YIELD POTENTIAL ESTIMATION IN GRAIN SORGHUM (*Sorghum bicolor* L.), AND EFFECTS OF PLANT HEIGHT, SENSING ANGLE AND HEIGHT ON YIELD PREDICTION OF CORN (Zea mays. L)

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CHAPTER I

YIELD POTENTIAL ESTIMATION IN GRAIN SORGHUM (*Sorghum bicolor* L.)

ABSTRACT

Sensor based nitrogen management helped to improve fertilizer recommendations for various crops. The objective of this study was to estimate the yield potential of grain sorghum (*Sorghum bicolor* L. Moench) at different nitrogen levels using a self illuminated hand held optical sensor designed at Oklahoma State University. A total of six experiments with four levels of nitrogen (50,100,150,200 kg ha^{-1}) and there types of applications (Preplant, topdress and split) were arranged in a randomized complete block design in three replications at Efaw, Lake Carl Blackwell and Hennessey, OK in summers of 2004 and 2005. Sensor readings were taken using red (650 10 nm full width half magnitude (FWHM)) and green (550 ± 12.5 nm FWHM) head sensors at five growth stages (2, 3, 5, 6 and 7) from two middle rows out of four rows in each experimental unit. Results from statistical analysis have shown that sorghum grain yield and grain nitrogen content are highly correlated to both green and red NDVI readings at growth stage 3. In-season estimated yield (INSEY) was also found highly correlated with final grain yield. Over all results of these experiments suggest that

INSEY can be used as a tool to predict yield and to determine mid-season fertilizer N rate.

INTRODUCTION

Grain sorghum (*Sorghum bicolor* L. Moench) is grown on 42 million hectar worldwide and 3.6 million hectar in the United States (FAO, 2002). It is a major feed ingredient for both cattle and poultry in the United States, and it is grown for grain or silage in different parts of the Southern Great Plains. Research with grain sorghum, a relatively low acreage crop to Oklahoma, has shown sorghum to be a more water-use-efficient-crop than corn (*Zea mays* L.). It has been recognized as a more drought tolerant crop (Bennett et al., 1990; Khosla et al., 1995) and an alternative to corn and grows best in places with warm conditions with low moisture and high temperatures. Sorghum is generally grown in rotation with winter wheat (*Triticum aestivum* L.) and often double cropped with soybeans (*Glycine max*). However, in-sufficient data on N fertilization of grain sorghum are available for this region.

Successful crop growth is achieved through proper management of necessary mineral nutrients required by the crop. One of the most demanded nutrients by sorghum is nitrogen. Every cropping season substantial amount of N fertilizer is applied to sorghum due to its high biomass production. In fact, efficient utilization of nitrogen by crops is often governed by the cumulative effects of different factors including available soil moisture, fertilization time and growth stage of the crop. Devising a nutrient management program which synchronizes these factors to recommend optimum rates of nitrogen (N) for maximum economic yield has always been a challenge (Mengel et al., 1982; Touchton and Hargrove, 1982; Rao and Dao, 1992). Besides economic consequences, excess N fertilization may result in contamination of surface and ground water (Feinerman et al., 1990).

Several researchers have shown that more than half of the N applied is lost from fields by processes other than crop harvest during the first year after application (Sanchez and Blackmer, 1988). As per the report of Sanchez and Blackmer (1988), about 49 to 64% of the fall-applied fertilizer N was lost from the upper 1.5 m of the soil profile through pathways other than plant uptake. Therefore, potential contamination of groundwater from nitrates dictates that N fertilizer applications be timed so that crop N use is high (Gravelle et al., 1988). Identifying the period of peak demand of crops for water (Passioura, 1994) and nutrients (Baethgen and Alley, 1989) could potentially enable us to design more efficient nutrient management schemes that can improve nitrogen use efficiency (NUE) and boost grain yield.

A major factor limiting NUE for traditional N management schemes is routine application of large doses of N early in the season, before the crop can effectively utilize it. This stored N fertilizer is at considerable risk to environmental losses as noted in a review by Raun and Johnson (1999). They pointed out that previous research has shown that NUE could be greatly improved by moving away from early season application and towards a greater emphasis on mid-season applications of N fertilizer in amounts that better coincide with crop needs.

Most conventional methods of N fertilizer recommendations were developed on a state or regional scale, so it is questionable whether these methods can reasonably be used for variable-rate N management that attempts to account for within-field spatial and temporal variability (Hergert et al., 1997). Several research studies have found large differences in crop yield and crop N response within individual fields (Kitchen et al., 1995; Vetch et al., 1995), confirming the need for reliable methods to generate site-specific N recommendations (Hergert et al., 1997). Farmers often use uniform rates for N fertilization based on expected yield (yield goal) that could be inconsistent from field to field and year to year. In most instances expected yield can be higher or lower than the actual yield depending on factors that are difficult to predict prior to fertilization.

Spatial (field to field or within field) variability of crop yields can be the product of biotic and abiotic factors in any production environment (Machado et al., 2000; Sadler et al., 2000). Biotic factors including plant genotype, pests, diseases, and abiotic factors include soil physical and chemical properties, moisture, temperature and climate. The effects of soil physical and chemical properties on crop yields are easily predictable (Morn et al., 1997; Machado et al., 2000) and can be manipulated for good crop growth. On the other hand, effects of temporal variability on crop yields are very difficult to predict (Morn et al., 1997; Machado et al., 2000) and could have substantial impact on nutrient budget of the crop.

Thus, it is very important to consider spatial and temporal variability in any nutrient management program for efficient utilization of farm inputs. As crop growth depends on the prevailing biotic and abiotic factors it would be vital to monitor crop growth patterns in the process of a site-specific nutrient management program that could possibly address the problem of spatial and temporal variability at the same time. Because crop yields vary spatially and temporally, using yield goal based fertilizer recommendations may result in the misuse of resources that incur extra costs or reduce revenue from over or under fertilization.

According to Pierce and Nowak (1999) there are three basic management approaches currently being tested for variable-rate N application. The first involves determining plant-available N levels from field grid sampling and interpreting N rates based on current recommendations (i.e., N balance equation). The second approach bases N rates on observed crop N responses using replicated strips with varying N rates across the landscape. The third approach involves determining crop N status by monitoring (i.e., light reflectance or chlorophyll content). Currently the last method is the most widely used in site-specific nutrient management programs as it minimizes time, labor and cost of fertilizer application.

Crop monitoring through remote sensing using indirect and non-destructive methods has become one of the best techniques to enhance fertilizer application on-the-go as it avoids cumbersome activities like soil sampling and processing. Early research by Colwell (1956) showed that infrared aerial photography could be used to detect loss of vigor from disease in wheat (*Triticum aestivum* L.) and other small grains. One of the earliest digital remote-sensing analysis procedures developed to identify the vegetation contribution in an image was the ratio vegetation index , created by dividing near-infrared reflectance (NIR) by red reflectance (Jordan, 1969). The basis of this relationship is the strong absorption (low reflectance) of red light by chlorophyll and low absorption (high reflectance and transmittance) in the NIR by green leaves (Avery and Berlin, 1992). Dense green vegetation produces a high ratio while soil has a low value, thus yielding a contrast between the two surfaces. The red normalized difference vegetation index (RNDVI), where RNDVI = (NIR - Red)/(NIR + Red), was originally proposed as a means of estimating green biomass (Tucker, 1979). The basis for the relationship between NDVI and green biomass appears to be related to the amount of photosynthetically active radiation absorbed by the canopy (Sellers, 1985). The NDVI relates the reflectance in the red region (near chlorophyll *a* absorption max.) and NIR region to vegetation variables such as leaf area index, canopy cover, and the concentration of total chlorophyll.

Numerous researchers (Teillet, 1992; Wade et al., 1994; Ramsey et al., 1995; Roderick et al., 1996) have utilized NDVI, derived from a very high resolution radiometer collected from satellite platforms, to assess the health and condition of crops and natural vegetation over large geographical regions. Alternatively, Gitelson et al. (1996) proposed the use of the green normalized difference vegetation index (GNDVI) (where the green band is substituted for the red band in the NDVI equation), which may prove to be more useful for assessing canopy variation in green crop biomass. Shanahan et al. (2001) showed that the green normalized difference vegetation index (GNDVI) values derived from images acquired during mid-grain filling were the most highly correlated with grain yield. Blackmer and Schepers (1994) found that chlorophyll meters were useful for monitoring N status in irrigated corn. Blackmer et al., (1994) and Thomas and Oerther (1972) found that light reflectance near 550 nm was best for separating N-deficient from non-N-deficient corn and sweet pepper (*Capsicum annuum* L.) leaves, respectively. Bausch and Duke (1996) investigated using a ratio of NIR/green reflectance as an N-sufficiency index. Walburg et al. (1982) showed that N-deficient corn canopies had increased red reflectance and decreased NIR reflectance when compared with N-sufficient corn canopies. A ratio of the average reflectance from 760 to 900 nm divided by reflectance from 630 to 690 nm exhibited a good separation between N treatments. Aase and Tanaka (1984) reported a relationship between green leaf dry matter and NIR/red ratios, and suggested that reflectance measurements could be used to estimate leaf dry matter or leaf area measurements in spring and winter wheat (*Triticum aestivum* L.). Work by Stone et al. (1996) demonstrated that total plant N could be estimated using spectral radiance measurements at the red (671 nm) and NIR (780 nm) wavelengths. They calculated a plant-N-spectral-index for the amount of fertilizer N required to correct in-season N deficiency in winter wheat.

The majority of sorghum N research has focused on preplant and in-season fertilization regardless of the prevailing soil-plant nutrient status within the growing season. Observations during the grain sorghum growing season reveals that luxuriant crop growth can occur when the crop receives adequate to excessive rainfall in the early part of the growing season and has adequate to excessive N available. However, this luxury vegetative growth does not necessarily result in higher grain yields because heavy rainfall during the early growing season may leach NO_3-N from the soils resulting in late-season N deficiency. Also, early season luxurious vegetative crop growth significantly increases the daily crop water use (Khosla and Persaud, 1997). Consequently, plants may experience severe water stress later in the growing season causing early leaf senescence, poor head development and grain filling, and resulting in lower grain yields. Optimum grain yields therefore depend on whether there is an adequate supply of N and water stored in the soil to meet the plant N and water needs. Thus, the objective of this experiment is (1) to determine the optimum amount of N which will give the best yield (2) to identify the specific growth stage when sorghum grain yield can be predicted using sensor readings from vegetative stages and; (3) to identify the peak nutrient demanding growth period which is highly responsive to fertilization.

Role of CV in Mid-Season Grain Yield Prediction

Coefficient of variation (CV) provides a relative measure of data dispersion compared to the mean. It is defined as the ratio of standard deviation to the sample mean (Lewis, 1963 and Steel et al., 1997) and usually expressed in terms of percentage (%). In accordance with the definition of CV, when a high standard deviation is observed, it is likely that the coefficient of variation will be large (Taylor et al., 1997). The coefficient of variation can be used to compare the results of two dissimilar experiments which have similar measurement units (Steel et al., 1997) conducted by different experimenters. The coefficient of variation in practice “scales” the standard deviation by the size of the mean, making it possible to compare coefficient of variation across variables measured on different scales. It is a relative measure of variability and often changes with every individual comparison made and its meaning largely depends on the existence of previous data which would help in determining its meaning (large or small) (Steel et al., 1997). Taylor et al., (1997) have shown that here is a remarkable negative relationship between wheat grain yield and coefficient of variation. They further showed that plot size and coefficient of variation are directly related to each other. Soil nutrient application and response could possibly be fine tuned by predicting mid-season coefficient of variation (Washmoon et al., 2002). Better prediction of yield could be achieved by incorporation of the coefficient of variation in the in-season estimated yield (INSEY) prediction equation. Therefore, coefficient of variation from sensor readings could be used to refine the prediction yield.

MATERIALS AND METHODS

Experimental Design and Treatment Structure

In the summers of 2004 and 2005, a total of six experiments were conducted at three locations, Lake Carl Blackwell (Port fine-silty, mixed, superactive, thermic Cumulic Haplustoll), Hennessey and Efaw (Easpur loam fine-loamy, mixed, superactive, thermic Fluventic Haplustoll), Oklahoma. Initial soil analysis results are presented in Table 1. Four pre-plant, three split and four topdress nitrogen rates were applied in a randomized complete block design with three replications at all the experiments (Table 2).

In the first cropping season (summer 2004), sorghum was planted May 6, 2004 at Efaw, Lake Carl Blackwell and Hennessey using a John Deere Max Engine planter set at 75 cm row spacing and at a population of about 111,150 plants per hectare. An amount of 24.4 kg P per hectare was applied pre-plant and incorporated to the soil by using a tractor mounted barber spreader. The pre plant nitrogen rates were applied before planting and incorporated by a field cultivator harrow. Urea (46-0-0) was used as the pre-plant source of nitrogen in all experiments. Top dress nitrogen was applied as UAN (28-0-0) at sorghum growth stage 3 (growing point differentiation) between June 14 and 16. In the second cropping season (summer 2005) sorghum was planted May 17, 2005 at Efaw and Lake Carl Blackwell and May 18, 2005 at Hennessey, Oklahoma and the same management practices were carried as in 2004.

Plot sizes were about 3 m x 6 m (18 m^2). There were four rows of sorghum plants in each plot where the two middle rows were used for physical and sensor measurements and for collecting final grain yield.

Sensor Measurements

A GreenSeeker® Hand Held Optical Sensor (NTech Industries, Inc.) was used to collect normalized difference vegetative index (NDVI) measurements. This device uses a patented technique to measure crop reflectance and to calculate NDVI. The unit senses 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. The sensed dimensions remain approximately constant over the height range of the sensor. The sensor unit has self-contained illumination in the red (650 10 nm full width half magnitude (FWHM)), green (550 ± 12.5 nm FWHM) and NIR (770 15 nm FWHM) bands. The device measures the fraction of the emitted light in the sensed area that is returned to the sensor (reflectance). These fractions are used within the sensor to compute Red (RNDVI) and Green (GNDVI) according to the following formula:

$$RNDVI = \frac{F_{NIR} - F_{\mathrm{Re}d}}{F_{NIR} + F_{\mathrm{Re}d}}$$

$$GNDVI = \frac{F_{NIR} - F_{Green}}{F_{NIR} + F_{Green}}$$

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

F_{Red} – Fraction of emitted Red radiation returned from the sensed area (reflectance).

F_{Green} – Fraction of emitted Green radiation returned from the sensed area (reflectance).

The sensor unit is designed to be “hand-held” and measurements were taken nadir as the sensor is passed over the crop surface. It samples at a very high rate (approximately 1000 measurements per second) and averages measurements between outputs. The sensor outputs NDVI at a rate of 10 readings per second. The sensor was passed over the crop at a height of approximately 0.7 m above the crop canopy and oriented so that the 0.6 m sensed width was perpendicular to the row and centered over the row. With advancing stage of growth, sensor height above the ground increased proportionally. Travel velocities were at a slow walking speed of approximately 0.5 m s^{-1} resulting in NDVI readings averaged over distances of < 0.05 m.

Sensor readings for each year were taken at growth stage 2 (collar of 5th leaf is visible: occurs approximately 20 days after emergence), 3 (growing point differentiation: 35 days after emergence), 5 (boot stage), 6 (half bloom) and 7 (soft dough). Duration of growth stages may vary depending on the existing weather condition in the growing season. Sensor readings were taken from the two middle rows by sensing each row at a time. Plot NDVI readings were estimated by averaging readings from the two middle rows.

Grain Yield Sampling

Final plot grain yield was obtained from two middle rows which were harvested using a plot harvesting Massey Ferguson combine which has automated moisture and weighing scales. Grain yield was adjusted for standard moisture content of grain sorghum (13%) using the following formula:

$$Moisture\,adjusted\ yield = harvested\ yield * \left[\frac{100 - actual\,moiture}{100 - statndard\ moisture}\right]$$

Total N in the grain was determined using a Carlo Erba (Milan, Italy) NA-1500 dry combustion analyzer (Schepers et al., 1989) after grain samples were dried (70 ^{o}C for three days) and grounded to pass a 0.125 mm (120-mesh) sieve and analyzed.

Data Analysis

In-season estimated yield (INSESY) was calculated as a ratio of average plot NDVI and growing degree days (GDD> 0). GDD represents the duration of biomass production where only days with optimum temperature for growth are considered throughout the growth cycle. INSEY and GDD were calculated using the following formulas:

$$INSEY = \left[\frac{NDVI}{Days\,where\,GDD > 0}\right]$$

$$GDD = \left[\frac{T_{\max} + T_{\min}}{2}\right] - 4.4\,^{0}C$$

Where T_{min} and T_{max} represent daily ambient minimum and maximum temperatures, respectively.

Coefficient of variation for red and green NDVI for each plot were calculated automatically by the software in the Greenseeker.

The relationship among grain N uptake, grain yield, in-season estimated yield (INSEY) and GNDVI and RNDVI at different growth stages were evaluated using simple regression analysis proc reg procedure using SAS (SAS, 1999) statistical software.

RESULTS

Grain Yield

Crop Year 2004

Average grain sorghum yield was somewhat higher at Lake Carl Blackwell (6482 kg ha^{-1}) when compared to Efaw (4278 kg ha^{-1}). Over all grain yields ranged from 3703 to 5062 kg ha^{-1} and from 5465 kg ha^{-1} to 7440 kg ha^{-1} at Efaw and Lake Carl Blackwell, respectively (Table 3). The range in sorghum grain yields was largely attributed to the response to fertilizer N. At all locations, sorghum grain yields increased with increasing N applied, but the significance of this trend over locations varied by site (Table 4). Maximum yields were generally achieved at the 100 or 150 kg N ha^{-1} rates, and yield increases over the 0-N check were more than 700 kg ha^{-1} over all sites (Table 3).

Crop Year 2005

Average grain yield of sorghum was 3420, 2399 and 8476 kg ha^{-1} at Efaw, Hennessey and Lake Carl Blackwell, respectively (Table 3). The highest yield was obtained from mid-season applied 150 kg N ha^{-1}, split applied 100 kg N ha^{-1} and split applied 150 kg N ha^{-1} with corresponding yields of 4442, 3125 and 9245 kg ha^{-1} at Efaw, Hennessey and Lake Carl Blackwell, respectively (Table 3). For the 5 site-years included in this work, only Lake Carl Blackwell in 2004 showed limited response to fertilizer N.

Over all sites, differences in preplant, topdress, and split methods of N application produced variable results. Split applied N was expected to be better where irrigation was available and yield levels were higher (Lake Carl Blackwell), but results were inconsistent (Table 3), evidenced in the lack of significant effects from single degree of freedom contrasts (Table 4).

Sensor Measurements

Crop Year 2004

Results of simple linear regression analysis showed that there was a significant relationship between NDVI and final sorghum grain yield from sensor readings collected at growth stage 3. When evaluating this relationship over stages of growth, the best correlation between grain yield and GNDVI and RNDVI was obtained at growth stage 3 (coefficient of simple determination (r^2) of 0.70 (RNDVI) and 0.65 (GNDVI) (Figures 1 and 2). Similarly, simple regression analysis of the combined location data revealed that in-season estimated yield (INSEY) was significantly correlated with both red (r^2=0.68) and green (r^2=0.71) NDVI (Figures 3 and 4). It should be noted that the use of INSEY did not significantly improve this relationship over that of NDVI alone for either red or green. At the same growth stage grain N uptake was also significantly correlated with red (r^2= 0.48) and green (r^2= 0.48) NDVI (Figures 5 and 6). Coefficient of variation (CV%) from RNDVI (r^2 = 0.46) and GNDVI (r^2=0.50) was also correlated with grain yield at growth stage 3 (Figures 7 and 8). Over sites, CV's decreased with increasing NDVI (red and green, Figures 9 and 10) at growth stage 2, while similar results were noted for green NDVI at stage 3 (Figure 11). As surface coverage increases (higher NDVI), it seems plausible that CV's would decrease due to decreased soil background detected using the Greenseeker sensor.

Crop Year 2005

Results over sites (Efaw and Hennessey) from simple regression analysis of grain yield on red NDVI showed only limited correlation for growth stages 2 and 3 (Figures 12 and 13). Similar results were noted for green NDVI at growth stage 3 (Figure 14). There was only a weak relationship between grain yield and NDVI at growth stages beyond growth point differentiation. In-season estimated yield (INSEY) where NDVI values were divided by the number of days from planting to sensing did not improve this relationship over sites.

Similar to 2004 results, combined location data for coefficient of variation (CV) data from sensor readings regressed on red NDVI resulted in highly significant negative correlation at sorghum growth stages 2, 3, 5, and 6 (Figures 15 – 18). Although the correlation was somewhat improved the same trend was noted for CV regressed on green NDVI (Figures 19-22).

DISCUSSION

Grain Yield

In 2004 no grain was harvested from the Hennessey experimental site due to severe bird damage after seed set. The majority of the experimental plots in the third replication at this site were water logged for some part of the growing period. The water logging problem led to uneven emergence, planting skips, ultimately poor crop stands in both years. Moreover, extended moisture stress due to erratic and low rainfall was responsible for very low yields at this site.

In the 2004 cropping year there was only limited yield response to nitrogen rates at Lake Carl Blackwell. Non-responsiveness or negative-responsiveness of grain sorghum yields in the 2004 cropping year were attributed to high levels of residual mineral N present in the soil profile at planting. Also, erratic rainfall patterns that promoted early season luxuriant crop growth caused severe water stress conditions later in the season. These conditions translated into poor early season growth, later season head development and grain fill. Consequently, grain yields were lower and only limited response was noted to applied N fertilizer. Analysis of soil samples collected from the experimental area prior to planting showed that there was substantial residual nitrogen (Table 1). Soil test results indicated relatively high residual ammonium N present at all sites in the 15 cm soil surface (Table 1). Khosla et al (2000) has also suggested that residual mineral N levels greater than 45 kg N ha^{-1} in the surface 0.3 m of soil were sufficient to support the crop growth until midseason fertilizer was applied.

These results demonstrate the importance of soil testing at each experimental site prior to planting.

