# EFFECT OF ROW SPACING, GROWTH STAGE, AND NITROGEN RATE ON SPECTRAL IRRADIANCE IN WINTER WHEAT

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## INTRODUCTION

Improving field management techniques can increase productivity and reduce the environmental impact of modern agriculture. A problem of efficient field management is applying fertilizers where they are needed and in sufficient, but not excessive, amounts. Scientists as well as field practitioners have observed that soil nutrient levels vary within fields. Nevertheless, fertilizers are usually applied uniformly based on one composite soil sample from each field. Thus, the entire field receives the same fertilizer rate. Sawyer (1994) highlighted the concepts of variable rate technology (VRT) and indicated that the major factors which constrain VRT on a large scale are: (i) the cost of implementation (sampling, mapping, equipment, personnel); (ii) lack of expected increase in crop yield; and (iii) lack of input savings. Also, Sawyer (1994) suggested that interpretation of data and reliable recommendations should be of major concern for further study. He stated that determination of crop yield variability with on-the-go sensors was still futuristic. However, work by Stone et al. (1996) demonstrated that it would be possible to use on-the-go sensing methods to monitor soil and yield variability.

It is advisable to know the optimum field element size before applying variable fertilizer rates. Solie et al. (1996) showed that the optimum field element size could be less than $1m^2$, and that variable rates should be adjusted to the resolution of $1m^2$ in order to optimize fertilizer inputs. They defined field element size as the "area which provides the most precise measure of the available nutrient where the level of that nutrient changes with distance". In other words, the area on which a single rate of nutrient fertilizer is applied represents the field element size. Raun et al. (1998b) observed soil test variability for immobile and mobile nutrients on a submeter level (0.3 x 0.3 m). Taking into account significance of variation in nutrient content among small areas, application of variable fertilizer rates could be highly beneficial in precision farming since variable rates increase fertilizer use efficiency, and could considerably reduce fertilizer contamination of the environment (Raun et al, 1998a).

## LITERATURE REVIEW

The successful use of spectral irradiance in variable rate technology depends on a better understanding of indices that predict spatial distribution of yield limiting factors within a field. Application of reflectance measurement devices in agriculture began in the 1970s, when near infrared spectrometers were used to measure chlorophyll content in plant leaves, and moisture content in forage and plant samples. In 1978, Karl H. Norris received the Alexander Von Humboldt award for inventing the near infrared reflectance spectroscopy (NIRS) analyzer (Pierce and Sherman, 1985). The analyzer measures the vibration induced by stretching and bending of hydrogen bonds with nitrogen, oxygen and carbon. These bonds have specific light-absorption characteristics in the near infrared region that can be used as an estimate of plant nitrogen (N) status (Pierce, and Sherman, 1985). Coleman et al. (1985) used near-infrared reflectance spectroscopy (NIRS) to predict species composition of forage mixtures. They found that NIRS gave an accurate estimation of species composition and had a "potential for estimating species composition from ground samples of pasture and conserved forages". Near-infrared analysis (NIRA) proved to be a reliable and rapid method for N content prediction in cotton leaves (Saranga et al., 1998). The critical issue for application of the NIRA method in measuring N status was to determine analytical limitations under various conditions such as sample moisture content, deficiency of other nutrients, growth regulator application, etc. Hattey et al. (1994) applied NIRS to evaluate N and starch content of dry, ground cotton leaves. They concluded that NIRS could be used to predict N and starch content of cotton leaves in a rapid non-destructive method with no greater loss of accuracy than laboratory measurements.

Wood et al. (1992) used a hand-held chlorophyll meter (SPAD-502) for N status evaluation in corn. The method of chlorophyll content measurement is based on the light attenuation difference through leaves at wavelengths of 430 nm, the spectral transmittance peak for chlorophyll *a* and *b*, and 750 nm, the near infrared region. The results of this experiment showed that chlorophyll meter measurements were highly correlated with tissue N concentrations at V10 (10-leaf stage) and midsilk growth stages. Significant relationships between SPAD readings and corn grain yield suggested that chlorophyll measurements could be a good predictor of corn grain yield.

Thomas and Oerther (1972) used a "Beckman Model DK-2A spectrophotometer" to estimate a relationship between N content and spectral data obtained from the 500 to 2500 nm region. They reported the ability to predict leaf N content in sweet peppers (*Capsicum annum*, L. var. 'Yolo Wonder') from reflectance measurements at 550 nm (green) and 675 nm (red) because of the direct relationship between N and chlorophyll concentration in leaf tissue. Later, Thomas and Gausman (1977) showed that 550 nm was superior to 450 and 670 nm wavelengths to predict the leaf chlorophyll content. They concluded that concentration of carotenoids does not affect the reflectance sensitivity to chlorophyll content in leaves of cantaloupe (*Cucumis melo* L. cv. *Reticulatus* Naud.), corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), cucumber (*Cucumis sativus* L.), lettuce (*Lactuca sativa* L. cv. *Capitala* L), sorghum (*Sorghum bicolor* (L.) Moench), spinach (*Spinacia oleracea* L.), and tobacco (*Nicotiana tabacum* L.).

Kleman and Fagerlund (1987) investigated the relationship between spectral signature of barley (*Hordeum distichum* L.) and various growth factor conditions like irrigation and fertilizer treatments. They selected spectral reflectance factors $R(\lambda)$ with values of $\lambda$ equal to 480, 560, 680, 800, 1650, and 2150 nm as indicators of biomass and grain yield for experimental plots. To find better relationships between the state of vegetation and the spectral signatures of plants, they studied different ratios of those bandwidths, and particularly:

$$IR/red = R(800)/R(680), \text{ and } R(800)/R(1650) \text{ in mid infrared range.}$$

Another indicator of water status and biomass was defined as Z or the blue color coordinate, which is: $Z = \frac{R(480)}{R(480)+R(560)+R(680)}$. They concluded that IR/red ratio was related to the amount of biomass and barley grain yield. The Z coordinate better indicated the difference between irrigated and non-irrigated treatments. Comparing different spectral indices with chlorophyll *a* content, N concentration, and leaf area index, Filella et al. (1995) found significant correlation between canopy chlorophyll *a* content and R550, R680, and all red edge parameters. Chlorophyll *a* content was found by multiplying chlorophyll *a* concentration by leaf area index. The reflectance at both 550 and 680 nm correlated with chlorophyll *a* concentration, however, reflectance at 550 nm had a higher sensitivity for chlorophyll *a*.

Blackmer et al. (1994) studied light reflectance of corn leaves from plots with different N treatments within the 400-700 nm range. The ability to evaluate differences in N treatments was best at 550 nm. They found relatively strong correlation between reflectance readings near 550 nm and grain yield. Later, Blackmer et al. (1996) studied reflected radiation from irrigated corn canopies with different N treatments at the R5 (dent) physiological growth stage. They stated that absolute scale measurements were affected by many factors, such as sensor and illumination angles, solar radiation and canopy architecture. To avoid the interference of illumination factors, the data were referenced to the radiation measurements taken from the plot with highest N application (relative reflectance was set equal to 1 for this plot). Measurements at 550 and 710 nm were the most sensitive to N treatment and highly correlated with grain yield. A ratio of 550 or 710 nm to 800-900 nm also showed high correlation with relative grain yield. However, single wavelength reflectance measurements had significant hybrid by N interactions. In the same work, Blackmer et al. (1996) used reflected radiation expressed as a ratio of red/NIR to demonstrate differences in N status of several corn hybrids. Here, reflectance was measured from plant canopies as the ratio of [(550-600)/(800-900)]. The idea to use ratios implied that there might be an advantage of compensating for other factors such as light conditions, soil background reflectance and canopy architecture.

Studying radiometric characteristics of winter wheat (*Triticum aestivum* cv. Astral) under various N and water supply, Fernandez et al. (1993) concluded that NDVI was better related to the leaf area and leaf area index (LAI) than to N and chlorophyll content. In his study, spectral measurements were taken with a hand-held field radiometer (Model Mark II) with nine filters at wavelengths from 400 to 2200 nm. NDVI (normalized difference vegetative index (NIR - red/NIR + red)) was calculated using 660 nm in red and 842 nm in infrared bandwidth.

Wanjura and Hatfield (1987) studied the sensitivity of several vegetative indices (VI) based on spectral irradiance. They also indicated that VI (NIR/red) and NDVI had relatively high correlation with fresh and dry biomass for cotton (*Gossypium hirsutum* L.), soybeans (*Glycine max* L.), sunflower (*Helianthus annus* L.) and grain sorghum (*Sorghum bicolor* L.). They pointed out that sensitivity of the latter two indices was higher when plants were in the early stages of growth, due to the contribution of the ground reflectance.

Perry and Lautenschlager (1984) indicated that spectral measurements made from satellites were influenced by vegetative characteristics as well as by soil background and atmospheric conditions. Green vegetation had higher reflectance in the infrared spectrum over the soil background from 750 nm and up (Deering et al., 1975). Lawrence and Ripple (1998) assessed several indices, SR, and NDVI among them, and demonstrated high correlation of those indices with green vegetation cover. They showed good predictability of green vegetation cover by NDVI = (Band4 - Band3) / (Band4 + Band3), and SR = Band4 / Band3 where Band4 was 760 – 900 nm and Band3 was 630 – 690 nm. Tucker (1979) found high sensitivity of IR/red ratio, square root of the IR/red ratio, IR – red difference, NDVI = [(IR - red)/(IR + red)], and transformed vegetation Index (TVI) = $(NDVI+0.5)^{1/2}$ to the amount of photosynthetically active vegetation present in the plant canopy. These indices showed similar applicability for biomass evaluation. Among the tested indices were DIF/SUM = [(IR – red)/(IR + red)] similar to NDVI and VI = [(IR + red)/(IR - red)] similar to PNSI. Coefficients of determination for the simple regression of canopy variables – total wet biomass, total dry biomass, leaf water content and green biomass on VI and SUM/DIF spectral indices ranged from 0.88 to 0.96. However, these indices did not explain the variability in dry brown biomass. Coefficients of determination for the simple regression of dry brown biomass on VI and SUM/DIF were equal to 0.56 and 0.22, respectively. Todd et al. (1998) studied biomass estimation on grazed and ungrazed rangelands using spectral indices. NDVI and Red indices worked differently on ungrazed versus grazed sites. Todd determined that red bandwidth and NDVI indices gave good biomass estimation on grazed sites. However, on ungrazed sites, NDVI poorly correlated with standing crop, while Red index still worked. This effect could be explained by the presence of dead vegetation on ungrazed sites. Therefore, Red index was a better estimator of biomass on ungrazed sites compared to NDVI. Comparing spectra from senesced and live corn leaves, Gausman et al. (1976) found a significant difference in intensity of the NIR band. Dead leaf tissue had an upward–sloping curve over the range 500 – 1500 nm, whereas green vegetation had a trough in the red (600 - 650 nm) region and a steep plateau over the 700 – 1200 nm region.

