CHANGES IN RESPONSE INDICES AS A FUNCTION OF TIME IN WINTER WHEAT (*Triticum aestivum* L.) AND USE OF OPTICAL SENSORS FOR DETECTING YIELD DIFFERENCES AT DIFFERENT RESOLUTIONS IN CORN (*Zea mays* L.)

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CHANGES IN RESPONSE INDICES AS A FUNCTION OF TIME IN WINTER WHEAT

ABSTRACT

Nitrogen (N) responsiveness of crops can change with time since it is strongly influenced by in-season environmental conditions. This study was conducted to determine the relationship of N responsiveness using a response index (RI) as a function of time at 5 locations over a 3-year period. For this work, RI was plotted against days where growing degree days (GDD) were more than zero to determine the ideal stage for predicting N responsiveness. Sensor normalized difference vegetative index (NDVI) readings from a non-N limiting strip (N Rich Strip) divided by the farmer practice provides an estimate of the N responsiveness or RI_{NDVI} and that can be used to determine crop needs for mid-season N. Subplots (2.0 x 2.0 m) were established within five existing long-term trials employing a randomized complete block design at Efaw, Stillwater, Lake Carl Blackwell, Perkins and Lahoma, Oklahoma. From each plot, Greenseeker™ NDVI sensor readings were collected at various stages of growth where RI_{NDVI} was subsequently determined. At all sites, RI_{NDVI} increased with advancing stage of growth. Excluding Perkins 2005 and Stillwater 2006, the relationship between RI_{NDVI} and days where GDD>0 was positive and highly correlated. Severe moisture stress was encountered throughout the season at Perkins 2005 and Stillwater 2006. When the number of days from planting to sensing where GDD>0 (GDD=(Tmin+Tmax)/2–4.4°C) was less than 60, it is unlikely that a reliable estimate of RI_{NDVI} could be obtained since values were all small (close to 1.0), consistent with limited growth at the early stages of

growth. Averaged over years and sites for all growth stages, the correlation of RI_{NDVI} and $RI_{Harvest}$ was positive and increased taking place up to the Feekes 7 growth stage, declining at later stages. Our results suggest that once RI_{NDVI} is collected it should be adjusted using the equation $RI_{NDVI\ adj}=RI_{NDVI} \times \{1.87/(\text{Days where GDD}>0 \times 0.00997)+0.5876\}$.

INTRODUCTION

Farmers aim to achieve maximum crop yields with modest amounts of agricultural inputs, which lead to increased profits. Intensive fertilization has been one of the practices employed by farmers to meet the increasing demand for food crops. However, this approach has deteriorated the environment and has increased human health risk (Huggins and Pan, 1993; Raun et al., 2002). Furthermore, increasing prices of N fertilizer, combined with liberal applications of nitrogen (N) fertilizer, has resulted in reduced economic return (Huggins and Pan, 1993). Improved N management can increase grain production and reduce environmental risk (Lukina et al., 2001; Flower et al., 2004).

Nitrogen use efficiency (NUE) of winter wheat was improved by more than 15% when N rate recommendations were based on mid-season predictions of yield potential (YP0) and a response index (RI) compared to conventional N rate recommendations (Raun et al., 2002). This indicated that applied fertilizer N loss in the soil-plant system can be minimized using a sensor based N approach. Supplying fertilizer N when crop response is expected can improve grain production and reduce the risk of applying too much N. This has become more important today since N is the main nutrient needed for growth and development of plant tissues and yield (Chung et al., 1999; Thomason et al., 2002).

Worldwide fertilizer N consumption was 85,529,551 Mg in 1999 (FAO, 2001) and 60% of this consumed fertilizer N was used for cereal production (FAO, 1995). Nitrogen use efficiency for cereal crop production has remained low, near 33% (Raun and Johnson, 1999). An increase in cereal NUE of 1% was estimated to be worth $234,658,462 in 1999 for the world (Raun and Johnson, 1999) and that would be significantly higher today. A large amount of N fertilizer that is applied can remain in the soil after harvest and can be hazardous (Chen et al., 2004; Embelton et al., 1986). The presence of excess N fertilizer in the soil-plant system, which is the primary source of NO_3-N accumulation in the soil (Vyn et al., 1999), which can lead to high NO_3-N concentrations in perched groundwater (Spruill et al., 1996). Often NO_3-N concentration in surface waters exceeds 10 mg L^{-1}, which is the USEPA's maximum contaminant level (MCL) for drinking water (Jaynes et al., 1999; Mitchell et al., 2000). Thus, it is important to develop techniques that will improve N management to increase efficiency (Washmon et al., 2002). Current N fertilization recommendations in Oklahoma winter wheat (*Triticum aestivum L.*) production are estimated by potential yield and fixed removal rates (Lukina et al., 2001). Washmon et al. (2002) showed that knowledge of the amount of variability within a field, estimated from the coefficient of variation from NDVI readings, could be equated to the fertilizer response index. As it is understood today, RI_{NDVI} has the ability to estimate crop N response in season. Therefore, accurate prediction of RI_{NDVI} would help optimize in-season fertilizer N rates and increase both NUE and yield.

LITERATURE REVIEW

Agricultural food production on irrigated cropland essentially doubled during the 35 year period from 1963 to 1998 due to increased nitrogen fertilization (Tilman, 1999). Nitrogen is the most limiting nutrient in cereal production and it can be applied at accurate rates based on plant needs when potential yield is predicted in-season (Raun et. al., 2002; Lukina et al., 2001). Due to varying weather conditions, N needed for optimal growth is difficult to determine, and as such may require repeated N fertilization to reach the potential yield (Chen et al., 2004). Farmers avoid multiple N applications during the growing season for convenience (Raun and Johnson, 1999). Instead, they apply large amounts of N at one time to assure that potential yield is attainable (Schepers et al., 1991). Many farmers in the developed world apply too much N,which results in loss of N by leaching (Raun and Johnson, 1999). On the other hand, farmers in the developing world cannot afford multiple N applications to recover reduced yield (Hubbell, 1995; Raun and Johnson, 1999), thus they only produce enough yield to sustain their families (Campbell et al., 1995). Although the needed outcomes are somewhat different, improved N management in the developed and developing world is needed.

Higher NUE can increase grain yield to meet the demands of a dramatically growing world population (Raun and Johnson, 1999). Raun and Johnson (1999) suggest that NUE can be increased by applying N fertilizer at prescribed rates consistent with in-field variability of a particular crop measured by sensor-based systems and low N rates applied at flowering. Fertilizer use efficiency of winter wheat depends on time and rate of application (Ellen et al., 1980). Johnson and Raun (2003) showed that NUE of winter wheat was 49% at 22.4 kg N $ha^{-1}yr^{-1}$ and 34% at a rate of 112 kg N $ha^{-1}yr^{-1}$ over 30 years in non-irrigated winter wheat. In-season applied fertilizer N increased NUE in 4 out of 5 years over preplant applications in winter wheat (Olson and Swallow, 1984; Sowers et al., 1994). Wuest and Cassman (1992a, 1992b) showed that late-season applied N increased grain yield and NUE in spring wheat. However, the disadvantage of applying N several times during the growing season is increased application costs (Mullen et al., 2003).

There are many pathways by which N is lost in the soil. Most of the plant N losses in cereal production range from 20 and 50% (Raun and Johnson, 1999). Losses of N from the plant as NH_3 in winter wheat are reported to be 21% (Harper et al., 1987) to 41% (Daigger et al., 1976). Moreover, significant loss of N through denitrification (Burford and Bremner, 1975; Olson et al., 1979; Burkart and James, 1999; Aulakh et al., 1982), runoff (Gascho et al., 1998; Burkart and James, 1999; Blevins et al., 1996; Chichester and Richardson, 1992), leaching (Goss and Goorahoo, 1995; Paramasivam and Alva, 1997; Drury et al., 1996) and volatilization (Fowler and Brydon, 1989; Hargrove et al., 1977) have been well documented. Aulakh et al. (1982) noted that N losses from denitrification were 9.5% in winter wheat and were doubled if straw was incorporated and/or applied on the surface of no-till plots, while loss of fertilizer N via surface runoff was reported from 1 to 13% (Blevins et al., 1996; Chichester and Richardson, 1992).

Drury et al. (1996) found that 23% of the total N applied could be lost via leaching in areas with cooler temperate climates. In soils with higher temperatures, soil pH, and surface residue, NH_3 volatilization was estimated at 40% (Fowler and Brydon, 1989; Hargrove et al., 1977). However, determining an N requirement using data on past N loss in the soil-plant system is not a good approach because more often than not, N loss is over estimated (Francis et al., 1993; Kanampiu et al., 1997) and N losses from the various pathways discussed are highly dependent upon the temporal conditions present.

Stanhill et al. (1972) explained that the amount of biomass on the soil surface can account for differences of visible and infrared reflectance in wheat. Remote sensing is inexpensive, it can be used to estimate N status of larger areas, and can be used to monitor N status in the field (Filella et al., 1995). It is important to note that there is an effect of soil background on reflectance if plant coverage densities are less than 50% (Heilman and Kress, 1987). Work by Huete et al. (1985) showed that soil background affects canopy reflectance, especially at low vegetation densities. However, Lukina et al. (2000) found that soil irradiance was not an important factor when plant coverage densities were more than 40%. Thus, the spectral radiance of wheat changes with plant biomass, percent vegetation coverage, and posture and structure of the plants (Lukina et al., 2000).

Normalized difference vegetative index (NDVI) (Rouse et al., 1973), is a widely used spectral vegetation index and has been utilized to determine crop yield potentials using simple regression equations (Raun et al., 2001; Teal et al., 2006). The equation established between in-season estimated yield (INSEY) and actual yield was used to compute predicted the yield potential from early season NDVI readings. The sensor based system that was initially developed at Oklahoma State University, measured spectral reflectance using an integrated sensor with photodiode-based sensors and interference filters. Spectral reflectance measurements were originally determined passively using upward and downward looking photodiode sensors that collect readings in red and near infrared bandwidths (Stone et al., 1996). Upward looking photodiode sensors measured solar incident radiation (incoming light from the sun) and the downward looking photodiode sensor measured plant and/or soil surface reflected radiation (light reflected by plants and/or the soil surface). The ratio of the solar incident radiation, and plant and/or soil surface reflected radiation was then used to calculate NDVI. The GreenSeeker® active hand held optical sensor measures crop reflectance and calculates the NDVI in both the red (650 ± 10nm) and NIR (770 ± 15nm) bandwidths in an area of 60 cm X 10 cm when the sensor is held approximately a distance of 60 cm to 100 cm above the crop canopy.

Nitrogen requirements of winter wheat have been estimated by early season estimates of N uptake and potential yield (Lukina et al., 2001; Raun et al., 2002). Plant N uptake can be determined using the self-illuminated reflectance (GreenSeeker™) sensor and that is related to NDVI measured at Feekes physiological growth stages 4 (leaf sheaths lengthen) to 6 (first node of stem visible) (Lukina et al., 2001; Large,1954; Stone et al., 1996; Solie et al., 1999). The NDVI was calculated using the following equation:

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \quad (1)$$

Where: ρ_{NIR} – Fraction of emitted NIR radiation returned from the sensed area (reflectance)

ρ_{RED} – Fraction of emitted red radiation returned from the sensed area (reflectance)

As a further refinement, the index in-season estimated yield (INSEY) was developed to predict potential grain yield using NDVI measurements (between Feekes 4 and 6) and subsequently divided by the number of days from planting to sensing (where growing degree days, GDD>0, GDD={(Tmax+Tmin)/2}-4.4 ºC). Topdress fertilizer N rates were estimated by determining the difference between the amount of grain N uptake and early season plant N uptake (Lukina et al., 2001), and then dividing by and expected efficiency factor.

The RI as proposed by several authors has predicted actual crop response to applied N thus improving NUE in cereal production within a given year (Johnson and Raun, 2003; Johnson et al., 2000; Raun et al., 2002; Mullen et al., 2003). The RI estimated in-season (RI_{NDVI}) was used to predict the RI at harvest ($RI_{Harvest}$) at Feekes physiological growth stages 5, 9, and 10.5 by Mullen et al. (2003). The $RI_{Harvest}$ is calculated using the following equation:

$$RI_{Harvest} = \frac{\text{Highest Mean Yield N Treatment}}{\text{Mean Yield of the Check Treatment}} \quad (2)$$

Crop N response can be estimated by RI_{NDVI} using the equation:

$$RI_{NDVI} = \frac{\text{Highest Mean NDVI N Treatment}}{\text{Mean NDVI Check Treatment}} \quad (3)$$

In-season estimated yield (INSEY) and RI_{NDVI} combined were used to estimate fertilizer rates to optimize in season fertilizer application (Mullen et al., 2003). The objectives of this study were to determine the relationship of N responsiveness, RI_{NDVI} and $RI_{Harvest}$ and to determine how RI_{NDVI} changes as a function of time over several sites and years in winter wheat.

MATERIALS AND METHODS

Five locations in Oklahoma were used in a 3 year study to evaluate changes in RI_{NDVI} over time. At each site, main plots ranged in size from 3.1 x 9.1 m to 6.1 x 15.2 m. Subplots (2.0 x 2.0 m) were then established within the main plots at five existing long-term experiments, each of which employed a randomized complete block experimental design. Soil description, year of establishment and fertilizer rates sampled are reported in Tables 1 and 2. While these long-term trials have diverse treatment structures with multiple nutrients, only those treatments that received pre-plant N applications were selected for evaluation (pre-plant N rates and established applications are reported by location in Table 2). Unless indicated, constant phosphorus (P) and potassium (K) rates were applied for all N treatments evaluated, and were also included in the 0-N checks. Hard red winter wheat varieties were planted in the fall at all study sites (varieties, seeding rates, and planting dates are reported in Table 3). Composite soil samples were taken from the entire site, 0-30 cm deep, air-dried, processed and analyzed for pH, NH_4-N, NO_3-N, phosphorus and potassium, and reported in Table 4.

Normalized difference vegetation index measurements, that are known to provide accurate estimates of plant biomass, were collected using a GreenSeeker™ Hand Held Optical Sensor (NTech Industries, Inc.) from the entire 2.0 x 2.0 m subplot area at each site. The GreenSeeker sensor uses self-contained illumination in the red (650±10 nm full width half magnitude (FWHM)) and NIR (770±15 nm FWHM) bands to determine the reflectance of emitted light from the crop canopy of the sensed area. The GreenSeeker sensor views a 0.6 x 0.01 m area when held at a distance of approximately 0.6 to 1.0 m from the illuminated surface and samples approximately 1000 measurements per second at a rate of 10 averaged output measurements per second. Each plot was sensed in 3 strips in order to obtain an average NDVI from the entire plot at various stages of growth for potential yield and response to N. The average NDVI from the N treated and average NDVI from the check (0 N rate) were used to compute RI_{NDVI} as defined in equation 3.

A Massey Ferguson 8XP combine was used for harvesting wheat grain from the entire plot at all sites. Grain weights and percent moisture were recorded using a Harvest Master yield-monitoring computer and sub-samples were taken for total N analysis. Sub-samples were dried in a forced air oven at 66 ˚C, ground to pass a 140 mesh sieve (0.10 mm), and analyzed for total N content using a Carlo-Erba NA 1500 dry combustion analyzer (Schepers et al., 1989). Data were analyzed using descriptive statistics and analysis of variance procedures within SAS V.9.0 (SAS Institute, 2002). The general linear model procedure was used for analysis of variance of RI at each sensing for the five study sites, and simple correlation was used to evaluate the relationships between $RI_{Harvest}$, RI_{NDVI} and days from planting to sensing where GDD>0. A linear plateau model of RI_{NDVI} on days where GDD>0 was developed using the NLIN SAS procedure.

RESULTS AND DISCUSSION

The relationship between RI_{NDVI} versus days where GDD>0 for Lake Carl Blackwell, Perkins, and Stillwater (all years included for each site) are illustrated in Figures 1, 2, and 3, respectively. In general, similar increases in RI_{NDVI} with advancing stage of growth were observed at all locations. The exceptions were noted at Stillwater in 2006, and Perkins in 2005 where severe moisture stress was encountered throughout the season thus, limiting any kind of observable response to applied N (Figures 2 and 3, respectively).

