BY-PLANT PREDICTION OF CORN (Zea mays L.)

GRAIN YIELD USING HEIGHT

AND STALK DIAMETER

By

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CHAPTER I

ABSTRACT & INTRODUCTION

Abstract

Current methods for determining midseason nitrogen (N) rates in corn have used

normalized difference vegetation index (NDVI), and in some cases, plant height and

intra-specific plant competition.   Another parameter that can be linked to potential yield

is stalk diameter; thus incorporating collectively the parameters of NDVI, plant height,

and stalk diameter should result in a better prediction of yield potential. This could lead

to more efficient methods for midseason fertilizer N applications. The objective of this

study was to analyze the relationship of stalk diameter, as well as plant height and NDVI,

with final grain yield, and to refine the method of predicting yield potential using a

combination of these factors. In this 2-year study at 4 locations, we selected several rows

of corn plants, each with varying amounts of pre-plant nitrogen fertilizer, from 0 to 145

kg ha^{-1}, and where no additional nitrogen was applied throughout the growing season.

Measurements of plant spacing, stalk diameter, plant height, and NDVI were taken from

growth stages V8 (eight fully collared leaves) to VT (corn tasselling), and all corn plants

were harvested by-plant to determine grain yield or dry biomass. Individual plant height

measurements proved to be a good predictor of by-plant grain yield (r^2 = 0.52, 0.53; V10,

V12, respectively). Using a value of stalk diameter X plant height gave the best

correlation with grain yield (r^2 = 0.34, 0.55, 0.67; V8, V10, V12, respectively). By-plant

biomass was also highly correlated with stalk diameter, with an r^2 of 0.68 at growth stage

V15, using a polynomial function. This work showed that stalk diameter X plant height

was highly correlated with by-plant corn grain yields, and this parameter could possibly be used for refining midseason fertilizer N rates from growth stages V8 to V12.

Introduction

It has been estimated that worldwide Nitrogen Use Efficiency (NUE) of applied nitrogen fertilizers is about 33% {NUE = [(total cereal N removed)-(N coming from the soil + N deposited in the rainfall)] / (fertilizer N applied to cereals)} (Raun and Johnson, 1999). Nitrogen use efficiency rates are very low because of several environmental factors, including leaching of N through the soil profile, ammonia volatilization, denitrification, and plant N losses as NH_3 (Raun and Johnson, 1999; Raun et al., 1997). Current nitrogen management practices for corn production in the United States are largely inefficient, and are commonly blamed for the eutrophic "Dead Zone" at the mouth of the Mississippi River Delta in the Gulf of Mexico. It is estimated that more than $750,000,000 worth of excess N annually flows down the Mississippi River into the Gulf of Mexico (Malakoff, 1998).

Because of this extensive misuse of N fertilizer, there is a pronounced need in the United States, as well as worldwide, to increase NUE among cereal crops, especially corn. Several methods can be used to improve NUE worldwide, including selection of better hybrids or cultivars, conservation tillage, NH_4-N source, in-season and foliar-applied N, irrigation, or the application of precision agriculture (Raun and Johnson,1999). Precision agriculture is defined as a "management strategy that employs detailed, site-specific information to precisely manage production inputs" (Searcy, 1997). This paper examines the possible use of physiological measurements, such as stalk diameter and plant height, as a method of predicting corn grain yield in order to precisely manage N fertilizer inputs.

CHAPTER II

LITERATURE REVIEW

Application Resolution

Common N management practices often implement a field element size of the entire field in question, and N rates are often applied at a flat rate across an entire field. At best, zone or grid management systems are used to match N rates to a smaller field element size, which can be 0.2 to 4 or more hectares in size. However, significant soil test and biomass differences have been detected at resolutions equal to or less than 1 m² (Solie et al., 1996; Raun and Johnson, 1999). When considered on a by-plant basis, Martin et al. (2005) found that significant variability in by-plant corn yields can be expected in distances less than 0.5 m. Raun et al. (1998) and Solie et al. (1999) found significant soil test differences of N, P, and K values within resolutions of less than 1 m² in 0.3 x 0.3 m bermudagrass plots.

With these findings of variability within a resolution size often less than 1 m², it would make sense that agricultural inputs, especially fertilizers, should be variably applied as needed at those resolutions in which differences are shown. However, soil sampling of an entire field at a resolution of 1 m² would be cost-prohibitive, and therefore, other methods of variable rate applications must be considered. One of the most promising applications of applying fertilizers at such a small resolution size

is that of using optical sensors to make the recommendation based on yield potential.