One of the factors affecting spectral measurements is soil moisture. Jackson et al. (1983) showed that dry soil had higher reflectance in the visible and near infrared regions than wet soil. The visible and near-IR measures changed proportionally to soil water content, with no apparent changes in greenness on soils with no vegetation. When soil is partially covered with vegetation, more of the near-IR reflectance from plant canopy interacts with that of the underlying soil due to transmittance through vegetation. Therefore, variations in soil water content will affect measurements in the near-IR region more than in the visible band, leading to corresponding changes in the reflectance signal. The 40 – 80 percent ground coverage range showed the most prominent effect of soil moisture on the near - IR measurements.

Stone et al. (1996) used the plant nitrogen spectral index (PNSI) in winter wheat fields where visual N differences were known to exist. Sensor readings were obtained *in-vivo*, from irradiance measurements of the wheat canopy. The narrow bandwidths 780 $\pm$ 6 nm for NIR and 671 $\pm$ 6 nm for red were used to calculate PNSI using the equation [(NIR + red)/(NIR - red)]. They found high correlation between PNSI and total forage N uptake. They utilized PNSI readings to abate spatial variation among the fields and found smaller variance in grain and forage yield compared to a fixed N application rate.

Spectral irradiance readings are affected by amount of green biomass under the sensor's view, or biomass density. Jackson (1983) pointed out that "as vegetation grows on the soil, the red radiance decreases and near infrared increases". Studying the relationship of physiological growth stages with reflectance of wheat cultivars, Leamer et. al. (1980) found that as ground cover reached more than 25 percent, the reflectance curves of the experimental plots, acquired the characteristic shape for vegetated surfaces with relatively low reflectance in visible (400 to 700 nm) and sharply increasing in the near infrared (750 to 1350 nm) region. Reflectance in the near – infrared region (750 to 1350 nm) was correlated with wheat stage of physiological development until crop reached Feekes growth stage 9. As soon as wheat reached Feekes growth stage 9 no further vegetation development took place and lower leaves started to lose chlorophyll, turning brown, resulting in lower near infrared reflectance measurements. They concluded that the near infrared region at wavelengths 750 to 1350 nm was the best indicator of plant growth.

In early experiments with visible and infrared reflectance from wheat canopies, Stanhill et al. (1972) suggested that the difference in crop absorbivity could be accounted for by differences in the amount of the biomass and degree of ground cover. Therefore, application of N fertilizer could affect spectral measurement from wheat canopies by altering the optical properties of plant material due to changes in the amount of plant biomass, the percent of vegetation coverage, and the posture and structure of the plants. Spectral irradiance from plant canopies is highly dependent on the optical properties of the underlying soil and which fluctuate considerably with soil type. Heilman and Kress (1986) measured the spectral irradiance of different types of soil, a highly reflecting Padina fine sandy loam, an intermediate reflectance Norwood silt loam, and a low reflectance Houston Black sandy clay. They found that the soil background reflectance at the intermediate levels, 50 to 75 percent, of soil coverage includes a significant component of the irradiance transmitted through plant canopies. This effect was not observed at the coverage densities less than 40 percent, which suggested that below this level the soil irradiance could not be significantly affected by vegetation. Huete et al. (1985) indicated that soil background influences on canopy reflectance would approach a maximum level at low vegetation densities. The effect of difference in soil brightness on spectral response was greater at higher level of vegetation coverage, 60 to 75 percent, than at the lower ones, when the NIR/red ratio was used as an indicator of greenness. The normalized difference NDVI = (IR – red)/(IR + red) and transformed normalized difference (TND) equal to $(NDVI + 0.5)^{1/2}$ were independent of soil influence when vegetation coverage was greater than 75 percent.

Huete (1987) studied the contribution of soil background reflectance from plots with variable canopy coverage. The first order interaction model was applied to separate vegetation (*Gossypium hirsutum*) and soil–dependent components. He measured the reflectance over cotton canopies during the vegetation period (percent coverage changed from 1 to 100%). To create different soil backgrounds, four types of soil placed in trays were slid below the plant canopies. Huete (1987) showed that the soil component of the total soil–canopy reflectance became negligible only when the percent vegetation coverage was over 92 percent. In this study, separate soil and canopy spectral components for NIR/red, the perpendicular vegetation index (PVI) and 7-band greenness vegetation indices were evaluated. The NIR/red ratio index included mixed soil–dependent and vegetation–dependent components, and was constant only at low levels of vegetation coverage. Huete (1987) described the spectral response from bare soil in the visible part of the spectrum as the "greenness signal", or the signal that had the shape similar to that obtained from green vegetation. In his study with the soils of various colors, he found that darker soils had higher absorbance and provided higher vegetation–like signals in the NIR/red band, when light colored soils with brighter reflectance produced a higher greenness signal when the PVI and green vegetation index (GVI) were used.

The biomass density may vary with different row spacings, seeding rates and growth stages of a crop. When 15.2 cm row spacing is used, a 100 m width field contains 656 rows. However, at 30.5 cm row spacing, this number two times less. Plants growing in wider rows have more room and nutrients to form larger canopies.

Lafond (1994) found that the number of plants and spikes varied with different row spacings. The wider the row spacing, the fewer plants and spikes produced. However, wide row spacings resulted in more kernels per spike. Grain yield increased by 3 percent at the low N rate with 30 cm row spacing compared to that of 10 cm, and the opposite was found at the high N rate. Row spacing 10 cm wide had a 2 percent increase in yield versus the 30 cm row spacing. Nevertheless, the interaction of N and seeding rate was significant for durum wheat and spring wheat yields because of a positive seeding rate response to increased N application.

Koscelny et al. (1990, 1991) found that increasing seeding rate from 67 to 134 kg $ha^{-1}$ increased yield of cheat *(Bromus secalinus)* free and cheat infested winter wheat seeded in late October. They did not find a significant yield difference between row spacings of 7.5 and 15 cm; although the further widening of the distance between rows to 22.5 cm led to a decrease in grain yield by 8%. The best grain yield was at a seeding rate of 101 kg $ha^{-1}$, which was 3.5 percent greater than the yield at 67 kg $ha^{-1}$, but which was not significantly different from a seeding rate of 134 kg $ha^{-1}$. However, on fields highly infested with cheat, decreasing row spacing and increasing the seeding rate led to higher wheat grain yields.

Johri et al. (1992) studied nutrient uptake by different categories of weed and the availability of nutrients to wheat related to different management practices. They found that a higher seeding rate (150 kg $ha^{-1}$) and a row spacing of 15 cm, compared with 22 cm, did not greatly affect the N uptake by wheat, however, it did significantly decrease weed N removal.

## OBJECTIVES

The main objective was to determine the critical percentage of vegetation coverage needed for precise forage N uptake calibration with indirect spectral irradiance measurements. Secondary objectives of this study were: to estimate the soil background interference with the spectral irradiance of wheat; to determine soil background interference relationship with soil color; to evaluate how differences in vegetation cover affect soil background interference; and to evaluate the impact of each of these variables on calibration of indirect spectral measures with wheat forage N uptake.

## MATERIALS AND METHODS

Two field experiments with winter wheat (*Triticum aestivum* L.) "Tonkawa" were planted in the beginning of October, 1996 and 1997 at Perkins, Oklahoma on a Teller sandy loam (Udic Argiustoll) and at Tipton, Oklahoma on a Tipton silt loam (Pachic Argiustoll). Initial surface (0-15 cm) soil chemical characteristics are reported in Table 1. The color of the Perkins soil (dark brown 10YR 4/3) is lighter than that of Tipton (very dark grayish brown 10YR 3/2), therefore providing variable soil background interference. Soil color depends on soil moisture, therefore soil moisture was measured gravimetrically whenever spectral readings were taken. Each plot was 2.6m x 6.1m. A complete factorial arrangement of N rate and row spacing treatments were randomly distributed withing row spacings as main plots in three replications. Four N rates of 0, 56, 112, 168 kg N $ha^{-1}$ as ammonium nitrate were applied before planting. Planting, and harvest dates for forage and grain are reported in Table 2.

To estimate the influence of soil background interference, treatments with the same plant density but different row spacings and therefore various seeding rates were used. The seeding rates were 98.6, 79.5, 59.4 and 49.3 kg $ha^{-1}$, at row spacings of 15.2, 19.0, 25.4 and 30.5 cm, respectively. Percent vegetation coverage was estimated using images taken with a Kodak DC40 Digital Camera with resolution 756 x 504 pixels. The estimation of percent vegetation coverage was performed as per the method of Lukina et al. (1998). Digital images were converted from 8-bit red green blue (RGB), tagged image file format (TIFF) to binary pseudo-color images and percent of pixels corresponding to the vegetation color was estimated and used as the percent coverage for each plot. Spectral irradiance readings were taken from wheat canopies using an integrated photodiode-based sensor with interference filters for red (671 $\pm$ 6 nm) and near infrared (780 $\pm$ 6 nm) wavelengths, developed at Oklahoma State University (Stone et al., 1996). Spectral irradiance readings, digital images, and forage yield were collected from 0.91m x 0.91m areas at Feekes growth stage 4 (pseudo-stem erect) and 5 (leaf sheath starts to lengthen) at both locations and years (Large, 1954). Wet and dry forage weights were measured and then ground to pass a 140 mesh screen. Grain was harvested from 2.0m x 6.1m area. Sensor readings in red and near infrared bandwidths were collected from all plots of these two sites. NDVI was calculated using the formula: NDVI = (NIR - Red)/(NIR + Red). Spectral irradiance readings collected from each 0.84 $m^2$ area within each plot (average of 9 readings per plot) were further evaluated. In order to determine within plot variability, the coefficient of variation on these by-plot spectral irradiance readings was computed. The relationship between plot CV's and vegetation coverage was then determined using linear regression. Total N content in forage and grain was analyzed using a Carlo-Erba NA 1500 dry combustion analyzer (Schepers et al., 1989). Statistical analysis was performed using SAS software (SAS Institute, 1985).