For Lake Carl Blackwell, the increase in RI_{NDVI} as a function of days where GDD>0 was very similar for 2004 and 2006 (Figure 1). No data for 2005 was collected at this site. Similarly, this relationship was consistent for 2004 and 2006 at Perkins (Figure 2). However, as noted earlier, at Stillwater, this relationship was significantly different for 2006 when compared to 2004 and 2005. This was likely due to limited rainfall received over the winter months restricted both growth and the potential for N response. However, it should be noted that excluding this year and location, the linear increase in RI_{NDVI} was somewhat consistent over locations.

In 2006, severe moisture stress was encountered throughout the growing season. In fact, no moisture was received for 120 days, and as a result, response to fertilizer N was not affected due to the complete lack of responsiveness when compared to the other sites. The relationship between RI_{NDVI} and days where GDD>0 determined between Feekes growth stages 3 (tillers formed, leaves often twisted spirally) and 8 (last leaf visible, but still rolled up, ear beginning to swell) (Large, 1954) combined over sites and years is illustrated in Figure 4. Data for Stillwater in 2006 was not included for the over site equation generated between days where GDD>0 and $RI_{NDVI.}$ Similarly, limited response was noted at Perkins in 2005, largely because this is an extremely sandy soil that dries out rapidly, and as a result limited to no response was observed. Even though early season differences in N response have been seen at this site, late season N responsiveness has in general been thwarted because of the very limited moisture holding capacity, and thus, limited resiliency to conditions where reduced rainfall is encountered. Excluding Perkins 2005 and Stillwater 2006, it was important to find that the relationship between RI_{NDVI} and days where GDD>0 was highly significant ($r^2 = 0.44$, $p < 0.001$) (Figure 4). The linear relationship with a significantly positive slope clearly indicated that RI increases with advancing stage of growth. Furthermore, this was found to be positive and similar at all 5 locations. The positive relationship suggests that RI could theoretically be adjusted upwards or downwards based on the known number of days where GDD>0. When the number of days where GDD is less than 60, the reliability of obtaining an accurate estimate of RI decreases. Observed RI_{NDVI} values were all small early on (close to 1.0), which is consistent with limited growth expected at these early stages of growth (Figure 4). However, with this in mind, it is not uncommon for farmers to push the envelope whereby they are interested in topdressing with fertilizer N earlier in the winter. Thus, it is important to understand the mathematical relationship between time (estimated with days from planting where GDD>0) and estimated RI.

The basic premise of this work is that early season N responsiveness can be determined using RI_{NDVI}, and this can be accomplished in time to be used to prescribe mid-season, environment-specific N rates that are known to be more efficient (Mullen et al., 2003). Furthermore, in-season fertilizer can help increase NUE and yield (Mullen et al., 2003). Applying N prior to Feekes 6, even when severe N stress is encountered, ensures that maximum yields can still be produced. Early season N application at planting is less effective in increasing grain yields than late season N applications (Wuest and Cassman, 1992). Alternatively, N applications later in the season can produce maximum yields without preplant N application. Delayed fertilization like topdress N applications in mid-season, resulted in maximum yields without preplant N application at Lake Carl Blackwell in 2003, and Covington, Lake Carl Blackwell and Tipton in 2004 (Morris et al., 2006).

As was noted earlier, midseason fertilizer N applications are known to increase NUE (Sowers et al., 1994) when compared with preplant applications, due to the greater demand for N later in the season, and by applying N when it is needed. It is therefore not surprising to find that leaching and denitrification losses are larger when fertilizer N is applied preplant. Woolfolk et al (2002) noted that applying fertilizer N as UAN (urea ammonium nitrate) before or immediately following flowering increased grain protein levels but seldom resulted in increased yields. Alternatively, Ellen and Spiertz (1980) found that late-season applications resulted in both increased grain yields and grain protein. However, applications after hollow stem may decrease yield due to physical damage of the crop incurred from machinery and/or foliar plant damage. Nevertheless, if the response to fertilizer N applied late in the season is large enough, later applications may outweigh the loss from equipment damage.

Sembiring (1998) reported average N uptake of winter wheat at Feekes 5 to be 60 kg ha^{-1} while only 30 kg ha^{-1} N was removed by the Feekes 4 growth stage. Garabet et al. (1998) stated that N uptake at stem elongation in a 3 year study ranged from 30 to 65 kg ha^{-1}. The low demand for N during the early growth stages of winter wheat (Feekes 3 and Feekes 4) helps explain the lack of finding a relationship between RI_{NDVI} and $RI_{HARVEST}$ at those stages (data not reported). Early in the growth cycle, the soil system has the capability to supply the crop with adequate levels of N. For every 1% organic matter in the soil, 23 to 46 kg N ha^{-1} can be available for plant uptake (Zhang and Raun, 2006), depending on the environmental conditions which dictate N mineralization. Even without accounting for residual soil N from the previous crop year, the N level in the soil is often sufficient to prevent deficiencies until Feekes 5. However, by the time the plant approaches stem elongation, the level of N removed by the crop is much greater and the ability to detect differences in the farmer practice and the N-rich strip is improved. Differences in the two plots that develop (high and low N fertility) at early stages are small, and therefore the RI_{NDVI} determined at these stages can underestimate $RI_{HARVEST}$.

As was noted, even though we attempted to detect early season N responsiveness (RI_{NDVI} versus $RI_{Harvest}$) this was virtually undetectable at Feekes growth stages 3-4. The relationship between RI_{NDVI} and $RI_{Harvest}$ for Feekes growth stages 6 to 9 is reported in Figures 5 – 8, respectively. The coefficient of simple determination for the relationship between RI_{NDVI} and $RI_{Harvest}$ was highest at Feekes growth stage 7. Limited observations were recorded for this data set at Feekes growth stage 9. However, a positive and significant relationship between RI_{NDVI} and $RI_{Harvest}$ was observed at Feekes growth stage 6 (Figure 5), similar to findings from Mullen et al. (2003). Averaged over years and sites for all growth stages, the correlation of RI_{NDVI} and $RI_{Harvest}$ was found to increase with advancing stage of growth up to Feekes 7 (Figure 9). This was expected since the demand for added N (or lack thereof) should be more pronounced as the growth cycle continues, especially in those environments where N stress is expected. Considering that the response was consistent for most of the sites included in this work, results presented in Figure 4 offer the opportunity to adjust RI_{NDVI} based on the known days from planting to sensing where GDD>0. Once RI_{NDVI} is determined, it should be adjusted using the equation $RI_{NDVI\ adj} = RI_{NDVI} \times \{1.87/ (\text{Days where GDD>0} \times 0.00997) + 0.5876\}$ when the number of days where GDD>0 is less than 128. This essentially uses the linear relationship from the linear-plateau model but using an inverse function where the numerator represents the plateau. This in turn weights RI upwards at low GDD's and to a lesser extent when GDD's approach the plateau (x = 128) where theoretically there should no longer be an adjustment. In the past, RI determinations mid-season have been adjusted upwards as per the work of Hodgen et al. (2005), however, this approach was not sensitive to the time when RI was determined. The approach presented here is what we believe is a needed improvement to RI values that are known to be affected by the number of days from planting to sensing where GDD>0.

CONCLUSIONS

Based on the 3 years of data collected in this winter wheat study conducted at five locations across Oklahoma, it was found that estimated RI_{NDVI} increases with advancing stage of growth. This was observed at all locations except Stillwater in 2006 and Perkins in 2005 due to severe moisture stress that was encountered during these seasons. According to these results, the RI could be adjusted based on known days where GDD>0.

When the number of days where GDD was <60, a reliable estimate of N responsiveness using RI_{NDVI} was not considered possible. The relationship between RI_{NDVI} and $RI_{Harvest}$ was inconsistent at Feekes growth stages 2, 3 and 4. Beyond this point, the correlation of RI_{NDVI} and $RI_{Harvest}$ increased with advancing stage of growth up to Feekes 7, and subsequently stabilized. This study shows that RI_{NDVI} can be used to estimate crop N responsiveness and that could be used to optimize in-season fertilizer N rate recommendations that will ultimately lead to increased NUE and yield, and reduce the risk of over application of nutrients to the environment. Our results suggest that once RI_{NDVI} is collected, it should be adjusted using the equation $RI_{NDVI\ adj} = RI_{NDVI} \times \{1.87/(\text{Days where GDD}>0 \times 0.00997) + 0.5876\}$. The $RI_{NDVI\ adj}$ equation can be used to get better nitrogen rate.

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Table 1. Soil classification at study sites, Oklahoma.

Location	----------------------------------Soil classification----------------------------------
Stillwater	Easpur loam fine-loamy (mixed, superactive, thermic Fluventic Haplustoll)
Perkins	Teller sandy loam (fine, mixed, thermic Udic Argiustoll)
Efaw	Norge loam (fine mixed, thermic Udertic Paleustoll)
LCB	Pulaski fine sandy loam (coarse-loamy, mixed, nonacid, thermic, Typic Ustifluvent)
Lahoma	Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll)

LCB: Lake Carl Blackwell

Table 2. Pre-plant N rates and the year each study was established.

Location	Pre-plant N rate, kg ha^{-1}	Year established
Stillwater	0**, 0, 44.8, 89.6, 134.4	1969
Perkins	0, 56, 112, 168	1996
Efaw	0, 44.8, 89.6, 179.2, 268.8, 537.6	1993
LCB	0, 50.4, 100.8	2002
Lahoma	0†, 0, 22.4, 44.8, 67.2, 89.6, 112	1970

LCB: Lake Carl Blackwell

Stillwater – constant P and K rate of 29 and 37 kg ha^{-1} applied to all treatments
Perkins – constant P rate of 29 kg ha^{-1} applied to all treatments
Efaw – no P or K needed
LCB – no P or K needed
Lahoma – constant P and K rates of 19 and 56 kg ha^{-1} applied to all treatments

** no P or K applied
† no P or K applied
N source used at all locations was ammonium nitrate (38-0-0) in 2004 and 2005
N source used at all locations was Urea (46-0-0) in 2006
P source and K source was triple superphosphate (0-46-0) and potassium chloride (0-0-60)

Table 3. Winter wheat variety, seeding rate and planting date at study sites in Oklahoma, 2003-2005.

Location	Winter wheat Varieties	Seeding rate, kg ha^{-1}	Planting date
Stillwater	Custer	89.7	10/6/2003
Stillwater	2174	100.9	10/21/2004
Stillwater	Endurance	94.1	10/7/2005
Perkins	Jagger	89.7	9/26/2003
Perkins	Jagger	100.9	9/26/2004
Perkins	Jagger	89.7	10/11/02005
Efaw	Custer	89.7	10/21/2003
Efaw	2174	95.3	10/17/2004
Efaw	Endurance	89.7	10/11/2005
LCB	Jagalene	112.1	10/8/2003
LCB	2174	89.7	10/24/2005
Lahoma	Custer	86.3-87.4	10/15/2003
Lahoma	Custer	89.7	9/29/2004
Lahoma	Overley	75.8	10/15/2005

LCB: Lake Carl Blackwell

Table 4. Soil chemical properties determined prior to experiment from initial surface soil samples (0-30 cm) at five locations, Oklahoma.

Site	pH	mg kg^{-1}			
		NH_4-N	NO_3-N	P	K
Stillwater	5.8	21.6	7.0	25.8	143.1
Efaw	6.3	11.0	31.5	34.3	234.8
LCB	5.9	15.6	6.8	24.3	97.0
Perkins	6.2	9.2	8.1	14.5	117.6
Lahoma	6.1	9.2	8.2	74.9	405.2

LCB: Lake Carl Blackwell
pH – 1:1 soil:water; K and P – Mehlich III; NH_4-N and NO_3-N – 2M KCI

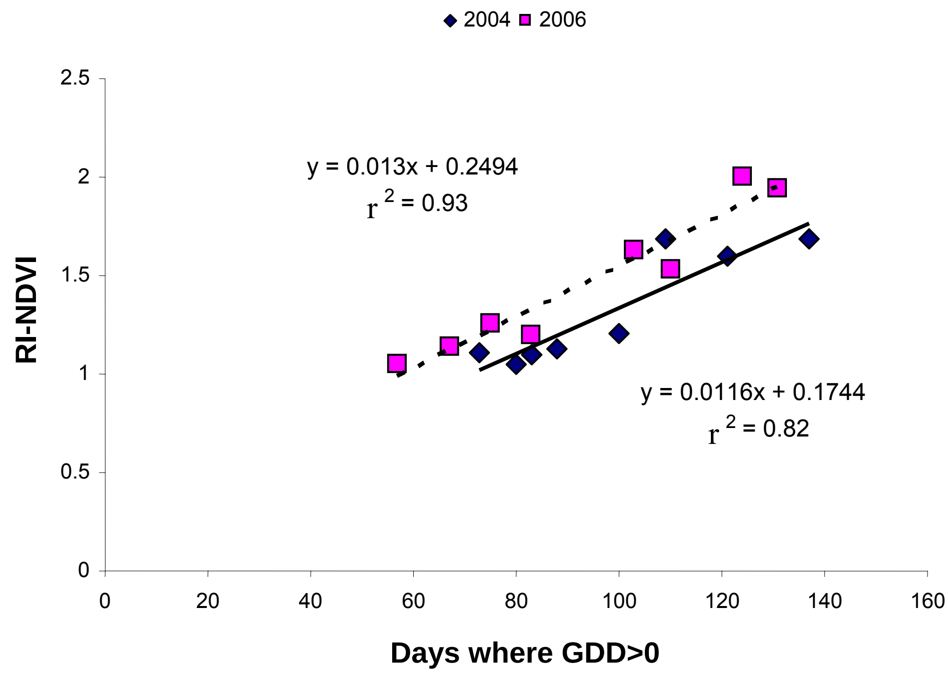

Figure 1. RI_{NDVI} plotted as a function of days where GDD>0, Lake Carl Blackwell 2004 ($p<0.001$) and 2006 ($p<0.001$).

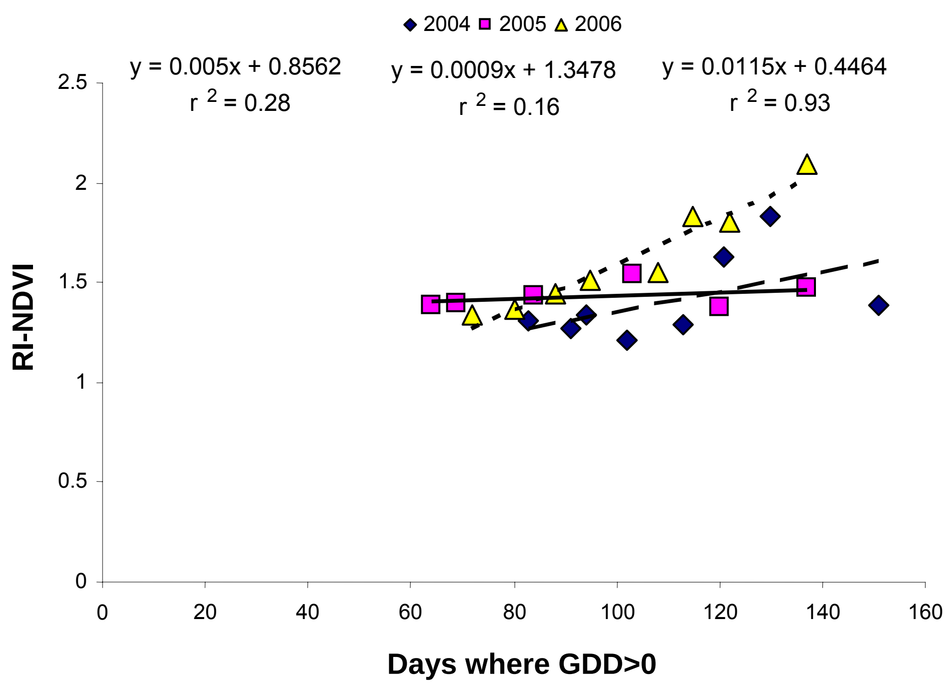

Figure 2. RI_{NDVI} plotted as a function of days where GDD>0, Perkins, 2004 ($p> 0.1$), 2005 ($p> 0.1$) and 2006 ($p< 0.001$).