Active sensors, such as the GreenSeeker® sensor, have been successfully used to make

variable-rate applications of N fertilizer at a resolution of 0.4 m² (Raun, 2010). Teal et al.

(2004) noted that NUE can increase over 10% in corn and 15% in winter wheat using

mid-season N fertilizer rates based on predicted yield potential and a response index

system, such as those used by Oklahoma State University.

By-Plant Sensing

By-plant variability in corn yields is well-documented (Martin et al., 2005; Teal,

2004; Freeman et al., 2007), expressing the need for management of N on a by-plant

basis for corn. A study by Freeman et al. (2007) revealed that NDVI, along with plant

height measurements, can be used to predict by-plant corn forage yield. This study found

that an index of NDVI X plant height had a strong relationship ($r^2 = 0.77$) with N uptake

from V10 to R1 growth stages (Freeman et al., 2007). Additionally, Freeman et al.

(2007) found that plant height alone was a strong predictor ($r^2 = 0.81$) of dry plant

biomass at growth stages V8-V10.

Other studies (Martin et al. 2007; Teal et al. 2007; Raun et al., 2005) have shown

that the coefficient of variation (CV) from NDVI measurements taken down the row

varies widely throughout the growing season. Martin et al. (2007) and Raun et al. (2005)

showed that CV's of NDVI measurements were highest in corn from growth stages V6-

V8, and lowest from V10-VT. Variability within the plants were expressed most during

the V6 to V8 growth stages, because larger plants started covering the rows, and smaller

plants still allowed bare soil to be measured in the NDVI readings; thus indicating a

higher CV of NDVI measurements at these growth stages. However, from V10 to VT,

the plants were larger, more uniform, and had more complete canopy closure. This allowed the CV of NDVI measurements to reach its lowest point. Because of these findings, it is possible that NDVI alone could be used to predict by-plant corn yield potential at the earlier growth stages of V6 to V8. However, from V10 on to VT, using NDVI alone should not be as successful in determining by-plant yield potential, because it will be impossible to distinguish individual plants due to leaf canopy closure.

Stalk Diameter in Yield Prediction

With the findings of Martin et al. (2007) using the CV of NDVI values in corn, and the positive relationship of using a NDVI X plant height index for predicting yield potential (Freeman et al., 2007), it is evident that in order for by-plant yield estimation in corn to be successful, other plant characteristic measurements need to be included with NDVI measurements. Other factors which may be considered are corn stalk diameter, area occupied by the individual plants, and competition factors among corn plants. Shaw and Loomis (1950) showed that correlation of stalk diameter to final corn grain yield is variable, depending on environmental conditions, and showed that both stalk height and diameter were subject to differences among corn varieties. Another study by Pordesimo et al. (2004) showed that regression equations using both stalk diameter and height may be used to predict both fresh and dry weight of corn stover, resulting in a maximum r^2 value of 0.76. With regard to stalk diameter only, a study by Jones et al. (1995) showed that stalk diameter increased with increasing N rates, from 0 to 180 kg ha^{-1}, but decreased with an increase in plant density. Sorensen et al. (2006) studied the effects of single- and twin-row planting methods and planting densities on grain yield, test weight, and stalk diameter. They found no difference in stalk diameter and grain yield between single- and

twin-row planting at the same population, but there was a difference in stalk diameter and grain yield between single- and twin-row plantings of the same population and a twin-row planting of two times the population. This suggests that as corn planting density increases to a certain amount, stalk diameters and final grain yields decrease. Based on this conflicting information, this study was carried out to determine if stalk diameter could be used to predict yield.

Normalized difference vegetation index, plant height, plant density, and stalk diameter are all factors that play a role in final corn grain yield. A better understanding of these factors may help to predict yield potential in corn, and thus help in determining the optimum N rates for better mid-season N application. This could possibly lead to an increase in NUE in corn production in the U. S., as well as worldwide.

Objective

The objective of this study was to determine the relationship of stalk diameter, plant height, and NDVI measurements, with final corn grain yield.