In 2005 the Lake Carl Blackwell experimental site was irrigated and as a result, grain yields in excess of 9000 kg ha^{-1} were realized. At this site statistical data analysis showed that there was a remarkable response of grain yield to nitrogen treatments. The main effect of nitrogen rate was linear ($P<0.01$) or quadratic ($P<0.05$) for all pre-plant, top dress and split nitrogen applications methods. Sorghum grain yields peaked at 200, 150 and 150 kg N ha^{-1} treatments for pre-plant, top dress and split application methods, respectively. However only limited differences in application methods were noted for grain yield at all sites (Table 4).

Sensor Measurements

In both 2004 and 2005 crop years it was observed that the relationship of NDVI and grain yield was better at the stage of growing point differentiation (growth stage 3). This stage (35 days after emergence) is a period of rapid growth and nutrient uptake by the sorghum plant (Vanderlip, 1993). In-season estimated yield (INSEY) is a measure of mid-season potential yield using NDVI (estimate of biomass) as a function of the number of days transpired to the time sensor measurements are collected. Invariably the relationship with final grain yield was improved at growth stage 3 when compared to other stages evaluated. This enhances the importance of collecting early season sensor measurements for projecting grain yield, for ensuing adjustments in nutrient needs.

Combined data over all locations and years appeared to show a trend somewhat similar to what was found from data on individual locations on grain yield and NDVI relationships at growth stage 3. The scatter plot diagram of grain yield on both green and red NDVI illustrated a discernable trend for most sites, excluding the 2005 Lake Carl Blackwell site (Figures 23, and 24). Since this site was irrigated throughout the growth period, higher grain yields were realized compared to the other locations (Figures 23 and 24), and response was also detectably different. Therefore, this site resulted in a data cluster much different than the rest that were produced under dryland conditions. This finding is consistent with the need for highly specialized yield prediction equations reported on the NUE web site (http://www.nue.okstate.edu/Yield_Potential.htm). However, it should be noted that when using INSEY the combined data were in fact normalized and the outer boundary for detecting yield potential was quite clear using the green NDVI sensor (Figure 23). Scatter below the outer boundary is expected since post sensing conditions can lead to the underestimation of yield potential (drought stress, disease, insect damage, etc.). But, what is important to note is that both rainfed and irrigated sites could be combined on one graph (Figure 25) when using INSEY (green NDVI sensor), further suggesting that early season detection of growth rate (biomass produced per day, estimated using NDVI divided by the number of days from planting to sensing) is in fact related to final grain yield.

This same trend was noted when using the red NDVI at growth stage 3 over sites and years versus sorghum grain yield (Figure 26). However, for this data, INSEY failed to normalize all sites, as was noted for INSEY when using green NDVI (Figure 25). Excluding the Lake Carl Blackwell site, red NDVI and INSEY did provide reasonable detection of sorghum grain yield potential (outer left hand boundary of the data). In general the combined location and year data showed that the INSEY and grain yield relationship could be explained by red and green NDVI with green having slightly better performance. Similar scenario was observed when INSEY from cumulative growing degree days is related to grain yield (data not presented).

The coefficient of variation computed automatically from NDVI sensor readings tended to increase with decreasing grain yields (Figures 7 and 8). As growth proceeds the canopies grow closer together and thus it becomes more difficult to accurately determine plant biomass. The average maximum CV of RNDVI was obtained at sorghum growth stage 2 (collar of the fifth leaf visible) 23.8% and 22.9% at Efaw and Lake Carl Blackwell, respectively. At this stage there was irregular spacing of sorghum plants, resulting from skips by the planter and this in association with limited tillering at this stage, certainly resulted in low canopy closure. This is the reason why higher CV's are encountered at earlier stages of growth as has been noted by others. The average minimum CV of RNDVI was obtained at growth stage 5 (head enclosed in swollen flag leaf sheath) 6.6% and 6.2% at Efaw and Lake Carl Blackwell, respectively (data not reported).

Analysis of data from this experiment suggest that the there is a direct relationship between coefficient of variation and the existing plant population in the field. This is in turn related to final grain yield which has also been reported in the literature. Work by Raun et al. (2005) and Arnall et al. (2005) have shown that there is significant relationship between grain yield and coefficient of variation, and that is tied to plant population in corn and wheat.

CONCLUSIONS

The results obtained from this experiment suggest that yield potential prediction in sorghum using spectral measurements should be carried out at a stage of critical biomass production and nutrient demand. This was shown by the relationship of INSEY and final grain yield at sorghum growth stage 3 (growing point differentiation) which starts approximately 35 days after planting. Red and the green NDVI sensor data collected at growth stage 3 were highly correlated with final sorghum grain yield. However, the use of INSEY as has been employed in wheat and corn trials was not as effective in normalizing sites whereby one yield prediction equation could be established. Further work will need to focus on the use of cumulative growing degree days and/or other denominators for the INSEY equation in order to refine yield potential prediction equations for sorghum.

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Table 1. Initial surface (0-15 cm) test soil characteristics of the experimental plots at Efaw, Lake Carl Blackwell and Hennessey, OK, 2004 and 2005

	Crop year				
	2004			2005	
	LCB	Efaw	Hennessey	LCB	Hennessey
Soil pH	5.4	4.7	4.8	4.9	4.2
Organic C, %	0.58	1.23	1.22	0.57	1.16
Total N, %	0.04	0.17	0.08	0.04	0.07
NH_4-N, mg kg^{-1}	19	21	24	15	13
NO_3-N, mg kg^{-1}	8	9	5	8	10
P mg kg^{-1}	17	26	100	26	106
K , mg kg^{-1}	98	149	454	104	434

Organic C and total N – dry combustion, NH_4-N and NO_3-N – 2 *M* KCl extractions.

Table 2. Treatment structure for sorghum yield potential study experiments at Efaw, Lake Carl Blackwell and Hennessey, OK, 2004 and 2005.

Treatment	Pre-plant N rates (kg/ha)	Top dress N rate † (kg/ha)	Total N (kg/ha)	P (kg/ha) ‡
1	0	0	0	25
2	50	0	50	25
3	100	0	100	25
4	150	0	150	25
5	200	0	200	25
6	0	50	50	25
7	0	100	100	25
8	0	150	150	25
9	0	200	200	25
10	50	50	100	25
11	75	75	150	25
12	100	100	200	25

† Top dress N is applied 30 days after emergence as UAN (28-0-0).
‡ P is applied pre-plant as Triple super phosphate (TSP) (0-46-0).

Table 3. Average gain yield of sorghum yield potential experiment at Lake Carl Blackwell, Hennessey and Efaw, OK, 2004 and 2005.

Trt. No.	N rate (kg ha^{-1})	Application method	2004		2005		
			Efaw	LCB[+]	Efaw	Hennessey	LCB
			------------------- kg ha^{-1}				--------------------
1	0	Preplant	3703	6127	2987	1943	6760
2	50	Preplant	4710	6752	2628	2187	8220
3	100	Preplant	5062	5465	4246	2547	8539
4	150	Preplant	4199	6909	3471	2694	8597
5	200	Preplant	4032	6141	3356	2145	8677
6	50	Top dress	4264	6035	3161	2022	7776
7	100	Top dress	4847	6504	3492	1780	8803
8	150	Top dress	4088	6833	4442	2375	8958
9	200	Top dress	3858	6358	3091	2687	8631
10	100	Split	4004	6340	3804	3125	8677
11	150	Split	4537	6878	3994	2984	9245
12	200	Split	3835	7440	2575	2321	8831
Mean			4278	6482	3420	2399	8476
SED[++]			655	734	812	588	923

[++] Standard error of the difference between two equally replicated means [+]Lake Carl Blackwell

Table 4.Test of significance using single degree of freedom non-orthogonal contrasts of overall N treatments for grain yield at Efaw and Lake Carl Blackwell (LCB) in 2004 and 2005.

source	2004		2005	
	Efaw	LCB	Efaw	LCB
N rate	NS	NS	*	*
Pre-plant N linear	*	NS	NS	**
Pre-plant N quad.	NS	NS	NS	*
Top dress N linear	<0.1	NS	NS	**
Top dress N quad.	NS	NS	<0.1	*
Split N linear	NS	*	NS	**
Split N quad.	NS	NS	**	*
Pre-plant vs. top	NS	NS	NS	NS
Pre-plant vs. split	NS	NS	NS	NS
Split vs. top dress	NS	NS	NS	NS

*, **, indicate significance at 0.05 and0.01 probability levels, respectively;

[†] NS non significant at 0.1.

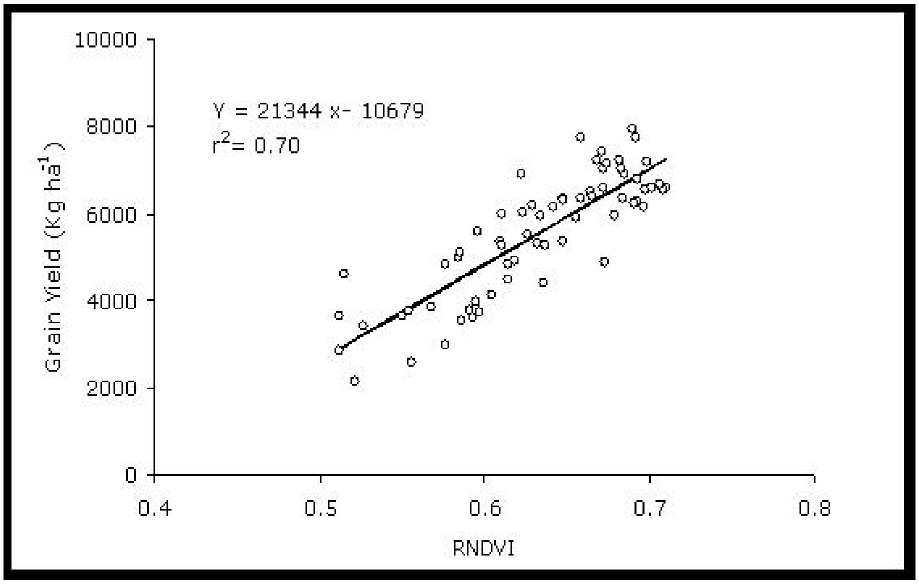

Figure 1. Relationship of RNDVI and Sorghum grain yield at Growth stage 3 at Efaw and Lake Carl Blackwell, OK, 2004.

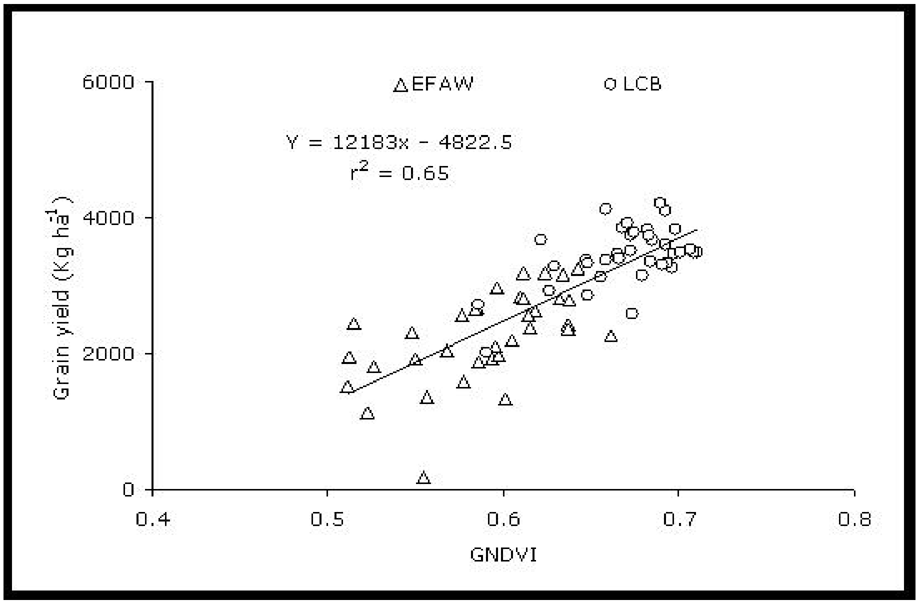

Figure 2. Relationship of GNDVI and sorghum grain yield at growth stage 3 at Efaw and Lake Carl Blackwell, OK, 2004.

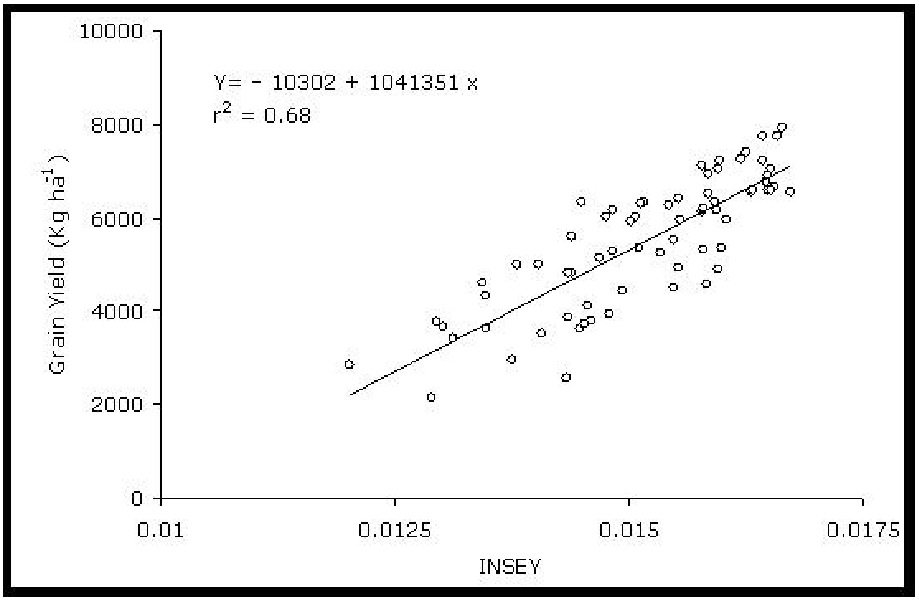

Figure 3. Relationship of red INSEY and sorghum grain yield at growth stage 3 at Efaw and Lake Carl Blackwell, OK, 2004.

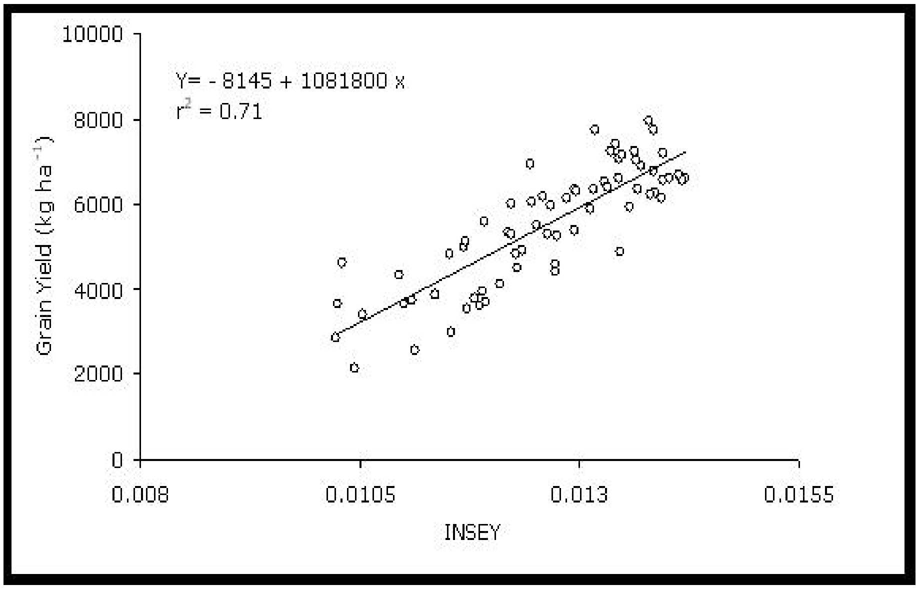

Figure 4. Relationship of green INSEY and sorghum grain yield at growth stage 3 at Efaw and Lake Carl Blackwell, OK, 2004.

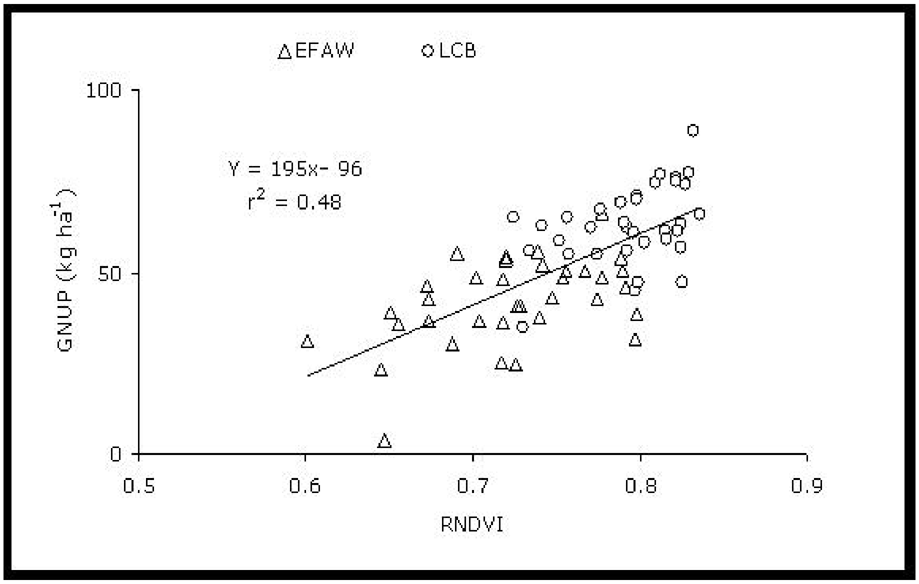

Figure 5. Relationship of RNDVI and sorghum grain N uptake at growth stage 3 at Efaw and Lake Carl Blackwell, OK, 2004 (GNUP, grain nitrogen uptake).

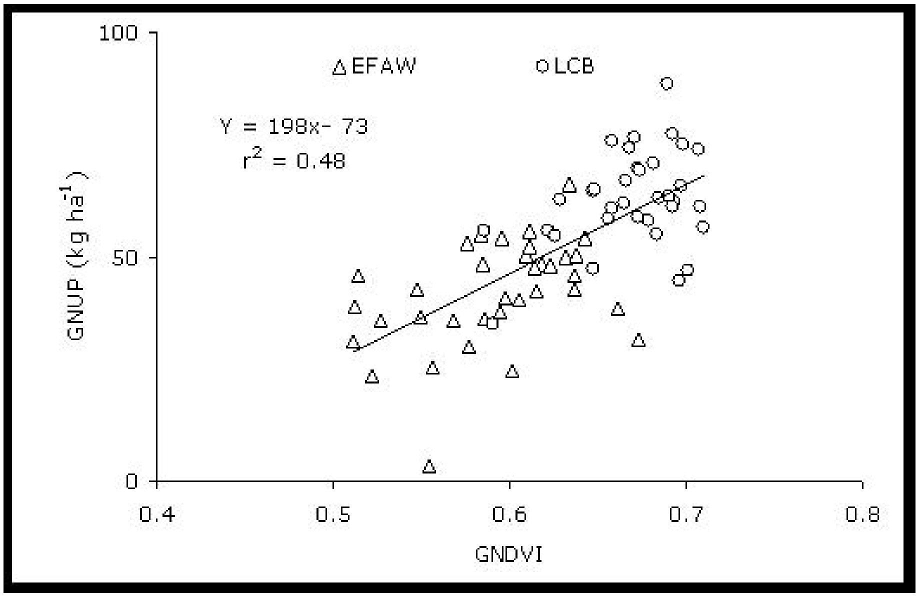

Figure 6. Relationship of GNDVI and sorghum grain N uptake at Growth stage 3 at Efaw and Lake Carl Blackwell, OK, 2004 (GNUP, grain nitrogen uptake).

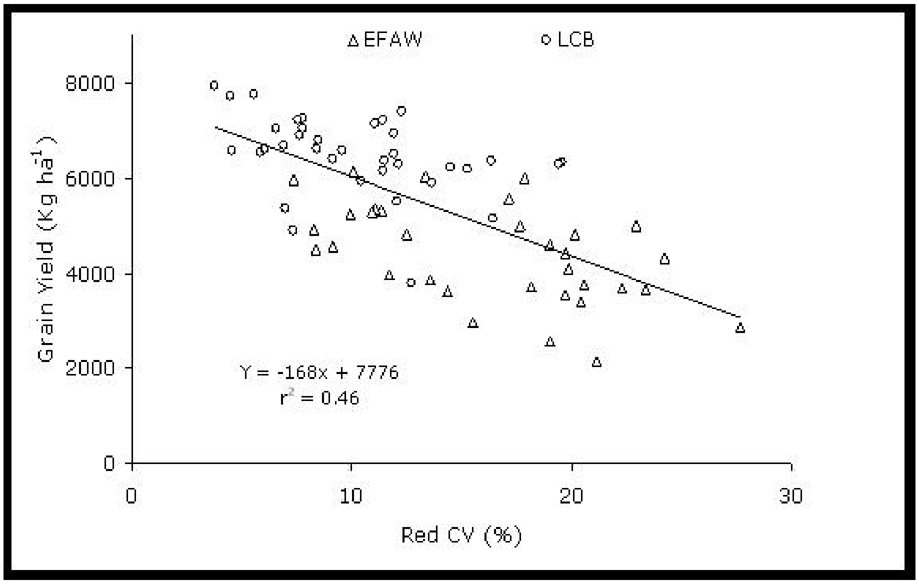

Figure 7. Relationship of red CV and sorghum grain yield at growth stage 3 at Efaw and Lake Carl Blackwell, OK, 2004.