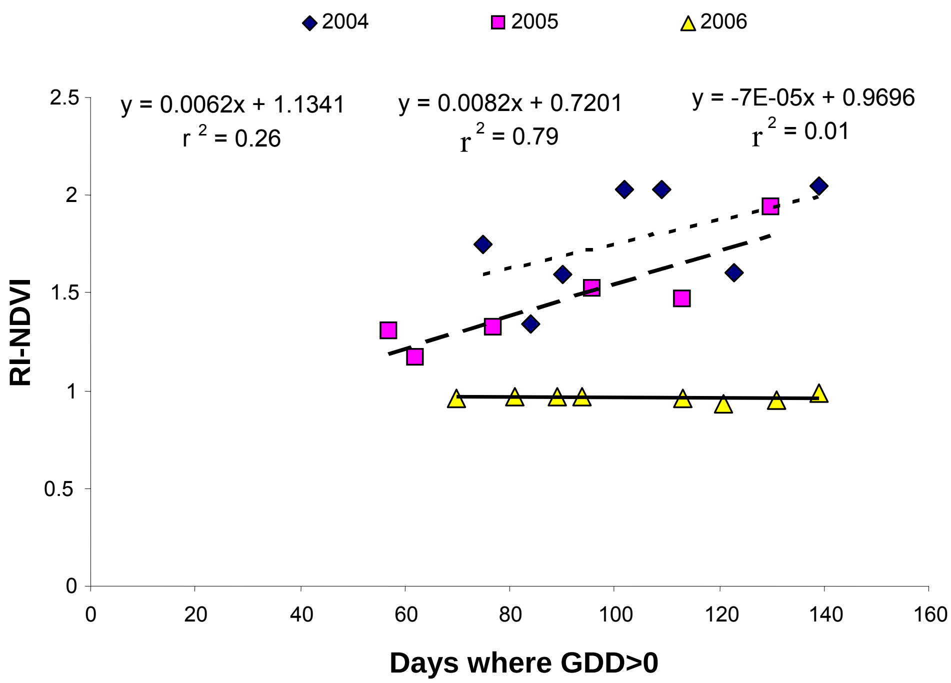

Figure 3. RI_{NDVI} plotted as a function of days where GDD>0, Stillwater, 2004 ($p > 0.1$), 2005 ($p < 0.01$) and 2006 ($p > 0.1$).

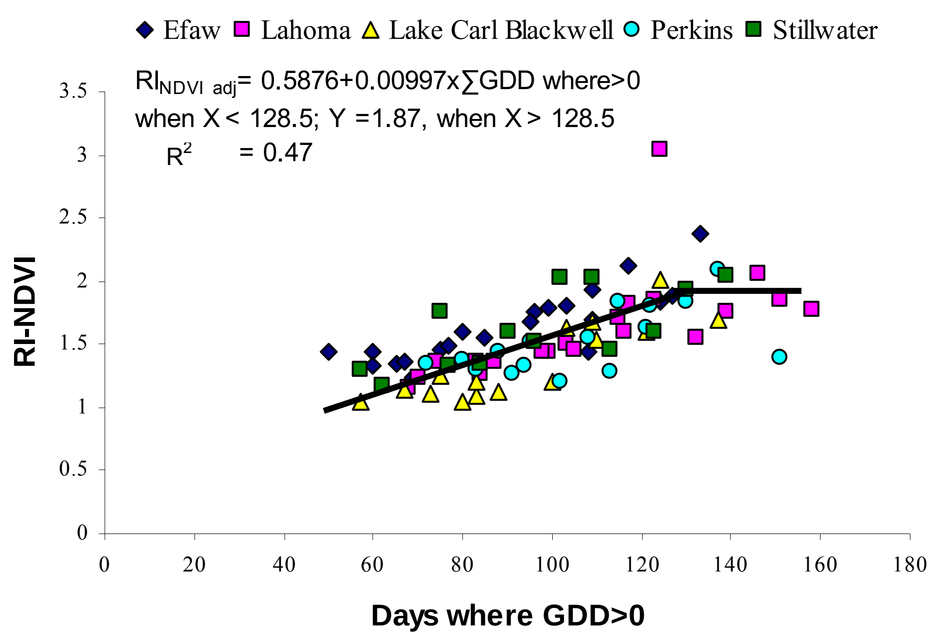

Figure 4. RI_{NDVI} vs. days where GDD>0 at all locations, 2004–2006 ($p<0.01$), excluding Perkins, 2005 and Stillwater, 2006.

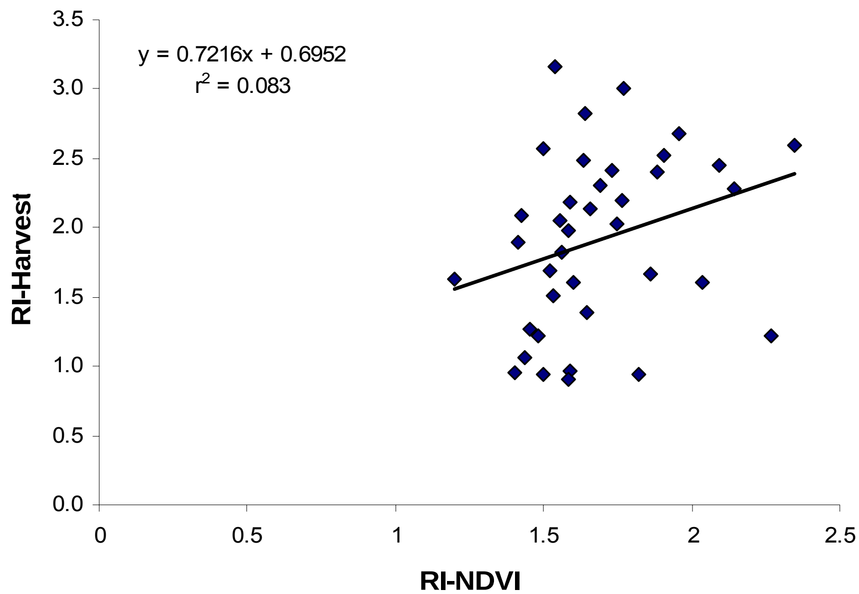

Figure 5. Relationship between RI_{NDVI} and $RI_{Harvest}$ using a linear model ($p>0.1$), Feekes 6 growth stage, 2004–2006.

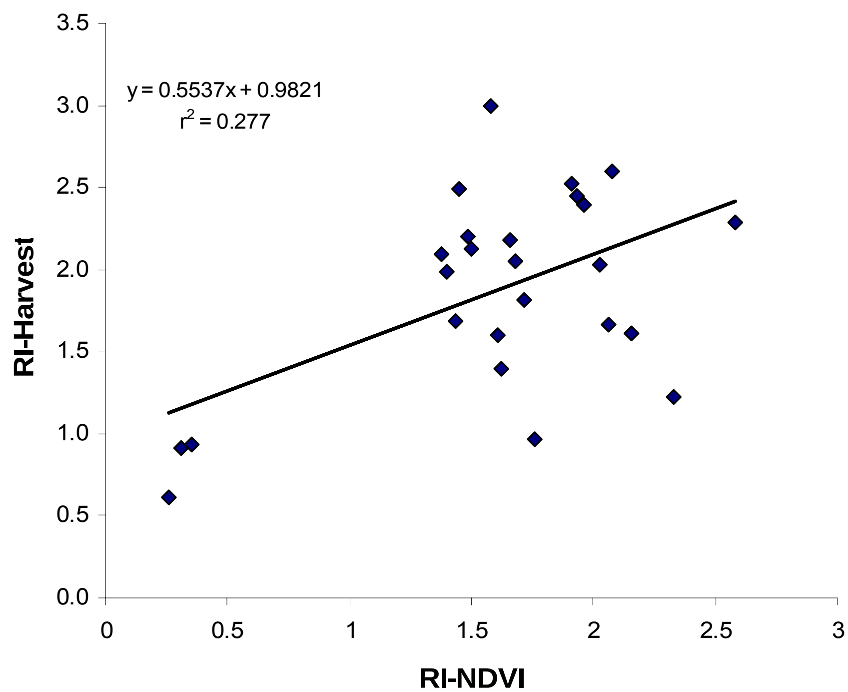

Figure 6. Relationship between RI_{NDVI} and $RI_{Harvest}$ using a linear model ($p<0.05$), Feekes 7 growth stage, 2004–2006.

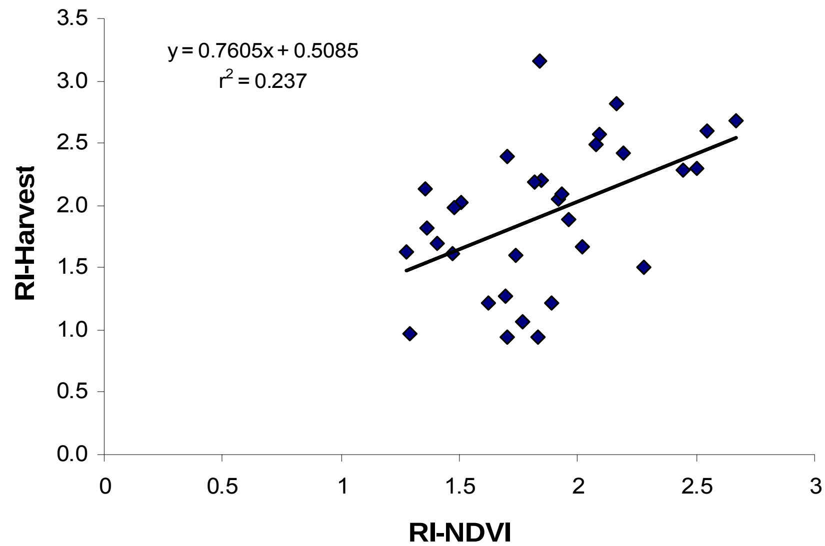

Figure 7. Relationship between RI_{NDVI} and $RI_{Harvest}$ using a linear model ($p<0.05$), Feekes 8 growth stage, 2004–2006.

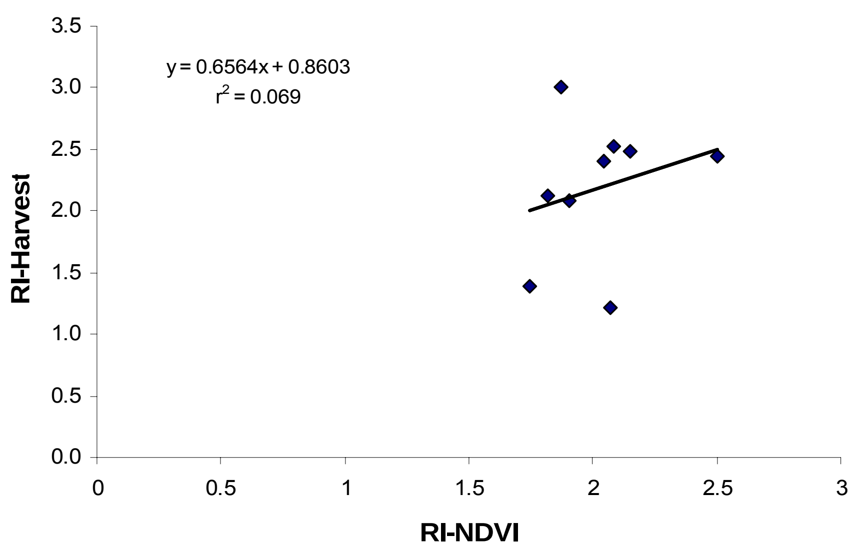

Figure 8. Relationship between RI_{NDVI} and $RI_{Harvest}$ using a linear model ($p>0.1$), Feekes 9 growth stage, 2004–2006.

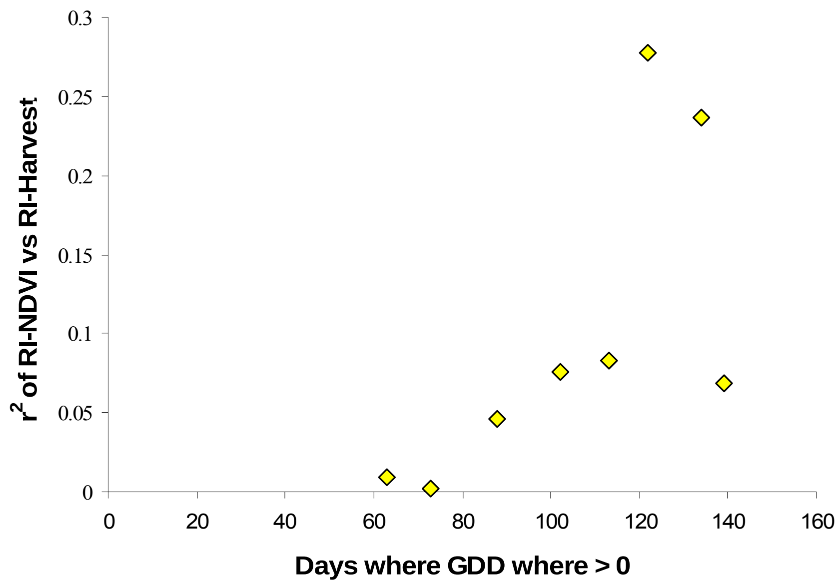

Figure 9. Coefficient of simple determination (r^2) of RI_{NDVI} vs. $RI_{Harvest}$, by days where GDD>0 at all locations, 2004–2006.