# RESULTS

Analysis of variance and treatment means by year and location for forage dry matter, NDVI, percent vegetation coverage, forage N content and N uptake at Feekes growth stage 4 and 5, and grain yield are reported in Tables 3 – 10. Single-degree-of-freedom contrasts are also included in each AOV table. With few exceptions, no significant interaction between N rate and row spacing was observed for forage dry matter, vegetation coverage, NDVI, forage N content, total N uptake, grain yield, grain N content, and grain N uptake at either location, year or stage of growth, thus allowing interpretation of main effect means.

<u>Forage dry matter yield</u>

Forage dry matter yield increased with increasing N rate at all locations, years and stages of growth (significant N rate linear contrast) excluding Perkins, Feekes growth stage 4, in 1997-98. Forage dry matter yield increased with decreasing row spacing (Tables 4, 6, 8, 10). However, this was not always consistent. In 1996-97 at Feekes growth stage 4, row spacing had a significant influence on forage dry matter yield at both locations. Nevertheless, at Feekes growth stage 5, row spacing had little effect on dry matter yield probably because plants were able to form more tillers in the wide row spacings at the later stage of growth. In 1997-98, results were inconsistent with those of the first year of study. At Tipton and Perkins, dry matter yield decreased with increasing row spacing at both growth stages.

<u>Vegetation coverage</u>

Vegetation coverage increased with increasing N rate, and decreased with wider row spacings (Tables 4, 6, 8, 10). Excluding Feekes growth stage 4 at

Perkins, in 1996-97, no interaction between N rate and row spacing was found for percent vegetation coverage.

Regardless of the growth stage, vegetation coverage decreased with increasing row spacing at both locations. Percent vegetation coverage increased with increasing N rate at Perkins Feekes growth stage 4, in 1997-98. Wide row spacing and low N rate resulted in lower vegetation coverage compared to that of narrow row spacing and high N rate.

At Tipton, percent vegetation coverage ranged from 51.8 to 98.5 throughout the experiment. However at Perkins, variability in percent vegetation coverage ranged from 13.3 to 98.5. Over 90 percent of all experimental plots had less than 50 percent vegetation coverage at Perkins, Feekes growth stage 4, in 1997-98.

NDVI

Analysis of variance showed that row spacing and N rate significantly affected NDVI at Feekes growth stage 4 (Table 3, 5, 7, 9). In general, NDVI increased and then decreased at the highest N rate (significant quadratic response at 5% level) at Perkins. A significant quadratic response of NDVI to row spacing was not observed at the Perkins location, Feekes growth stage 4, 1997-98.

At Feekes growth stage 5, N rate and row spacing affected spectral measurements differently. NDVI increased with increasing N rates regardless of growth stage at both locations (significant linear response at 1% level). At Tipton, Feekes growth stage 5, 1996-97, NDVI had a quadratic relationship with N rate, and increased up to 112 kg $ha^{-1}$.

Forage N content

Forage N content tended to increase with increasing row spacing and N rate (Tables 4, 6, 8, 10). Treatment means showed that the highest N content were found at the widest (30.5 cm) row spacing and at the highest N rate at all locations, years, and stages of growth. Forage N content was affected by row spacing and N rate at both locations, at Feekes growth stage 4. At Feekes growth stage 5, row spacing no longer affected N content at Perkins.

Total N uptake

Total N uptake in wheat forage at Feekes growth stage 4 was highest at the 168 kg $ha^{-1}$ N rate. The highest total N uptake tended to be on the narrowest (15.2 cm) row spacing (Table 4, 6, 8, 10). Total N uptake increased with increasing N rate at both locations, years and stages of growth. Total N uptake was significantly influenced by row spacing at Feekes growth stage 4, but this effect was less pronounced by Feekes 5 (Table 4), probably due to tillering.

Grain yield, grain N content, and total grain N uptake

In 1996-97, grain yield, grain N content and total grain N uptake increased with increasing N rate, while row spacing had no effect on those same variables at both locations. In 1997-98, Tipton, grain yield was affected by row spacing as well as N rate; however, grain N content and total grain N uptake had no response to row spacing. Grain yield increased with increasing N rate. The highest grain yields were observed on the narrowest, 15.2 cm, row spacing; however, there was no definite relationship between grain yield and row spacing. Excluding Perkins in 1996-98, where grain yield, and total grain N uptake were independent of N rate and row spacing, all yield variables were significantly affected by N rate.

## DISCUSSION

Spectral readings in the red and near infrared bandwidths were affected by both biomass and bare soil surface. Irradiance from bare soil and wheat canopy plots measured using the spectrometer is illustrated in Figure 1. Bare soil had higher reflectance in the visible region of the spectra and lower in near infrared when compared with that of the green wheat canopy. Because NDVI is a combination of irradiance in red and near infrared bandwidths, this is affected by the portion of the area covered by green plants under the sensor view. Therefore, bare soil can significantly decrease NDVI. At Tipton, NDVI values for bare soil ranged from 0.114 to 0.121 at 14 percent soil moisture. At Perkins, spectral data were measured at 9 percent soil moisture, and NDVI ranged from 0.127 to 0.165.

Most of the time, greenness expresses plant N sufficiency. Although NDVI values depended on amount of green vegetation, variation in tissue N content and/or dry matter alone did not explain all the variability in spectral index. Pearson correlation coefficients for NDVI and forage N content ranged from 0.04 to 0.61, and between NDVI and forage dry matter ranged from 0.33 to 0.80. Changes in either tissue N content or dry matter considerably affected spectral measurements. Vegetation density was higher at narrow row spacings and resulted in higher NDVI values compared to those of wide row spacings. On the other hand, plants from high plant density plots may assimilate fewer nutrients, particularly N, per plant. For instance, at Perkins, Feekes growth stage 5 in both years, fertilized plots with wide row spacing (30.5 cm) had high forage N content and low dry matter compared to plots with other narrow spacings (Tables 6 and 10). A combination of these factors possibly diminished NDVI variation due to row spacing. The complex impact of dry matter and forage N content can be taken into account by including another variable (total N uptake) in the analysis. Since total N uptake is a product of forage N content and dry matter, it should be a better predictor of NDVI. The correlation coefficients between NDVI and total N uptake were considerably higher than those of NDVI and N content or NDVI and biomass, and ranged from 0.47 to 0.83 (Table 11). Due to high infestation of annual ryegrass in the experimental field at Perkins, correlation's between NDVI and forage N content were poor. Correlation coefficients between grain yield and NDVI showed promising results in term of predicting grain yield. They ranged from 0.32 to 0.71 (Table 12) and were considerably higher at Feekes growth stage 5 at both locations.

A highly significant linear relationship was observed between NDVI and vegetation coverage with correlation coefficients ranging from 0.80 to 0.98 (Figures 2 and 3). Changes in NDVI and vegetation coverage depending on N rate by different row spacings are illustrated in Figure 4. The patterns of these two charts were very similar, thus suggesting that NDVI was highly dependent on percent vegetation coverage. It was interesting to note that both NDVI and vegetation coverage increased with increasing N rate at the narrow row spacing for all locations years and stages of growth. NDVI and vegetation coverage estimates for the narrow row spacing were apparently less affected by soil background interference.

The ability to detect differences in N rates at early growth stage was better for the narrow row spacings with higher vegetation coverage, which resulted in higher NDVI values. The highest NDVI values in plots with no N were found for narrow row spacings (Figure 5).

Regression of the CV's from by-plot NDVI values on the percent vegetation coverage is illustrated in Figure 6. As vegetation coverage increased, the CV's from NDVI values decreased. These results suggest that less variable NDVI values (CV less than 10 %) might be obtained from plots where vegetation coverage exceeded 50 percent.

## CONCLUSION

To improve the calibration of NDVI with forage N uptake it is necessary to adjust for soil background interference. However, the critical vegetation coverage needed for precise forage N uptake calibration could not be determined from this work. This is largely because we seldom had any plots with less than 50 percent vegetation coverage, previously thought to be a breaking point in terms of calibration.

What was very exciting to show was that row spacing and N rate could be indirectly determined independent of one another since no significant interactions were detected. Row spacing did alter forage dry matter, NDVI, and N uptake; however, these were predictable based on vegetation coverage. In essence, vegetation coverage was a good predictor of the other dependant variables measured in this study (Table 13), which could indirectly be determined using NDVI regardless of row spacing.

Use of CV's on NDVI values showed some promise in being able to detect critical vegetation coverage, although this method will need to be further refined.

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Table 1. Initial surface (0-15 cm) soil chemical characteristics and classification at Perkins and Tipton, OK.

| Location | pH | $NH_4$-N | $NO_3$-N | P | K | Total N | Organic C |
|---|---|---|---|---|---|---|---|
| | ---------- mg kg$^{-1}$ ---------- | | | | | ---------- g kg$^{-1}$ ---------- | |
| Perkins | 5.41 | 2.6 | 9.1 | 16.5 | 132 | 0.79 | 7.00 |
| Classification: Teller sandy loam (fine-mixed, thermic Udic Argiustoll) | | | | | | | |
| Tipton | 7.39 | 4.4 | 8.6 | 31.8 | 462 | 0.86 | 8.30 |
| Classification Tipton silt loam (fine-loamy, mixed, thermic, Pachic Argiustoll) | | | | | | | |

pH – 1:1 soil:water, K and P – Mehlich III, Organic C and Total N – dry combustion.