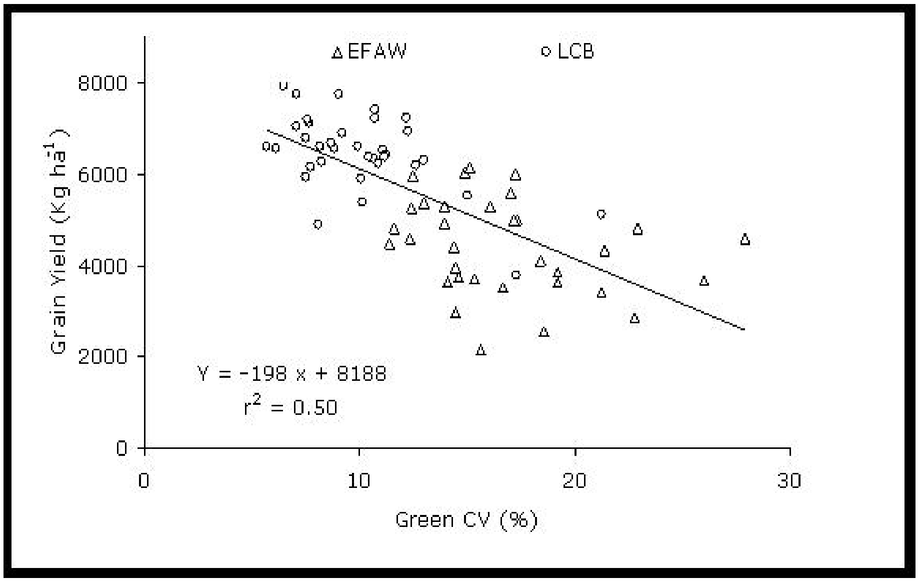

Figure 8. Relationship of green CV and sorghum grain yield at growth stage 3 at Efaw and Lake Carl Blackwell, OK, 2004.

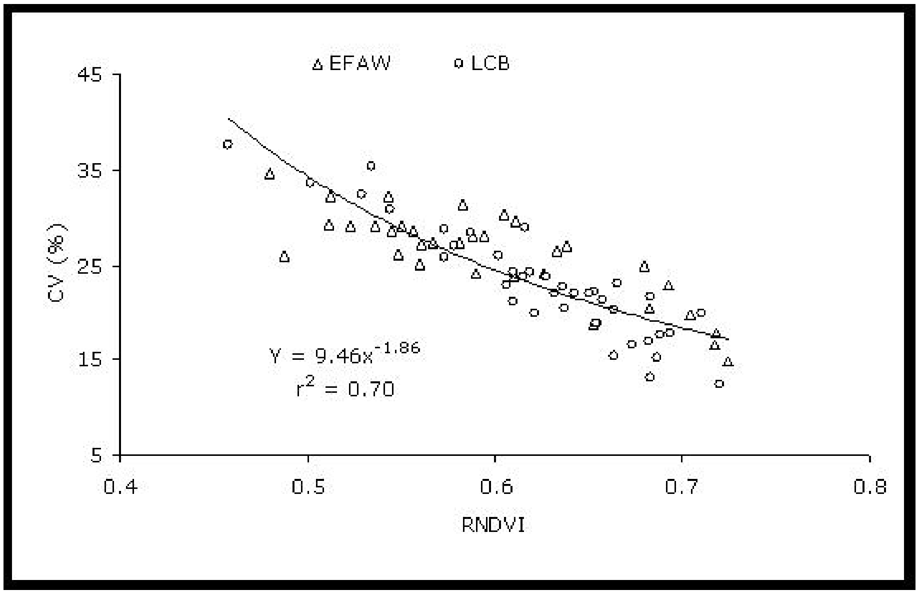

Figure 9. Relationship of CV and RNDVI at growth stage 2 at Efaw and Lake Carl Blackwell, OK, 2004.

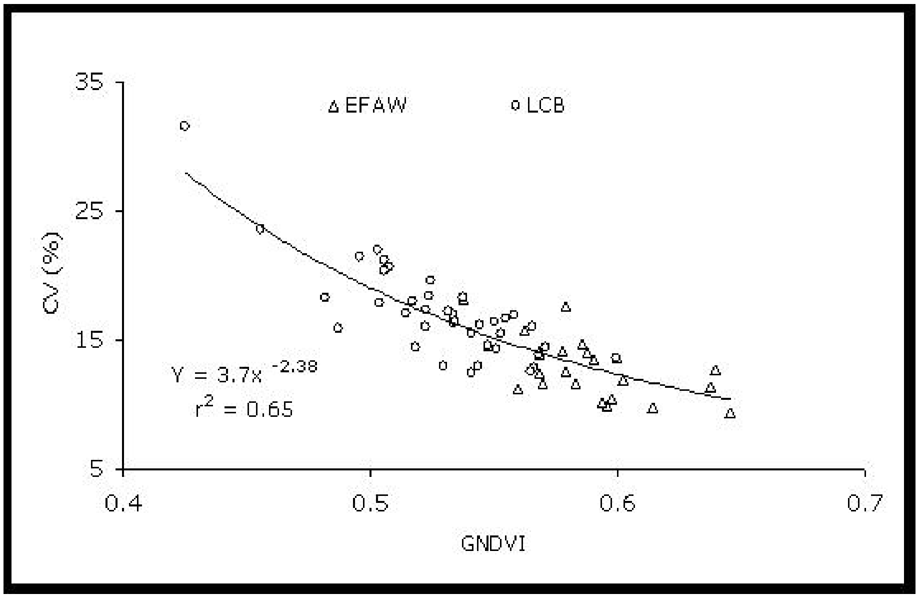

Figure 10. Relationship of CV and GNDVI at growth stage 2 at Efaw and Lake Carl Blackwell, OK, 2004.

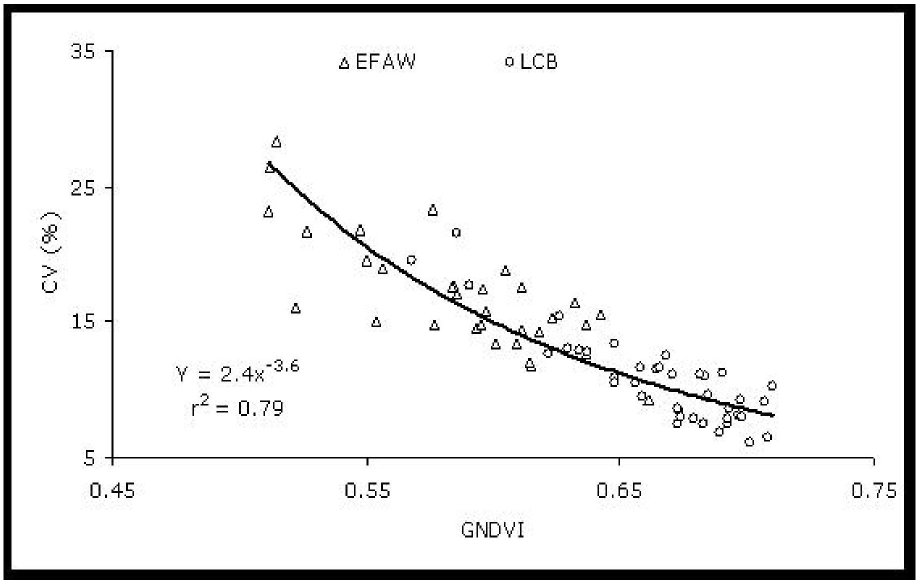

Figure 11. Relationship of CV and GNDVI at growth stage 3 at Efaw and Lake Carl Blackwell, OK, 2004.

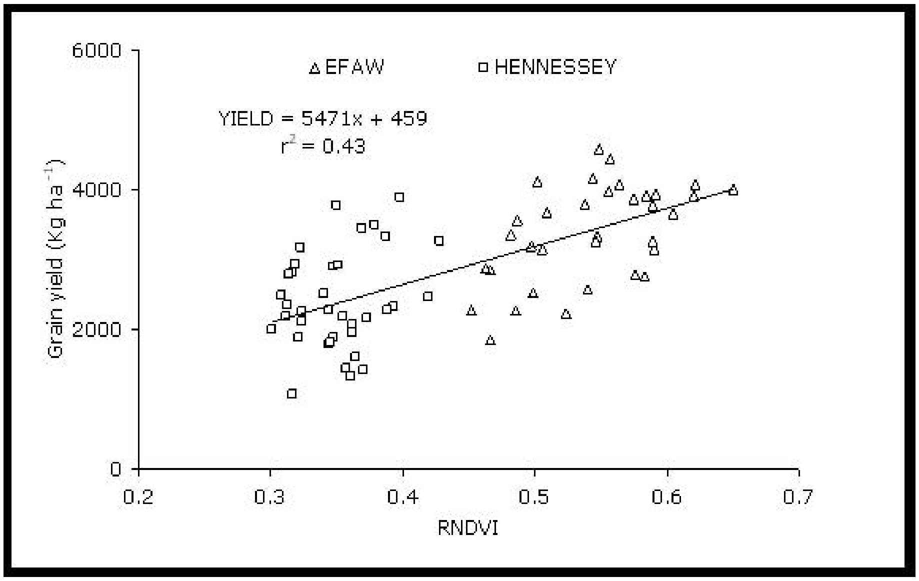

Figure 12. Relationship of RNDVI and grain yield at sorghum growth stage 2 at Efaw and Hennessey, OK, 2005.

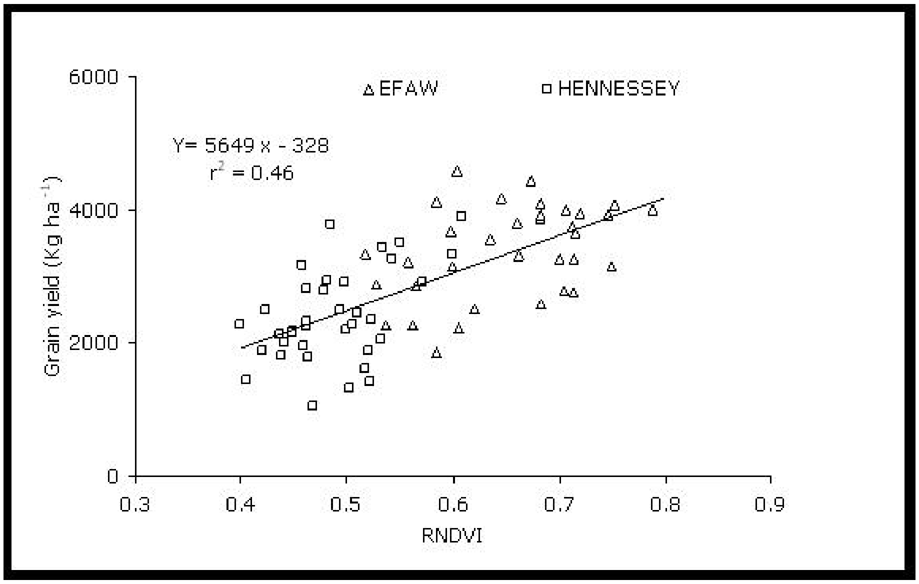

Figure 13. Relationship of RNDVI and grain yield at sorghum growth stage 3 at Efaw and Hennessey, OK, 2005.

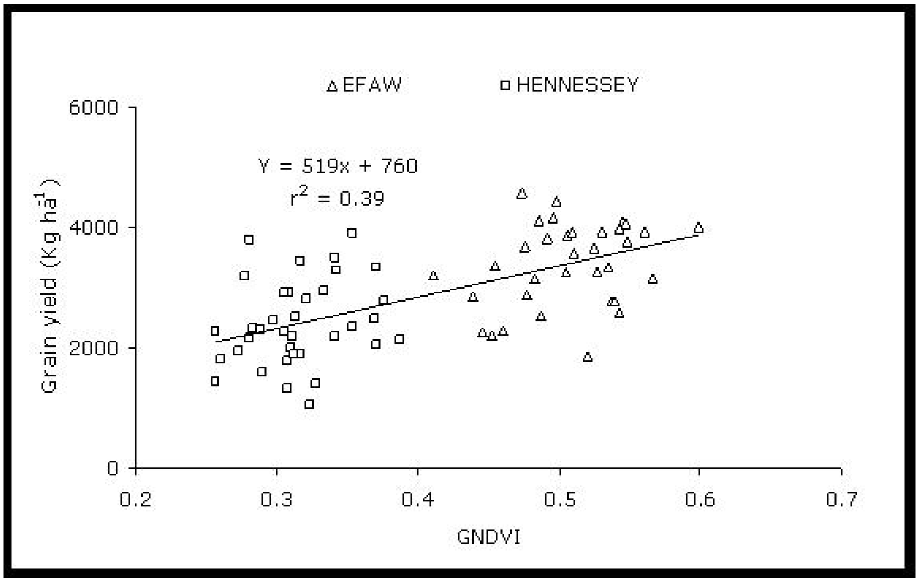

Figure 14. Relationship of GNDVI and grain yield at sorghum growth stage 3 at Efaw and Hennessey, OK, 2005.

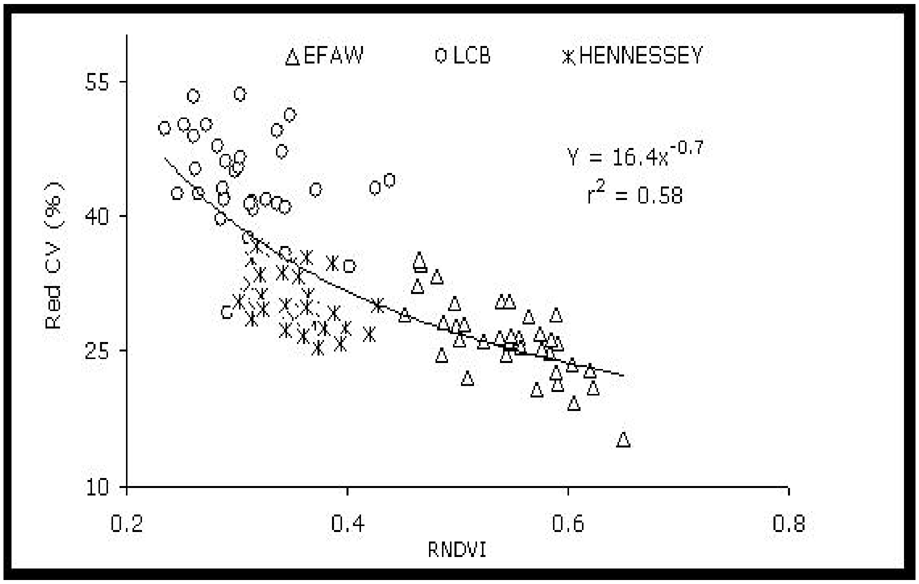

Figure 15. Relationship of RNDVI and CV at sorghum growth stage 2 at Efaw, Hennessey and Lake Carl Blackwell, OK, 2005.

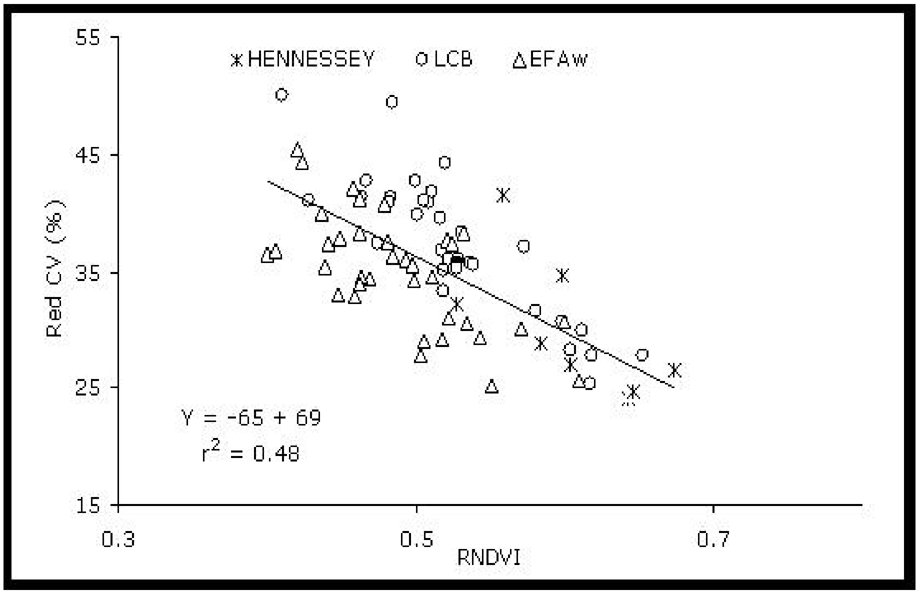

Figure 16. Relationship of CV and RNDVI at sorghum growth stage 3 at Efaw, Hennessey and Lake Carl Blackwell, OK, 2005.

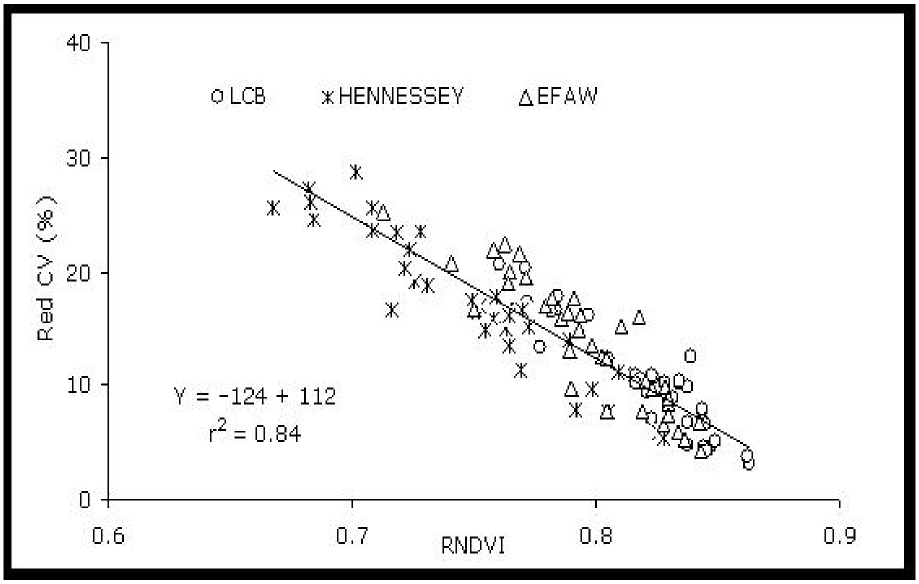

Figure 17. Relationship of CV and RNDVI at sorghum growth stage 5 at Efaw, Hennessey and Lake Carl Blackwell, OK, 2004.

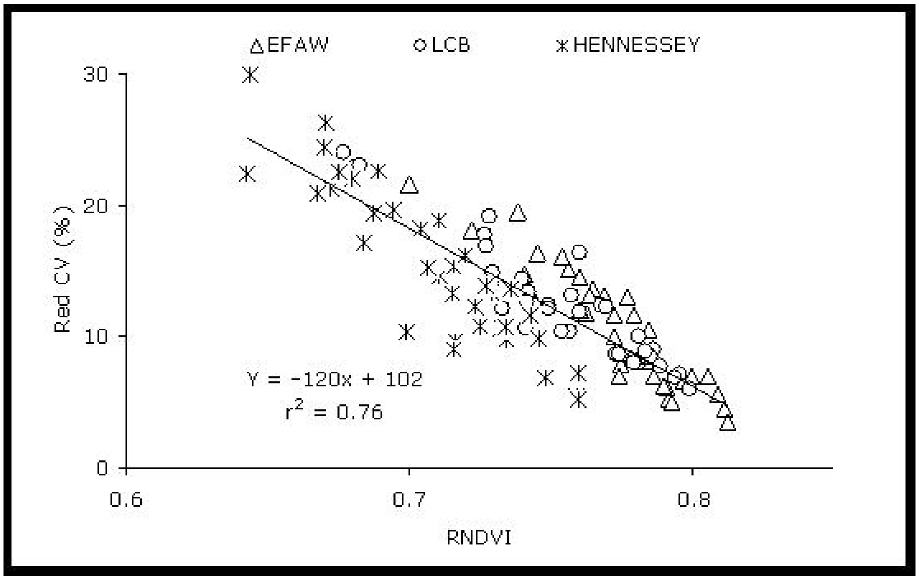

Figure 18. Relationship of CV and RNDVI at sorghum growth stage 6 at Efaw, Hennessey and Lake Carl Blackwell, OK, 2005.

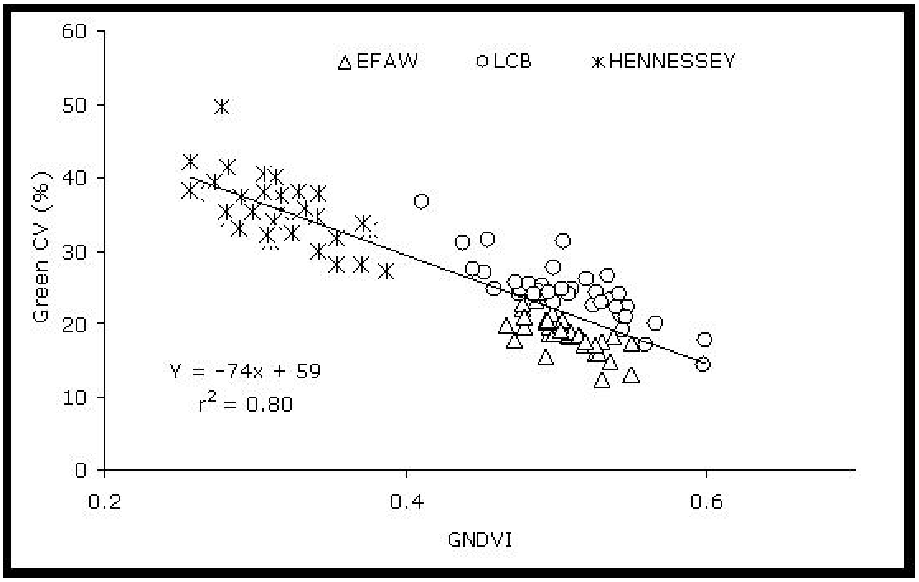

Figure 19. Relationship of CV and GNDVI at sorghum growth stage 3 at Efaw, Hennessey and Lake Carl Blackwell, OK, 2005.