APPENDIX

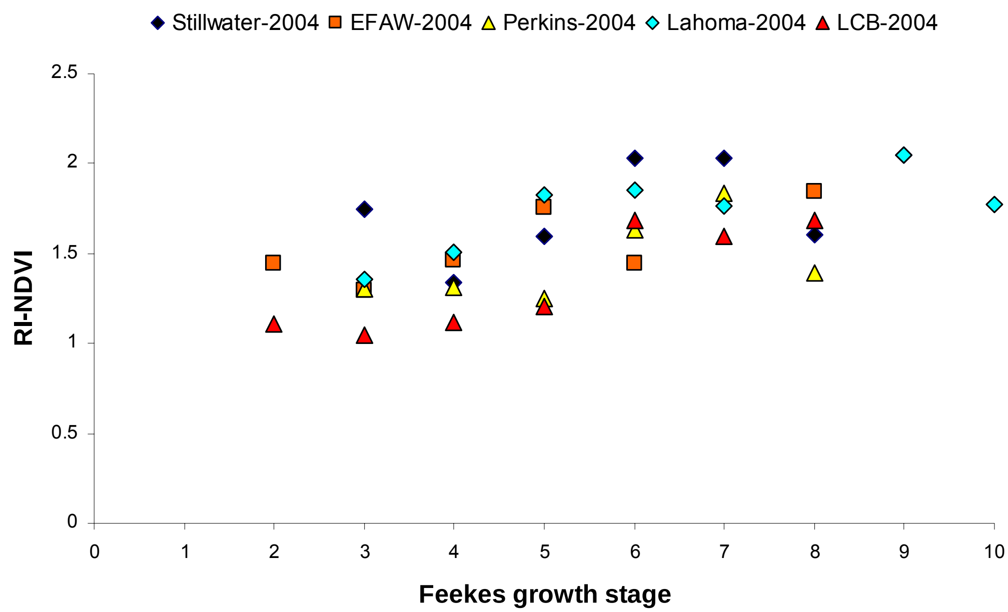

Figure A1. RI_{NDVI} vs. Feekes growth stage at all locations in 2004

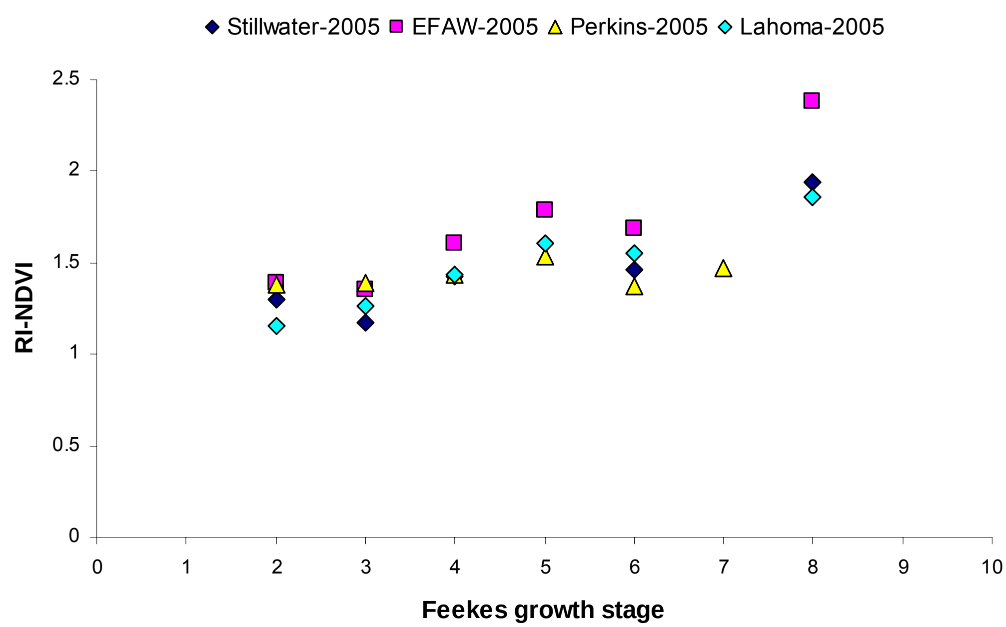

Figure A2. RI_{NDVI} vs. Feekes growth stage at all locations in 2005

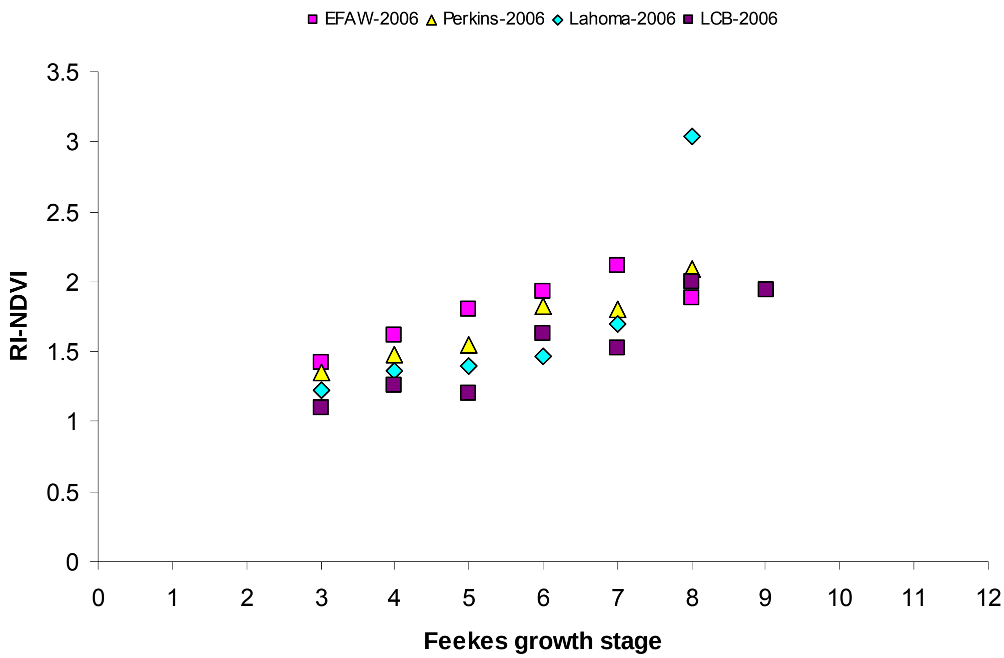

Figure A3. RI_{NDVI} vs. Feekes growth stage at all locations in 2006

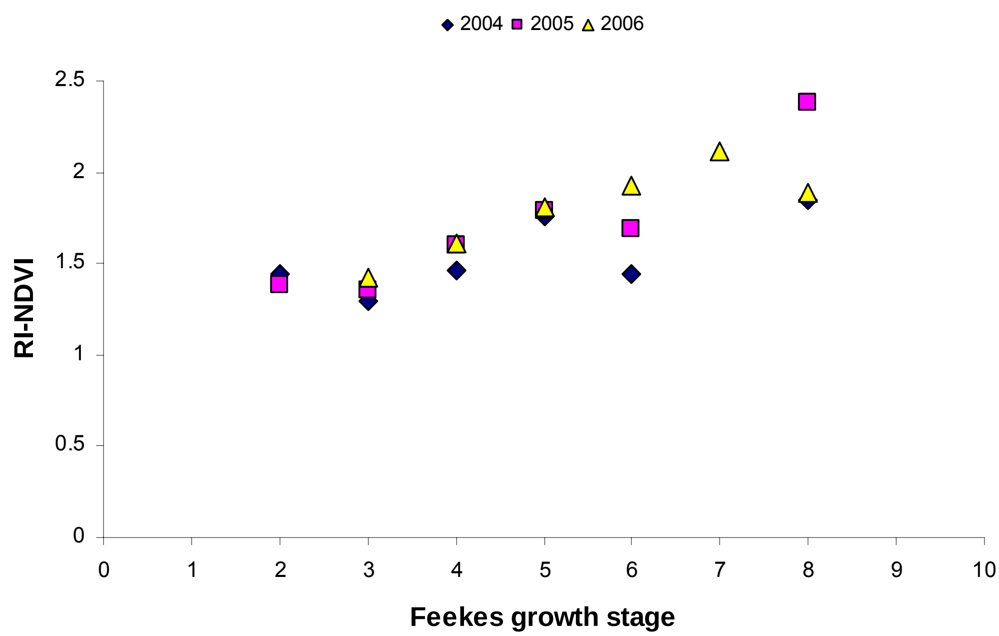

Figure A4. RI_{NDVI} over Feekes growth stages, EFAW 2004-2006

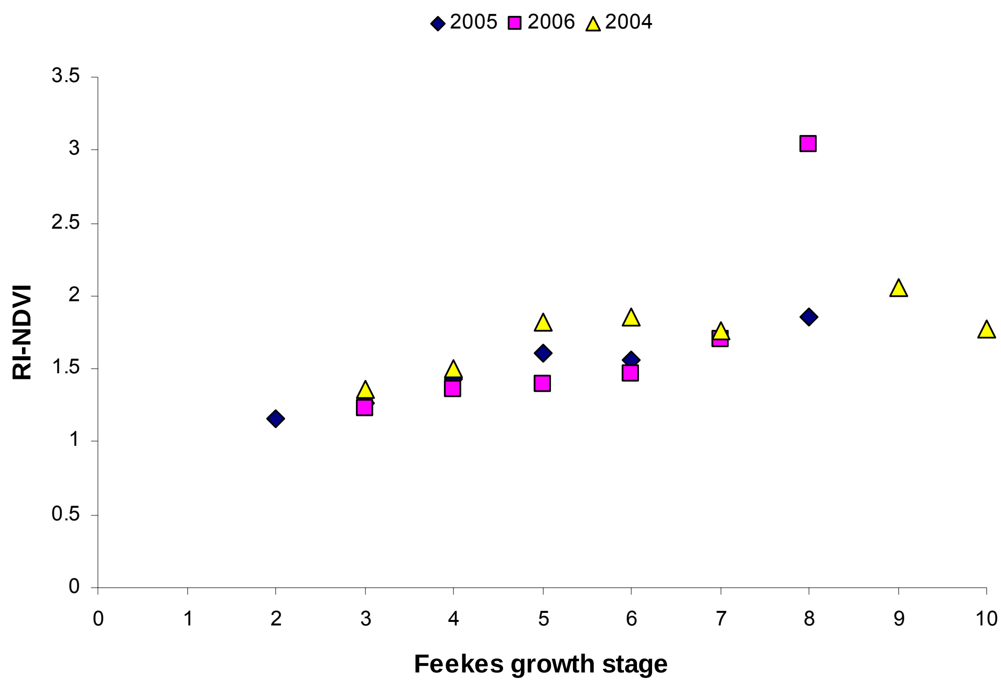

Figure A5. RI_{NDVI} over Feekes growth stages, Lahoma 2004–2006

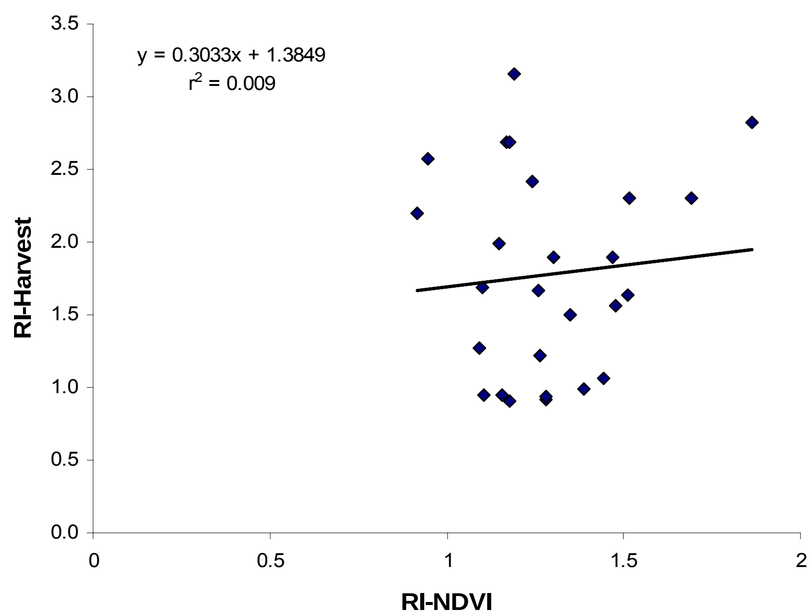

Figure A6. Relationship between RI_{NDVI} and $RI_{Harvest}$ using a linear model (p>0.1), Feekes 2 growth stage, 2004–2006.

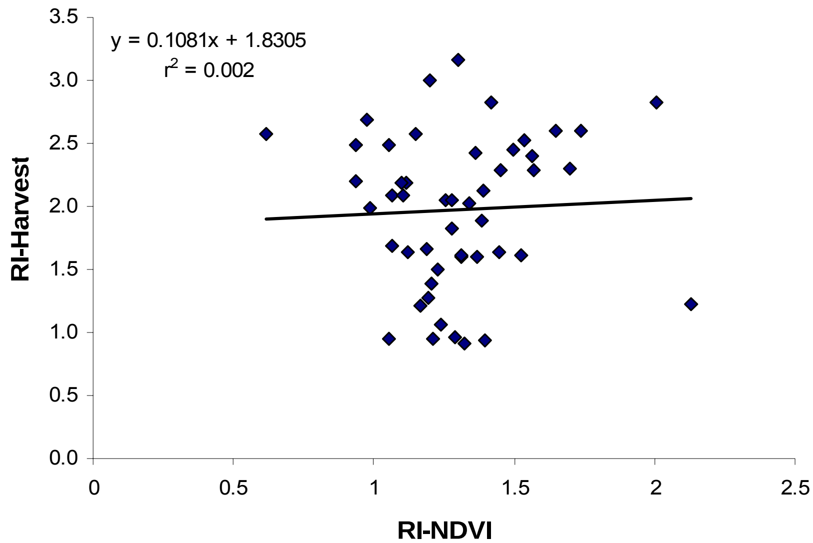

Figure A7. Relationship between RI_{NDVI} and $RI_{Harvest}$ using a linear model (p>0.1), Feekes 3 growth stage, 2004–2006.

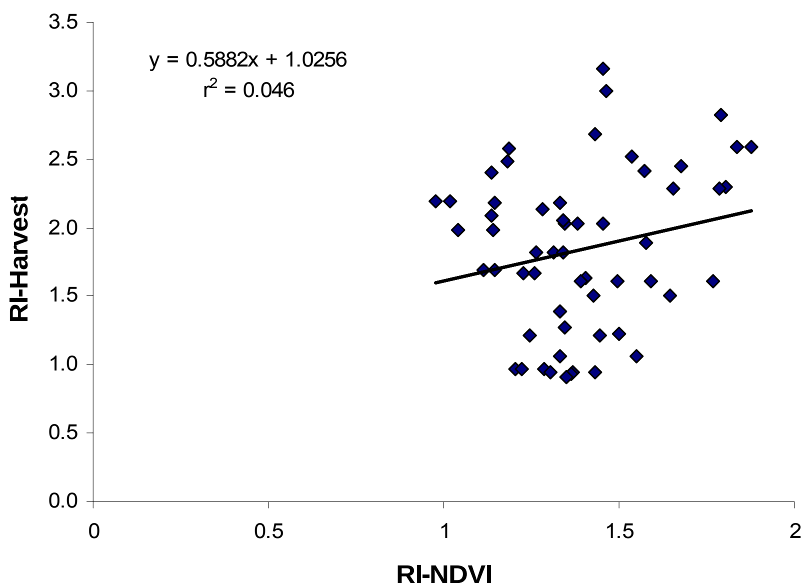

Figure A8. Relationship between RI_{NDVI} and $RI_{Harvest}$ using a linear model (p>0.1), Feekes 4 growth stage, 2004–2006.

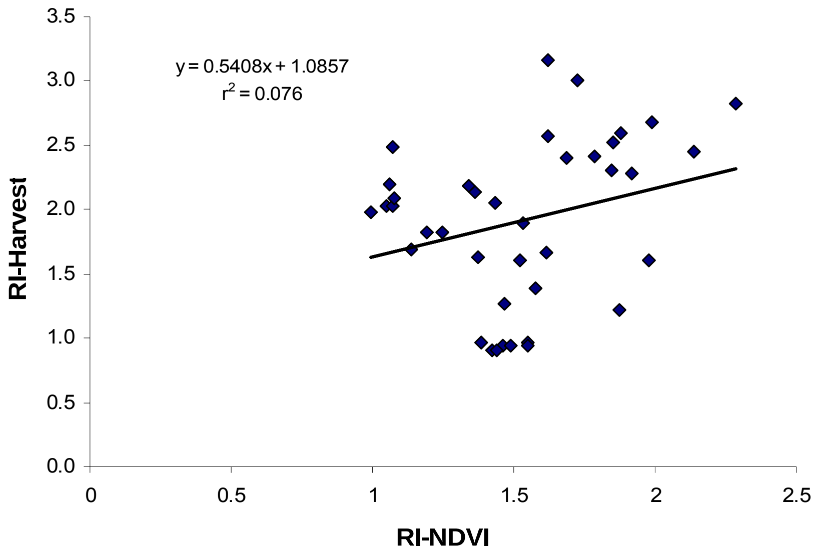

Figure A9. Relationship between RI_{NDVI} and $RI_{Harvest}$ using a linear model (p>0.1), Feekes 5 growth stage, 2004–2006.

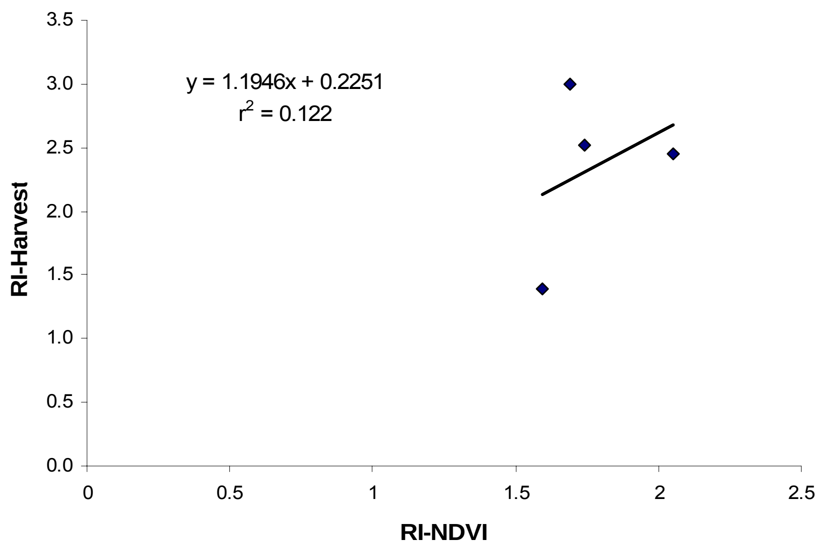

Figure A10. Relationship between RI_{NDVI} and $RI_{Harvest}$ using a linear model (p>0.1) , Feekes 10 growth stage, 2004–2006.

Table A1. Intercepts and slopes obtained from the linear relationship between RI_{NDVI} and GDD for Efaw, Lake Carl Blackwell, Perkins, and Lahoma, 2004–2006.