Table 2. Planting and harvest dates, Perkins and Tipton, OK

| | Perkins | Tipton |
|---|---|---|
| Planting Date: | | |
| First year of study 1996-97: | October 4, 1996 | October 8, 1996 |
| Second year of study 1997-98: | October 21, 1997 | October 7, 1997 |
| | First year of the study | |
| Forage at Feekes 4: | | |
| Harvest area: | 0.91 x 0.91 m | 0.91 m x row spacing |
| Harvest date: | December 16, 1996 | January 21,1997 |
| Forage at Feekes 5: | | |
| Harvest area: | 0.91 x 0.91 m | 0.91 m x row spacing |
| Harvest date: | March 4, 1997 | February 4,1997 |
| Grain: | | |
| Harvest area: | 2.0 x 6.1 m | 2.0 x 6.1 m |
| Harvest date: | June 20, 1997 | June 13, 1997 |
| | Second year of the study | |
| Forage at Feekes 4: | | |
| Harvest area: | 0.91 x 0.91 m | 0.91 x 0.91 m |
| Harvest date: | February 24,1996 | January 27,1997 |
| Forage at Feekes 5: | | |
| Harvest area: | 0.91 x 0.91 m | 0.91 x 0.91 m |
| Harvest date: | April 6,1997 | February 26,1997 |
| Grain: | | |
| Harvest area: | 2.0 x 6.1 m | 2.0 x 6.1 m |
| Harvest date: | June 15, 1997 | June 3, 1997 |

Table 3. Analysis of variance and single-degree-of-freedom-contrasts for dry matter, NDVI, N content, total N uptake, percent vegetation coverage, and grain yield at Tipton, OK, Feekes growth Stage 4 and 5, 1996-97 crop year.

| Source of Variation | df | Feekes 4 | | | | | Feekes 5 | | | | | Grain | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Dry Matter | NDVI | Cover | N | N uptake | Dry Matter | NDVI | Cover | N | N uptake | yield | N | N uptake |
| | | *kg ha⁻¹* | | *%* | *g kg⁻¹* | *kg ha⁻¹* | *kg ha⁻¹* | | *%* | *g kg⁻¹* | *kg ha⁻¹* | *kg ha⁻¹* | *g kg⁻¹* | *kg ha⁻¹* |
| | | mean squares | | | | | | | | | | | | |
| Rep | 2 | 143564 | - | 20 | 34.6* | 232 | 282422 | 0.0058** | 38 | 27.6 | 1391* | 193769** | 0.7 | 241** |
| Row spacing | 3 | 3655993** | - | 282** | 86.5** | 2230** | 3914689** | 0.0019 | 76* | 167.4* | 1132* | 97278 | 1.7 | 125 |
| Rep * Row Spacing | 6 | 84220 | - | 8 | 4.1 | 123 | 150990 | 0.0018 | 10 | 32.4 | 187 | 34264 | 2.6 | 43 |
| N rate | 3 | 747123** | - | 674** | 133.1** | 3033** | 1447727** | 0.0571** | 757** | 92.5* | 3774** | 97265* | 8.3** | 143* |
| N rate * Row spacing | 9 | 94297 | - | 12 | 11.5 | 192 | 114772 | 0.0013 | 13 | 10.3 | 223 | 39978 | 2.0 | 46 |
| Residual | 24 | 114375 | - | 15 | 9.1 | 230 | 113660 | 0.0007 | 15 | 22.1 | 318 | 25583 | 1.7 | 33 |
| Contrast: | | | | | | | | | | | | | | |
| N rate linear | 1 | 2023088** | - | 1826** | 356.2** | 8884** | 3160904** | 0.1567** | 2161** | 257.3** | 9086** | 174830* | 18.5** | 314** |
| N rate quadratic | 1 | 200855 | - | 257** | 26.4 | 20 | 1178447** | 0.0105** | 99* | 13.8 | 2047* | 73756 | 4.9 | 53 |
| Row spacing linear | 1 | 244947 | - | 50* | 18.1 | 33 | 697211 | 0.0012 | 6 | 12.0 | 172 | 74927 | 3.4 | 106 |
| Row spacing quadratic | 1 | 440853 | - | 737** | 26.6* | 268 | 8178399** | 0.0013 | 203** | 481.8** | 509 | 3210 | 1.4 | 9 |

*, ** - significant at 0.05, and 0.01 probability levels, respectively.

Table 4. Treatment means for dry matter, NDVI, N content, total N uptake, percent vegetative coverage, and grain yield at Tipton, OK, Feekes growth stages 4 and 5, 1996-97 crop year.

| Treatment means | Feekes 4 | | | | | Feekes 5 | | | | | Grain | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dry Matter | NDVI | Cover | N | N uptake | Dry Matter | NDVI | %Cover | N | N uptake | yield | N | N uptake |
| | *kg ha*$^{-1}$ | | *%* | *g kg*$^{-1}$ | *kg ha*$^{-1}$ | *kg ha*$^{-1}$ | | *%* | *g kg*$^{-1}$ | *kg ha*$^{-1}$ | *kg ha*$^{-1}$ | *g kg*$^{-1}$ | *kg ha*$^{-1}$ |
| N rate | | | | | | | | | | | | | |
| 0 | 1970 | - | 72 | 32.1 | 62 | 2424 | 0.626 | 69 | 25.5 | 60 | 822 | 32.2 | 27 |
| 56 | 2248 | - | 82 | 32.2 | 70 | 2951 | 0.723 | 77 | 28.0 | 82 | 744 | 33.1 | 25 |
| 112 | 2483 | - | 87 | 36.2 | 90 | 3204 | 0.753 | 84 | 31.0 | 99 | 879 | 34.1 | 30 |
| 168 | 2503 | - | 89 | 38.7 | 96 | 3105 | 0.786 | 86 | 31.4 | 95 | 958 | 33.7 | 32 |
| Row spacing | | | | | | | | | | | | | |
| 15.2 | 2003 | - | 87 | 36.1 | 73 | 3325 | 0.728 | 81 | 25.4 | 85 | 936 | 33.5 | 31 |
| 19.0 | 2695 | - | 85 | 32.7 | 89 | 3270 | 0.726 | 81 | 26.4 | 88 | 760 | 32.7 | 25 |
| 25.4 | 2829 | - | 82 | 32.6 | 94 | 2998 | 0.732 | 78 | 30.7 | 93 | 787 | 33.4 | 26 |
| 30.5 | 1676 | - | 76 | 37.8 | 64 | 2092 | 0.703 | 75 | 33.4 | 70 | 920 | 33.5 | 31 |
| SED | 276 | - | 3 | 2.5 | 12 | 275 | 0.02 | 3 | 3.8 | 15 | 131 | 1.1 | 5 |
| CV | 15 | - | 5 | 9 | 19 | 11 | 3.7 | 5 | 16 | 21 | 19 | 4 | 20 |

SED – standard error of the difference between two equally replicated means.
CV – coefficient of variation, %

Table 5. Analysis of variance and single-degree-of-freedom-contrasts for dry matter, NDVI, N content, total N uptake, percent vegetation coverage, and grain yield at Perkins, OK, Feekes growth Stage 4 and 5, 1996-97 crop year.

| Source of Variation | df | Feekes 4 Dry Matter | NDVI | %Cover | N | N uptake | Feekes 5 Dry Matter | NDVI | %Cover | N | N uptake | Grain yield | N | N uptake |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *kg ha⁻¹* | | *%* | *g kg⁻¹* | *kg ha⁻¹* | *kg ha⁻¹* | | *%* | *g kg⁻¹* | *kg ha⁻¹* | *kg ha⁻¹* | *g kg⁻¹* | *kg ha⁻¹* |
| | | mean squares | | | | | | | | | | | | |
| Rep | 2 | 131752 | 0.0525** | 886** | 28.1 | 347* | 1401806* | 0.0389 | 983* | 61.4 | 286 | 283266* | 3.0 | 291** |
| Row spacing | 3 | 374867* | 0.0673** | 2199** | 5.5 | 423 | 946745 | 0.0218 | 792 | 65.6 | 379 | 37830 | 4.4 | 28 |
| Rep * Row Spacing | 6 | 69235 | 0.0042 | 84 | 47.1 | 185 | 1982018** | 0.0072 | 215 | 55.0 | 493 | 42443 | 1.9 | 49 |
| N rate | 3 | 394598* | 0.517** | 847** | 113.4* | 753** | 1891353** | 0.0618** | 1118* | 118.9** | 2556** | 441423** | 79.8** | 912** |
| N rate * Row spacing | 9 | 50611 | 0.0032 | 312** | 32.5 | 27 | 742845 | 0.0197 | 378 | 34.6 | 266 | 58823 | 1.5 | 52 |
| Residual | 24 | 95667 | 0.0057 | 85 | 36.5 | 92 | 388383 | 0.0118 | 271 | 22.5 | 275 | 52687 | 1.9 | 47 |
| Contrast: | | | | | | | | | | | | | | |
| N rate linear | 1 | 1041096** | 0.1132** | 1713** | 308.7** | 2071** | 4975949** | 0.1620** | 2913** | 344.3** | 6540** | 1154807** | 234.2** | 2575** |
| N rate quadratic | 1 | 132258 | 0.0417* | 871** | 41.7 | 227 | 694360 | 0.0074 | 341 | 5.6 | 875 | 160743 | 1.6 | 160 |
| Row spacing linear | 1 | 598441* | 0.0195 | 905* | 0.1 | 674 | 598504 | 0.0063 | 477 | 17.5 | 66 | 74370 | 2.2 | 27 |
| Row spacing quadratic | 1 | 523113* | 0.1821** | 5894** | 0.1 | 603 | 7764 | 0.0428* | 1877* | 133.5 | 522 | 6446 | 8.9 | 38 |

*, ** - significant at 0.05, and 0.01 probability levels, respectively.