CHAPTER III

MATERIALS AND METHODS

Experimental Sites were established at the R. L. Westerman Irrigation Research

Center, Lake Carl Blackwell, near Stillwater, OK, and the Eastern Research Station, near

Haskell, OK, for the years 2009 and 2010. Another location was added for spring 2010

at the Efaw site of the Stillwater Agronomy Research Station, and an additional location

in Ciudad Obregón, Mexico was added in 2011. The site at the R. L. Westerman

Irrigation Research Center was irrigated, and is located on a Pulaski fine sandy loam

(coarse loamy, mixed, superactive, nonacid, Udic Ustifluvent). The Efaw site was

located on a Norge loam, 3 to 5 percent slope, eroded (fine-silty, mixed, active, thermic

Udic Paleustolls), while the site at the Eastern Research Station was located on a Taloka

silt loam, 1 to 3 percent slope (fine, mixed, active, thermic Mollic Albaqualfs). All

locations were planted to corn (*Zea mays* L.) with a John Deere MaxEmerge 2, four-row

vacuum planter, with a row spacing of 0.76 m. The Haskell and Efaw locations were

dry-land locations planted at a targeted population of 61,775 seeds ha^{-1} and 49,667 seeds

ha^{-1}, respectively, while the irrigated site was planted at a target population of 85,000

seeds ha^{-1} (Table 1). The location in Mexico had a seeding rate of 67,700 seeds ha^{-1}.

Two years of data were taken from the Haskell and the LCB irrigated sites, one year at

the Efaw site, and one year at the Ciudad Obregón, Mexico site for a total of 6 site-years.

Four rows of corn 6.1 m long were selected within an existing trial at each location in Oklahoma with different pre-plant N rates (no top-dress N applied). Five rows of corn 12 m long and 0.8 m row spacing were selected at the Mexico site. The pre-plant N rates were 0, 45, 90, and 180 kg N ha^{-1} in Oklahoma, and 35, 70, and 245 kg N ha^{-1} in Mexico, and were applied merely to effect a change in the measurements taken. Even though this experiment was located inside of a replicated field trial, treatments were not applied and replications not considered because each plant was analyzed with yield individually. Phosphorus and potassium levels were applied based on a sufficiency level according to Oklahoma State University Department of Plant and Soil Sciences guidelines for respective locations. Weed control was achieved via pre-emergence herbicide and mid-season application of glyphosate. Within each row, the distance down the row from a pre-determined point was recorded, and each plant was tagged with a unique identifying tag. At growth stages V8 (8th leaf collar unfolded), V10 (10th leaf collar unfolded), V12 (12th leaf collar unfolded), and VT (last branch of tassel visible) (Ritchie et al., 1996), plant height, NDVI, and stalk diameter were taken from each tagged plant within the selected row. These growth stages were chosen because most mid-season N application will take place prior to V10. Therefore, yield prediction possibilities were examined before and after this point. Plant height was taken by measuring the height from the soil surface to the top arch of the uppermost leaf that is more than 50% emerged from the whorl (Hager, 2010). Stalk diameter was taken using a digital caliper, with measurements collected on the major (widest part of stalk) and minor (thinnest part of stalk) axes 10 cm above the soil surface in an internodal area of the corn stalk.

Normalized difference vegetation index values from each plant were taken using a bicycle-mounted GreenSeeker Hand Held sensor (Trimble Navigation, Sunnyvale, CA) with a shaft encoder that recorded NDVI every centimeter of linear distance down the row. The GreenSeeker Hand Held unit measures NDVI in a 0.6 by 0.01 m area when held 0.6 to 1.0 m above the crop canopy. The sensor contains a self illuminated light source in the red (650 ± 10 nm) and near infrared (NIR, 770 ± 15 nm) bandwidths (Freeman et al., 2007). The GreenSeeker calculates NDVI as follows:

$$NDVI = (\rho_{NIR} - \rho_{red}) / (\rho_{NIR} - \rho_{red}),$$

Where ρ_{NIR} = the fraction of emitted NIR radiation returned from the sensed area (reflectance), and ρ_{red} = the fraction of emitted red radiation returned from the sensed area (reflectance). The bicycle-mounted GreenSeeker was pushed down the middle of the corn rows, while the sensor maintained a position centered over the row at about 0.9 m above crop canopy, and travelled parallel to the row. The GreenSeeker was situated over the row in a way where the light emitted was perpendicular to the row. As the bicycle moved down the middle of the row, the shaft encoder logged NDVI readings each centimeter of linear distance travelled. By starting at the pre-determined point where each individual corn plant's distance was marked, it was then possible to calculate NDVI for each individual plant. This was done by calculating the average NDVI from readings that occurred halfway in front and halfway behind the individual corn plant (Freeman et al., 2007).