Year	site- site	all data		except Stillwater in 2006		except some of Perkins data in 2005 and Stillwater in2006	
		intercept	slope	intercept	slope	intercept	slope
2004	Stillwater-Efaw	NS	NS	NS	NS	NS	NS
2005	Stillwater-Efaw	NS	NS	NS	NS	NS	NS
2006	Stillwater-Efaw	NS	***	-	-	-	-
2004	Stillwater-Lahoma	NS	NS	NS	NS	NS	NS
2005	Stillwater-Lahoma	NS	NS	NS	NS	NS	NS
2006	Stillwater-Lahoma	*	**	-	-	-	-
2004	Stillwater-LCB	NS	NS	NS	NS	NS	NS
2005	Stillwater-LCB	-	-	-	-	-	-
2006	Stillwater-LCB	***	***	-	-	-	-
2004	Stillwater-Perkins	NS	NS	NS	NS	NS	NS
2005	Stillwater-Perkins	*	*	*	*	NS	NS
2006	Stillwater-Perkins	*	**	-	-	-	-
2004	Lahoma-LCB	NS	NS	NS	NS	NS	NS
2005	Lahoma-LCB	-	-	-	-	-	-
2006	Lahoma-LCB	NS	NS	NS	NS	NS	NS
2004	Lahoma-Perkins	NS	NS	NS	NS	NS	NS
2005	Lahoma-Perkins	*	*	***	***	*	NS
2006	Lahoma-Perkins	NS	NS	NS	NS	NS	NS
2004	Lahoma-Efaw	NS	NS	NS	NS	NS	NS
2005	Lahoma-EFaw	NS	NS	NS	NS	NS	NS
2006	Lahoma-Efaw	NS	NS	NS	NS	NS	NS
2004	Perkins-Efaw	NS	NS	NS	NS	NS	NS
2005	Perkins-Efaw	*	**	*	**	NS	NS
2006	Perkins-Efaw	NS	NS	NS	NS	NS	NS
2004	Perkins-LCB	NS	NS	NS	NS	NS	NS
2005	Perkins-LCB	-	-	-	-	-	-
2006	Perkins-LCB	NS	NS	NS	NS	NS	NS
2004	Efaw-LCB	*	NS	*	NS	*	NS
2005	Efaw-LCB	-	-	-	-	-	-
2006	Efaw-LCB	NS	NS	NS	NS	NS	NS

NS: not significantly different

*, **, ***, significant at the 0.05, 0.01 and 0.001 probability levels, respectively.

LCB : Lake Carl Blackwell

GDD=[{(Tmax + Tmin)/2}–4 ºC]

Table A2. Average annual temperature and rainfall at Stillwater, Perkins, Efaw, LCB, and Lahoma, encountered during the growing seasons included in this study.

Location	Year		Average annual temperature		
			Maximum (ºF)	Average (ºF)	Rainfall (in)
Stillwater	2004	Sept 2003 – July 2004	68.8	57.8	3.2
		May 2004 – June 2004	83.5	73.0	4.7
		June 2004 – July 2004	86.5	76.4	7.0
	2005	Sept 2004 – July 2005	70.6	58.8	2.5
		May 2005 – June 2005	84.5	73.5	3.8
		June 2005 – July 2005	90.5	79.3	2.5
	2006	Sept 2005 – July 2006	73.5	60.5	2.0
		May 2006 – June 2006	86.5	74.7	2.9
		June 2006 – July 2006	94.0	81.3	2.8
Perkins	2004	Sept 2003 – July 2004	68.8	58.0	2.8
		May 2004 – June 2004	84.0	72.9	4.1
		June 2004 – July 2004	86.5	76.3	5.3
	2005	Sept 2004 – July 2005	70.3	59.1	2.5
		May 2005 – June 2005	85.0	73.5	4.1
		June 2005 – July 2005	91.5	79.5	3.7
	2006	Sept 2005 – July 2006	73.7	60.9	1.9
		May 2006 – June 2006	87.5	75.0	2.7
		June 2006 – July 2006	95.0	81.5	2.2
Efaw	2004	Sept 2003 – July 2004	68.8	57.8	3.2
		May 2004 – June 2004	83.5	73.0	4.7
		June 2004 – July 2004	86.5	76.4	7.0
	2005	Sept 2004 – July 2005	70.6	58.8	2.5
		May 2005 – June 2005	84.5	73.5	3.8
		June 2005 – July 2005	90.5	79.3	3.5
	2006	Sept 2005 – July 2006	73.5	60.5	2.0
		May 2006 – June 2006	86.5	74.7	2.9
		June 2006 – July 2006	94.0	81.3	2.8
LCB	2004	Sept 2003 – July 2004	68.6	57.6	2.8
		May 2004 – June 2004	82.5	72.1	3.9
		June 2004 – July 2004	85.5	75.4	4.9
	2006	Sept 2005 – July 2006	73.0	60.4	1.8
		May 2006- June 2006	86.0	74.3	2.1
		June 2006 – July 2006	93.0	80.5	2.7
Lahoma	2004	Sept 2003 – July 2004	67.8	56.1	2.1
		May 2004 – June 2004	86.0	73.0	2.7
		June 2004 – July 2004	89.0	76.7	3.5
	2005	Sept 2004 – July 2005	69.1	57.1	2.4
		May 2005 – June 2005	85.5	72.9	3.6
		June 2005 – July 2005	92.5	79.3	3.6
	2006	Sept 2005 – July 2006	73.1	59.2	1.3
		May 2006 – June 2006	88.0	74.6	2.1
		June 2006 – July 2006	95.5	81.4	2.5

LCB: Lake Carl Blackwell

USE OF OPTICAL SENSORS FOR DETECTING YIELD DIFFERENCES AT DIFFERENT RESOLUTIONS IN CORN

ABSTRACT

There has not been enough information documented in the literature concerning the plant spacing and resolution at which differences in corn (*Zea mays* L.) grain yield can be detected using optical sensors. Identifying the recognizable resolution where differences in corn grain yields are detectable could theoretically improve nitrogen (N) management, thereby resulting in economic and environmental benefits to producers and the public at large. The objective of this study was to determine the optimum resolution for prediction of corn grain yield using indirect sensor measurements. Corn rows, 15-30 m long were randomly selected at three locations where the exact location of each plant was determined. In 2005 and 2006, 4 out of 8 rows at each location were fertilized with 150 kg N ha^{-1} as urea ammonium nitrate (28% N). A GreenSeeker™ optical sensor was used to determine average Normalized Difference Vegetative Index (NDVI) across a range of plants and over fixed distances (20, 40, 45.7, 60, 80, 91.4, 100, 120, 140, 160, 180, 200, 220, and 240 cm). Individual corn plants were harvested and grain yield was determined. Correlation of corn grain yield versus NDVI was evaluated over both increasing distances and increasing number of corn plants. Then, the squared-correlation coefficients from each plot (used as data) were fitted to a linear plateau model for each resolution treatment (fixed distance and number of corn plants). The linear-plateau coefficient of determination (R^2) was maximized when averaged over every 4-plants in 2004 and 2006, and over 11-plants in 2005. Likewise, R^2 was maximized at a fixed distance of 95, 141, and 87 cm in 2004, 2005, and 2006, respectively. Averaged over

sites and years, results from this study suggest that in order to treat spatial variability at the correct scale, the linear fixed distances should likely be <87 cm or <4 plants as an optimum resolution for detecting early-season differences in yield potential and making management decisions based on this resolution.

INTRODUCTION

With increasing N fertilizer costs and risk to the environment, farmers need to maximize crop yield using N management strategies other than increased N rates. Yield prediction based N management has tremendous importance from both economical and environmental viewpoints. Application of N fertilizer as per the corn crop requirement in specific areas within a field resulted in increased yield and decreased contamination (Dinnes et al., 2002; Doerge, 2002). Alternatively, under N fertilization resulted in lower corn yields (Derby et al., 2004) and over fertilization resulted in N loss through several routes including volatilization, leaching, and denitirification (Kauppi and Sedjo, 2001). Precision agriculture research in corn has focused on uniform plant spacing within the row to increase grain yield (Liu et al., 2004). According to past research, within row corn grain yield depends on plant competition (Duncan, 1984). Plant competition in turn depends on how near and how numerous the neighboring plants are within a given environment (Liu et al., 2004).

Nitrogen deficiency of wheat (*Triticum aestivum* L.) and bermudagrass (*Cynodon dactylon* L.) was found to occur in areas less than 100 by 100 cm (Stone et al., 1996). Moreover, Solie et al. (1996) suggested that N fertilizer needs to be placed in each 150 by 150 cm area. In corn, few studies have attempted to assess the optimum resolution of N management using optical sensing techniques. Using a remotely sensed vegetation index Zhang et al. (1999) found that a 9 to 12 m resolution optimized R^2 between NDVI and corn grain yield. Martin et al. (2005) established the optimum resolution in corn to be ≤50 cm averaged for data combined from several countries and regions of the U.S. The resolution set by Zhang et al. (1999) tended to ignore variability that can occur among plants in a small area. Past research (Martin et al., 2005) showed that plant-to-plant variability in corn grain yield can be expected and averaged more than 2765 kg ha^{-1} over sites and years. Thus, to reduce the cost of N fertilizer inputs and risk to the environment, potential corn grain yield should be predicted accurately prior to calculation of the N fertilizer requirement.

LITERATURE REVIEW

In 2003, farmers in the United States grew 38% (US Grain Council, 2003) of the world's corn amounting to 638 million tons (FAO, 2004). Corn, being one of the most important crops used by man, should be produced efficiently to supply the needs of the world's increasing population, which is projected to reach 7.5 billion by 2020 (FAO, 2004). One of the inputs that needs to be better managed to increase efficiency and reduce the risk to the environment is N, which is the main nutrient needed for growth and development of plant tissues and yield (Chung et al., 1999; Washmon et al., 2002).

Farmers often apply large amounts of N fertilizer to avoid deficiencies. In the entire world, about 8.5 million metric tons of N fertilizer was applied in 2002 (FAO data, 2002), and 8.4 million metric tons of N in 2005 (FAO, 2005). Sixty-seven percent of the N fertilizer applied for cereal production is lost (Raun and Johnson, 1999) which leads to increased production costs, increased environmental and human risk (Sharpe et al., 1988), and poor nitrogen use efficiency (Sowers et al., 1994). Many researchers reported that excessive preplant fertilizer N application has resulted in loss of N or immobilization before plant uptake, significantly affecting NUE (Welch et al., 1996; Olson and Shallow, 1984; Lutcher and Mahler, 1988; Fowler and Brydon, 1989; Wuest and Cassman, 1992). Despite these reports, wheat farmers in the Great Plains still over apply N fertilizer before planting (Kelly, 1995).

Huggins and Pan (1993) noted that among the benefits of increasing NUE are decreasing environmental degradation and human risk, and increasing profit in crop production by reducing N fertilizer input. Researchers are developing N management strategies that can replace or augment the conventional method of N fertilization. Remote sensing, which is a low cost and nondestructive technology (Mulla and Schepers, 1997) can be used to estimate the N status of growing crops in the field during the growing season (Osborne et al., 2002).

Light reflectance near 550 nm (green) can be used to monitor N deficiencies of corn (Blackmer et al., 1994). Blackmer et al. (1996) found that N treatments in irrigated corn canopies could be easily discriminated in the 550 to 900 nm band. Stone et al. (1996) on the other hand reported that the total N of winter wheat plants could be evaluated between 671 nm and 780 nm wavelengths. Remote sensing has been used to evaluate other nutrient deficiencies such as P concentrations of soybean [*Glycine max* (L.) Merr.] (Milton et al., 1991), S, Mg, K, P and Ca of corn leaves (Al-Abbas et al., 1974), Fe, S, Mg, and Mn in corn, wheat, barley (*Hordeum vulgare* L.), and sunflower (*Helianthus annuus* L.) (Masoni et al., 1996) and P uptake of bermudagrass [*Cynodon dactylon* (L.) Pers.] (Sembiring et al., 1998). Reflectance, the ratio of incoming to reflected radiance, can be used to estimate total N and chlorophyll content of fresh plant samples (Yoder and Pettigrew-Crosby, 1995). Raun et al. (2001) showed that mid-season sensor reflectance measurements could be used to predict yield potential of winter wheat (measured between Feekes growth stages 4 and 6). These basic principles in remote sensing led the Oklahoma State University precision agriculture team to develop optical sensor based variable rate technology (S-VRT). This on-the-go technology determines yield potential of the crop and applies N at variable rates based on its predicted needs.

Plant biomass has been shown to affect reflectance measurements in South Carolina (Sadler et al., 2000) and thus can be used to refine yield prediction. Spatial variability exists on measured plant height and biomass at specific growth stages of corn (Sadler et al., 2000). It is important to determine at which scale to sense and treat the variation existing in the field that will result in a more precise yield prediction and improved NUE. Raun et al. (1998) noted that misapplication for a specific field element size identified (where yield potential differences exist) could pose a risk to the environment and revenues. In wheat, Solie et al. (1996) stated that the optimum field element size provides the most precise measure of the available nutrient where the level of that nutrient changes with distance. They suggested that the field element size should have an 80 to 140 cm range. To date, there is no research work on potential yield prediction of corn using different resolutions. Therefore, this study was designed to accurately determine the resolution where grain yield potential of corn could be predicted. The working hypothesis of the project was that resolutions greater than 100 - linear cm will lead to decreased precision in predicting corn grain yield.

The objective of this study was to determine the optimum resolution for predicting corn grain yield using sensor based technology.

MATERIALS AND METHODS

Three locations in Oklahoma were used for a 3-year (2004-2006) study. The sites included Efaw near Stillwater (Norge silt loam: fine silty, mixed, active, thermic Udic Paleustolls), Lake Carl Blackwell (Pulaski fine sandy loam: coarse-loamy, mixed, superactive, nonacid, thermic, Udic Ustifluvent) and Hennessey (Shellabarger fine sandy loam: fine-loamy, mixed, superacitve, mesic, thermic Udic Argiustoll), Oklahoma. Composite soil samples were taken from the entire site, 0-15 cm deep, air-dried, processed and analyzed for pH, NH_4-N, NO_3-N, phosphorus and potassium, and reported in Table 1. The Lake Carl Blackwell site has been irrigated since 2004. The Efaw site is rainfed with custom made supplemental irrigation when rainfall was not available for extended periods while the Hennessey site was purely rainfed where rainfall is generally the limiting factor for optimum corn growth. Due to this limitation, the experiment was conducted at this site only in 2004. The experimental plots were conventionally tilled in the fall and disced before planting in early spring. The corn hybrid “33B51” (Pioneer Hi-Bred International Inc., Johnston, IA) was planted at all sites in late March or early April using a John Deere 'MaxEmerge' planter. Plant populations were 79,000 plants ha^{-1}at Lake Carl Blackwell and 54,000 plants ha^{-1} at Efaw and Hennessey.

In 2004, 4-rows, 30 m in length were randomly selected at each of the three locations. In 2005 and 2006, 8-rows, 15 m in length were selected at Efaw and Lake Carl Blackwell. Four of the 8-rows were fertilized at the V6 growth stage with 150 kg N ha^{-1} as urea ammonium nitrate (28% N) while the other half received no fertilizer.

The distance from the beginning of the row to the center of each plant was measured and recorded along with the row number and plant number for identification. The area that each plant occupied was determined by knowing the distance to and from its nearest neighbor (Equation 1).

$$\text{Area (cm)} = [(1/2)\,B - A] + [(1/2)\,C - B] \times (R) \qquad [1]$$

Where:

A is the plant before the plant in question.

B is the plant in question.

C is the plant following the plant in question.

R is the row spacing.

Normalized difference vegetation index measurements were collected using a GreenSeeker™ Optical Sensor Unit (NTech Industries, Inc.). However, for this research, the sensor was developed to collect NDVI as a function of distance with a conventional bicycle as the building framework. An adjustable pole was installed on the bicycle that extended vertically up to 200 cm. The sensor was installed on a horizontal bar protruding 38.1 cm from the adjustable pole (Figure 1). The sensor height, which was adjustable, was held constant at 92 cm from the top of the crop canopy when measuring NDVI in each row (Figure 1). A shaft encoder installed on the back tire of the bicycle was used to collect a consistent number of pulses for each revolution of the wheel. This allowed us to calculate the distance traveled between each pulse and determine the exact position of each sensor reading.

When the sensor began to measure NDVI with distance, a dull white cardboard strip was placed on the ground at the exact beginning and end of each row. The NDVI value measured by the sensor when it looked at this cardboard was close to 0. The NDVI values over the soil surface or plant material were all greater than 0.20. Thus, the dull white cardboard strip was used to identify the exact beginning and ending point in each row. Subsequently, NDVI measurements were averaged for each plant using half the distance to and from the neighboring plants within the row as described in Equation 1.

Normalized Difference Vegetation Index was measured over pre-determined distances of 20 (0.66), 40 (1.31), 45.7 (1), 60 (1.97), 80 (2.63), 91.4 (3), 100 (3.28), 120 (3.97), 140 (4.59), 160 (5.25), 180 (5.91), 200 (6.56), and 240 (7.87) cm (ft) within each row. Simultaneously, the number of corn plants within the set distances was recorded. The number of corn plants and distances measured were used to determine the resolution required for treating spatial variability, and to estimate yield potential.