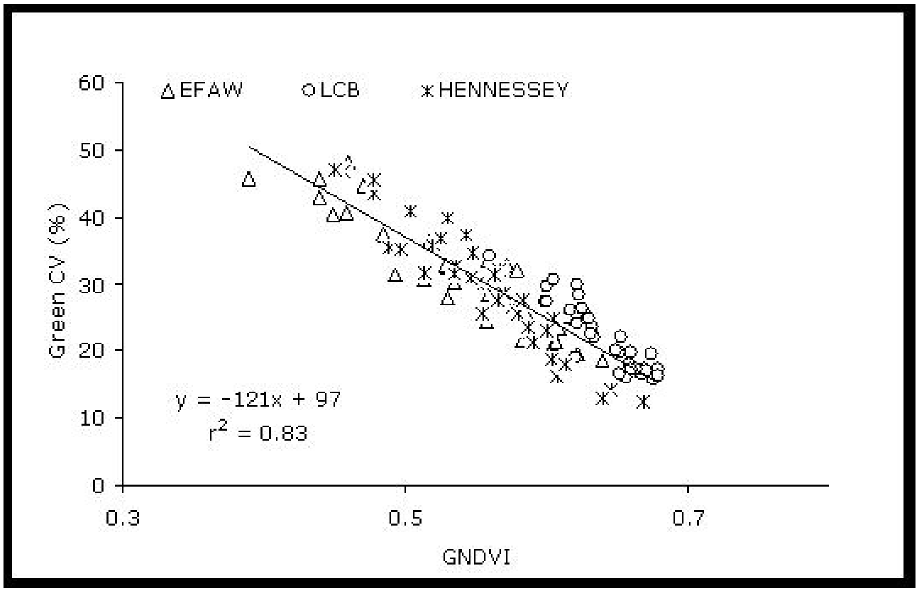

Figure 20. Relationship of CV and GNDVI at sorghum growth stage 5 at Efaw, Hennessey and Lake Carl Blackwell, OK, 2005.

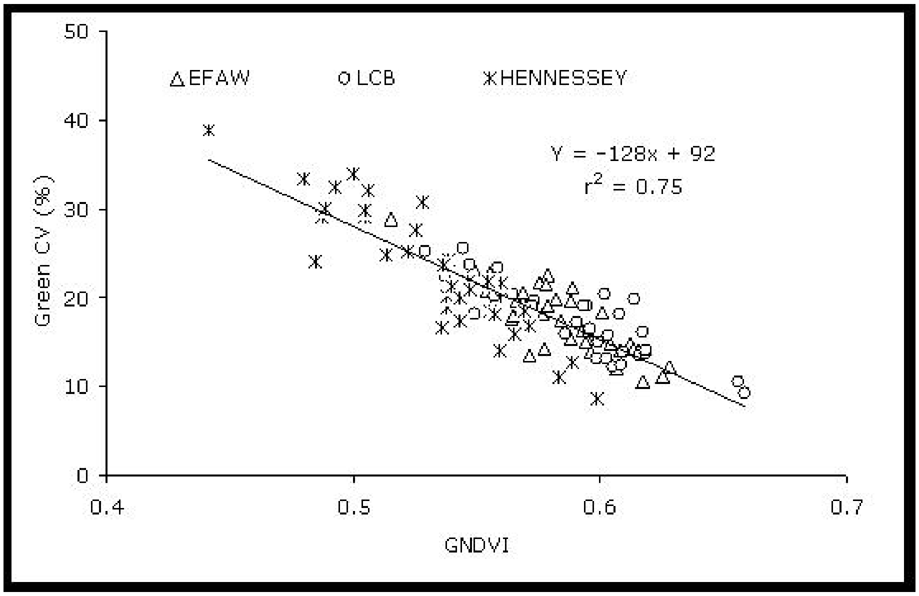

Figure 21. Relationship of CV and GNDVI at sorghum growth stage 6 at Efaw, Hennessey and Lake Carl Blackwell, OK, 2005.

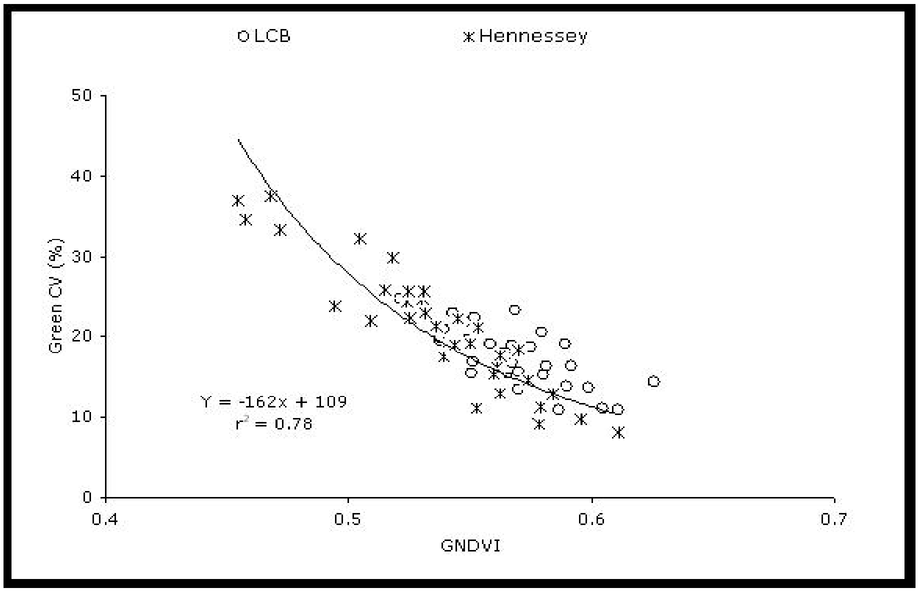

Figure 22. Relationship of CV and GNDVI at sorghum growth stage 7 at Hennessey and Lake Carl Blackwell, OK, 2005.

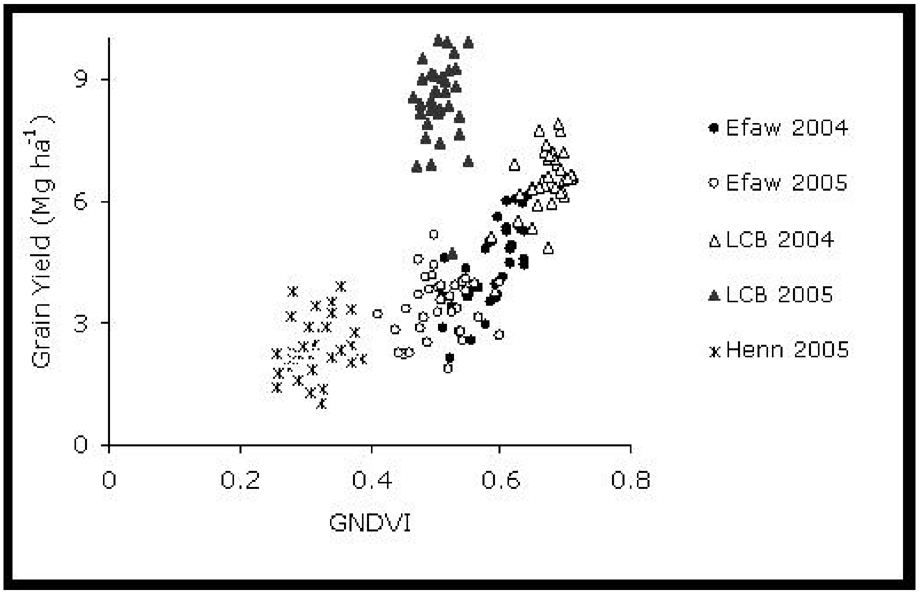

Figure 23. Relationship of GNDVI and grain yield at growth stage 3 combined over all locations and years, 2004-2005.

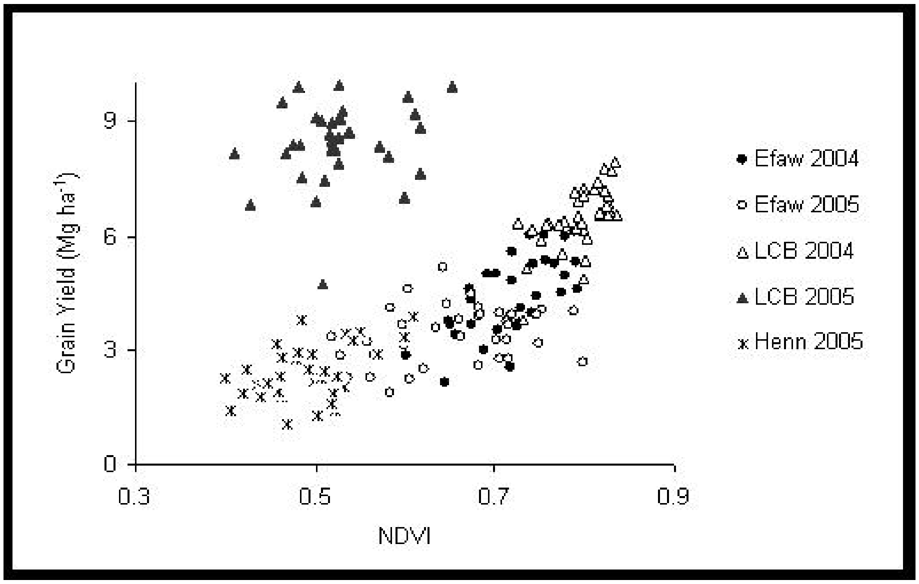

Figure 24. Relationship of RNDVI and grain yield at growth stage 3 combined over all locations and year, 2004-2005.

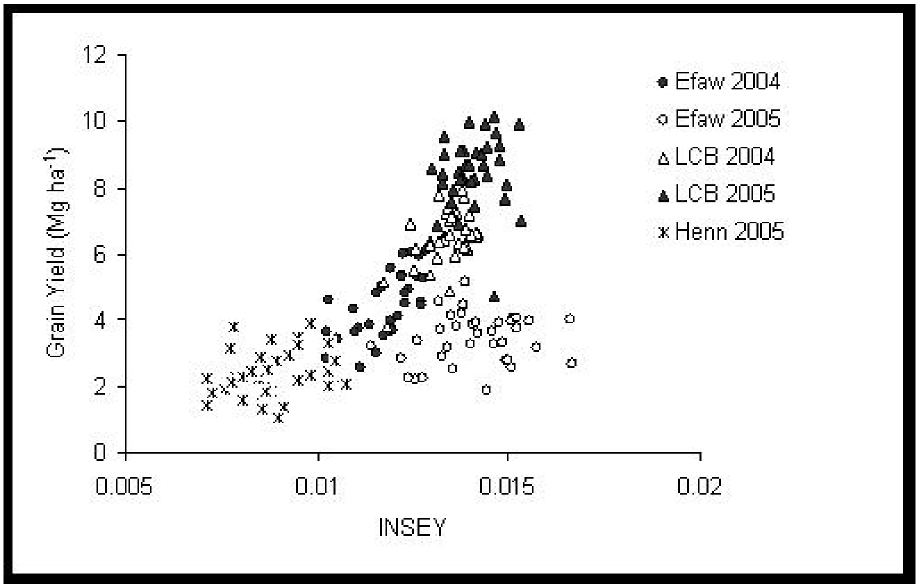

Figure 25. Relationship of Green INSEY and grain yield at growth stage 3 combined over all locations and years, 2004-2005.

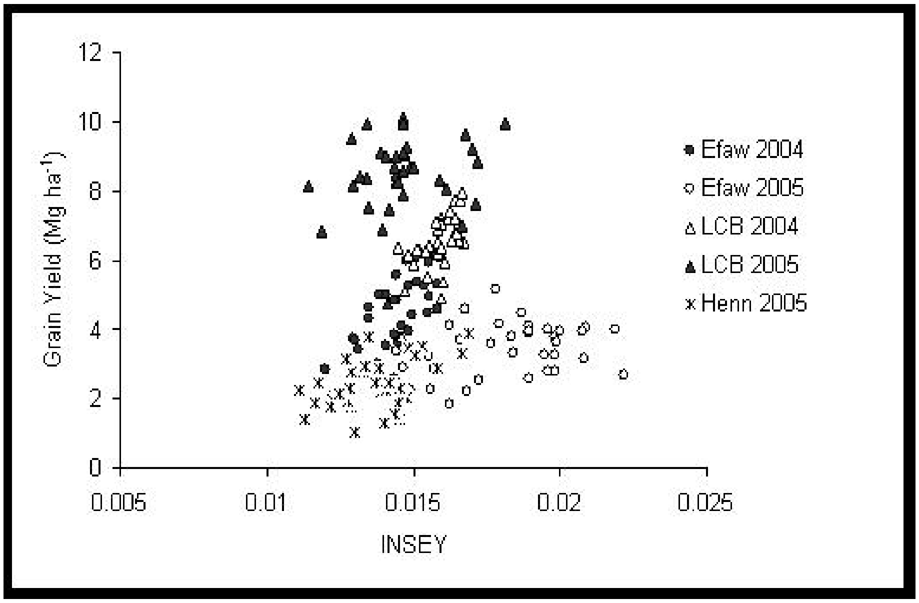

Figure 26. Relationship of Red INSEY and grain yield at growth stage 3 combined over all locations and years, 2004-2005.

CHAPTER II

EFFECT OF PLANT HEIGHT, SENSING ANGLE AND HEIGHT ON YIELD PREDICTION OF CORN (Z*EA MAYS* L.)

ABSTRACT

Plant to plant corn (Z*ea mays* L.) yield variability is one of the most important issues that should be addressed to delineate the appropriate scale of operations in a crop demand based nutrient management program specially nitrogen. The objectives of these experiments were to determine the magnitude of variability in mid season measured corn plant heights and their relationships with final grain yield and to determine the best sensing height and angle where sensors should be positioned that will provide the best relationship of NDVI and grain yield. A total of 20 transects (each 20 m long) were used in one experiment from which measurements of individual plant heights (at growth stages V8, VT and R1) and grain yield were made at Efaw, Perkins and Lake Carl Blackwell, OK in summer of 2004 and 2005. In another experiment a total of 4 transects (50 plants per transect) were used for optical sensor (bicycle mounted) and grain yield measurements. Data analysis showed that plant height was consistently correlated with grain yield at growth stage VT at all locations and years and sensor readings taken at 0.76 m above the canopy at nadir showed better relationship of NDVI and grain yield.

INTRODUCTION

Excess fertilizer is applied for corn (*Zea mays* L.) throughout North America. Aiming to obtain the highest yield in the growing season, farmers traditionally apply nitrogen (N) fertilizers at uniform rates across a field as either a pre-plant or early-season side dress application. But, plant nutrient uptake varies with growth stage and weather conditions. The amount of nutrient available in a soil of a certain field may vary over time (temporal) and space (spatial). Fertilizer management practices that fail to consider these variables may result in low N use efficiency (NUE). Since N fertilizer has been relatively inexpensive and weather conditions vary from year to year along with yield potential (Wilhelm et al., 1987), producers typically apply N at levels so as not to limit yield in good years. This can result in excess N applied beyond which the plant can remove from the soil. In fact, Raun and Johnson (1999) estimated that NUE for world cereal grain production systems to be only 33%, with the unaccounted 67% representing a $15.9 billion annual loss of fertilizer N. With the increasing costs of N fertilizer due to natural gas shortages, unaccounted fertilizer N is now estimated to be worth more than $20 billion dollars annually. Failure to recover the applied fertilizer may contaminate surface and subsurface water supplies. Nitrogen losses during corn production are of special concern because large areas are planted to this crop, and N is applied at relatively high rates, with substantial amounts of NO_3–N found in water that drains from these soils (Gast et al., 1978; Baker and Johnson, 1981). Several research works have shown that more than half of the N applied is lost from fields by processes other than crop harvest during the first year after application (Blackmer, 1987; Sanchez and Blackmer, 1988; Timmons and Cruse, 1990).

Paramasivam et al. (2002) showed that 21 to 36% of fertilizer N leached below the root zone, while plant uptake accounted for 40 to 53%. Sanchez and Blackmer (1988) reported that 49 to 64% of the fall-applied fertilizer N was lost from the upper 1.5 m of the soil profile through pathways other than plant uptake. They speculated that transport of this N to the Gulf of Mexico results in the creation of a hypoxic zone, with dissolved oxygen levels too low to sustain animal life, adversely impacting a $2.8 billon commercial and recreational fishing industry in the region. Sexton et al. (1996) observed that NO_3-N leaching increased rapidly as N rates exceeded 100 kg N ha^{-1} yr^{-1} for corn grown on a sandy loam soil in central Minnesota, and as N rates increased to about 250 kg N ha^{-1} (corresponding to maximum yield), NO_3-leaching increased exponentially. They also reported that reducing N application rates by 5% less than that required to achieve maximum corn yield reduced NO_3 leaching by 40 to 45%. Kranz and Kanwar (1995) estimated that 70% of the NO3-N leached came from less than 30% of cornfields. According to Dennis et al. (2002) spatial variability of corn yield creates a significant challenge for N fertility management because excessive N can result in NO3-N contamination of surface and ground water bodies and inadequate N results in yield and profit losses. Increasing use of spatial demand as a basis for N management can remarkably reduce surface and ground water contamination and loss of revenue (Dorge et al., 2002).

Amount and timing of N fertilization can significantly affect the outcome of any efficient nutrient management program. Various works on N management have developed a yield goal based N fertilizer recommendation, none of which addressed inherent field spatial and temporal variability in a growing season. As per the work of Katsvairo et al. (2003) yield goal based N application, based on yield map data, have resulted in over fertilization of N in about 25% of the field where corn yields were greatest and under fertilization on about 15% of the fields where corn yields were the poorest. The biggest challenge in the current nutrient management system is identifying areas in crop fields where response of N would be maximized with a minimum loss to the environment. This actually requires a through investigation and detailed measurement to understand why crop yield varies over time and space (Sadler et al., 2000; Machado et al., 2002).

One of the best ways to improve efficiency is via crop monitoring. Crop monitoring usually helps to improve control over temporal variation in crop growth and also provides information on crop development that is useful in developing management strategies that improve water and nutrient use efficiency. Water and nutrient applications made at periods of peak demand improve water (Passioura, 1994) and nutrient (Baethgen and Alley, 1989) use efficiency and increase grain yields. Furthermore, efficient use of nutrients could result in N savings without reduction in grain yield (Stone et al., 1996). Most research work on plant monitoring has been done by remote sensing (Nilsson, 1995; Moran, 1997). The main emphasis has been to increase the accuracy of estimating crop biomass (Bedford et al., 1993), leaf area index (Bouman et al., 1992), nutrient deficiency

(Thomas and Oerther, 1972; Peñuelas et al., 1994), water stress (Peñuelas et al., 1994), and diseases (Nilsson, 1995; Pederson and Nutter, 1982). However, little effort has gone into relating these measurements to final grain yield (Blackmer et al., 1996; Zhang et al., 1998) and determining how this information could be used for managing site-specific farming.

There have been several techniques tested to estimate N uptake and availability in corn, most which are time consuming and cumbersome. These include chlorophyll meter readings, destructive plant sampling and soil sampling. Increased scientific understanding of spectral responses of crops is increasing the potential for using remote sensing to detect nutrient stresses. One of the earliest digital remote-sensing analysis procedures developed to identify the vegetation contribution in an image was the ratio vegetation index, created by dividing near-infrared reflectance (NIR) by red reflectance (Jordan, 1969). The basis of this relationship is the strong absorption (low reflectance) of red light by chlorophyll and low absorption (high reflectance and transmittance) in the NIR by green leaves (Avery and Berlin, 1992). Blackmer et al. (1994) and Thomas and Oerther (1972) found that light reflectance near 550 nm was best for separating N-deficient from non-N-deficient corn and sweet pepper (*Capsicum annuum* L.) leaves, respectively. Bausch and Duke (1996) investigated using a ratio of NIR/green reflectance as an N-sufficiency index. Comparison of this method to the SPAD chlorophyll meter measurements (Minolta Corp., Ramsey, NJ) demonstrated that the NIR/green ratio and SPAD measurements exhibited a 1:1 relationship and that the ratio could be used to determine fertilization need for irrigated corn. Aase and Tanaka (1984) reported a relationship between green leaf dry matter and NIR/red ratios, and suggested that reflectance measurements could be used to estimate leaf dry matter or leaf area measurements in spring and winter wheat (*Triticum aestivum* L.). Work by Stone et al. (1996) demonstrated that total plant N could be estimated using spectral radiance measurements in the red (671 nm) and NIR (780 nm) wavelengths. They calculated a plant-N-spectral-index for the amount of fertilizer N required to correct in-season N deficiency in winter wheat.

Sensor based variable rate technologies nowadays widely used in site-specific nutrient management scheme. However, their practical application on a field is closely related to soil and crop parameters that could possibly alter the information collected from fields at different circumstances. Hence thorough investigation of the relationship between crop parameters and sensor readings would be of a great importance in the refinement of sensors used in crop measurements. Researches have shown that crop parameters such as plant height affect early season sensor readings, as it is related to final grain yield and yield variability in a field. Sadler et al. (2000) reported that Plant height and biomass during corn vegetative development showed significant spatial variability in an 8-ha cornfield in South Carolina. Plant height at the V12 (12th leaf stage) (Ritchie et al., 1993) correlated with grain yield in a dry year but not in a wet year in a 2.7 ha field in Texas (Machado et al., 2002). Plant height at 4 and 8 wk after emergence correlated with corn yield at three of five sites in the Corn Belt in the USA (Mallarino et al., 1999). They also reported that conditions that favored early season corn growth are the most important factors in explaining the spatial yield variability. Katsvairo et al. (2003) reported that plant height at the V6 and V10 stages were more sensitive indicators than biomass and N uptake at the V6, R1, and R6 growth stages in assessing the spatial variability in corn field.

Sensor measurements traditionally taken by holding the sensor at a certain height from the corn canopy disregarding the effect of individual plant height on biomass and grain yield estimation. Thus to study the effect of individual plants height on estimation of biomass and yield, considering individual plants in the course of sensing would be more informative.

Therefore two different experiments were designed with the following hypothesis.

1. individual corn plant height has significant effect on final grain yield
2. Sensor measurements taken at different geometric positions and height in reference to corn canopy surface can equally be used in estimating final grain yield.

The objectives of these experiments were,

1. to determine the best combination of sensing height and sensing angle where sensors would be positioned to get NDVI measurements that can be used to estimate final grain yield.
2. to determine the effect of individual plant height measurements on corn grain yield at different growth stages and to observe if plant height population is normally distributed over the mean height.