Table 6. Treatment means for dry matter, NDVI, N content, total N uptake, percent vegetation coverage, and grain yield at Perkins, OK, Feekes growth Stage 4 and 5, 1996-97 crop year.

| Treatment means | Feekes 4 | | | | | Feekes 5 | | | | | Grain | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dry Matter | NDVI | Cover | N | N uptake | Dry Matter | NDVI | Cover | N | N uptake | yield | N | N uptake |
| | *kg ha$^{-1}$* | | % | *g kg$^{-1}$* | *kg ha$^{-1}$* | *kg ha$^{-1}$* | | % | *g kg$^{-1}$* | *kg ha$^{-1}$* | *kg ha$^{-1}$* | *g kg$^{-1}$* | *kg ha$^{-1}$* |
| N rate | | | | | | | | | | | | | |
| 0 | 724 | 0.445 | 52 | 29.3 | 22 | 1317 | 0.492 | 40 | 24.8 | 32 | 996 | 27.9 | 28 |
| 56 | 934 | 0.545 | 66 | 33.4 | 31 | 1829 | 0.536 | 49 | 27.2 | 47 | 1043 | 29.7 | 31 |
| 112 | 1105 | 0.593 | 71 | 35.2 | 38 | 2141 | 0.637 | 62 | 30.6 | 64 | 1146 | 32.4 | 37 |
| 168 | 1106 | 0.574 | 68 | 36.0 | 39 | 2172 | 0.632 | 60 | 31.6 | 61 | 1425 | 33.5 | 48 |
| Row spacing | | | | | | | | | | | | | |
| 15.2 | 1206 | 0.627 | 81 | 33.8 | 41 | 1850 | 0.631 | 67 | 26.8 | 47 | 1173 | 30.3 | 36 |
| 19.0 | 922 | 0.571 | 69 | 33.1 | 31 | 1796 | 0.580 | 54 | 27.3 | 48 | 1099 | 30.7 | 34 |
| 25.4 | 959 | 0.498 | 57 | 32.5 | 31 | 2245 | 0.531 | 46 | 28.2 | 59 | 1222 | 30.8 | 38 |
| 30.5 | 781 | 0.460 | 50 | 35.0 | 28 | 1570 | 0.556 | 46 | 32.0 | 50 | 1116 | 31.7 | 36 |
| SED | 253 | 0.06 | 7.5 | 4.9 | 7.8 | 509 | 0.09 | 13 | 3.9 | 14 | 187 | 1.1 | 6 |
| CV | 32 | 14 | 14 | 18 | 29 | 33 | 19 | 31 | 16 | 32 | 20 | 4 | 19 |

SED – standard error of the difference between two equally replicated means.
CV – coefficient of variation, %

Table 7. Analysis of variance and single-degree-of-freedom-contrasts for dry matter, NDVI, N content, total N uptake, percent vegetation coverage, and grain yield at Tipton, OK, Feekes growth Stage 4 and 5, 1997-98 crop year.

| Source of Variation | df | Feekes 4 Dry Matter | NDVI | Cover | N | N uptake | Feekes 5 Dry Matter | NDVI | Cover | N | N uptake | Grain yield | N | N uptake |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *kg ha⁻¹* | | *%* | *g kg⁻¹* | *kg ha⁻¹* | *kg ha⁻¹* | | *%* | *g kg⁻¹* | *kg ha⁻¹* | *kg ha⁻¹* | *g kg⁻¹* | *kg ha⁻¹* |
| | | mean squares | | | | | | | | | | | | |
| Rep | 2 | 905290 | 0.0047* | 55 | 2.6 | 643* | 91644 | 0.0005 | 13 | 12.1* | 14 | 244171** | 20.3 | 335 |
| Row spacing | 3 | 2754702** | 0.0247* | 647** | 37.5* | 737 | 713424 | 0.0053* | 94* | 19.6* | 240 | 1012520** | 5.5 | 358 |
| Rep * Row Spacing | 6 | 262818 | 0.0034* | 59 | 7.8 | 205 | 151925 | 0.0008 | 19 | 2.2 | 86 | 16017 | 14.7 | 286 |
| N rate | 3 | 977559** | 0.0505** | 1230** | 247.1** | 5578** | 3816692** | 0.0715** | 1419** | 211.3** | 6552** | 10746629** | 28.4* | 7306** |
| N rate * Row spacing | 9 | 345576* | 0.0017 | 48 | 28.5 | 134 | 178997 | 0.0013 | 50 | 6.5 | 133 | 73862 | 5.4 | 91 |
| Residual | 24 | 120219 | 0.0014 | 36 | 14.3 | 172 | 198971 | 0.0017 | 44 | 6.9 | 224 | 107509 | 8.8 | 161 |
| Contrast: | | | | | | | | | | | | | | |
| N rate linear | 1 | 2733500** | 0.1385** | 3314** | 673.0** | 15794** | 11166634** | 0.2105** | 4159** | 514.3** | 17671** | 30160943** | 66.4* | 20192** |
| N rate quadratic | 1 | 115841 | 0.0052 | 9 | 53.3 | 586 | 258650 | 0.0016 | 53 | 131.7** | 2316** | 1175454** | 12.3 | 1602** |
| Row spacing linear | 1 | 760768 | 0.0064 | 107 | 18.4 | 93 | 1124157* | 0.0026 | 29 | 0.1 | 562* | 1865983** | 7.9 | 952 |
| Row spacing quadratic | 1 | 7421570** | 0.0677** | 1800** | 79.0* | 2099* | 1002213* | 0.0089* | 241* | 50.2** | 95 | 501187** | 13.4 | 0.1 |

*, ** - significant at 0.05, and 0.01 probability levels, respectively.

Table 8. Treatment means for dry matter, NDVI, N content, total N uptake, percent vegetative coverage, and grain yield at Tipton, OK, Feekes growth stages 4 and 5, 1997-98 crop year.

| Treatment means | Feekes 4 | | | | | Feekes 5 | | | | | Grain | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dry Matter | NDVI | Cover | N | N uptake | Dry Matter | NDVI | Cover | N | N uptake | yield | N | N uptake |
| | *kg ha⁻¹* | | *%* | *g kg⁻¹* | *kg ha⁻¹* | *kg ha⁻¹* | | *%* | *g kg⁻¹* | *kg ha⁻¹* | *kg ha⁻¹* | *g kg⁻¹* | *kg ha⁻¹* |
| N rate | | | | | | | | | | | | | |
| 0 | 2717 | 0.652 | 66 | 22.1 | 59 | 1622 | 0.698 | 67 | 23.1 | 38 | 3031 | 18.5 | 56 |
| 56 | 3103 | 0.743 | 79 | 24.3 | 73 | 1947 | 0.782 | 80 | 23.9 | 46 | 3672 | 17.9 | 66 |
| 112 | 3205 | 0.757 | 79 | 26.2 | 82 | 2317 | 0.822 | 85 | 25.8 | 60 | 4013 | 20.0 | 80 |
| 168 | 3395 | 0.807 | 90 | 32.6 | 110 | 2936 | 0.882 | 93 | 33.5 | 97 | 5280 | 21.4 | 113 |
| Row spacing | | | | | | | | | | | | | |
| 15.2 | 3630 | 0.791 | 87 | 24.6 | 90 | 2171 | 0.813 | 84 | 25.9 | 59 | 4220 | 20.0 | 85 |
| 19.0 | 3338 | 0.761 | 82 | 25.6 | 86 | 2548 | 0.804 | 83 | 24.6 | 62 | 3579 | 19.9 | 72 |
| 25.4 | 2916 | 0.718 | 73 | 26.2 | 76 | 1972 | 0.803 | 81 | 26.1 | 51 | 4034 | 19.4 | 79 |
| 30.5 | 2536 | 0.689 | 72 | 28.8 | 74 | 2132 | 0.765 | 77 | 28.6 | 63 | 4162 | 18.5 | 78 |
| SED | 283 | 0.03 | 5 | 3 | 11 | 364 | 0.03 | 5 | 2 | 12 | 268 | 2 | 10 |
| CV | 11 | 5 | 8 | 14 | 16 | 20 | 5 | 8 | 10 | 25 | 8 | 15 | 16 |

SED – standard error of the difference between two equally replicated means.
CV – coefficient of variation, %

Table 9. Analysis of variance and single-degree-of-freedom-contrasts for dry matter, NDVI, N content, total N uptake, percent vegetation coverage, and grain yield at Perkins, OK, Feekes growth Stage 4 and 5, 1997-98 crop year.

| Source of Variation | df | Feekes 4 | | | | | Feekes 5 | | | | | Grain | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Dry Matter | NDVI | Cover | N | N uptake | Dry Matter | NDVI | Cover | N | N uptake | yield | N | N uptake |
| | | $kg\ ha^{-1}$ | | % | $g\ kg^{-1}$ | $kg\ ha^{-1}$ | $kg\ ha^{-1}$ | | % | $g\ kg^{-1}$ | $kg\ ha^{-1}$ | $kg\ ha^{-1}$ | $g\ kg^{-1}$ | $kg\ ha^{-1}$ |
| | | mean squares | | | | | | | | | | | | |
| Rep | 2 | 137329 | 0.0296 | 746* | 65.4** | 30 | 348764 | 0.0086 | 371 | 1.4 | 259 | 299394 | 3.4 | 105 |
| Row spacing | 3 | 95272 | 0.0131 | 119 | 42.2* | 47 | 462667* | 0.0233 | 446 | 16.2 | 202 | 258987 | 3.6 | 105 |
| Rep * Row Spacing | 6 | 54255 | 0.0087 | 94 | 5.3 | 40 | 88053 | 0.0112 | 274 | 7.0 | 56 | 82341 | 1.1 | 35 |
| N rate | 3 | 34543 | 0.0099 | 226 | 77.4* | 46 | 239014 | 0.0398* | 665* | 52.8** | 226 | 45736 | 23.0** | 112 |
| N rate * Row spacing | 9 | 49181 | 0.0024 | 50 | 46.7 | 14 | 157565 | 0.0099 | 125 | 8.6 | 82 | 194869 | 1.1 | 100 |
| Residual | 24 | 50373 | 0.0035 | 84 | 20.8 | 27 | 176719 | 0.0124 | 206 | 7.2 | 90 | 113021 | 1.3 | 52 |
| Contrast: | | | | | | | | | | | | | | |
| N rate linear | 1 | 9259 | 0.0130 | 352 | 215.1** | 86 | 104761 | 0.1054** | 1631** | 155.4** | 353 | 111317 | 68.0** | 335* |
| N rate quadratic | 1 | 77151 | 0.0151* | 276 | 9.3 | 48 | 606082 | 0.0126 | 362 | 0.6 | 320 | 24227 | 0.4 | 2 |
| Row spacing linear | 1 | 99559 | 0.0002 | 81 | 2.3 | 61 | 275658 | 0.0081 | 286 | 0.1 | 159 | 391712 | 0.2 | 213* |
| Row spacing quadratic | 1 | 161104 | 0.0370 | 276 | 121.3** | 61 | 1071807* | 0.0599 | 954 | 34.1 | 399* | 316063 | 10.5* | 66 |

*, ** - significant at 0.05, and 0.01 probability levels, respectively.