At physiological maturity of corn, each plant was cut just above the soil surface and weighed. Then, the ear from each plant was shucked and weighed. The wet ears and stalks were dried in a forced air oven at 66 ˚C for 48 hours and passed through a hand turned 'NeverFail' (Root-Health MFG. CO., Plymouth, USA) corn sheller. The grain from each ear was weighed for dry weight to calculate grain yield. Preliminary data analysis was performed using SAS (SAS, 2003) statistical software. Normalized Difference Vegetation Index recorded over each of the fixed distances and the number of corn plants within the set distances was plotted against corresponding grain yield of each row (n=24 for each plot). Then the squared-correlation coefficients from each plot (used as data) were fitted to a linear plateau model for each resolution treatment (fixed distance and number of corn plants) using the non-linear (NLIN) procedure in SAS. The linear plateau model was:

$$Y = \beta_0 + \beta_1 X \quad \text{if } X < X_0 \qquad [2]$$
$$Y = p \quad \text{if } X > X_0 \qquad [3]$$

Where: Y is the squared-correlation coefficient, β_0 is the intercept (squared-correlation coefficient when X=0); β_1 is the coefficient of the linear plateau phase of the model; X is the number of corn plants or fixed distance (cm); X_0 denotes the critical number of corn plants or fixed distance at which the maximum squared-correlation coefficient was achieved (*p*).

RESULTS AND DISCUSSION

The variation in optimum resolution determined from the number of corn plants was very high across years, locations and corn growth stages. The linear-plateau model (the number of corn plants as a predictor) captured a significant ($p<0.05$) portion of the variability in squared-correlation coefficients (dependent variable) for most (85%) of the year-location-stage models with R^2 values ranging 0.40-0.95 (Table 3). Sixty-two percent of the year-location-stage models had $R^2 \geq 0.65$.

Averaged over years, locations and stages, the number of corn plants where R^2 values were maximized (NDVI versus yield) was every 7-plants (Table 3). The median value (6-plants) was also close to the average. It is important to note that the range in the number of plants that represented the optimum resolution was very wide (from 2 to 15), suggesting a highly variable joint (critical number of corn plants) using the squared-correlation coefficient data.

In 2004, a higher resolution (4-plants) was observed (small number of plants) when averaged over locations. The lowest resolution was 5-plants while the highest resolution was 2-plants. In this year, measurements were taken only at the V8 corn growth stage at the three locations (Table 3). The difference in the number of corn plants set as critical (the joint of each model) for this year were not different partly attributed to collecting data only at one stage. A lower resolution was obtained in 2005 (7- to 15-plants) with an average of 11-plants. In general, results from 2004 and 2006 were lower, averaging 4-plants. The best resolution was 2-plants while the worst was 6-plants, less than the smallest resolution of 7-plants in 2005. It could be that the resolution where yield potential could best be predicted when stress was less, and more plants were present (2005), whereas less plants when increased stress was present (2004 and 2006). The differences between individual plants will likely be exacerbated when moisture stress occurs, and less pronounced under non-limiting conditions, possibly explaining these results.

A closer examination of the joint by year, location and corn growth stage showed that in 2005 at Efaw a higher resolution was obtained for squared-correlation coefficients derived from NDVI measurements taken at V6 growth stage while at the V8 and V10 growth stages a relatively lower resolution was determined from each model. In 2006, almost the same resolution (2 to 2.5- plants) was determined across growth stages although the resolution was slightly lower at V10. At Lake Carl Blackwell at V6 in 2005 and at V8 in 2006, the linear-plateau model failed to converge. For the other stages, resolution did not change as the growth stages in which the squared-correlation coefficient of NDVI measurements were taken progressed. In general, the variability of the resolution determined using corn plants in a row was more pronounced across years and locations but not growth stages. This suggests that the number of corn plants that could theoretically be used for making management decisions based on yield potential could be implemented between V8 to V10 corn growth stages. Linear-plateau models were best when fitted for each year and location. It should however be noted that management decisions at resolutions greater than 15-plants will likely ignore detectable differences in grain yield. In general, when plant populations were low, the resolution at which yield potential was best recognized included less plants, especially at early stages of growth. Alternatively, when plant populations were high, the resolution where yield potential could be best predicted required more plants.

The use of distance to determine resolution was better than when using the number of corn plants when looking at the R^2 (0.5 to 0.95) in Table 4 (except Lake Carl Blackwell in 2006 at V6). The coefficient of determination would have improved at Lake Carl Blackwell if a linear model instead of linear- plateau model was used although it is difficult to have a critical resolution distance with the use of a linear model. Averaged over the three years, all locations and growth stages, a distance of 110 cm was determined as the optimum resolution. The highest resolution was 66 cm (in 2006 at Efaw at the V8 and V10 growth stages) while the lowest resolution was 171 cm (at Lake Carl Blackwell in 2005 at the V8 growth stage) with a range of 105 cm. Across years, 95, 141 and 87 cm were set as the optimum resolutions in 2004, 2005 and 2006, respectively. Across locations, resolution distance was 107, 100 and 115 cm at Efaw, Hennessey and Lake Carl Blackwell, respectively. In both 2005 and 2006 at Efaw resolution decreased as NDVI measurements progressed from the V6 to V10 growth stages. A similar trend was observed in 2005 at Lake Carl Blackwell. At this site in 2006, no trend was observed although the resolution at V6 was higher than the resolution at V8 and V10 (Table 4). The coefficient of determination at Efaw was maximized at the V8 growth stage in 2005 and at the V6 growth stage in 2006.

The optimum resolution was variable in each year suggesting that this too was influenced by temporal variability, and how temporal qualities influence growth. The R^2 of each linear-plateau model in each of the two approaches used to determine optimum resolution revealed that the fixed distance approach would be better. However, with all ranges of resolutions (i.e. high, medium or low), the number of corn plants and the distance generally coincided based on average distance from neighboring corn plants. Martin et al. (2005) established a critical sensing distance of 50 cm or less for treating factors that affect corn yield. Compared with his results, we found a lower resolution distance in all models (the best resolution was 66 cm, at Efaw in 2006 at both V6 and V8). Compared to a 900 to 1200 m spatial resolution recommended by Zhang et al. (1999) based on R^2, the distance we set can be considered to be high resolution.

The wide variation in optimum resolution at the Lake Carl Blackwell site in 2005 and 2006 could be due to differences in the planting dates. The planting dates for four of the eight rows on the south-east side in 2005 and on the west side in 2006 were April 11 and March 31, respectively. Alternatively, planting dates for the other four rows on the north-west side in 2005 and east side in 2006 were April 18 and 11, respectively. This delay, given the warm temperature in both years since late March, means active growth of corn and can influence the resolution at which yield potential is recognized. Some of the differences in the optimum resolution within a season and across locations could be due to plant biomass. In addition, post-sensing plant stress (such as drought, high temperatures, nutrient deficiency, insect damage, hail damage, poor pollination, and animal damage can result in a poor relationship between grain yield and NDVI in the linear-plateau model resulting in a poor R^2. Uneven emergence was reported as a possible cause of increased or decreased grain yield when soils were dry at the time of planting (Nafziger et al., 1991). In 2006, severe heat stress was encountered throughout the growing season at all sites. This severe heat had daily maximums that exceeded 38 ºC from mid July to early August in 2006 at Lake Carl Blackwell and Efaw.

CONCLUSIONS

The use of distance to determine resolution was relatively better than when using specific numbers of corn plants when looking at the R^2. Looking at the linear-plateau models generated from the squared-correlation coefficients (grain yield versus NDVI for different numbers of corn plants) the resolution where yield differences were best recognized was when averaged over every 4 plants in 2004 and 2006 and over 11 plants in 2005. Likewise, the R^2 was maximized at a fixed distance of 95, 141, and 87 cm in 2004, 2005 and 2006, respectively. Identifying the optimum resolution where spatial variability should be treated is a complicated task. Averaged over sites and years, this study suggests that in order to treat spatial variability at the correct scale, the linear fixed distances should likely be <87 cm or <4-plants as an optimum resolution for detecting early-season differences in yield potential and making management decisions based on this resolution.

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Table 1. Soil chemical properties determined prior to experiment from initial surface soil samples (0-15 cm) at three locations, Oklahoma.

Site	pH	mg kg^{-1}			
		NH_4-N	NO_3-N	P	K
Efaw	5.9	13.9	3.7	20	90
LCB	5.6	28.4	4.4	45	144
Hennessey	4.8	24	5	100	-

LCB: Lake Carl Blackwell

pH – 1:1 soil:water; K and P – Mehlich III; NH_4-N and NO_3-N – 2M KCI

Table 2. Planting dates, harvest dates, and growth stages for resolution determination study at Efaw, Hennessey and Lake Carl Blackwell, OK, 2004-2006.

Location	year	growth stage	planting date	sensing date	Harvest date
Efaw	2004	V8	4/7/04	5/26/04	8/25/04
Hennessy	2004	V8	4/27/04	6/16/04	9/13/04
LCB	2004	V8	4/3/04	5/28/04	8/2/04
Efaw	2005	V6	4/7/05	5/19/05	8/1/05 (row 1 to 3), 8/26/05 (4 to 8)
LCB	2005	V6	4/12/05	5/23/05	9/8/05 (row 1-2), 9/20/05 (row 3-8)
Efaw	2005	V8	4/7/05	5/27/05	8/1/05 (row 1 to 3), 8/26/05 (4 to 8)
LCB	2005	V8	4/12/05	5/27/05	9/8/05 (row 1-2), 9/20/05 (row 3-8)
Efaw	2005	V10	4/7/05	6/2/05	8/1/05 (row 1 to 3), 8/26/05 (4 to 8)
LCB	2005	V10	4/12/05	6/2/05	9/8/05 (row 1-2), 9/20/05 (row 3-8)
Efaw	2006	V6	3/30/06	5/19/06	8/24/06
LCB	2006	V6	3/31 row (5-8)	5/22 row (1-4)	8/14/06
			4/11 row (1-4)	5/17 row (5-8)	8/14/06
Efaw	2006	V8	3/30/06	5/24/06	8/24/06
LCB	2006	V8	3/31 row (5-8)	5/29 row (1-4)	8/14/06
			4/11 row (1-4)	5/22 row (5-8)	8/14/06
Efaw	2006	V10	3/30/06	6/2/06	8/24/06
LCB	2006	V10	3/31 row (5-8)	6/5 row (1-4)	8/14/06
			4/11 row (1-4)	5/29 row (5-8)	8/14/06

Table 3. Linear plateau model with critical number of corn plants (joint) and coefficient of determination (R^2) derived from the correlation between NDVI and corn grain yield versus number of corn plants at three growth stages at Efaw, Hennessey and Lake Carl Blackwell, 2004-2006.

Location	Year	Growth stage	Joint [¶] (number of corn plants)	Model	R^2
Efaw	2004	V8	5.1	Y=0.0557 + 0.0325x, when X < 5; Y=0.22, when X > 5 **	0.67
Lake Carl Blackwell	2004	V8	2	Y=-0.0267 + 0.169x, when X <2.; Y=0.55, when X > 2	0.30
Hennessey	2004	V8	3.5	Y=0.015 + 0.1499x, when X < 3.5; Y=0.51, when X > 3.5*	0.47
Efaw	2005	V6	7.2	Y=0.0333 + 0.027x, when X < 7.2; Y=0.23, when X > 7.2 ***	0.83
Lake Carl Blackwell	2005	V6		ǂ	
Efaw	2005	V8	9.5	Y=0.0709+0.0447x, when X < 9.5; Y=0.49, when X > 9.5***	0.86
Lake Carl Blackwell	2005	V8	15.3	Y=-0.00024+0.01341x, when X < 15.3; Y=0.2, when X > 15.3***	0.96
Efaw	2005	V10	9	Y= 0.0799+0.0395x, when X < 9; Y=0.44, when X > 9***	0.83
Lake Carl Blackwell	2005	V10	14.7	Y= 0.0055+0.0135x, when X > 14.7; Y=0.2, when X< 14.7***	0.95
Efaw	2006	V6	1.99	Y= 0.1921 + 0.069x, when X > 2; Y=0.33, when X < 2	0.22
Lake Carl Blackwell	2006	V6	6	Y= -0.00787 + 0.0099x, when X> 6; Y=0.05, when X < 6*	0.47
Efaw	2006	V8	2	Y= 0.1975+0.0989x, when X < 2; Y= 0.4, when X < 2 *	0.40
Lake Carl Blackwell	2006	V8		ǂ	
Efaw	2006	V10	2.5	Y= 0.0943+0.1498x, when X> 2.5; Y= 0.47, when X < 2.5***	0.71
Lake Carl Blackwell	2006	V10	6.2	Y= 0.0205+0.0169x, when X> 6.2; Y=0.13, when X < 6.2**	0.65

*, ** and *** model significant at the 0.05, 0.01, and 0.001 levels of probability, respectively

ǂ Critical plant number exceeded data boundary, convergence not met

¶ Joint, is critical point, is determined by defining the linear and plateau phases of the model separately.

Table 4. Linear plateau model with critical fixed distance resolution (joint) and coefficient of determination (R^2) derived from the correlation between NDVI and corn grain yield versus fixed distance at three growth stages at Efaw, Hennessey and Lake Carl Blackwell, 2004-2006.

Location	Year	Growth stage	Joint ¶(distance, cm)	Model	R^2
Efaw	2004	V8	93.4	Y= -0.063 + 0.0043x, when X < 93.4; Y=0.33, when X > 93.4***	0.95
Lake Carl Blackwell	2004	V8	92	Y= 0.0729 + 0.0026x, when X <92; Y=0.31, when X > 92***	0.66
Hennessy	2004	V8	100	Y= -0.0698 + 0.0033x, when X < 100; Y=0.26, when X > 100**	0.61
Efaw	2005	V6		ǂ	
Lake Carl Blackwell	2005	V6	140	Y= -0.0077 + 0.0007x, when X < 140;Y=0.09, when X > 140**	0.63
Efaw	2005	V8	171.1	Y= -0.0146 +0.0024x, when X < 171.1; Y=0.39, when X > 171.1***	0.90
Lake Carl Blackwell	2005	V8	132.9	Y= -0.0093 +0.0007x, when X < 132.9; Y=0.09, when X > 132.9***	0.70
Efaw	2005	V10	156.4	Y= 0.0212+0.002x, when X < 156.4; Y=0.34, when X > 156.4***	0.95
Lake Carl Blackwell	2005	V10	106.2	Y= -0.0094+0.0011x, when X > 106.2; Y=0.11, when X< 106.2***	0.72
Efaw	2006	V6	92.4	Y= 0.1573+0.0027x, when X > 92.5; Y=0.41, when X < 92.4***	0.75
Lake Carl Blackwell	2006	V6	100	Y= 0.0014+0.00001x, when X> 100; Y=0.01, when X < 100	0.15
Efaw	2006	V8	66.1	Y= 0.1158+0.0049x, when X < 66.1; Y=0.44, when X < 66.1***	0.94
Lake Carl Blackwell	2006	V8		ǂ	
Efaw	2006	V10	65.9	Y= 0.0677+0.006x, when X> 65.9; Y=0.47, when X < 65.9***	0.87
Lake Carl Blackwell	2006	V10	110.6	Y= 0.0887+0.0019x, when X> 110.6; Y=0.29, when X < 110.6***	0.71

*, ** and *** model significant at the 0.05, 0.01, and 0.001 levels of probability, respectively

ǂ Critical plant number exceeded data boundary, no convergence.

¶ Joint is critical point, is determined by defining the linear and plateau phases of the model separately.

Figure 1. Framework for the bicycle and the adjustable pole that holds the sensor parallel and directly above the corn row. The shaft encoder is used to determine the distance at which NDVI is recorded is shown on the rear tire of the bicycle.