MATERIALS AND METHODS

Sensing Height and Angle Experiment

Two already established corn fields were used in the summer of 2004, one near Stillwater (planted on April 7), at the Agronomy Research Station (Easpur loam fine-loamy, mixed, superactive, thermic Fluventic Haplustoll) and Perkins (planted April 2) (Teller sandy loam-fine-loamy, mixed, thermic Udic Argiustoll), Oklahoma. In summer of 2005 transects were selected, from corn field at Efaw (planted April 7) and Lake Carl Blackwell (planted April 12) (Oklahoma State university research site) located on a Port fine-silty, mixed, superactive, thermic Cumulic Haplustoll.

Bt corn variety was used at both locations with 113 days maturity at Efaw and 108 days maturity at Perkins. At each location two transects were selected from corn rows where there is detectible variability in plants. There were fifty sequential plants in each transect used for by-plant sensor readings and yield measurements. Distance of each individual plant in relation to and from its neighbor was measured in order to determine by-plant corn grain yield per area (based on the area occupied as a function of neighboring plants) and by-plant sensor reading. Plants were tagged at V6 (six leaf fully expanded) to avoid confusion of missing plants.

Sensor readings were taken using Oklahoma State University designed bike mounted (GreenSeeker™), which produces an infrared sensing strip of light, 24 inches long and 0.5 inches wide. Senor readings were taken by positioning the sensor 76 cm and 100 cm above corn canopy surface at growth stages V8 (eight full expanded leaves), VT (tasseling), and R1 (silking). Two sensing angles nadir (senor held parallel and directly above the canopy) and 45 degree (sensor tilted at 45 degree from the canopy) were used to take readings from the selected rows at each growth stage.

Ears from plants in each transect were harvested and weighed individually and recorded. Once removed from the stalk, ears were dried at 66°C for 48 hours and weighed before and after shelling. The weight taken from the dry, shelled corn was the final grain weight used for yield determination.

Percent grain N was determined using dried grain samples which were ground to pass a 0.125 mm (120-mesh) sieve and analyzed for total N using a Carlo Erba (Milan, Italy) NA-1500 dry combustion analyzer (Schepers et al., 1989). The relationship between NDVI versus grain yield and grain N was determined by simple linear regression method using proc reg procedure in SAS software program.

Effect of Plant Height on Grain Yield

This experiment was conducted on an already established corn field at Efaw and Perkins, in summer of 2004 and at Efaw and Lake Carl Blackwell in summer of 2005.

Plant height and grain yield measurements were made on five transects of 20 m length which were selected randomly from corn field at each location. At corn growth stage V6 individual plants in each transect were counted and distance between plants in each transect measured and recorded and each plant was tagged to track missing plants. The first and the last plant were not considered for analysis to avoid boarder effect. Distances between plants were used to calculated area occupied by each plant in relation to its neighbor.

Relative area occupied by a plant was calculated by the following formula:

$$A_i = \left[\frac{d_i - d_{i-1}}{2} + \frac{d_{i+1} - d_i}{2} \right] R$$

Where: A_i is the area occupied by the i^{th} plant,

d_{i-1},d_i,d_{i+1} are the distances to the i-1, i, and i+1 plants and

R is the row spacing

Individual corn plant height was measured at three growth stage V8 (V10 in fall of 2005), VT and R1 for each transect at each location. Plant height was measured by using centimeter graduated yard stick from the base of the plant up to the tip of fully expanded leaf (stretched vertically) at growth stages V8. At growth stages VT and R1 plant height measurement was made from the base of the plant to the collar of the last leaf which bundles the tassel.

Ears from plants in each transect were harvested and weighed and recorded individually. Once removed from the stalk, ears were dried at 66°C for 48 hours and weighed before and after shelling. The weight taken from the dry, shelled corn was the final grain weight used for yield determination. Relationship between plant height and grain yield was estimated using simple linear regression method using proc reg procedure in SAS (SAS institute, 1988) software program.

RESULTS AND DISCUSSION

Plant Height and Grain Yield

Crop Year 2004

After excluding dead or damaged plants a total of 514 (Efaw) and 383 (Perkins) individual plants in five transects were used for height and grain yield measurements. Average corn plant heights of combined transects were 107, 171 and 174 cm at Efaw and 80, 113 and 130 cm at corn growth stages V8, VT and R1 at Perkins, respectively (Table 1). Corn planted at Perkins was found to be relatively short due to the sandy texture of the soil and less efficient to conserve moisture during the growing cycle. As a result most plants at this site had stunted growth and resultant low grain yields.

There was significant variability observed in by-plant grain yield of corn. Grain yield of individual plants ranged from 979 kg ha^{-1} (15 bu/acre) to 14,160 kg ha^{-1} (226 bu/acre) at Efaw and from 1,151 kg ha^{-1} (18 bu/acre) to 8,837 kg ha^{-1} (141 bu/acre) at Perkins (Table 2). The average corn grain yield was 5,219 and 3,924 kg ha^{-1} with corresponding standard deviations of 2,070 and 1,321 Kg ha^{-1} at Efaw and Perkins, respectively (Table 2). At both locations close to 70 and 95 percent of by-plant grain yield measurements were in the range of one and two standard deviations from the mean grain yield, respectively (Table 2).

Simple regression analysis of the data showed that there was a significant relationship between corn grain yield and plant height at both locations in this year. At Efaw, grain yield calculated on an area basis was highly correlated with plant height at growth stage VT (r^2=0.61) (Figure 1). Similar results were found at growth stage R1 at Efaw (data not shown). This relationship was improved when by-plant corn grain yield was regressed with plant height, without considering area. This was shown by a coefficient of simple determination (r^2) of 0.74 obtained at VT (Figure 2). The improved relationship of by plant yields with plant height, not accounting for area was also observed at R1 (data not reported).

At Perkins an r^2 of 0.55 was obtained at growth stage R1 when by-plant grain yields accounting for area were regressed with individual plant height measurements (Figure 3). When by-plant grain yields without considering area were regressed on plant height, an r^2 of 0.69 was obtained at R1 (Figure 4). This same trend was observed at growth stage VT (improved correlation of non-area dependent data versus area dependent).

Crop year 2005

A total of 455 (at Efaw) and 540 (at Lake Carl Blackwell) plants in five transects were used for by-plant height and grain yield measurements. Average plant height was 128, 161 and 170 cm at Efaw and 130, 186, 206 cm at Lake Carl Blackwell at growth stage V8, VT and R1, respectively (Table 3). Corn plants were relatively taller at Lake Carl Blackwell as compared to the Efaw site. This was due to irrigation at the Lake Carl Blackwell site which resolved the water stress problem from planting to harvest and increased early season and late season biomass accumulation.

By-plant corn grain yields ranged from 258 kg ha^{-1} (4 bu/acre) to 15,881 kg ha^{-1} (226 bu/acre) at Efaw and from 2,327 (37 bu/acre) to 42,906 kg ha^{-1} (684 bu/acre) at Lake Carl Blackwell (Table 4). Average by-plant corn grain yields were 5,093 kg ha^{-1} (81 bu/acre) at Efaw and 16,757 kg ha^{-1} (267 bu/acre) at Lake Carl Blackwell (Table 4). At both locations 71 and 96 percent of individual plant yields were with in one and two standard deviations from the mean by-plant yield, respectively (Table 4) and appeared to be normally distributed.

Simple regression analysis of the data revealed that by-plant corn grain yield (calculated on an area basis) was related to plant height at growth stage VT ($r^2 = 0.53$) at Efaw (Figure 5). Similar results were found at growth stages V8 and R1 (data not shown). This relationship was somewhat better when by-plant yield (non-area based) was regressed with plant height at growth stages VT ($r^2=0.62$) and slightly weaker at V8 (data not shown) at the Efaw site (Figure 6). The same scenario of improved relationship between by-plant corn grain yield and plant height was observed in 2004 when non-area based yield was related to individual plant height measurements.

Sensing Height and Angle

Results of simple regression analysis of the data have shown that there was a significant variation in the relationship between grain yield and NDVI depending on height and geometric position of the sensor. Measurements of NDVI taken 0.76 m above the corn canopy surface and holding the sensor directly above the corn canopy (nadir) showed improved correlation with corn grain yield at growth stage V8 ($r^2=0.69$) when compared to 1m directly above the canopy, or at a 45 degree angle (Figure 7). Data for the 45 degree angle measurements were lost for the VT growth stage, however, similar to that noted at V8, improved correlation was found at the 0.76 m height when compared to 1m for readings collected at this growth stage (Figure 8). Identical to results at the V8 growth stage, 0.76m NDVI data collected directly above the corn canopy at R1 (Figure 9) resulted in improved correlation with final by-plant grain yield when compared to NDVI data collected at the 1m height either directly above the canopy or at a 45 degree angle.

In general the relationship of grain yield and NDVI was weaker when moving from 0.76 m to the 1 m height above the canopy surface and from nadir to the 45 degree position (Figures 7 and 9). This may be due to the sensor's loss of vision of crop canopy at increased height and 45 degree angles. The relationship between NDVI and by-plant grain yields remained positive when moving from 0.76m to 1m, but the correlation was significantly reduced (Figures 7, 8, and 9). However, consistent for both the V8 and R1 growth stages, sensing at 45 degree angles significantly decreased the correlation of NDVI and by-plant grain yield, especially at the 1m height (Figures 7 and 9).

CONCLUSIONS

Results from this study showed that part of the variability in corn grain yield can be explained by plant height data collected at either VT or R1 growth stages. Plant height is clearly an important variable when recognizing differences in yield potential in corn, evidenced in the consistency for the two stages of growth reported in this work. Similar studies by Machado et al. (2002) showed that 60% of variation in corn yield was explained by plant height.

Sensor NDVI measurements taken at two vertical distances above the corn canopy and two geometric sensor positions showed differences in performance of predicting by-plant corn grain yield. Results of regression analysis of the data showed the presence of a strong relationship between NDVI and grain yield when sensor measurements were taken at nadir position and 0.76 m above the corn canopy surface. This relationship was weak when sensor measurements were taken 1 m high either directly above or at 45 degree angles. By plant corn grain yields can be accurately predicted using sensor readings collected 0.76 m directly above the corn canopy, and using measured plant height.

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Table 1. Average corn height (cm) and corn by-plant yield for five transects at three growth stages and two locations at Efaw and Perkins, OK, 2004.

	…………….. Height (cm)………………						Grain yield (kg ha^{-1})	
	V8		VT		R1			
Efaw	Ave.[‡]	Std dev	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.
Transect 1	109	8	165	10	193	10	4393	1117
Transect 2	101	7	159	10	186	8	3927	1219
Transect 3	102	12	162	13	165	13	4718	1811
Transect 4	111	10	182	9	165	7	6179	2088
Transect 5	112	13	191	8	165	7	7169	2089
Average	107	11	171	16	174	15	5219	2078
Perkins								
Transect 1	79	8	107	16	125	12	3163	1100
Transect 2	80	7	109	14	128	10	4180	1090
Transect 3	79	9	112	16	129	10	3820	1390
Transect 4	80	8	117	15	132	11	4199	1390
Transect 5	82	8	120	15	136	9	4155	1330
Average	80	8	113	16	130	11	3920	1320

[‡] Average plant height std. Dev.=standard deviation

Table 2. Minimum, maximum, mean, standard deviation and CV for by-plant corn grain yields for individual transects at Efaw and Perkins, OK, 2004.

	No. of plants	Min	Max	Mean	Std. Dev.	±1 std dev (%)‡	±2 std dev (%)†	CV (%)
Transect				Efaw				
	………………………………...kg ha^{-1}…………………………..							
1	106	1885	6876	4393	1117	69	96	25
2	105	979	7621	3904	1202	67	95	31
3	108	1134	10370	4718	1811	68	97	38
4	96	2756	14160	6197	2089	68	91	34
5	99	2364	13270	7169	2089	67	94	29
Average	514	979	14160	5219	2070	70	95	40
				Perkins				
1	69	1151	5842	3164	1101	59	99	35
2	85	1270	7611	4184	1386	68	97	33
3	77	1819	6675	3820	1086	74	87	28
4	76	1249	7233	4199	1391	68	96	33
5	76	1742	8837	4155	1327	72	96	32
Average	383	1151	8837	3924	1321	69	96	34

std. Dev.=standard deviation, [†]Minimum [††]Maximum

‡ number plants with grain yield within one standard deviation

† number of pants with grain yield within two standard deviations

Table 3. Average corn height (cm) and corn by-plant yield for five transects at three growth stages and two locations at Efaw and Lake Carl Blackwell, OK, 2005.

	………………….. Height (cm)…………………						Grain yield (kg ha^{-1})	
	V8		VT		R1			
Efaw	Ave.[‡‡]	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.	Ave.	Std. Dev.
Transect 1	121	14	158	17	161	13	5247	3087
Transect 2	123	18	163	17	168	14	5417	2451
Transect 3	126	17	156	19	169	13	4950	2869
Transect 4	132	14	162	14	173	10	5281	2602
Transect 5	134	19	161	18	170	15	5266	2719
Average	128	16	161	15	168	11	5093	2123
Lake Carl Blackwell								
Transect 1	136	12	183	12	203	8	16404	7219
Transect 2	136	15	178	24	203	14	16408	7153
Transect 3	122	13	187	16	206	12	17456	7130
Transect 4	137	16	188	18	203	16	17424	7496
Transect 5	125	14	182	13	208	15	16042	6755
Average	130	15	186	14	206	12	16757	7081

[‡‡] Average plant height std.dev = standard deviation.

Table 4. Minimum, maximum, mean, standard deviation and CV for by-plant corn grain yields for individual transects at Efaw and Lake Carl Blackwell, OK, 2005.

	No. of plants	Min[†]	Max[††]	Mean	Std. Dev.	±1 std. dev. (%)	±2 std. dev. (%)	CV[‡] (%)
Transect				Efaw				
	………………………….Kg ha^{-1}…………………………..							
1	98	1380	28065	5301	3056	88	96	58
2	91	879	19503	5481	2392	78	98	44
3	90	440	20202	5062	2801	78	96	55
4	82	278	15949	5346	2550	73	94	48
5	94	258	18185	5266	2719	79	98	52
Average	455	258	15881	5093	2123	72	95	42
				Lake Carl Blackwell				
1	114	2327	46215	16404	7219	74	97	44
2	111	2126	38346	16408	7153	72	96	44
3	114	2361	39312	17456	7130	69	96	41
4	95	713	38733	17424	7496	71	93	43
5	102	2796	36908	16042	6755	78	96	42
Average	540	2327	42906	16757	7081	70	96	42

std. Dev.=standard deviation, [†]Minimum [††]Maximum

[‡] coefficient of variation

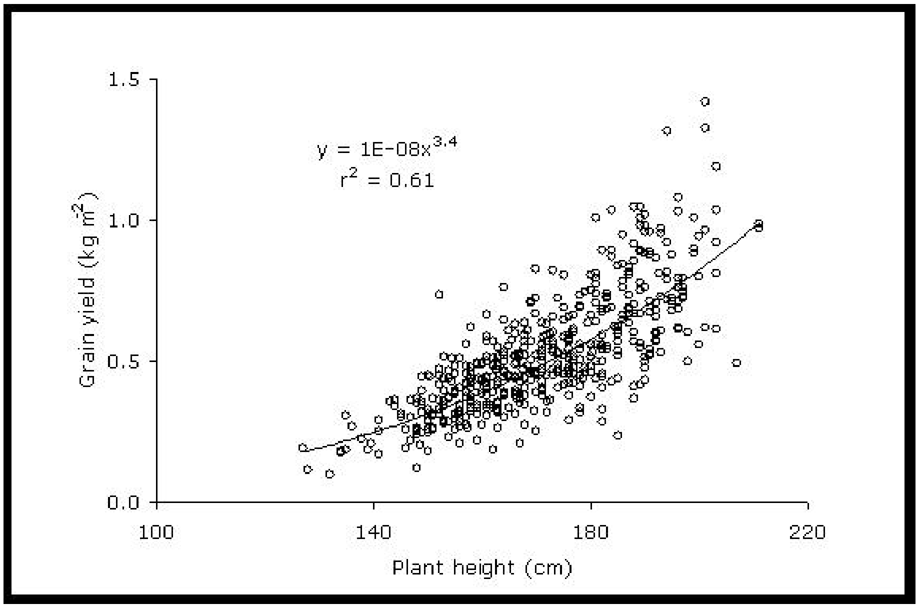


Figure 1. By-plant corn grain yield per area and plant height relationship at growth stage VT at Efaw, OK, 2004.

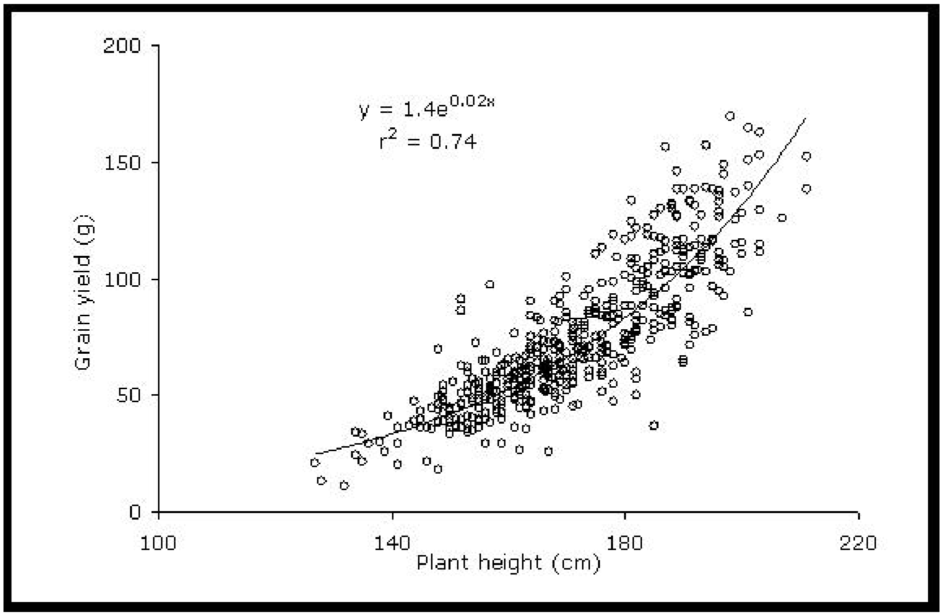


Figure 2. By-plant corn grain yield (grams per plant) and plant height relationship at growth stage VT at Efaw, OK, 2004.

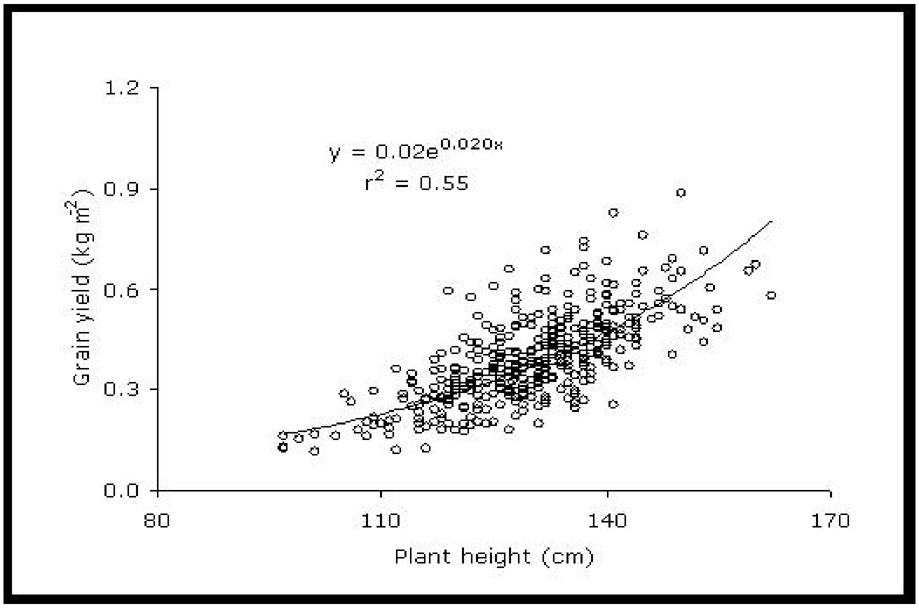


Figure 3. By-plant corn grain yield per area and plant height relationship at growth stage R1 at Perkins, OK, 2004.

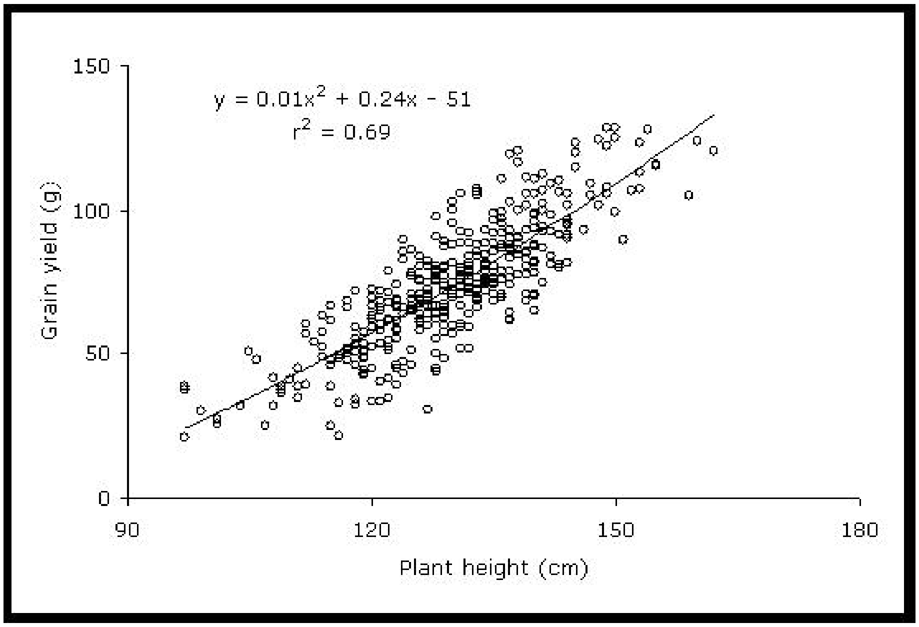


Figure 4. By-plant corn grain yield (grams per plant) and plant height relationship at growth stage R1 at Perkins, OK, 2004.

