---

Table B.3: NDVI ANOVA table for all three sites.

Site/year	Source	df	MSE	F-value	P-value
Western 2007	Manure	2	0.00694	0.51	0.6258
	Rep	3	0.0145	1.06	0.4331
	Manure*rep (error)	6	0.0137	---	---
Western 2008	Manure	2	0.0985	32.21	0.0006
	Rep	3	0.163	53.41	0.0001
	Manure*rep (error)	6	0.00306	---	---
Wooster 2008	Manure	2	0.0113	1.29	0.3416
	Rep	3	0.0474	5.41	0.0384
	Manure*rep (error)	6	0.00876	---	---

Table B.4: SR ANOVA table for all three sites.

Site/year	Source	df	MSE	F-value	P-value
Western 2007	Manure	2	0.00548	0.54	0.6067
	Rep	3	0.112	1.11	0.4165
	Manure*rep (error)	6	0.0101	---	---
Western 2008	Manure	2	0.0644	30.09	0.0007
	Rep	3	0.106	49.56	0.0001
	Manure*rep (error)	6	0.00214	---	---
Wooster 2008	Manure	2	0.00873	1.74	0.2529
	Rep	3	0.0198	3.96	0.0715
	Manure*rep (error)	6	0.000460	---	---

Table B.5: Soil NO_3-N ANOVA table for all three sites.

Site/year	Source	df	MSE	F-value	P-value
Western 2007	Manure	2	52.416	33.29	0.0006
	Rep	3	3.776	2.40	0.1667
	Manure*rep (error)	6	1.575	---	---
Western 2008	Manure	2	57.424	3.74	0.0882
	Rep	3	40.17	2.62	0.1459
	Manure*rep (error)	6	15.353	---	---
Wooster 2008	Manure	2	0.471	0.12	0.8853
	Rep	3	17.856	4.72	0.0509
	Manure*rep (error)	6	3.787	---	---

Table B.6: Earleaf %N ANOVA table for Western and Wooster OARDC sites in 2008.

Site/year	Source	df	MSE	F-value	P-value
Western 2008	Manure	2	1.604	79.19	<0.0001
	Rep	3	0.240	7.91	0.0166
	Manure*rep (error A)	6	0.0101	---	---
	Sidedress	4	0.868	13.65	<0.0001
	Manure*sidedress	8	0.135	2.13	0.0584
	Manure*sidedress*rep (error B)	36	0.0636	---	---
Wooster 2008	Manure	2	0.0180	2.16	0.1967
	Rep	3	0.0160	1.91	0.2286
	Manure*rep (error A)	6	0.0084	---	---
	Sidedress	4	1.804	58.03	<0.0001
	Manure*sidedress	8	0.0815	2.62	0.0227
	Manure*sidedress*rep (error B)	36	0.0311	---	---

Table B.7: Grain yield ANOVA table for all three sites.

Site	Source	df	MSE	F-value	P-value
Western 2007	Manure	2	24.09	1.48	0.3
	Rep	3	52.75	3.24	0.1024
	Manure*rep (error A)	6	16.26	---	---
	Sidedress	4	14.9	15.75	<0.0001
	Manure*sidedress	8	3.06	3.23	0.0071
	Manure*sidedress*rep (error B)	36	0.95	---	---
Western 2008	Manure	2	13.4	6.07	0.0362
	Rep	3	55.5	25.09	0.0009
	Manure*rep (error A)	6	2.21	---	---
	Sidedress	4	6.29	3.83	0.0108
	Manure*sidedress	8	3.28	2.00	0.0753
	Manure*sidedress*rep (error B)	36	1.64	---	---
Wooster 2008	Manure	2	1.92	4.29	0.0697
	Rep	3	2.64	5.89	0.0321
	Manure*rep (error A)	6	0.448	---	---
	Sidedress	4	16.5	71.3	<0.0001
	Manure*sidedress	8	0.343	1.48	0.1995
	Manure*sidedress*rep (error B)	36	0.232	---	---