Individual plant corn grain yield was recorded by harvesting the ear(s) from each individual marked corn plant. The ears were dried in a forced air oven at 70°C for seven days. Corn ears were weighed then shelled, and the grain was weighed for each

individual plant. In order to determine individual corn plant grain yield on an area basis, the distance halfway between the two bordering plants was calculated and multiplied by the row width (0.76 m). Final grain yield was adjusted to a standard moisture of 15.5%, and then expressed as kg ha^{-1}.

Average stalk diameter was calculated by averaging the major and minor axis of the stalk. A value of average stalk diameter multiplied by height was created in an attempt to better characterize each corn plant, and to normalize the stalk diameter data. Date, growth stage, days after planting (DAP), and growing degree days (GDD) were recorded at the time each set of measurements were collected, as well as the specific plant populations, planting date, cultivars, and harvest dates for each location (Table 1). The monthly average air temperature and rainfall for each location and year of the experiments are summarized in Table 2. Summary statistics, including minimum, maximum, range, mean, standard deviation, and coefficient of variation, for the variables stalk diameter, plant height, and NDVI are summarized in Table 3, for growth stages V8, V10, V12, and VT, with sites and years combined. The major variables observed in this study were stalk diameter, stalk diameter X height, and NDVI (Table 4). All data from V8 to VT, at all locations, and across all years, were combined and analyzed. Data was analyzed by each growth stage individually, as well as being divided into 3 groups for analysis: V8-V10, V10-V12, and V12-VT. An effort was made to look at all groups with sites and years combined, in order to come up with a yield prediction equation that would work across sites and years. Simple correlation in SAS (SAS, 2003) was used to identify variables highly correlated with grain yield in this study. Using the variables stalk diameter, stalk diameter X height, and NDVI as independent variables, linear and non-

linear regression analysis was performed, with by-plant corn grain yield (kg ha^{-1}) as the dependent variable. For the Mexico data, non-linear regression analysis was performed, with stalk diameter as the independent variable and by-plant corn biomass (kg plant^{-1}) as the dependent variable. The highest coefficient of determination (r^2) was used to select the models with the best fit to the data.

CHAPTER IV

RESULTS AND DISCUSSION

NDVI X Plant Height Index

Freeman et al. (2007) found that the index NDVI X plant height index exhibited

strong relationships with by-plant N uptake, corn biomass, and corn forage yield.

However, no previous studies have examined this relationship with by-plant corn grain

yield. When examined for this study, NDVI X height showed r^2 values of 0.29, 0.49,

0.50, and 0.37, for growth stages V8, V10, V12, and VT, respectively (Table 5), for sites

and years combined. When the growth stages were grouped together, the $r2$ values were

0.13, 0.39, and 0.43, for growth stage groups V8-V10, V10-V12, and V12-VT,

respectively. Table 5 also compares the correlations of the NDVI X height index to other

measurements taken in this experiment. While the NDVI X height index demonstrated

strong r^2 values, other measurements, such as stalk diameter, height, and stalk diameter X

height, provide even better relationships with final by-plant corn grain yield.

Stalk Diameter

Stalk diameter was significantly correlated with by-plant corn grain yield,

especially at growth stages V10 to V12 (Fig. 1). When sites and years were combined at

these growth stages, the relationship produced an r^2 value of 0.29, and when sites and

years were combined for growth stages V12 to VT, the resultant r^2 value was 0.16 (Fig. 2). However, when sites and years were combined for the earlier growth stages V8 to V10, the r^2 value was much lower at 0.06 (Fig. 3). This showed that stalk diameter had limited value in predicting grain yield by itself at early growth stages. This was supported by work from Shaw and Loomis (1950), which showed that stalk diameter was variable between varieties and years and not always correlated with yield. The best growth stages for using stalk diameter to predict yield were V10 to V12. All data were combined over sites and years, in order to produce a more robust model to be used over different environments and years. However, when examined by location and year, such as growth stage V12 at Lake Carl Blackwell, 2010, the relationship between stalk diameter and by-plant grain yield were greatly improved, resulting in an r^2 value of 0.71 (Fig. 4). There was a wide range in the values for stalk diameter, which may have contributed to differences in sampling procedures between people, and whether or not the lowermost leaf was still attached to the stalk. In the later growth stages, the lowermost leaf began to senesce and fall off of the stalk. Depending on when this occurred, it may have affected the stalk diameter measurement, because this leaf sheath would have been attached to the first intermodal area where the stalk diameter measurements were taken. This is thought to have contributed to the lower relationships between stalk diameter and grain yield.