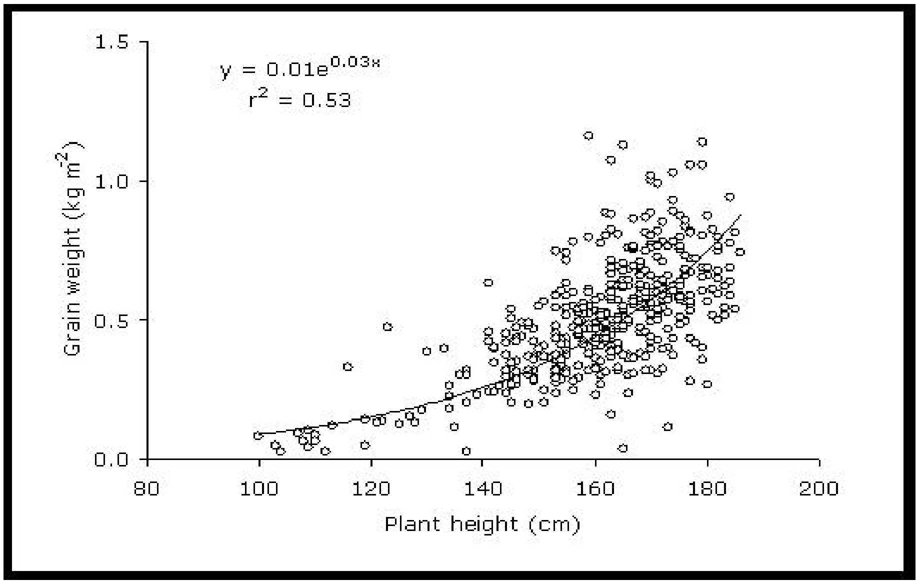


Figure 5. By-plant corn grain yield per area and plant height relationship at growth stage VT at Efaw, OK, 2005.

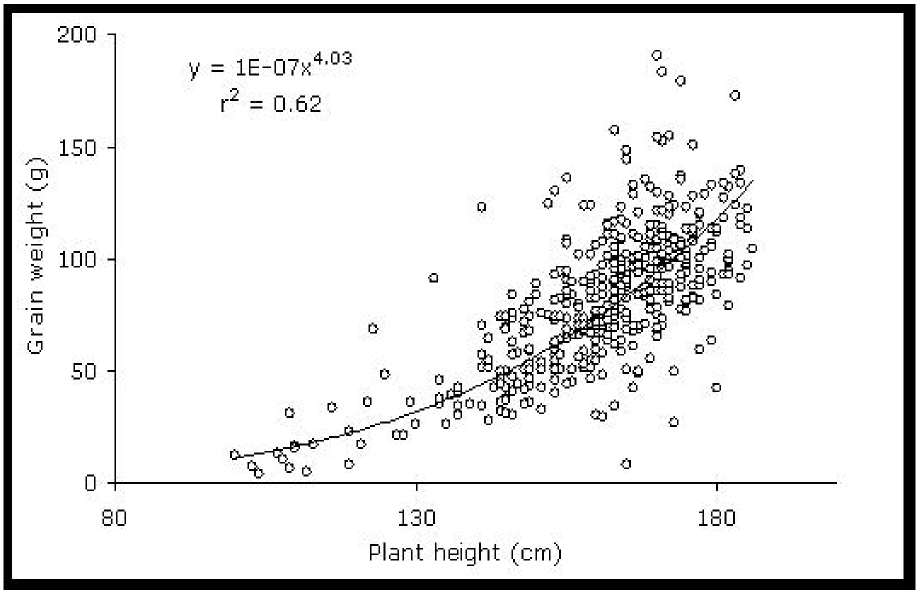


Figure 6. By-plant corn grain yield (grams per plant) and plant height relationship at growth stage VT at Efaw, OK, 2005.

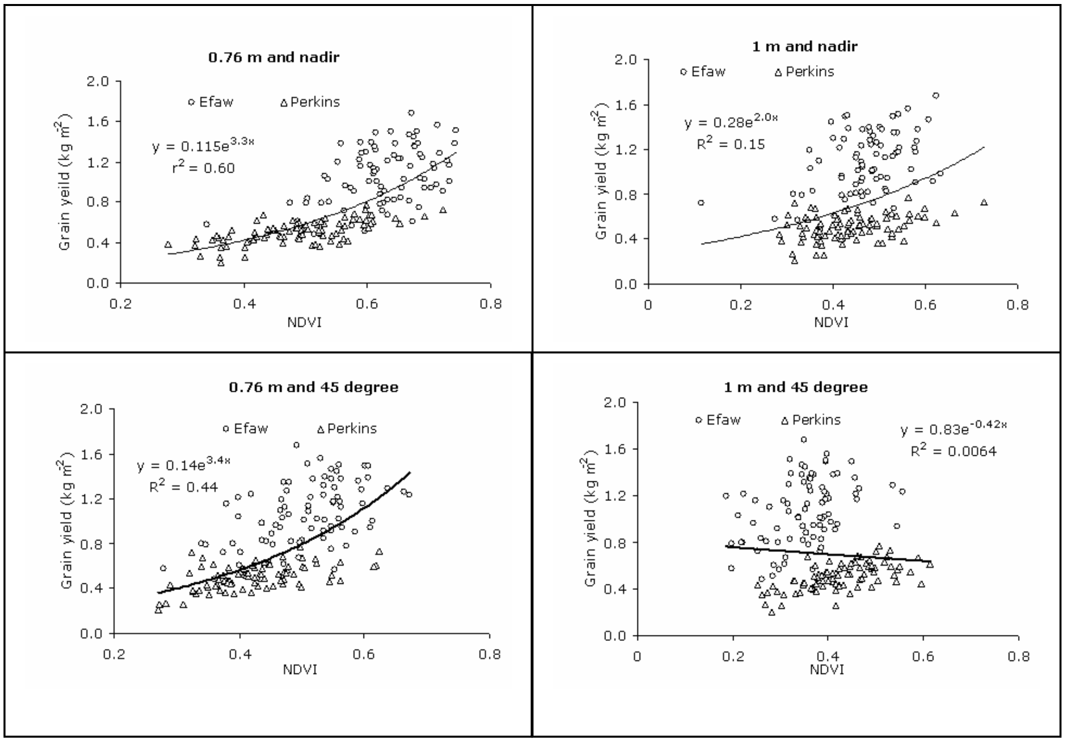


Figure 7. Grain yield and NDVI relationship at growth stage V8 at different sensing height and angle combination at Efaw and Perkins, OK, 2004.

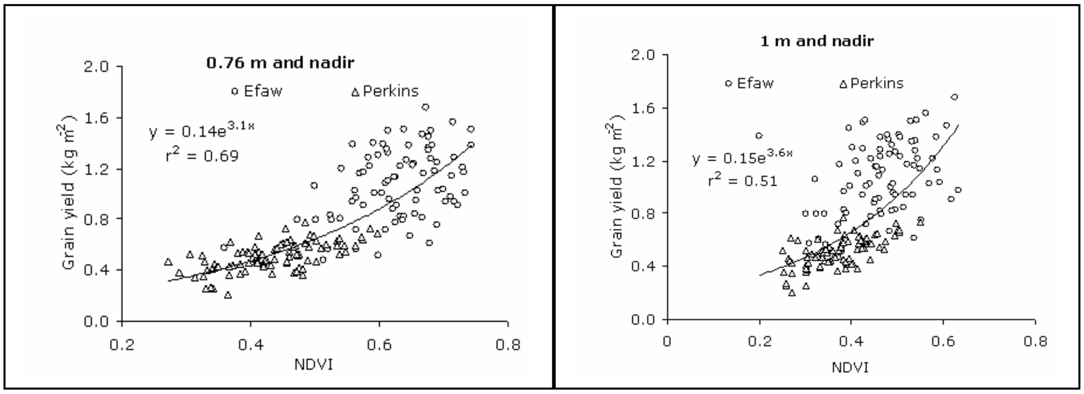


Figure 8. Grain yield and NDVI relationship at growth stage VT at 0.76 and 1 m sensing height at nadir at Efaw and Perkins, OK, 2004.

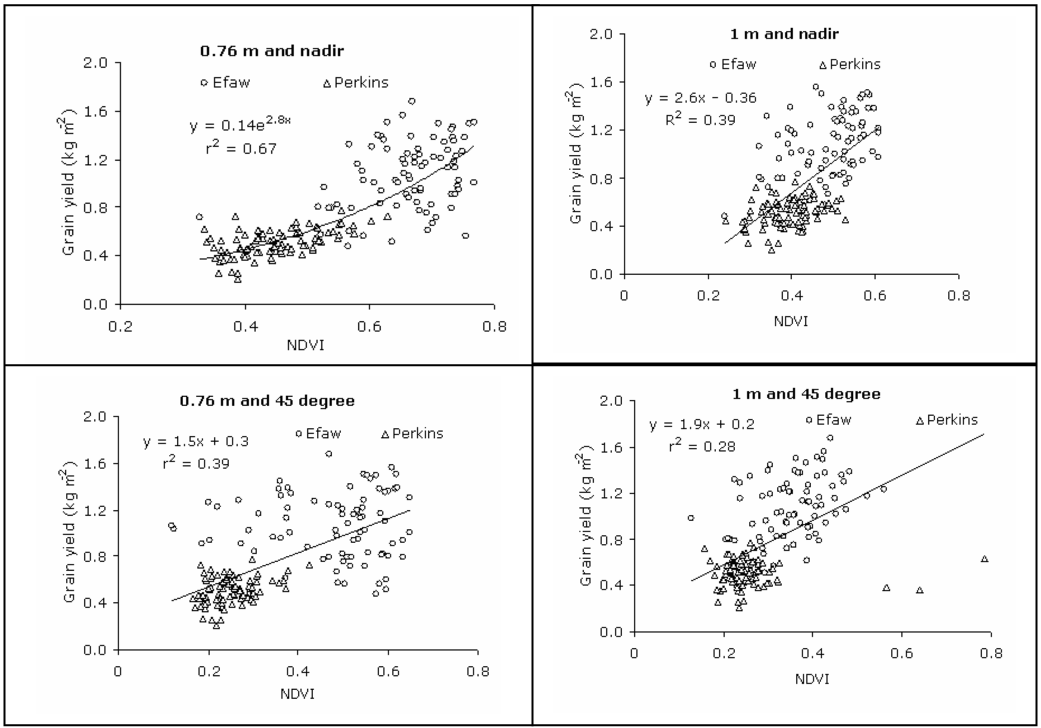
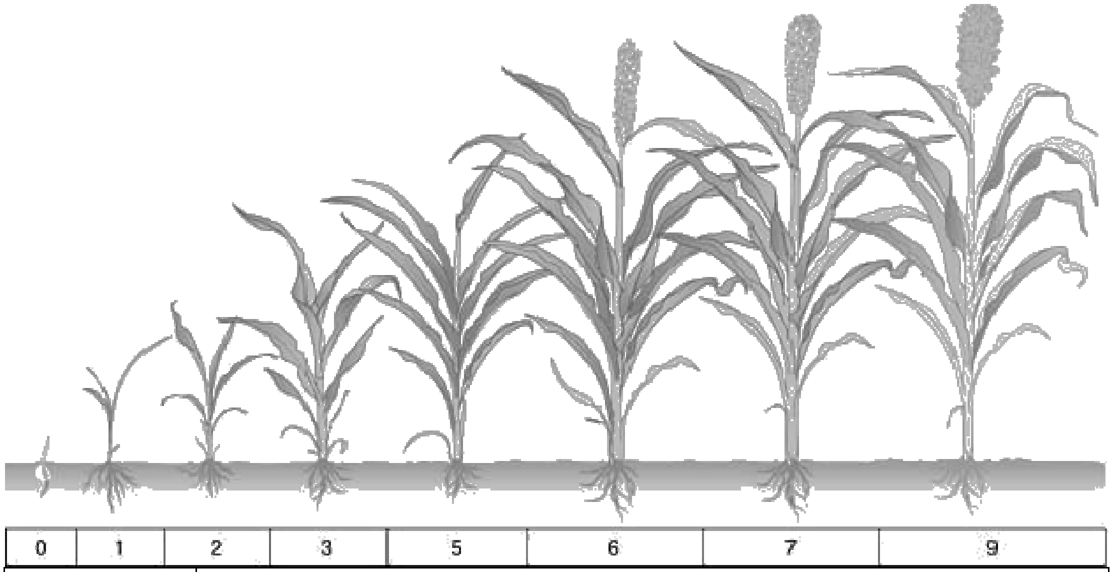


Figure 9. Grain yield and NDVI relationship at growth stage R1 at different sensing height and angle combination at Efaw and Perkins, OK, 2004.

APPENDICES



Growth stage	Description
0	Emergence occurs (coleoptile is visible at the soil surface) 3- 10 days
1	Three leaf (leaves fully expanded) 10 days after emergence
2	Five leaf (leaves full expanded) 3 weeks after emergence
3	Growing point differentiation (time of changing from vegetative to reproductive)
5	Boot stage (The head is full size and is encompassed by the flag-leaf sheath)
6	Half bloom (50% of the plants in the field at some stage of blooming)
7	Soft dough (grain has a dough-like consistency)
9	Physiological maturity (Maximum total dry weight of the plant has occurred)

Adopted from:
http://weedsoft.unl.edu/documents/GrowthStagesModule/Sorghum/Sorg.htm

Figure A.1. Schematic representation of growth stages in grain sorghum.

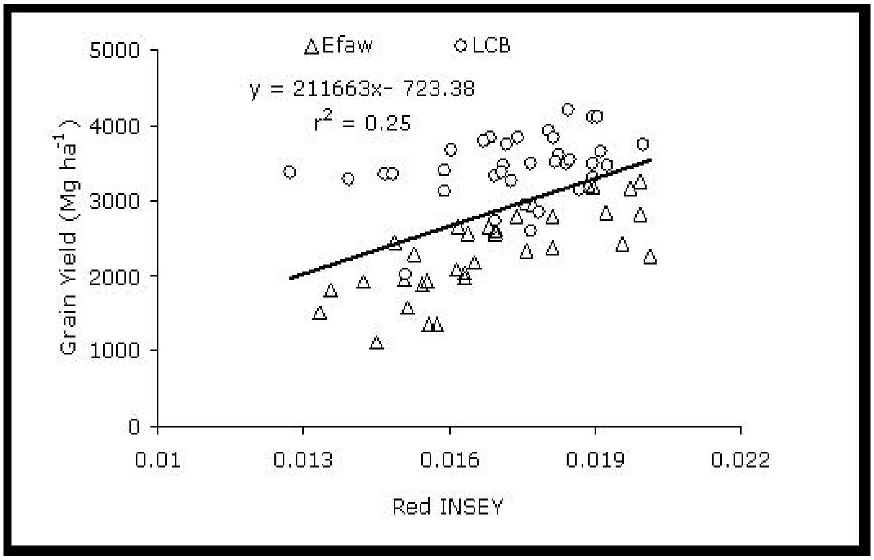


Figure A.2. Relationship of red INSEY and sorghum grain yield at growth stage 2 (five leaf stage) at Efaw and Lake Carl Blackwell, OK, 2004.

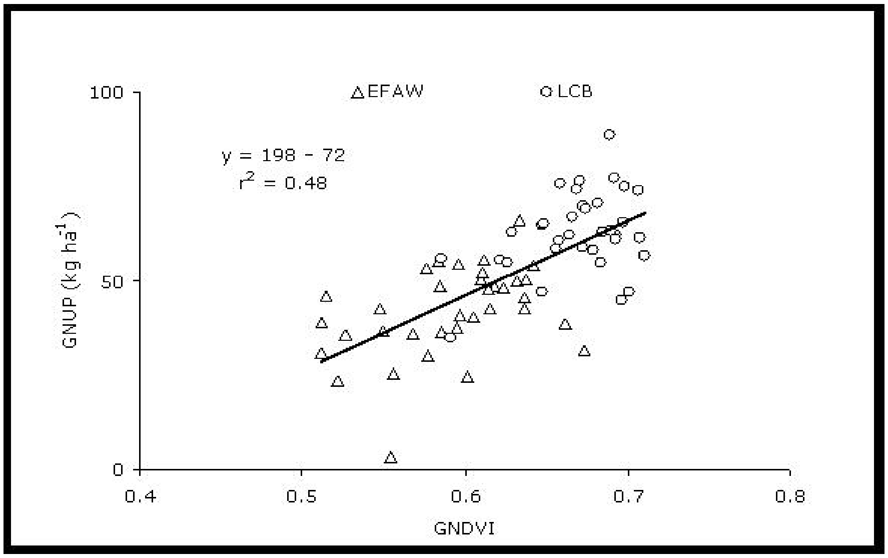


Figure A.3. Relationship of GNDVI and sorghum grain N uptake at growth stage 7 (soft dough) at Efaw and Lake Carl Blackwell, OK, 2004.

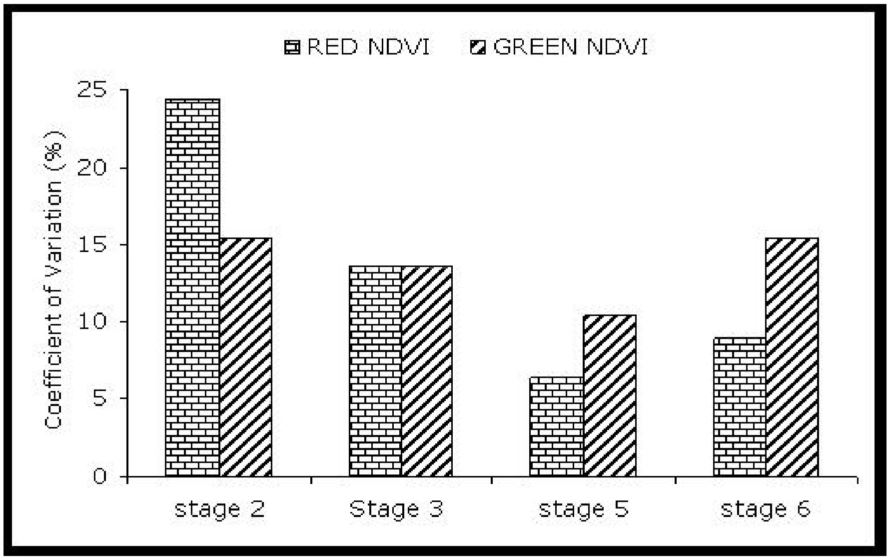


Figure A.4. Combined location average CV of green and red NDVI at each growth stage of sorghum at Efaw and Lake Carl Blackwell, OK, 2004.

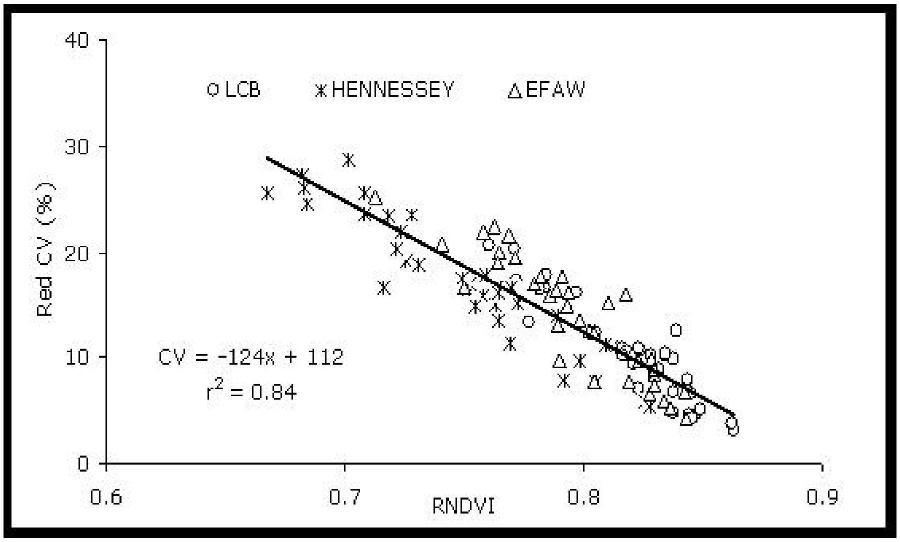


Figure A.5. Relationship of CV and RNDVI at sorghum growth stage 5 at Efaw, Hennessey and Lake Carl Blackwell, OK, 2004.

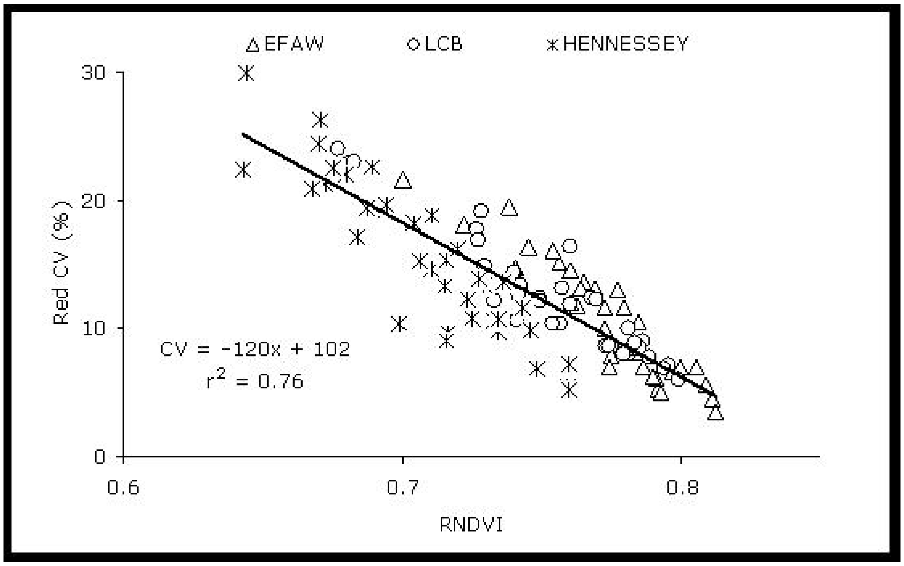


Figure A.6. Relationship of CV and RNDVI at sorghum growth stage 6 at Efaw, Hennessey and Lake Carl Blackwell, OK, 2005.