Table 10. Treatment means for dry matter, NDVI, N content, total N uptake, percent vegetation coverage, and grain yield at Perkins, OK, Feekes growth stage 4 and 5, 1997-98 crop year.

| Treatment | Feekes 4 | | | | | Feekes 5 | | | | | Grain | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| means | Dry Matter | NDVI | Cover | N | N uptake | Dry Matter | NDVI | Cover | N | N uptake | yield | N | N uptake |
| | *kg ha⁻¹* | | *%* | *g kg⁻¹* | *kg ha⁻¹* | *kg ha⁻¹* | | *%* | *g kg⁻¹* | *kg ha⁻¹* | *kg ha⁻¹* | *g kg⁻¹* | *kg ha⁻¹* |
| N rate | | | | | | | | | | | | | |
| 0 | 388 | 0.427 | 26 | 27.5 | 10 | 709 | 0.442 | 41 | 22.1 | 15 | 1314 | 20.3 | 27 |
| 56 | 515 | 0.488 | 35 | 27.8 | 13 | 955 | 0.507 | 51 | 23.1 | 21 | 1391 | 21.4 | 29 |
| 112 | 477 | 0.486 | 34 | 30.7 | 14 | 1028 | 0.564 | 57 | 25.3 | 25 | 1450 | 22.1 | 32 |
| 168 | 443 | 0.476 | 34 | 32.8 | 14 | 824 | 0.563 | 57 | 26.8 | 22 | 1437 | 23.6 | 34 |
| Row spacing | | | | | | | | | | | | | |
| 15.2 | 556 | 0.504 | 36 | 28.0 | 15 | 1143 | 0.567 | 58 | 23.6 | 26 | 1618 | 21.5 | 35 |
| 19.0 | 461 | 0.491 | 33 | 28.3 | 13 | 910 | 0.539 | 53 | 23.3 | 21 | 1339 | 21.3 | 28 |
| 25.4 | 467 | 0.438 | 31 | 30.5 | 13 | 761 | 0.506 | 51 | 24.3 | 18 | 1332 | 22.3 | 29 |
| 30.5 | 339 | 0.444 | 29 | 31.9 | 10 | 702 | 0.464 | 44 | 26.0 | 18 | 1305 | 22.4 | 29 |
| SED | 183 | 0.05 | 7 | 3.7 | 4 | 343 | 0.09 | 12 | 2.2 | 8 | 274 | 0.9 | 5.9 |
| CV | 49 | 13 | 28 | 15 | 41 | 48 | 21 | 28 | 11 | 46 | 24 | 5 | 23 |

SED – standard error of the difference between two equally replicated means.
CV – coefficient of variation, %

Table 11. Correlation coefficients for NDVI with forage N content, dry matter, and total N uptake at Perkins and Tipton, OK.

| Growth stage, and year of study | Forage N content | Forage Dry Matter | Forage N uptake |
|---|---|---|---|
| | Tipton, OK | | |
| Feekes growth stage 5, crop year 1996-97 | 0.35 | 0.56 | 0.70 |
| Feekes growth stage 4, crop year 1997-98 | 0.45 | 0.58 | 0.76 |
| Feekes growth stage 5, crop year 1997-98 | 0.61 | 0.73 | 0.75 |
| | Perkins, OK | | |
| Feekes growth stage 4, crop year 1996-97 | 0.35 | 0.71 | 0.80 |
| Feekes growth stage 5, crop year 1996-97 | 0.10 | 0.33 | 0.47 |
| Feekes growth stage 4, crop year 1997-98 | 0.13 | 0.35 | 0.52 |
| Feekes growth stage 5, crop year 1997-98 | 0.04 | 0.80 | 0.83 |

Table 12. Correlation coefficients for grain yield with NDVI, percent vegetation coverage, and forage N uptake at Perkins and Tipton, OK.

| Growth stage, and year of study | NDVI | Percent Vegetation Coverage | Forage N uptake |
|---|---|---|---|
| | Tipton, OK | | |
| Feekes growth stage 4, crop year 1997-98 | 0.60 | 0.63 | 0.69 |
| Feekes growth stage 5, crop year 1997-98 | 0.71 | 0.70 | 0.79 |
| | Perkins, OK | | |
| Feekes growth stage 4, crop year 1997-98 | 0.32 | 0.35 | 0.14 |
| Feekes growth stage 5, crop year 1997-98 | 0.48 | 0.51 | 0.66 |

Table 13. Correlation coefficients for percent vegetation coverage with forage N content, dry matter, and total N uptake at Perkins and Tipton, OK.

| Growth stage, and year of study | Forage N content | Forage Dry Matter | Forage N uptake |
|---|---|---|---|
| | Tipton, OK | | |
| Feekes growth stage 4, crop year 1996-97 | 0.30 | 0.56 | 0.68 |
| Feekes growth stage 5, crop year 1996-97 | 0.25 | 0.58 | 0.65 |
| Feekes growth stage 4, crop year 1997-98 | 0.50 | 0.59 | 0.81 |
| Feekes growth stage 5, crop year 1997-98 | 0.61 | 0.74 | 0.76 |
| | Perkins, OK | | |
| Feekes growth stage 4, crop year 1996-97 | 0.33 | 0.52 | 0.61 |
| Feekes growth stage 5, crop year 1996-97 | 0.02 | 0.32 | 0.42 |
| Feekes growth stage 4, crop year 1997-98 | 0.17 | 0.33 | 0.54 |
| Feekes growth stage 5, crop year 1997-98 | -0.04 | 0.81 | 0.82 |

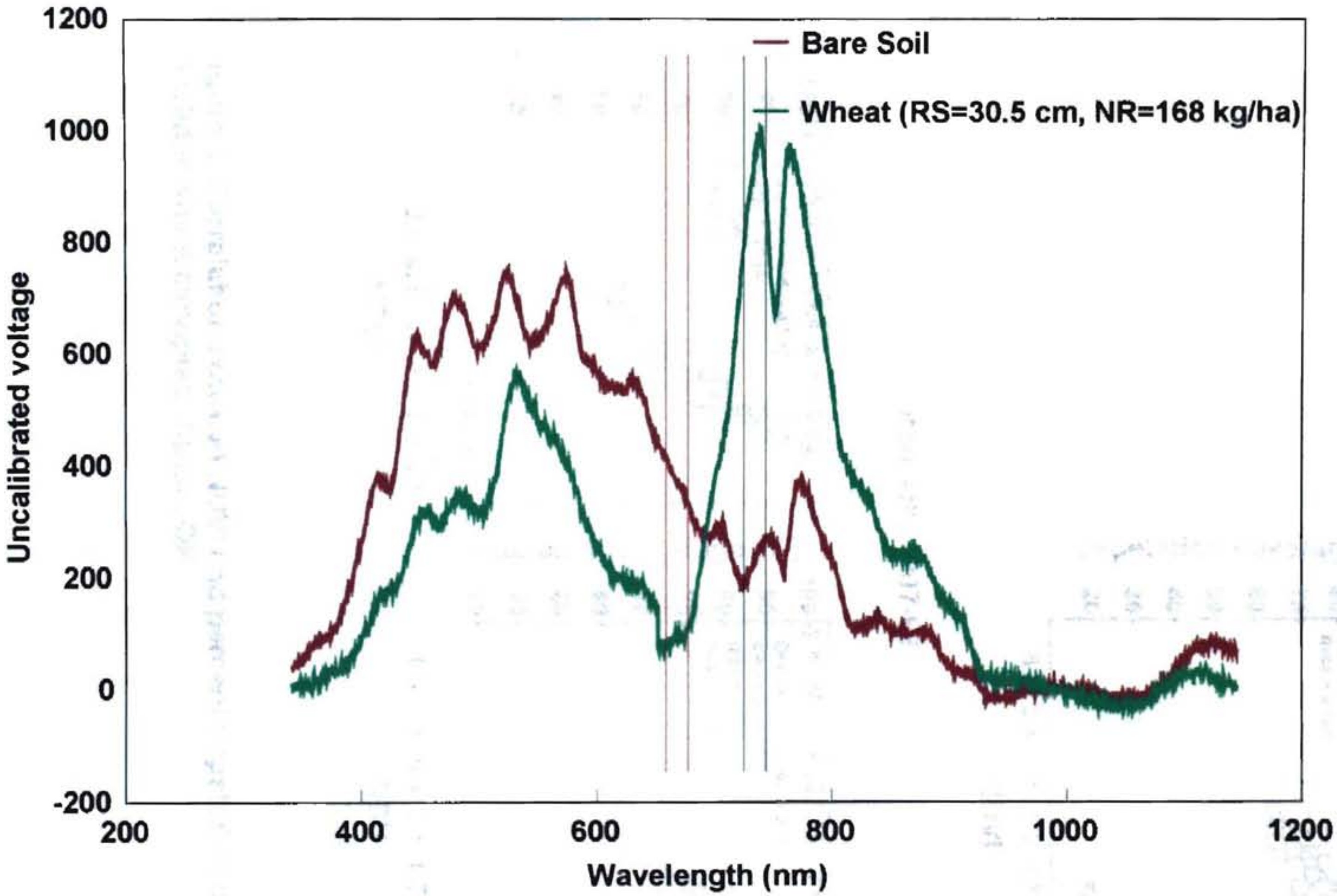



**Figure 1. Irradiance from bare soil and the wheat canopy. Sensor readings were taken from red 671 ± 6 nm and near infrared (NIR) 780 ± 6 nm bandwidths.**