Stalk Diameter X Plant Height

Across years and locations, when stalk diameter was multiplied times plant height, the relationship between this index and by-plant corn grain yield was much improved. As seen in Figure 5, when stalk diameter X plant height was regressed against grain yield, the resultant r^2 value was 0.56 across sites and years for growth stages V10 to V12. Similar to stalk diameter

only, the growth stages V10 to V12 exhibited the best relationship between stalk diameter X plant height and yield as compared to the other growth stages. At the Haskell location, at growth stage V10 only, an r^2 value of 0.55 for both years combined was recorded (Fig. 6). At growth stages V8 to V10, the r^2 value was much lower (0.15, Fig. 7), but when looking at growth stage V8, the r^2 value was 0.36 (Fig. 8). Using both plant height and stalk diameter increased correlation. This is consistent with the work from Freeman et al. (2007), where NDVI was multiplied with plant height to create a NDVI X plant height index and that proved to be a good predictor of by-plant forage yields. As is reported in Table 3, the r^2 values of stalk diameter X plant height was consistently greater than the correlation of stalk diameter by itself.

As the growth stage increased from V12 to VT, the r^2 values between stalk diameter X plant height and by-plant corn grain yield decreased when averaged over sites and years, resulting in a lower r^2 value of 0.49 (Fig. 9). When the data were evaluated separately, the relationship between stalk diameter X plant height and by-plant grain yield improved. For example, Lake Carl Blackwell in 2010 for growth stage V12 resulted in an r^2 of 0.67 (Fig. 10) for stalk diameter X plant height and grain yield. However, our purpose was to create a more robust equation that would work across sites and years. This index of stalk diameter X plant height was expected to improve prediction of by-plant corn grain yield potential, and that was found. This could then be used to refine midseason fertilizer N applications based on expected N removal by predicted yield. Nitrogen use efficiency can be increased using this method, as Raun et al. (2002) found when using projected differences in N uptake between N rich and farmer practice as the basis for prescribing midseason N rates. Normalizing the data using the INSEY method (Raun et al., 2002) produced only slightly better correlation than the previous methods described. For this INSEY method, the value of stalk diameter X plant height was divided by the cumulative growing degree days (GDD), and then correlated to by-plant corn grain yield. Normalizing stalk

diameter X height measurements using GDD data (over growth stages) did not assist in

improving the prediction of by-plant corn grain yield (data not reported).

Biomass

Another location in Mexico was examined to evaluate the relationship of stalk diameter

and by-plant corn biomass. Stalk circumference was measured at growth stage V15, and was

then converted to stalk diameter. Stalk diameter was highly correlated with plant biomass,

exhibiting a polynomial relationship and an r^2 value of 0.68 (Fig. 11). Area was not figured into

the biomass measurements, because prior research by Freeman et al. (2007) suggests that area

occupied by each plant was not related to dry biomass per plant. This suggests that stalk diameter

measurements can not only help predict by-plant grain yield, but biomass as well, without using

NDVI as a predictor variable.

Yield by Distance and NDVI

Figures 12 and 13 show stalk diameter X plant height and NDVI as compared to the by-

plant corn grain yield by distance down one row of corn. Figure 12 shows this data for Lake Carl

Blackwell at growth stage V8, and Figure 13 shows this data for Haskell at V10. One thing to

note about these figures is how stalk diameter X plant height shows more variability down the

row, and how closely it corresponds to the by-plant corn grain yield. However, when looking at

the corresponding NDVI measurements for the plants down the row, the NDVI values are less

variable. When examining the CV (coefficient of variation) for Figures 12 and 13, it can be seen

that the CV is higher for the stalk diameter X height measurement than the NDVI measurement in

both instances, indicating more variability in the values of stalk diameter X height. At growth

stage V8, the CV is 10.7% for stalk diameter X height, as compared to only 7.6% for NDVI (Fig.

12). At the later growth stages, such as at V10 in Figure 13, the difference in CV's are more

easily seen, with a CV of 17.2% for stalk diameter X height and 5.6% CV for NDVI. This

suggests that stalk diameter X plant height can be a more accurate indicator of individual corn

plant yield than NDVI. This is probably due to the overlapping of corn leaves across plants,

therefore averaging out differences between plants when using NDVI. A good example of this is

one corn plant at approximately 125 cm in Figure 13, which had no measurable yield. The stalk

diameter X plant height measurement was able to capture the difference in yield, but NDVI did

not. Again, this is likely due to the overlapping of leaves from the two larger neighboring corn

plants, which kept that corn plant from being able to be "seen" by the GreenSeeker sensor.