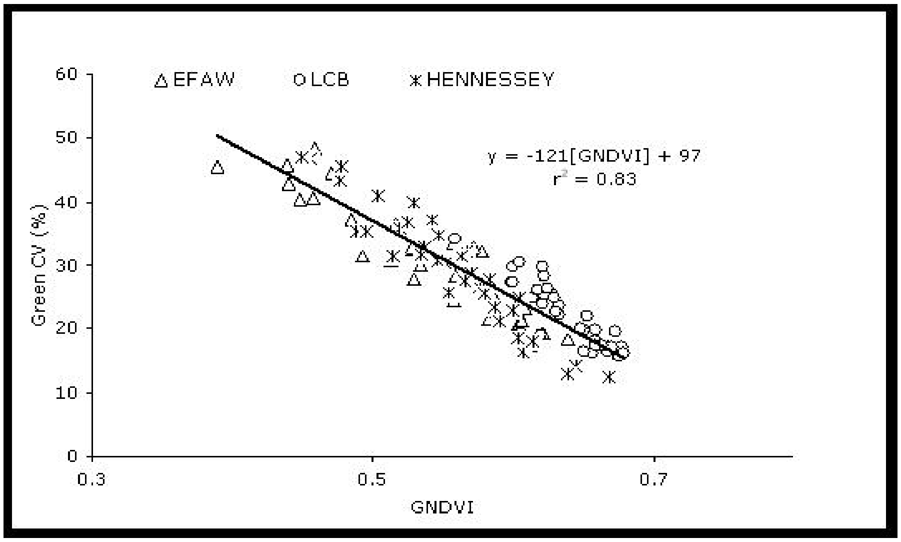


Figure A.7. Relationship of CV and GNDVI at sorghum growth stage 5 at Efaw, Hennessey and Lake Carl Blackwell, OK, 2005.

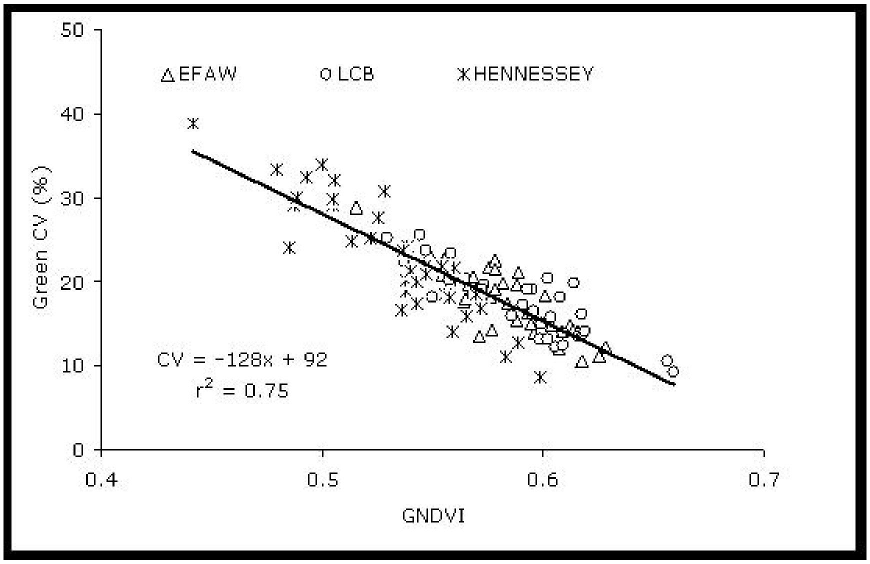


Figure A.8. Relationship of CV and GNDVI at sorghum growth stage 6 at Efaw, Hennessey and Lake Carl Blackwell, OK, 2005

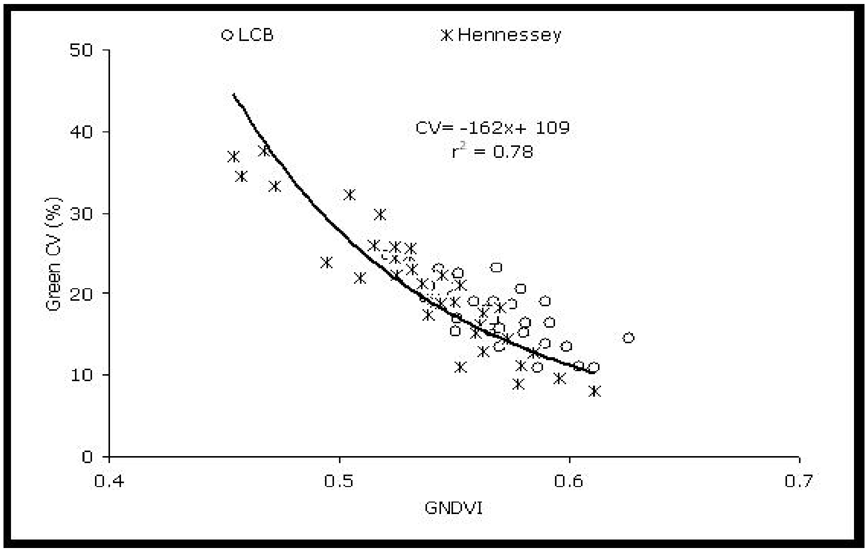


Figure A.9. Relationship of CV and GNDVI at sorghum growth stage 7 at Hennessey and Lake Carl Blackwell, OK, 2005.

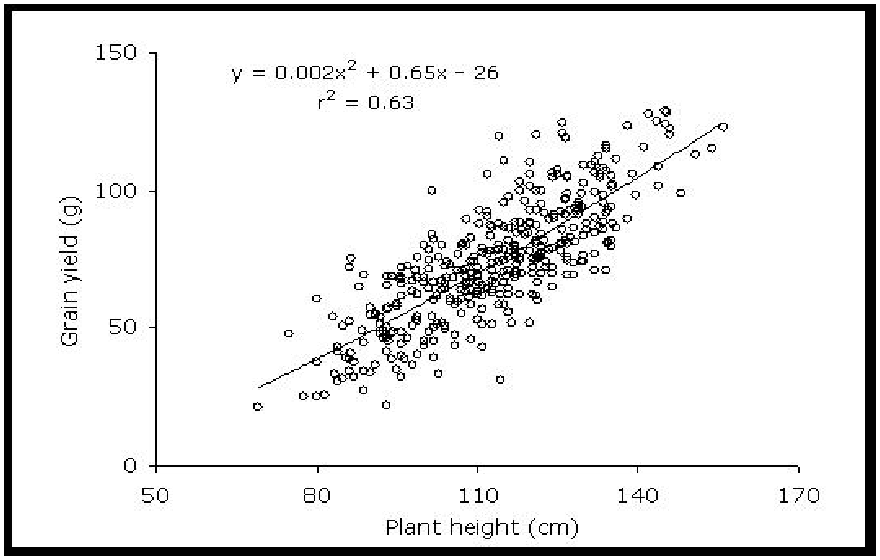


Figure A.10. By-plant corn grain yield and plant height relationship at growth stage VT at Perkins, OK, 2004

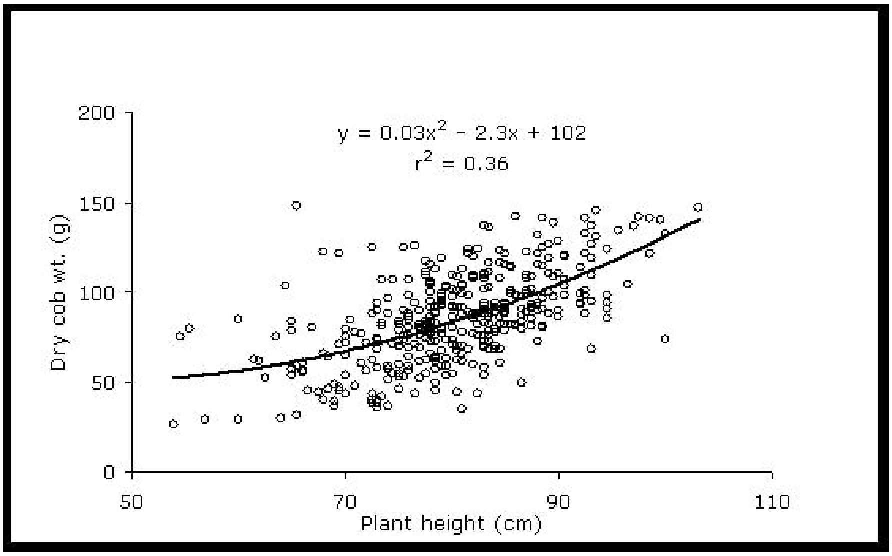


Figure A.11. By-plant corn dry cob weight and plant height relationship at growth stage V8 at Perkins, OK, 2004

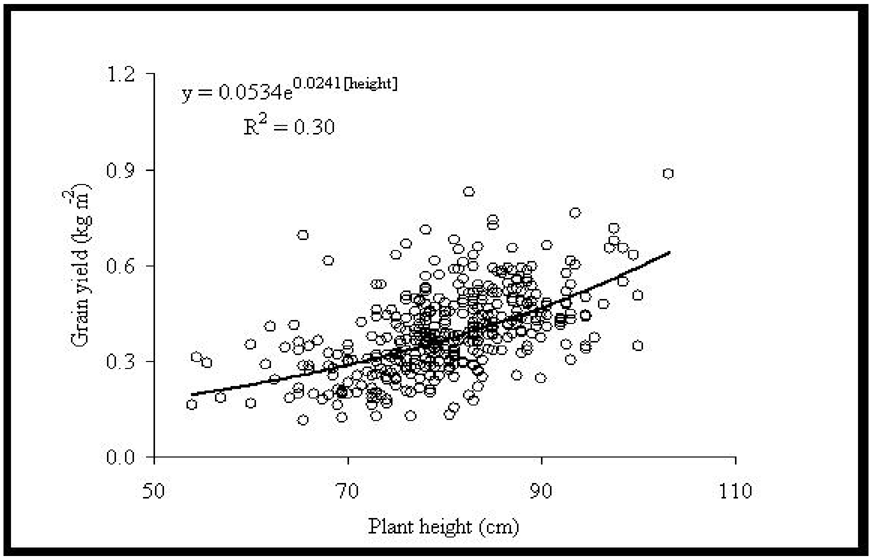


Figure A.12. By-plant corn grain yield and plant height relationship at growth stage V8 at Perkins, OK, 2004.

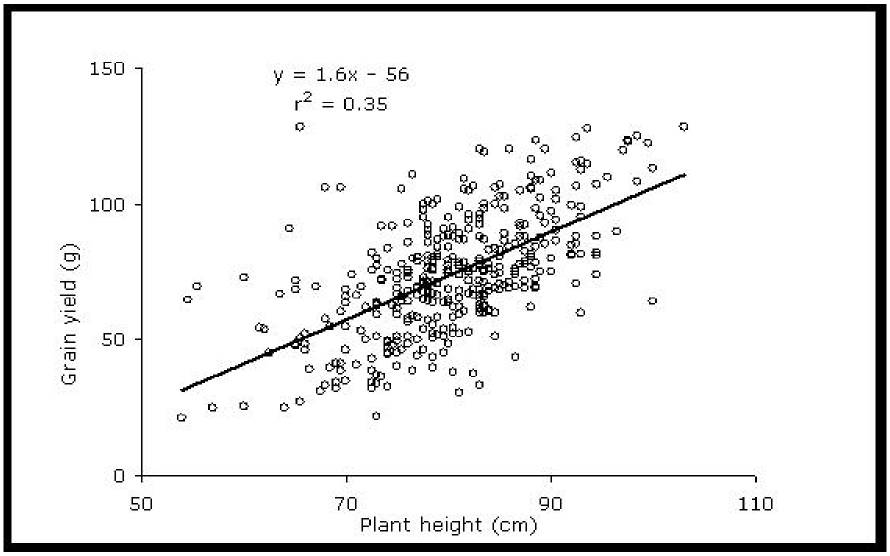


Figure A.13. By-plant corn grain yield and plant height relationship at growth stage V8 at Perkins, OK, 2004.

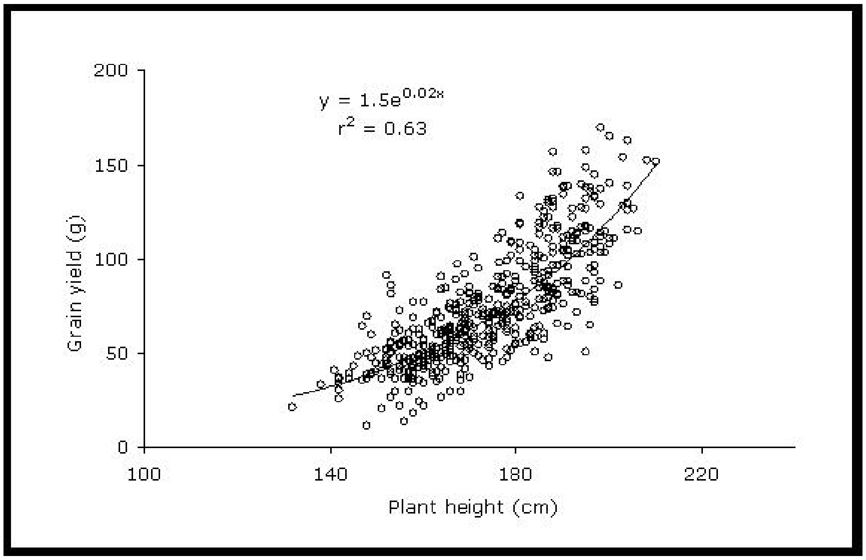


Figure A.14. By-plant grain yield and plant height relationship at growth stage R1 at Efaw, OK, 2004.

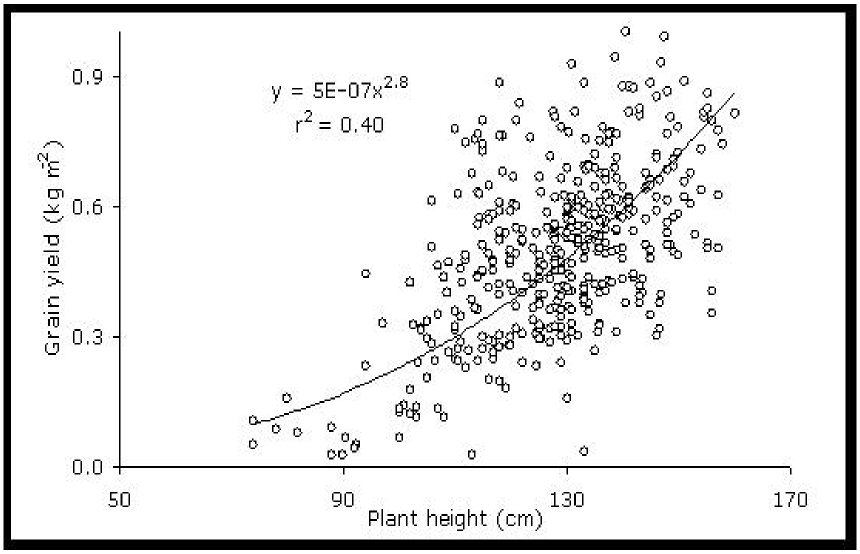


Figure A.15. Relationship of by-plant corn grain yield per area and plant height at growth stage V8 at Efaw, OK, 2005.

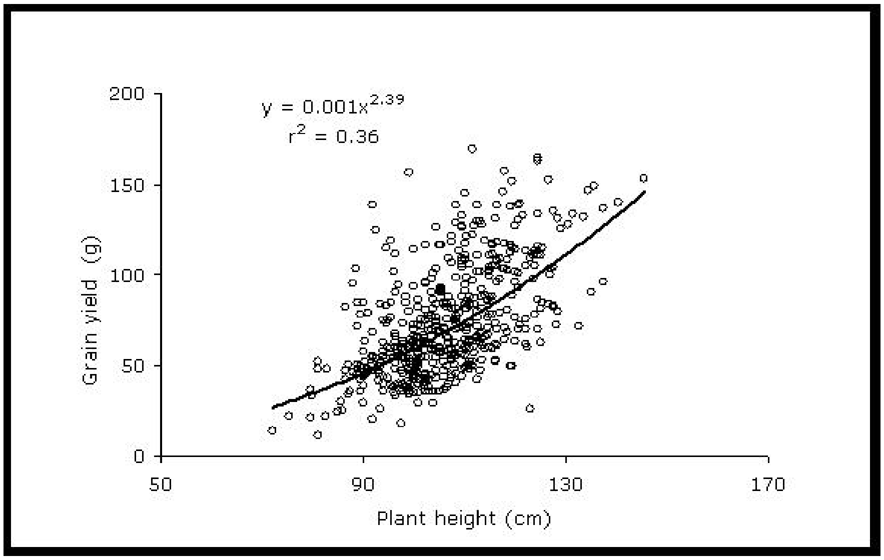


Figure A.16. Relationship of by-plant grain yield and plant height at growth stage V8 at Efaw, OK, 2004.

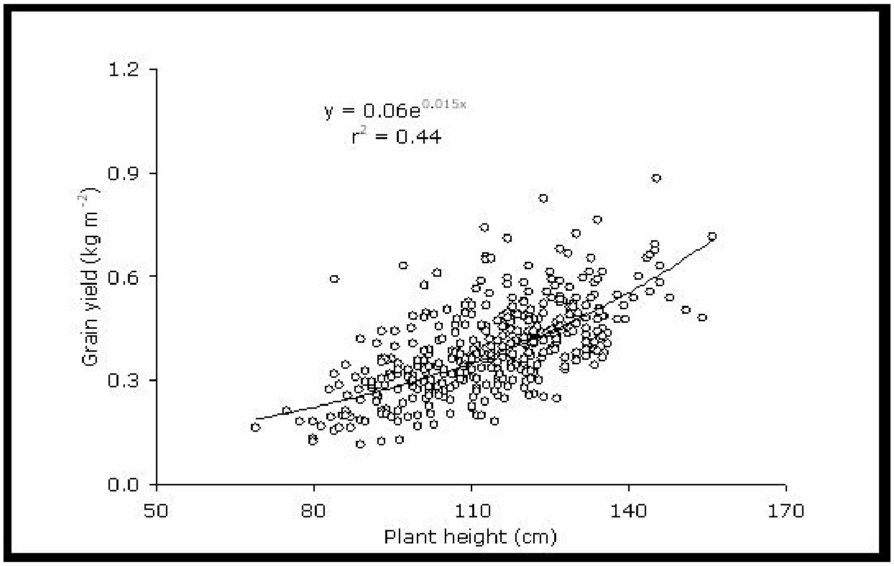


Figure A.17. By-plant corn grain yield per area and plant height relationship at growth stage VT at Perkins, OK, 2004.

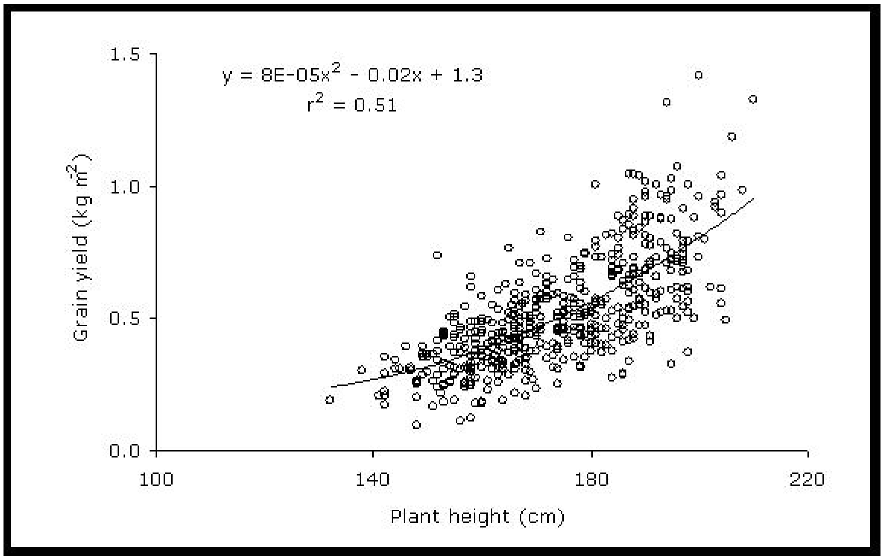


Figure A.18. Relationship of by-plant grain yield per area and plant height at growth stage R1 at Efaw, OK, 2004.