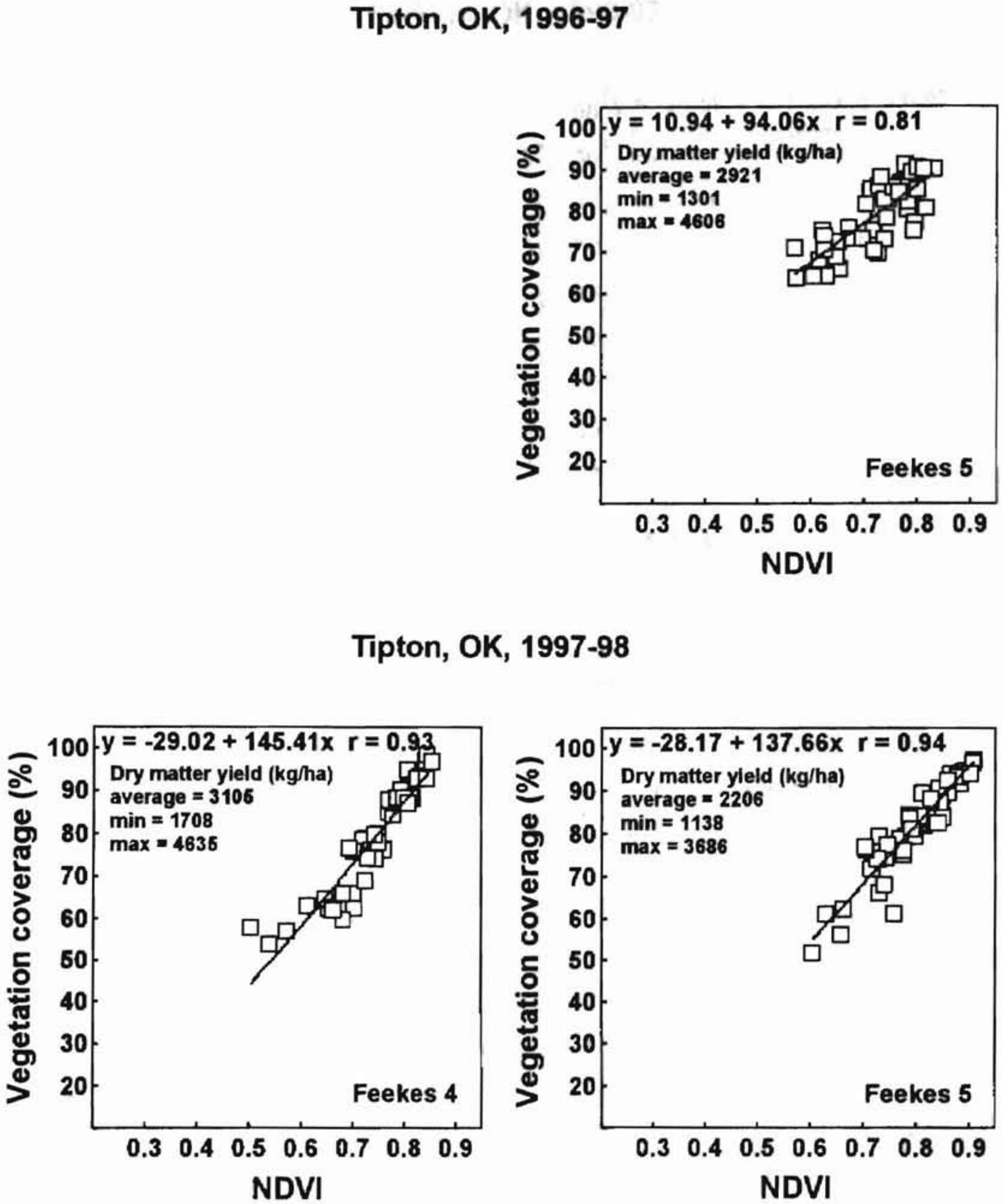



**Figure 2. Correlation between NDVI and percent vegetation coverage of winter wheat canopies, Tipton, OK.**

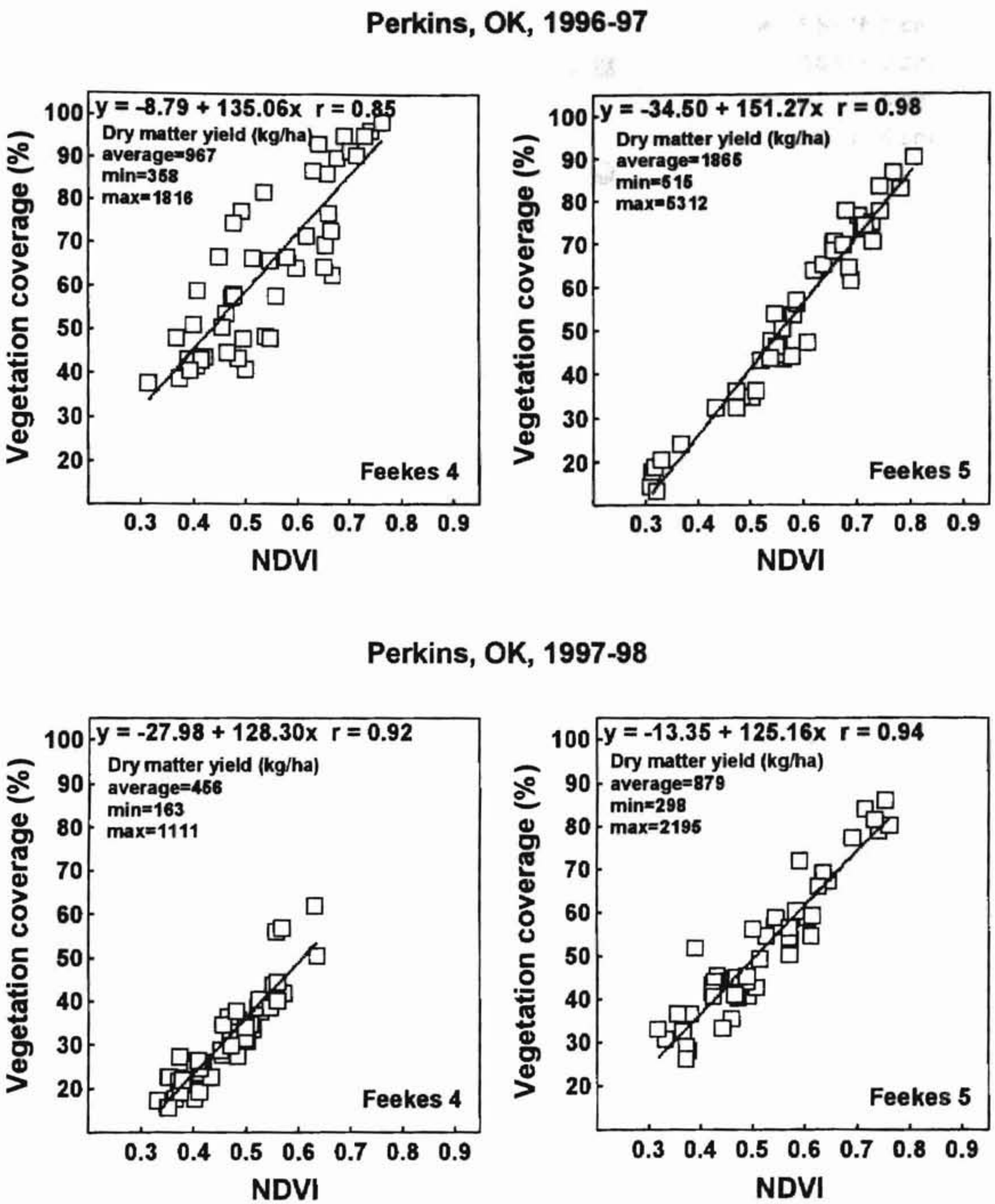
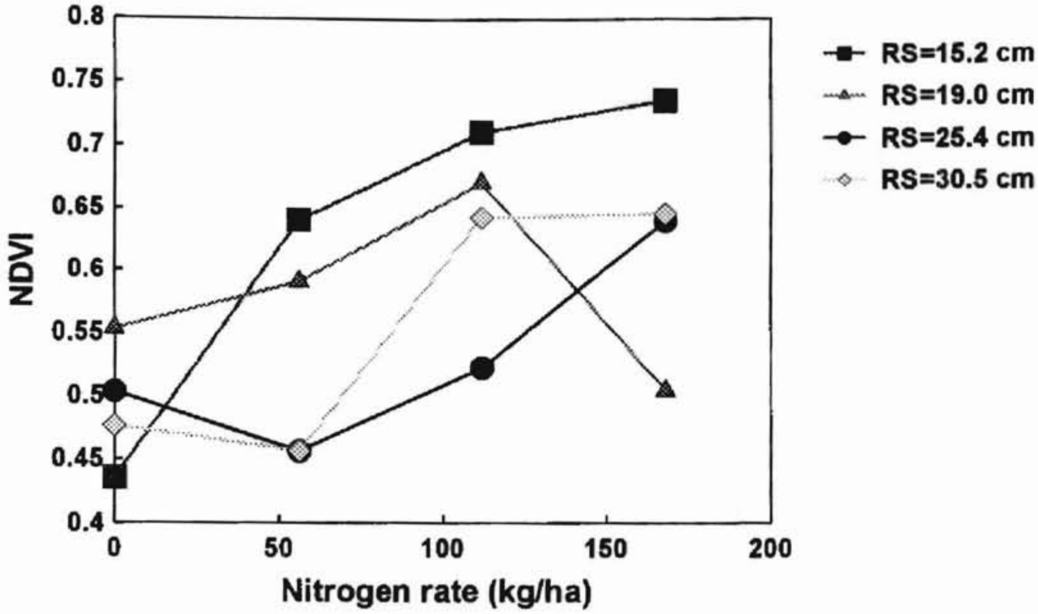
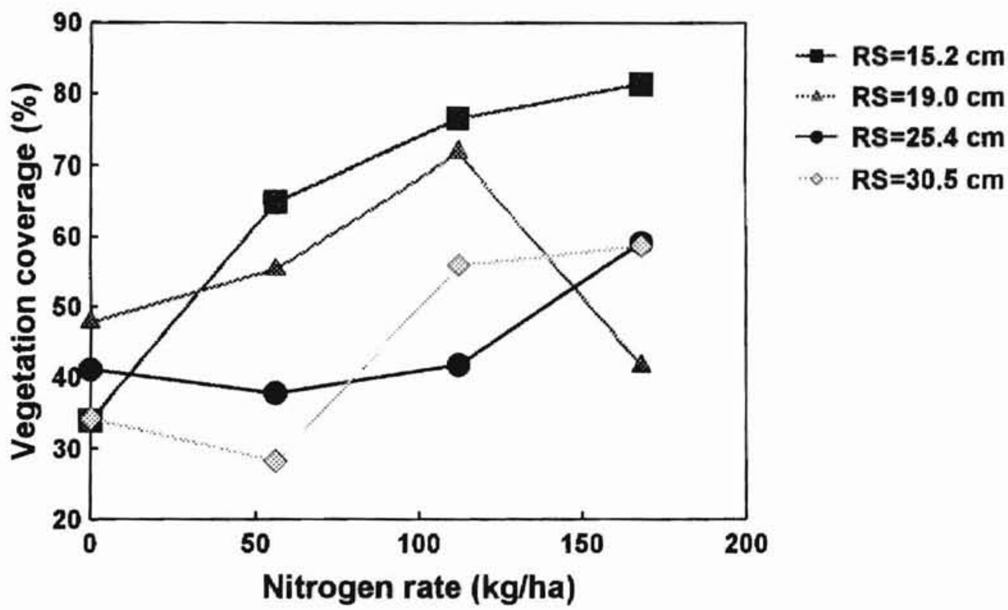