APPENDIX

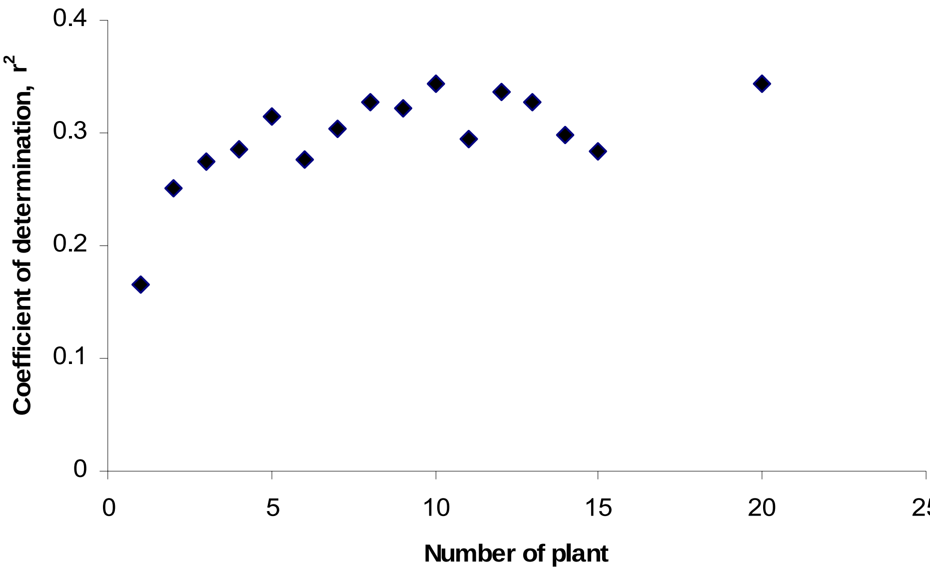

Figure A1. Correlation of grain yield and NDVI when both yield and NDVI were averaged over a fixed number of plants, V8 stage, all sites combined (EFAW, Lake Carl Blackwell, Hennessey), 2004.

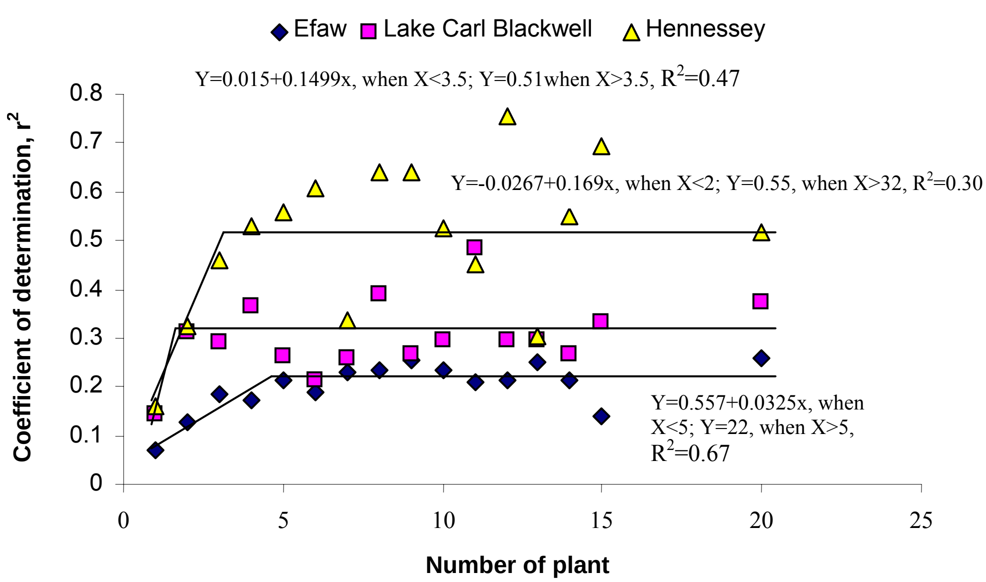

Figure A2. Correlation of grain yield and NDVI when both yield and NDVI were averaged over a fixed number of plants, V8 stage by site, EFAW, Lake Carl Blackwell, Hennessey, 2004. All models are significant at $p<0.05$.

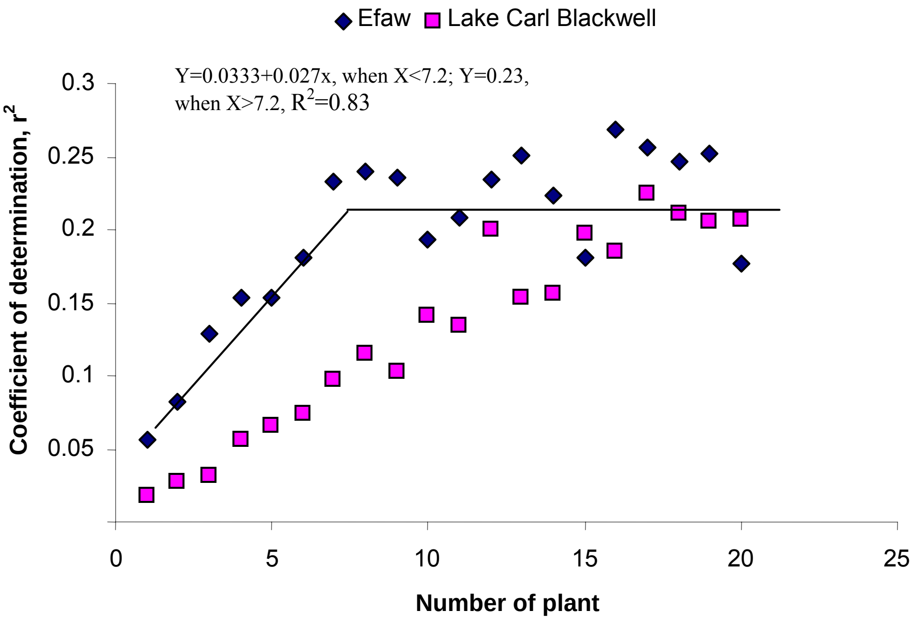

Figure A3. Correlation of grain yield and NDVI when both yield and NDVI were averaged over a fixed number of plants, V6 stage, EFAW, and Lake Carl Blackwell, 2005. The model at Efaw is significant at $p<0.001$.

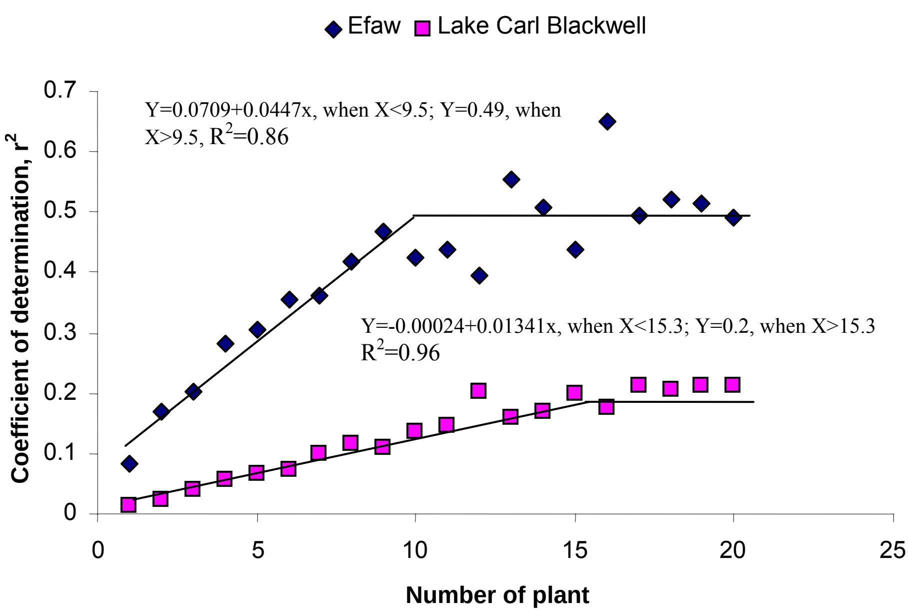

Figure A4. Correlation of grain yield and NDVI when both yield and NDVI were averaged over a fixed number of plants, V8 stage, EFAW, and Lake Carl Blackwell, 2005. All models are significant at $p<0.001$.

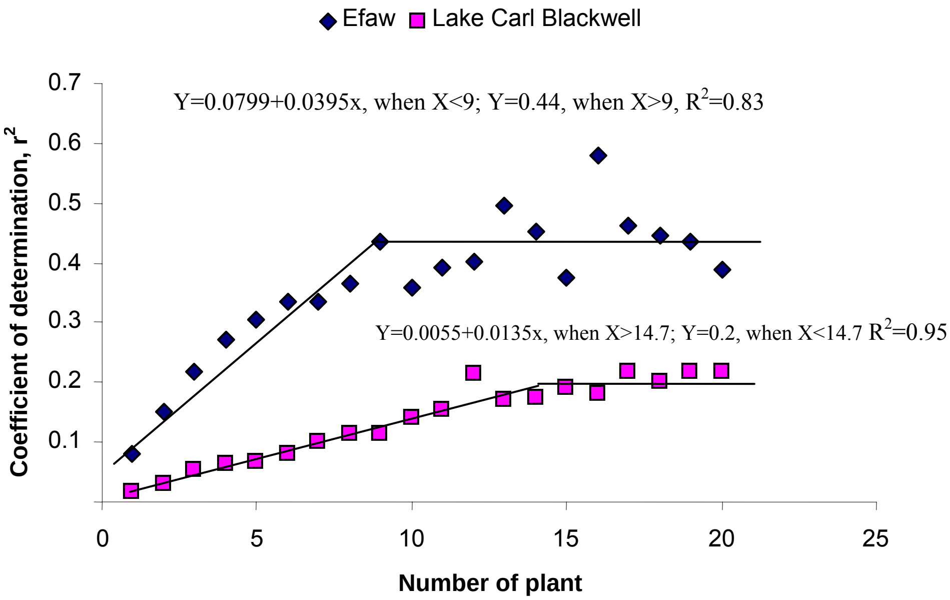

Figure A5. Correlation of grain yield and NDVI when both yield and NDVI were averaged over a fixed number of plants, V10 stage, EFAW, and Lake Carl Blackwell, 2005. All models are significant at $p<0.001$.

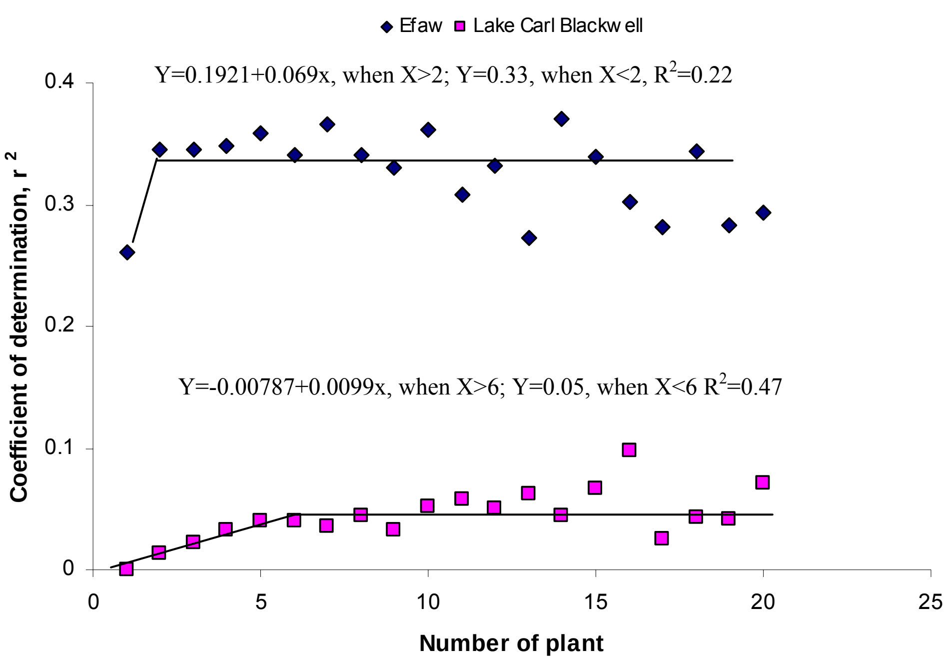

Figure A6. Correlation of grain yield and NDVI when both yield and NDVI were averaged over a fixed number of plants, V6 stage, EFAW, and Lake Carl Blackwell, 2006. The model at Lake Carl Blackwell is significant at $p<0.05$.

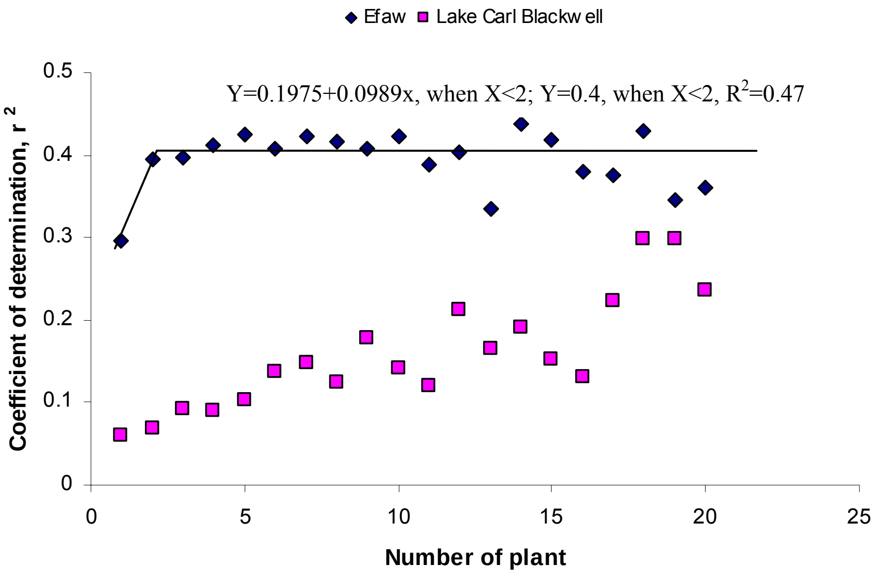

Figure A7. Correlation of grain yield and NDVI when both yield and NDVI were averaged over a fixed number of plants, V8 stage, EFAW, and Lake Carl Blackwell, 2006. The model at Efaw is significant at $p<0.05$.

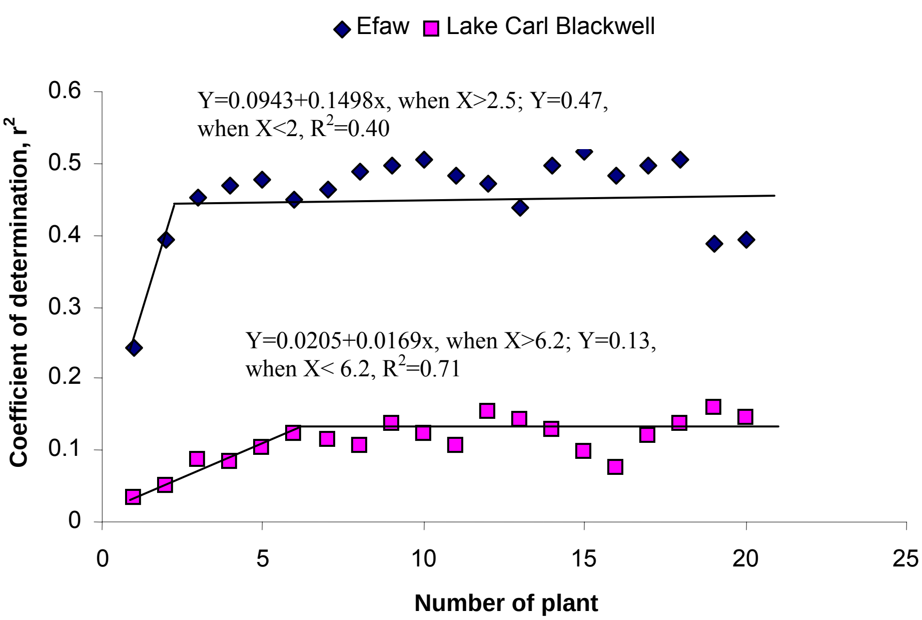

Figure A8. Correlation of grain yield and NDVI when both yield and NDVI were averaged over a fixed number of plants, V10 stage, EFAW, and Lake Carl Blackwell, 2006. The models at Efaw and Lake Carl Blackwell are significant at $p<0.05$ and $p<0.01$, respectively.