Additionally, when considering the relationship between NDVI and by-plant corn grain yield, the

correlation (r^2) increased from 0.04 at V8, to 0.26 at V10, to 0.32 at V12, and then decreased at

tasselling to 0.15 (Table 3). Alternatively, the r^2 values for stalk diameter X plant height for the

same growth stages were 0.36, 0.55, 0.67, and 0.10, respectively. This further suggests that

NDVI may not be the best variable for predicting by-plant corn yield.

CHAPTER V

CONCLUSIONS

The objective of this experiment was to determine if stalk diameter and plant height measurements could accurately predict final corn grain yield on a by-plant basis at different stages of corn development. The results from this experiment show that by-plant corn grain yields can be predicted using mid-season stalk diameter and plant height measurements. Stalk diameter measurements can also be used to predict in-season by-plant biomass. Multiplying stalk diameter times plant height gave the best prediction of by-plant grain yield on an area basis from growth stages V8 to V12.

The data collected from this experiment validate the need to use other physiological traits besides just NDVI in determining yield potential, and that will ultimately be used to make midseason fertilizer N recommendations. In addition, this data will be used to help refine the current yield prediction equations that are used for determining mid-season N rates. This work could also be used to substantiate the need for on-the-go by-plant monitoring and application of topdress N to individual corn plants. Further data collection will be needed for several more years and over more locations to help refine the data for more precise yield prediction using the stalk diameter X height method. Also, further studies on the effects of nitrogen rate and environment will be

needed to determine the effect that these factors have on the potential for yield prediction using the stalk diameter X height measurement. Future studies using the stalk diameter X height measurement will also look at how to implement this strategy for N management within a corn field. A possible solution will be to compare stalk diameter X height measurements from the majority of a field to the measurements within an N-rich strip. This N-rich strip will determine the maximum yield potential for the field, and will then help determine the response index for which N recommendations will be derived from. The need for more precisely placed N fertilizer, even down to the by-plant level, can be more easily achieved using methods such as stalk diameter X plant height indices for midseason N applications.

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Table 1. Planting and harvest dates, growth stages, days after planting, (DAP), growing degree days (GDD), and plant population of corn rows used for stalk diameter, height, and sensor measurements at Lake Carl Blackwell (LCB, irrigated), Haskell, Efaw, OK, and Ciudad Obregón, Mexico, 2009-2011.

	Planted	Population	Harvest	Date	Stage†	DAP	GDD
		Plants ha^{-1}					
2009							
Haskell[1]	28 May	61 775	21 October				
1.‡				7 July	V8	41	1113.8
2.				16 July	V10	50	1432.6
3.				27 July	VT	61	1726.8
2009							
LCB[2]	19 May	83 643	28 September				
1.				1 July	V8	44	1150.9
2.				15 July	VT	58	1628.9
2010							
Haskell[1]	4 May	61 775	17 August				
1.				25 June	V10	53	1300.8
2010							
LCB[1]	25 May	86 485	16 September				
1.				28 June	V8	35	1033.3
2.				7 July	V12	44	1287.0
2010							
Efaw[1]	28 April	49 667	24 August				
1.				17 June	V8	51	1083.4
2011							
Mexico[3]	14 Oct '10	67 700	14 Feb '11				
1.				10 Jan '11	V15	89	NA

[1] Variety planted: DeKalb DKC 52-59
[2] Variety planted: DeKalb DKC 67-23
[3] Variety planted: Cebu
† Corn growth stages V8, V10, and V12 defined as the 8th, 10th, and 12th leaves with collars visible. VT defined as the last branch of tassel being completely visible (Ritchie et al., 1996).
‡ Number of stalk diameter, height, and sensor measurements for each site-year.

Table 2. Average total rainfall and temperature during corn growing months at Lake Carl Blackwell, Efaw, and Haskell, 2009 and 2010.