**Figure 3. Correlation between NDVI and percent vegetation coverage of winter wheat canopies, Perkins, OK.**




a




b

**Figure 4. Influence of N rate and row spacing on vegetation coverage and NDVI at Perkins, Feekes growth stage 5, 1996-97.**

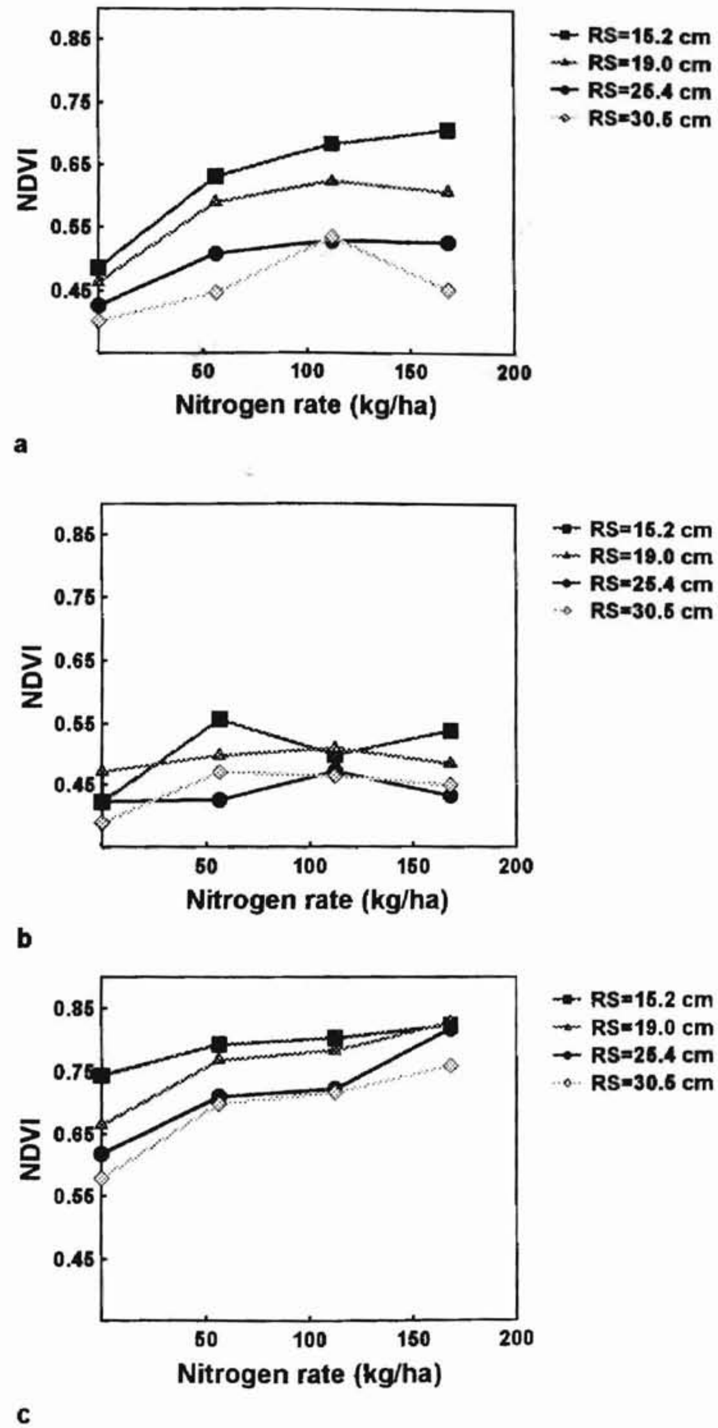



**Figure 5. Relationship between NDVI and N rate at Perkins, Feekes growth stage 4, 1996-97 (a), Perkins, Feekes growth stage 4, 1997-98 (b), Tipton, Feekes growth stage 4, 1997-98 (c).**

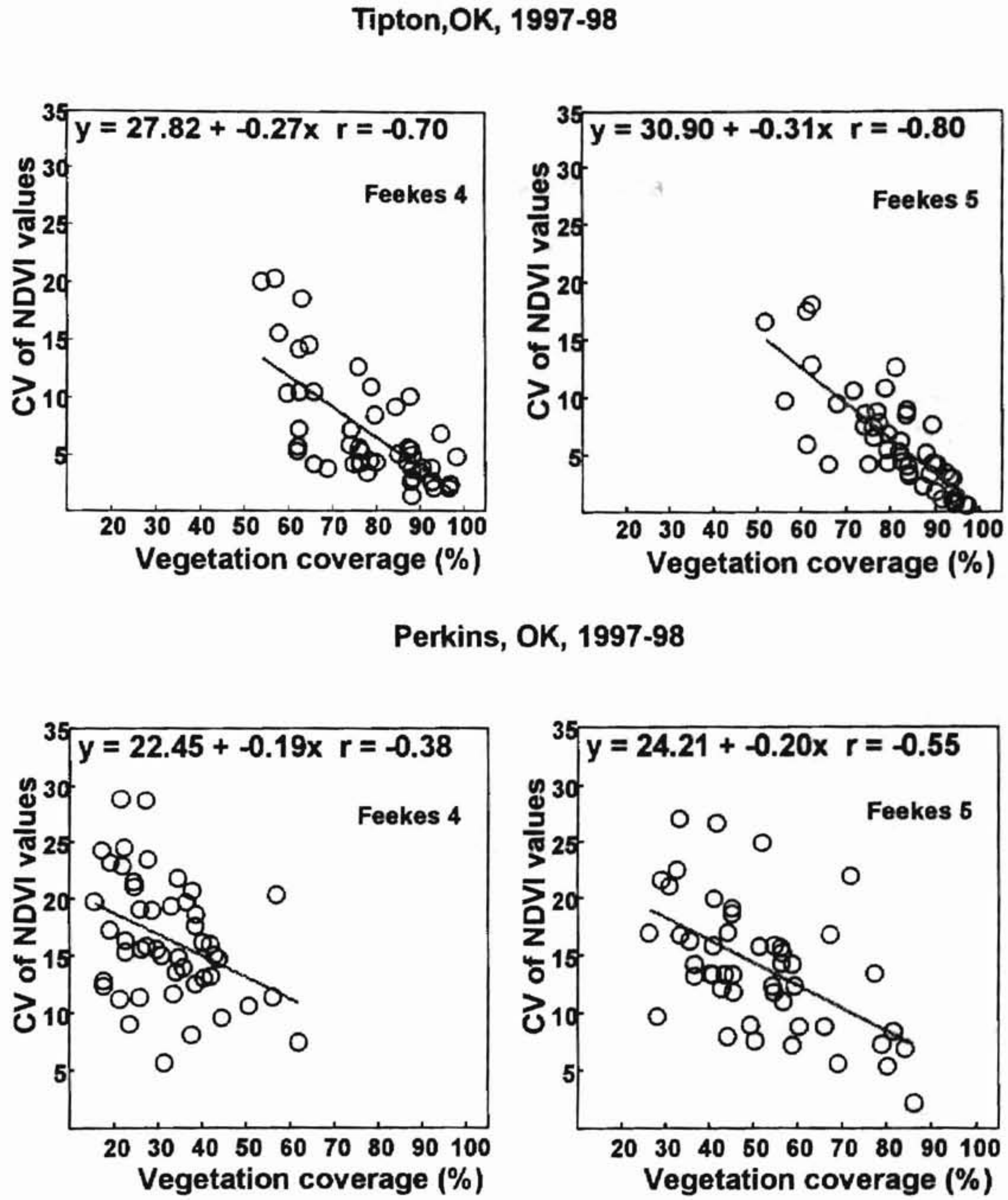



Figure 6. Relationship between CV's from by-plot NDVI values and percent vegetation coverage at Tipton and Perkins, OK, 1997-98.

2

# VITA

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