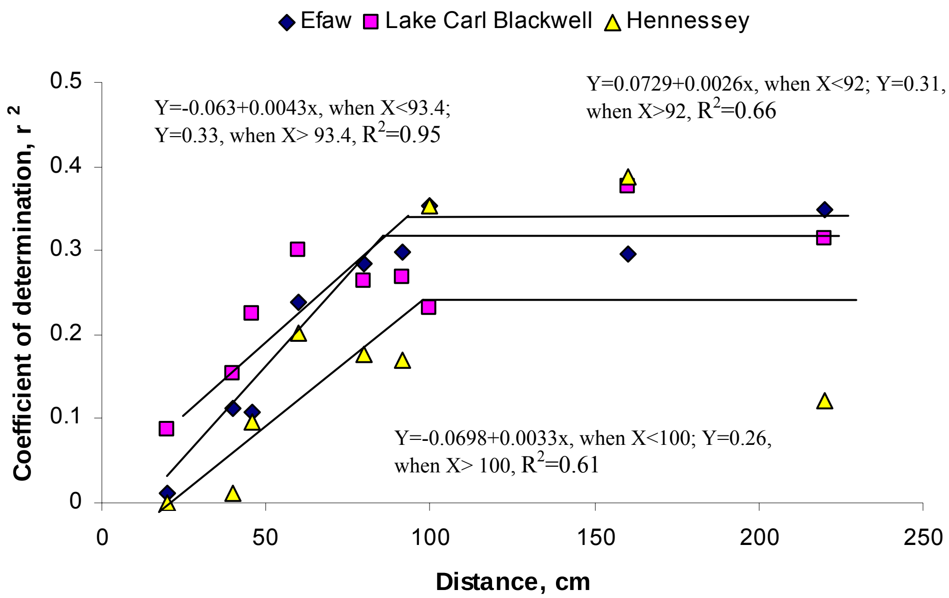

Figure A9. Correlation of grain yield and NDVI when both yields and NDVI were averaged over fixed distances, V8 stages, Efaw, Lake Carl Blackwell, and Hennessey, 2004. The models at Efaw, Lake Carl Blackwell and Hennessey are significant at $p<0.001$ and $p<0.01$ and $p<0.01$, respectively.

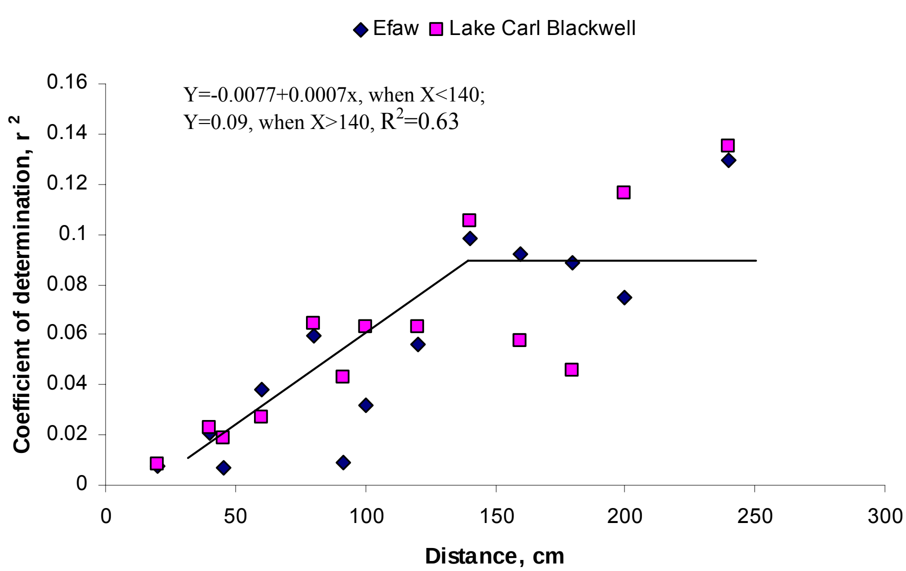

Figure A10. Correlation of grain yield and NDVI when both yields and NDVI were averaged over fixed distances, V6 stages, Efaw, and Lake Carl Blackwell, 2005. The model at Efaw is significant at $p<0.01$.

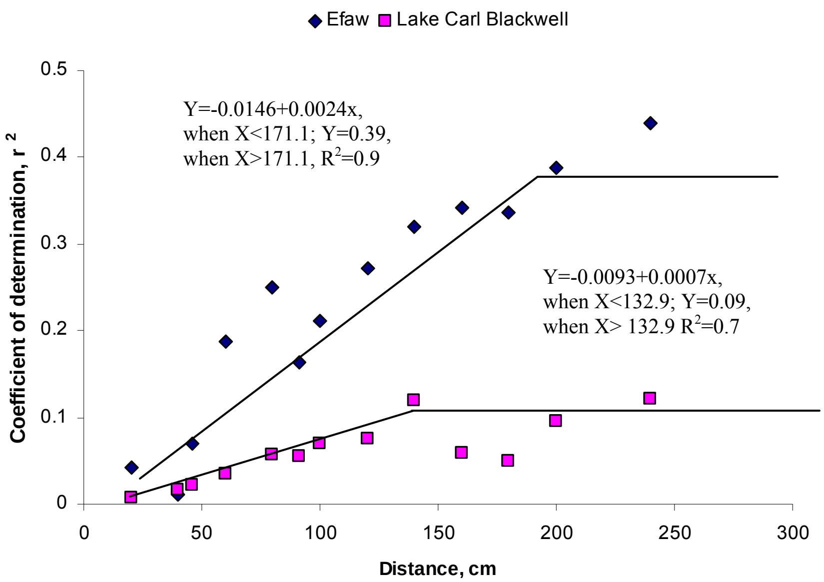

Figure A11. Correlation of grain yield and NDVI when both yields and NDVI were averaged over fixed distances, V8 stages, Efaw, and Lake Carl Blackwell, 2005. The models at Efaw and Lake Carl Blackwell are significant at $p<0.001$ and $p<0.01$ respectively.

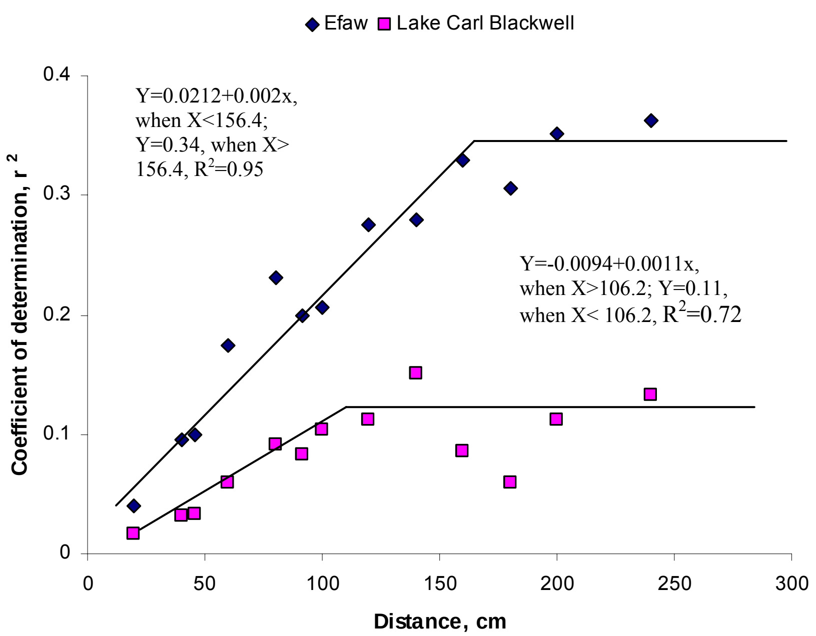

Figure A12. Correlation of grain yield and NDVI when both yields and NDVI were averaged over fixed distances, V10 stages, Efaw, and Lake Carl Blackwell, 2005. The models at Efaw and Lake Carl Blackwell are significant at $p<0.001$ and $p<0.01$, respectively.

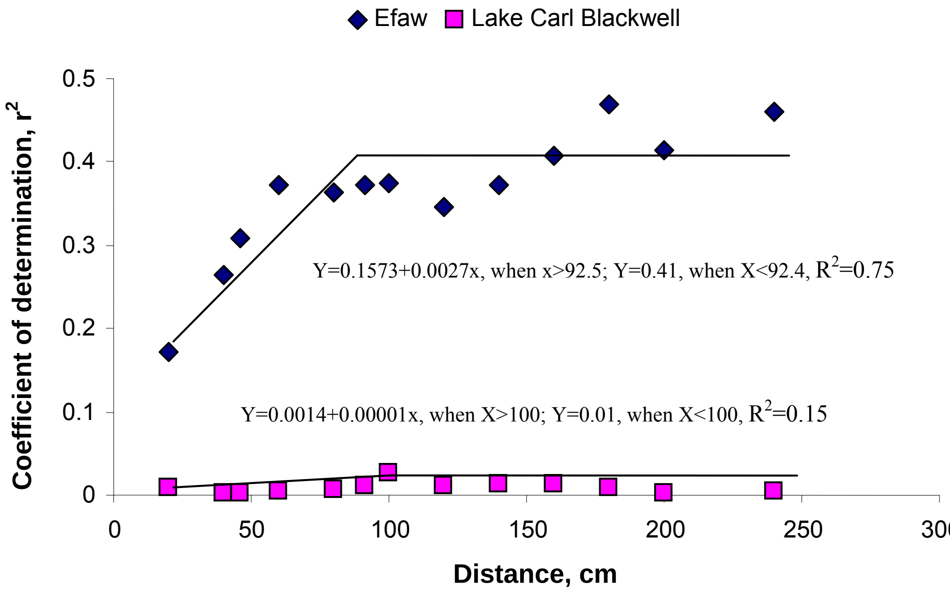

Figure A13. Correlation of grain yield and NDVI when both yields and NDVI were averaged over fixed distances, V6 stages, Efaw, and Lake Carl Blackwell, 2006. The models at Efaw and Lake Carl Blackwell are significant at $p<0.01$ and $p>0.1$, respectively.

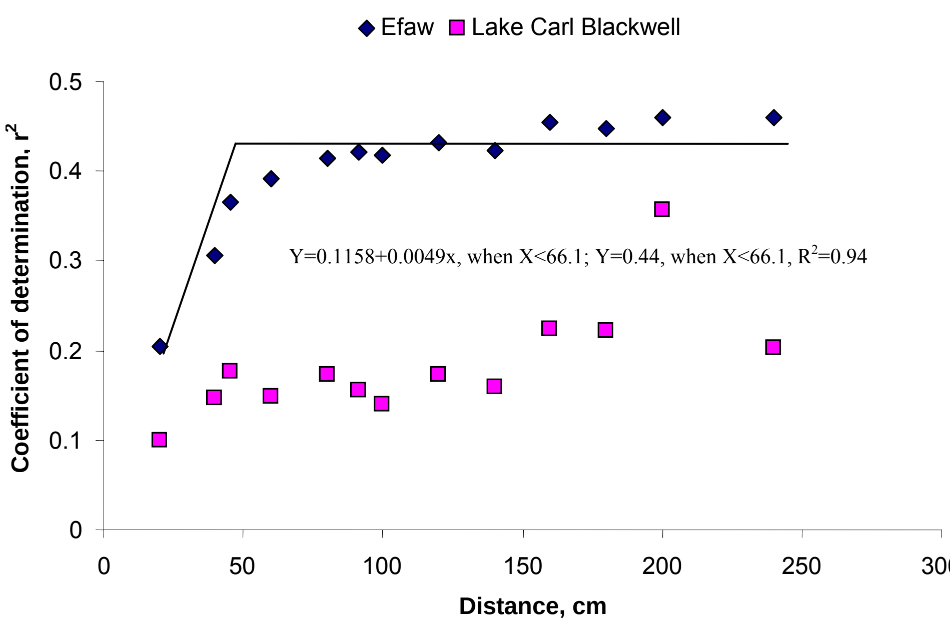

Figure A14. Correlation of grain yield and NDVI when both yields and NDVI were averaged over fixed distances, V8 stages, Efaw, and Lake Carl Blackwell, 2006. The model at Efaw is significant at $p<0.001$.

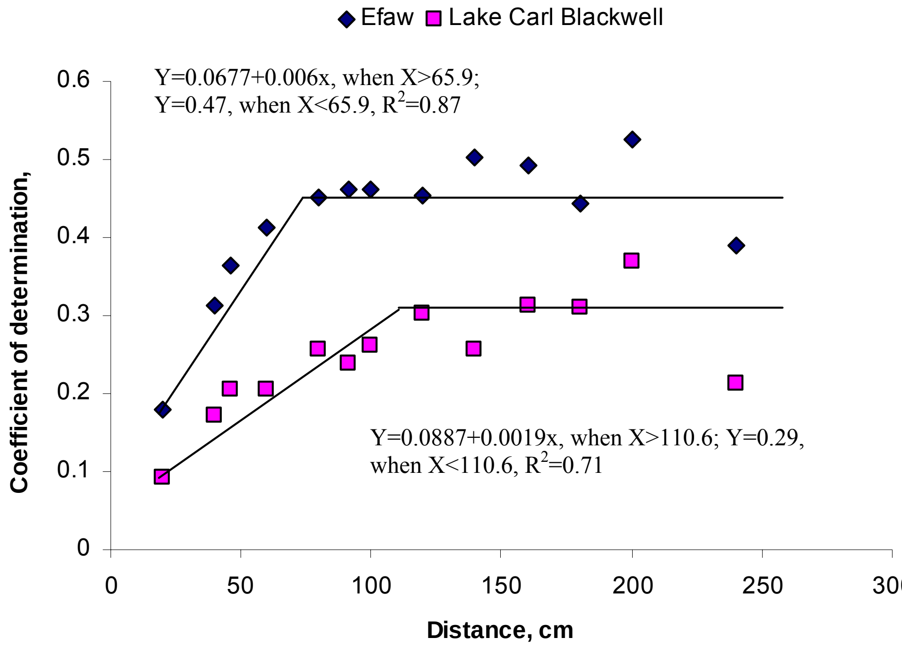

Figure A15. Correlation of grain yield and NDVI when both yields and NDVI were averaged over fixed distances, V10 stages, Efaw, and Lake Carl Blackwell, 2006. The models at Efaw and Lake Carl Blackwell are significant at $p<0.001$ and $p<0.01$, respectively.

VITA

Byungkyun Chung

Candidate for the Degree of

Doctor of Philosophy

Dissertation: CHANGES IN RESPONSE INDICES AS A FUNCTION OF TIME IN WINTER WHEAT (*Triticum aestivum* L.), AND USE OF OPTICAL SENSORS FOR DETECTING YIELD DIFFERENCES AT DIFFERENT RESOLUTIONS IN CORN (*Zea mays* L.)

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Experience: Employed by Oklahoma State University, Department of Plant and Soil Sciences as a graduate research assistant, 2003 to present.

Name: Byungkyun Chung Date of Degree: May, 2007

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: CHANGES IN RESPONSE INDICES AS A FUNCTION OF TIME IN WINTER WHEAT (*Triticum aestivum* L.)AND USE OF OPTICAL SENSORS FOR DETECTING YIELD DIFFERENCES AT DIFFERENT RESOLUTIONS IN CORN (*Zea mays* L.)

Pages in Study: 71 Candidate for the Degree of Doctor of Philosophy

Major Field: Soil Science

Scope and Method of Study: For chapter one, a study on hard red winter wheat was conducted to determine the nitrogen (N) responsiveness using a response index (RI) as a function of time at 5-locations over a 3-year period. Response index was plotted against days where growing degree days (GDD) were more than zero to determine the ideal stage for predicting RI. Sensor NDVI (normalized difference vegetation index) readings from a non-N limiting strip divided by the farmer practice was used to estimate RI_{NDVI}. Subplots (2 m^2) were established within five existing long-term trials employing a randomized complete block design. From each plot, Greenseeker^{TM} NDVI sensor readings were collected at various growth stages where RI_{NDVI} was subsequently determined. For chapter two, experiments were conducted to determine the optimum resolution for prediction of corn grain yield. Four corn rows, 30 m in length, were randomly selected at three locations in 2004, and 15 m length with 8 rows at two locations in 2005 and 2006. A GreenSeeker optical sensor was used to determine average NDVI across number of plants and over 12 fixed distances. Individual corn plants were harvested and grain yield was determined. Correlation of corn grain yield versus NDVI was evaluated over increasing distances and increasing number of corn plants.

Findings and Conclusions: For chapter one, RI_{NDVI} increased with advancing stage of growth. Excluding Stillwater 2006 and Perkins 2005, the relationship between RI_{NDVI} and GDD>0 was positive and highly correlated. The relationship between RI_{NDVI} and $RI_{Harvest}$ was best described using exponential equations. Averaged over years and sites for all growth stages, the correlation of RI_{NDVI} and $RI_{Harvest}$ was positive and increased up to Feekes 8. For chapter two, the linear-plateau model coefficient of determination (R^2) was maximized when averaged over every 4-plants in 2004 and 2006, and over 11-plants in 2005. Likewise, R^2 was maximized at a fixed distance of 95, 141, and 87 cm in 2004, 2005, and 2006, respectively. Based on the results collected, we recommend 95 cm or alternately, 4-plants as the optimum resolution for detecting early-season differences in yield potential and making management decisions.

ADVISOR'S APPROVAL: ___Dr. William Raun___