Month	Rainfall			Avg. air temperature		
	2009	2010	Average	2009	2010	Average
	--------------------- mm -----------------------			-------------- °C ------------------		
Haskell†						
April	121.2	45.7	151.1	14.5	16.7	15.4
May	113.0	150.4	176.8	18.9	20.5	20.5
June	60.7	100.8	154.9	25.8	26.7	24.4
July	45.2	115.1	123.4	26.0	27.4	27.2
August	21.8	29.7	104.6	25.1	28.3	27.1
September	187.2	149.9	131.6	20.6	22.7	22.4
Lake Carl Blackwell‡						
April	119.9	108.5	121.4	14.6	16.8	15.1
May	77.0	156.2	112.3	18.7	19.5	20.4
June	52.3	176.8	141.2	26.6	26.7	24.4
July	131.6	55.1	105.9	26.5	27.7	27.7
August	183.4	67.1	93.2	24.8	28.0	27.3
September	113.0	80.5	104.1	20.4	23.0	22.2
Efaw‡						
April	--^	91.7	121.4	--^	17.1	15.1
May	--	181.1	112.3	--	19.9	20.4
June	--	139.4	141.2	--	26.9	24.4
July	--	111.5	105.9	--	27.7	27.7
August	--	63.8	93.2	--	28.2	27.3
September	--	70.6	104.1	--	23.3	22.2

† Monthly averages from Haskell Mesonet© station, 1994 – 2004.

‡ Monthly averages for Efaw and Lake Carl Blackwell are from Stillwater Mesonet© station, 1994 – 2004.

^ No trial data was taken from Efaw in 2009.

Table 3. Summary statistics for plant height, stalk diameter, and NDVI measurements at growth stages V8, V10, V12, and VT, averaged over sites and years.

Growth Stage	Variable	Min	Max	Range	Mean	Std Dev	CV
V8	Stalk diameter	1.03	2.64	1.61	2.00	0.27	13.7
	Height	45	157	112	92.2	21.7	23.6
	NDVI	0.143	0.872	0.729	0.622	0.152	24.4
V10	Stalk diameter	1.22	2.76	1.54	2.24	0.22	9.8
	Height	92	195	103	134	25.2	18.8
	NDVI	0.442	0.838	0.396	0.704	0.091	12.9
V12	Stalk diameter	1.30	2.89	1.59	2.07	0.26	12.4
	Height	85	170	85	128.5	20.7	16.1
	NDVI	0.324	0.724	0.400	0.571	0.091	16.0
VT	Stalk diameter	1.36	2.65	1.29	2.05	0.24	11.6
	Height	100	216	116	149.6	27.9	18.7
	NDVI	0.252	0.791	0.539	0.586	0.111	18.9

Table 4. Linear relationship between by plant grain yield and measured plant height, stalk diameter, and NDVI, at V8, V10, V12, and VT corn growth stages, averaged across locations and years in Oklahoma, and polynomial relationship between by plant biomass and stalk diameter in Mexico, V15, 2011.

	Variable		
Growth stage of corn	**Independent**	**Dependent**	r^2‡
V8	Height	Grain yield, kg ha^{-1}	0.35**
V8	Stalk diameter		0.11**
V8	Stalk diameter*height		0.36**
V8	NDVI		0.04**
V10	Height	Grain yield, kg ha^{-1}	0.52**
V10	Stalk diameter		0.10**
V10	Stalk diameter*height		0.55**
V10	NDVI		0.26**
V12	Height	Grain yield, kg ha^{-1}	0.53**
V12	Stalk diameter		0.71**
V12	Stalk diameter*height		0.67**
V12	NDVI		0.32**
VT	Height	Grain yield, kg ha^{-1}	0.51**
VT	Stalk diameter		0.03*
VT	Stalk diameter*height		0.10**
VT	NDVI		0.15**
V15	Stalk diameter	Biomass, kg plant^{-1}	0.68**^

* Model significant at the 0.05 level of probability.

** Model significant at the 0.01 level of probability.

‡ r^2 denotes the proportion of variability in the dependent variable explained by the independent variable by the selected model.

¶ ns, not significant.

^ Relationship was a 2nd order polynomial.

V8 – eight fully collared leaves.

V10 – ten fully collared leaves.

V12 – twelve fully collared leaves.

V15 – fifteen fully collared leaves.

VT – corn tasseling.

Table 5. Relationship of NDVI X plant height, plant height, stalk diameter, stalk diameter X height, and NDVI to by-plant corn grain yield, for growth stages V8, V10, V12, VT, and growth stage groups V8-V10, V10-V12, and V12-VT, averaged over sites and years.