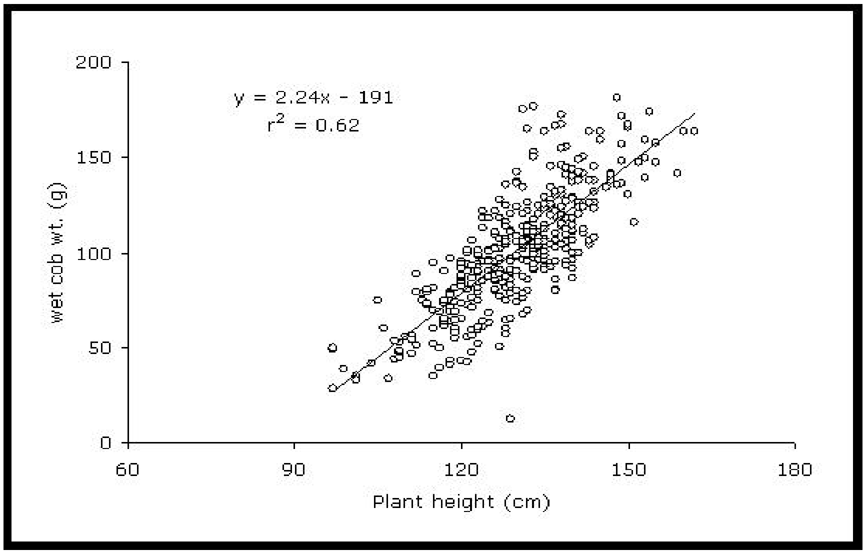


Figure A.19. By-plant corn wet cob weight and plant height relationship at growth stage R1 at Perkins, OK, 2004

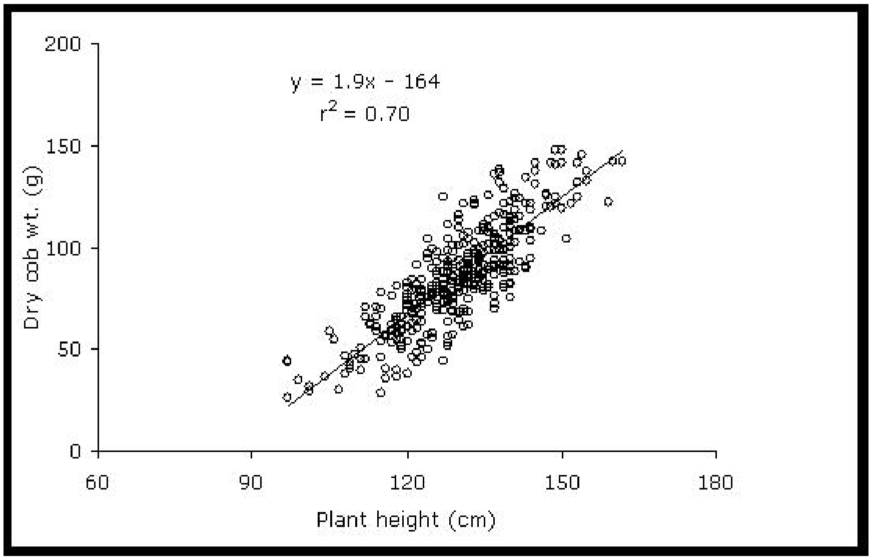


Figure A.20. By-plant corn dry cob weight and plant height relationship at growth stage R1 at Perkins, OK, 2004

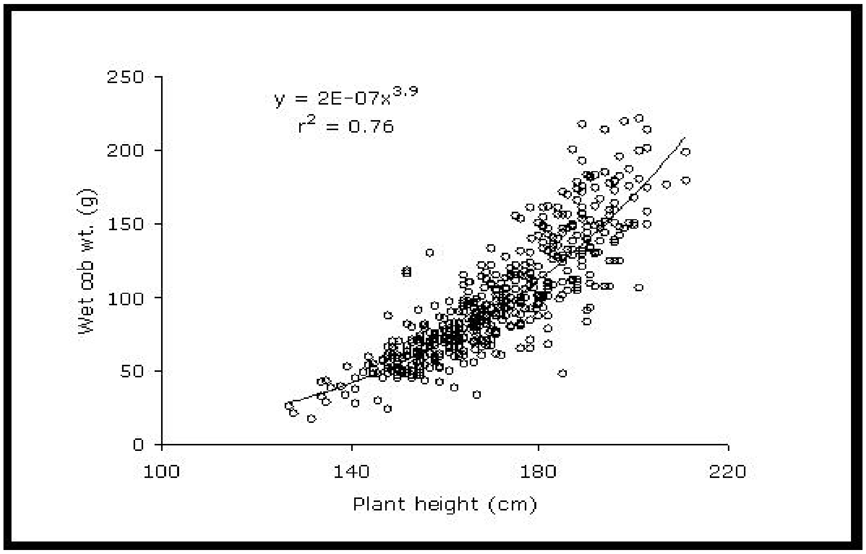


Figure A.21. Relationship of by-plant wet cob weight and plant height at growth stage VT at Efaw, OK, 2004.

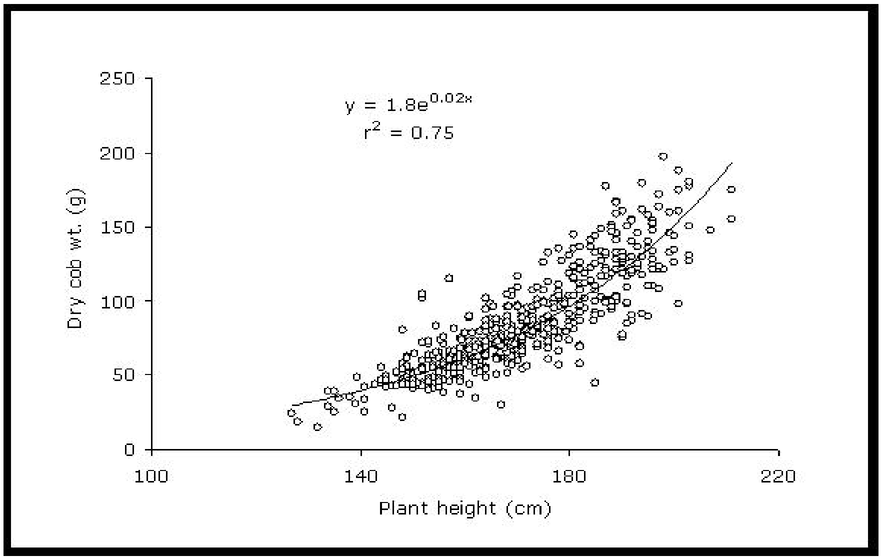


Figure A.22. Relationship of by-plant dry cob weight and plant height at growth stage VT at Efaw, OK, 2004.

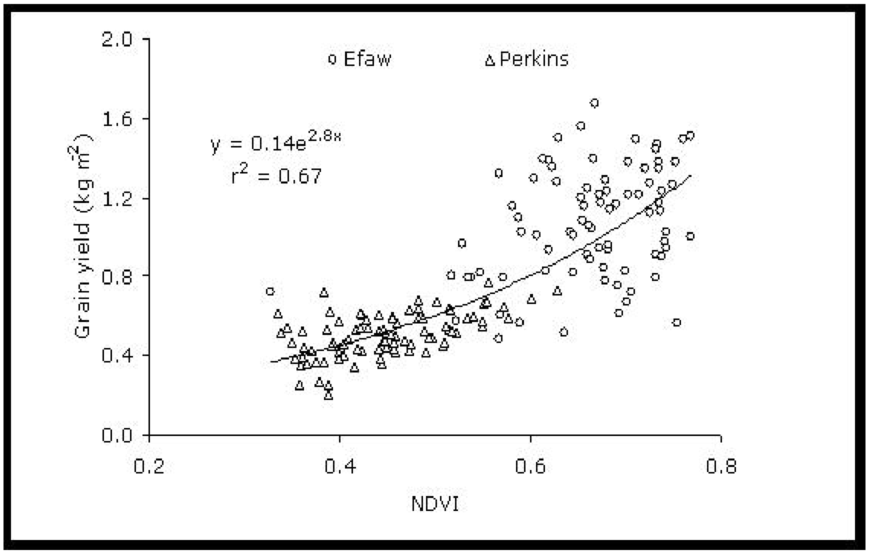


Figure A.23. By-plant NDVI and corn grain yield relationship at growth stage R1 (0.76 m nadir position) at Efaw and Perkins, OK, 2004.
at growth stage R1 at Efaw, OK, 2004.

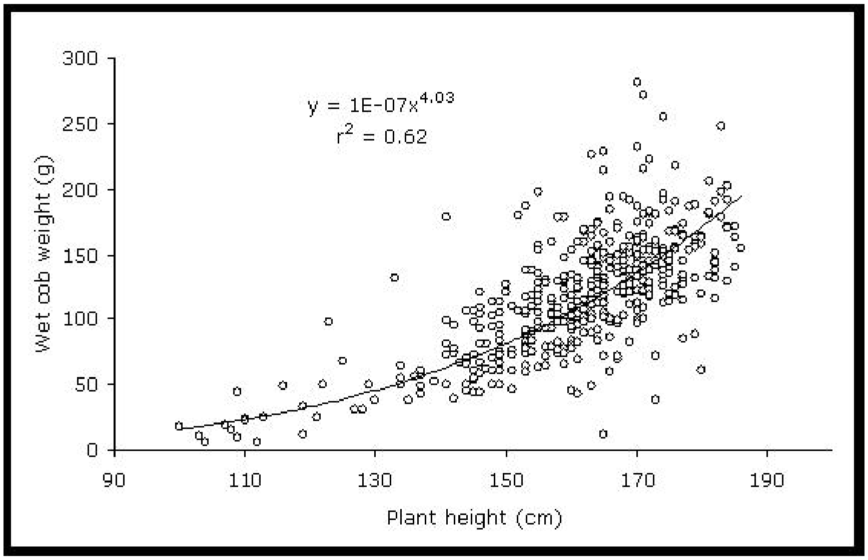


Figure A.24. Relationship of by-plant corn wet cob weight and plant height at growth stage V8 at Efaw, OK, 2005.

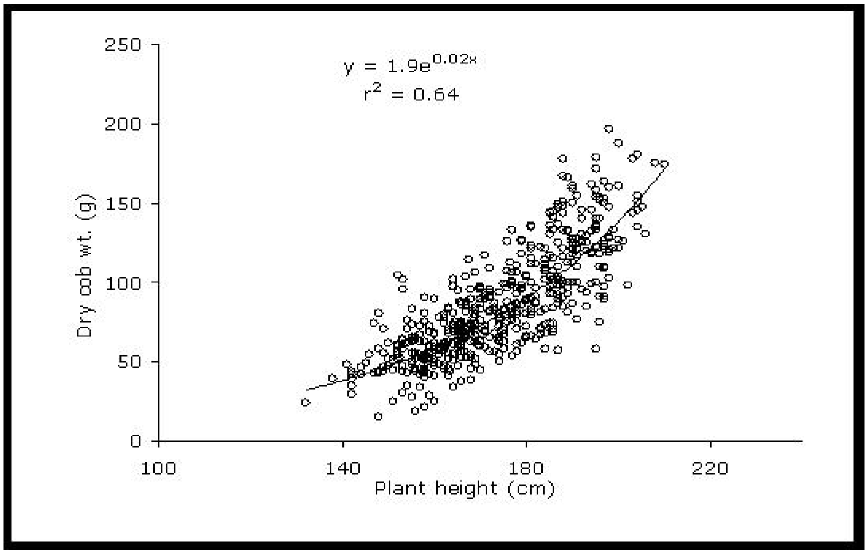


Figure A.25. Relationship of by-plant dry cob and plant height at growth stage R1 at Efaw, OK, 2004.

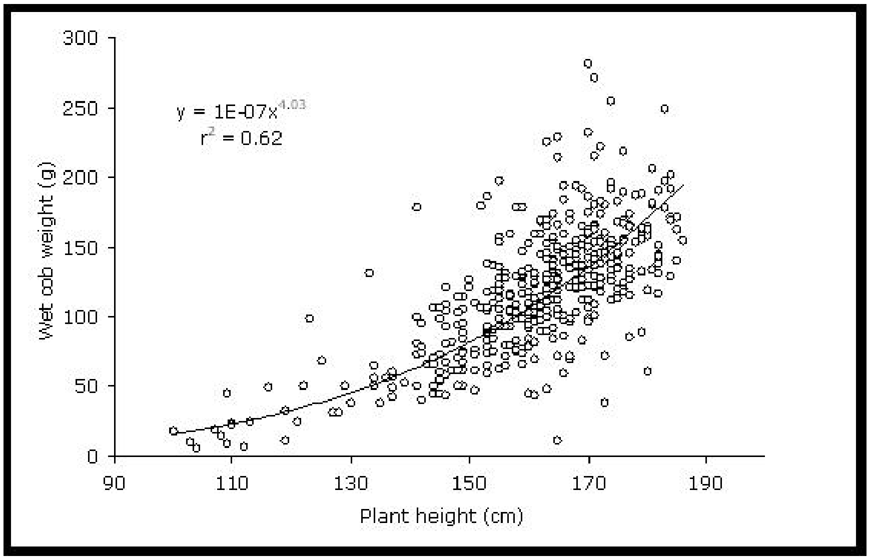


Figure A.26. Relationship of by-plant corn wet cob weight and plant height at growth stage V8 at Efaw, OK, 2005.

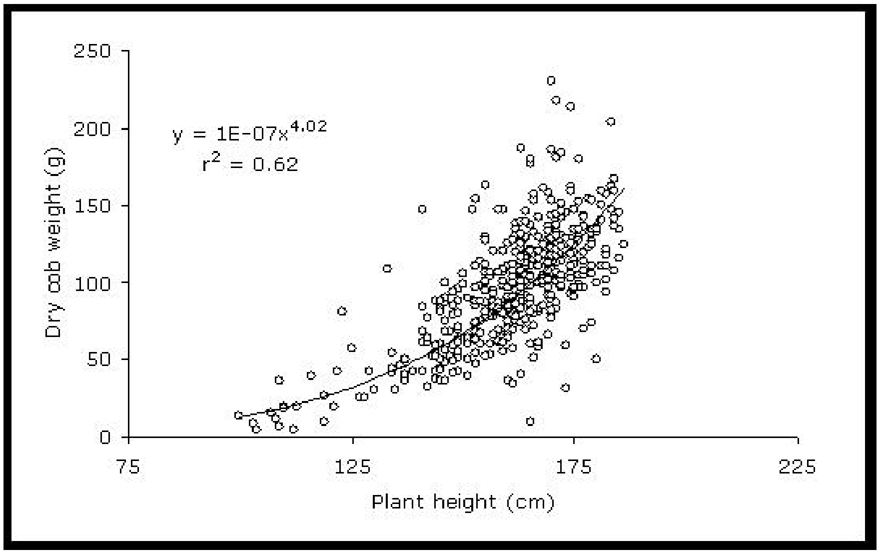


Figure A.27. Relationship of by-plant corn dry cob weight and plant height at growth stage V8 at Efaw, OK, 2005.

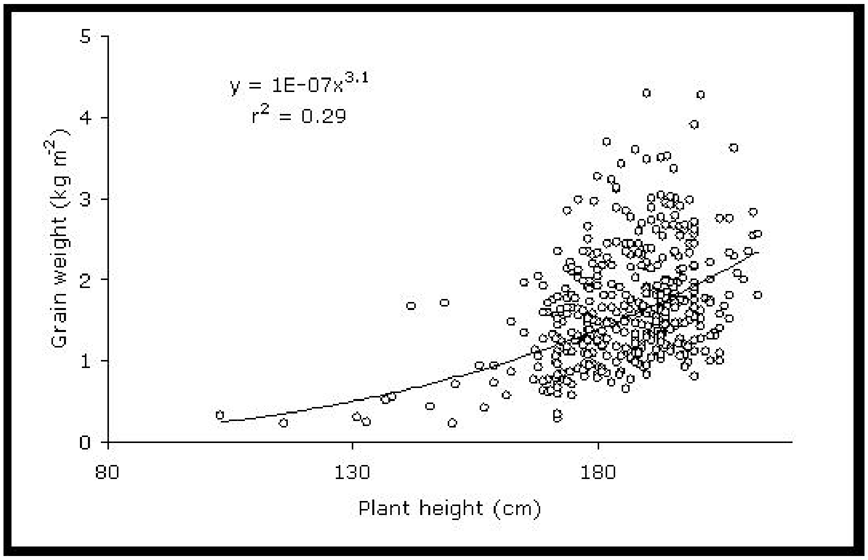


Figure A.28. Relationship of by-plant corn grain yield per unit area and plant height at growth stage VT at Lake Carl Blackwell, OK, 2005.

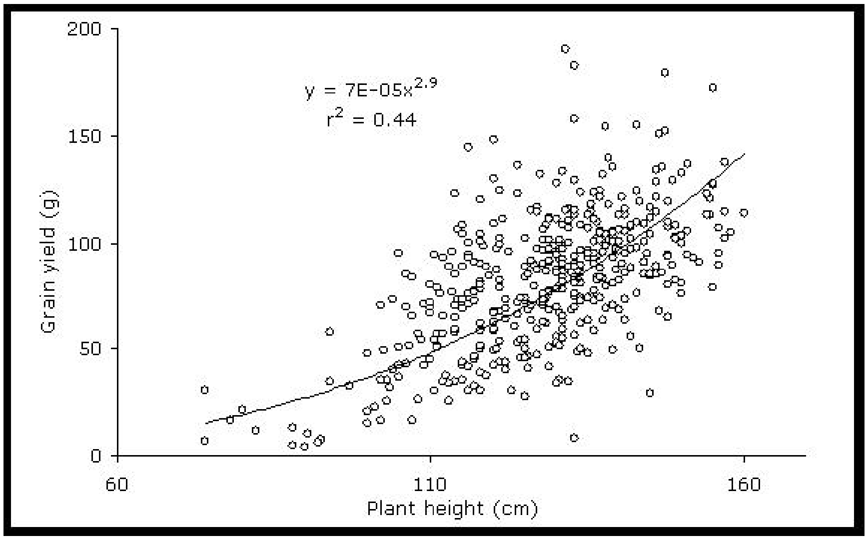


Figure A.29. Relationship of by-plant corn grain yield and plant height at growth stage V8 at Efaw, OK, 2005.

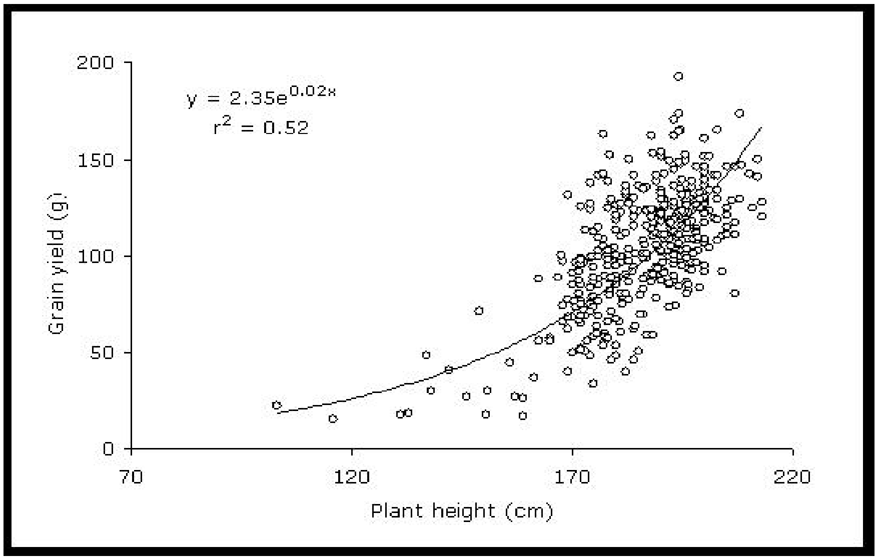


Figure A.30. Relationship of by-plant corn grain yield and plant height at growth stage VT at Lake Carl Blackwell, OK, 2005.

VITA

Shambel Maru Moges

Candidate for the Degree of

Doctor of Philosophy

Thesis: I. YIELD POTENTIAL ESTIMATION IN GRAIN SORGHUM *Sorghum bicolor* L.),
II. EFFECTS OF PLANT HEIGHT, SENSING ANGLE AND HEIGHT ON YIELD PREDICTION OF CORN (Zea mays. L)

Major Field: Soil Science

Biographical:

Personal Data: born in Nazareth, Ethiopia on May 12, 1970

Education: Graduated from Harar Meda Model High school, Arsi, Ethiopia in August 1988; received Bachelor of Science degree in Plant Sciences from Awassa College of Agriculture, Awassa, Sidamo, Ethiopia in July, 1997; received Master of Science degree in Plant and soil Sciences from Oklahoma State University, Stillwater, Oklahoma, 2002. Completed the requirements for the Doctor of Philosophy degree with a major in Soil Sciences and minor in Statistics at Oklahoma State University in December 2005.

Experience: Employed by Ethiopian Agricultural Research Organization (EARO) as Junior Agricultural Research Officer (December, 1997 – December, 2000); employed as a graduate research assistant for the Department of Plant & Soil Sciences, Oklahoma State University, 2001- 2005.

Professional Memberships: member of Ethiopian Weed science, Crop science, and Agronomy societies of Ethiopia since 1997.
Member of American Society of Agronomy, Since 2002.Name:

Name: Shambel Maru Moges Date of Degree: December, 2005

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: YIELD POTENTIAL ESTIMATION IN GRAIN SORGHUM
Sorghum bicolor L.), AND EFFECTS OF PLANT HEIGHT,
SENSING ANGLE AND HEIGHT ON YIELD PREDICTION
OF CORN (Zea mays. L)

Pages in Study: 88 Candidate for the Degree of Doctor of Philosophy

Major Field: Soil Science

Scope and method of study: For chapter one, grain sorghum (*Sorghum bicolor* L. Moench) experiments were conducted to estimate the yield potential of grain sorghum at different nitrogen levels using a self illuminated had held optical sensor. A total of six experiments with four levels of nitrogen (50,100,150,200 kg ha^{-1}) and there types of applications were arranged in a randomized complete block design in three replications. Sensor readings were taken at five different growth stages (2, 3, 5, 6 and 7). For the second chapter, in one set, a total of 20 transects of corn (*Zea mays* L.) each with 20 m length were used to estimate the relationship of plant height and grain yield. Plant height was measured at there different growth stages (V8, VT and R1) from the ground to the tip of extended last collar leaf at V8 and up to the base of the last collar leaf at stages VT and R1. In the other set, a total of four transects (50 plants each) were used to determine the effects of sensing height and angle on sensor readings and grain yield. Sensor measurements were taken at stages V8, VT and R1 and used to estimate the relationship of by-plant NDVI and grain yield.

Findings and Conclusions: For chapter one, over years and locations, grain yield was not significantly affected by N application methods. Sorghum has shown a response to N but there were no significant differences among treatments in 2004. Significant linear or quadratic responses were observed in 2005 for irrigated sites. Simple linear regression analysis showed that grain yield was highly related to green and red NDVI and INSEY at growth stage 3, with green slightly better than red. The results of this experiment has indicated that INSEY could be used as a good predictor of sorghum yield at growth stage 3. For the second chapter, plant height was highly related to grain yield at VT over locations and years. The data suggested that including plant height as one of yield prediction component can improve corn yield prediction model. Also sensor measurements taken at 0.76 m and nadir position have shown a better relationship with grain yield and NDVI at corn growth stage VT.

ADVISER'S APPROVAL: Dr. William R. Raun