Growth Stages	NDVI X HT[1]	HT	SD	SD X HT	NDVI
			r^2		
V8	0.29	0.35	0.11	0.36	0.04
V10	0.49	0.52	0.10	0.55	0.26
V12	0.50	0.53	0.71	0.67	0.33
VT	0.37	0.52	0.03	0.40	0.15
V8-V10	0.13	0.15	0.06	0.15	0.04
V10-V12	0.39	0.50	0.29	0.56	0.17
V12-VT	0.43	0.53	0.16	0.49	0.20

[1] NDVI = normalized difference vegetation index; HT = plant height; SD = stalk diameter.
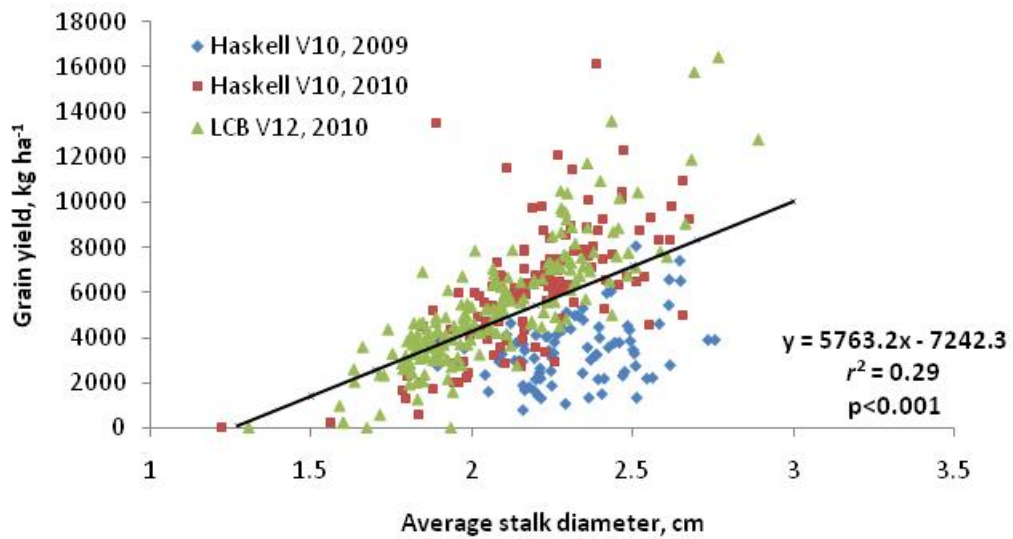
Fig. 1. Relationship between stalk diameter and by-plant corn grain yield for growth stages V10-V12, Haskell and Lake Carl Blackwell, 2009-2010.
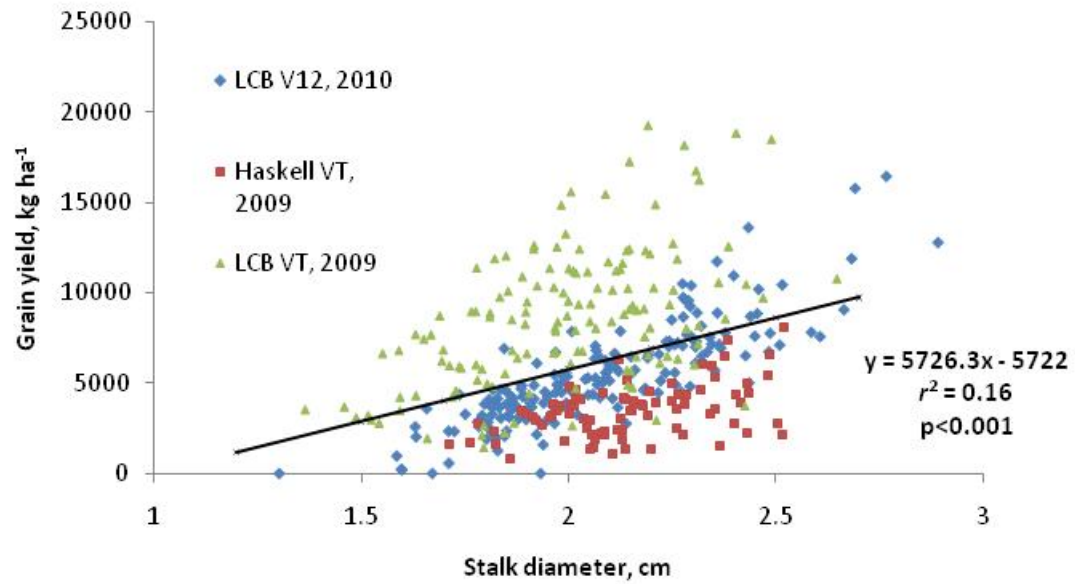
Fig. 2. Relationship between stalk diameter and by-plant corn grain yield, growth stages V12-VT, Haskell and Lake Carl Blackwell, 2009 - 2010.
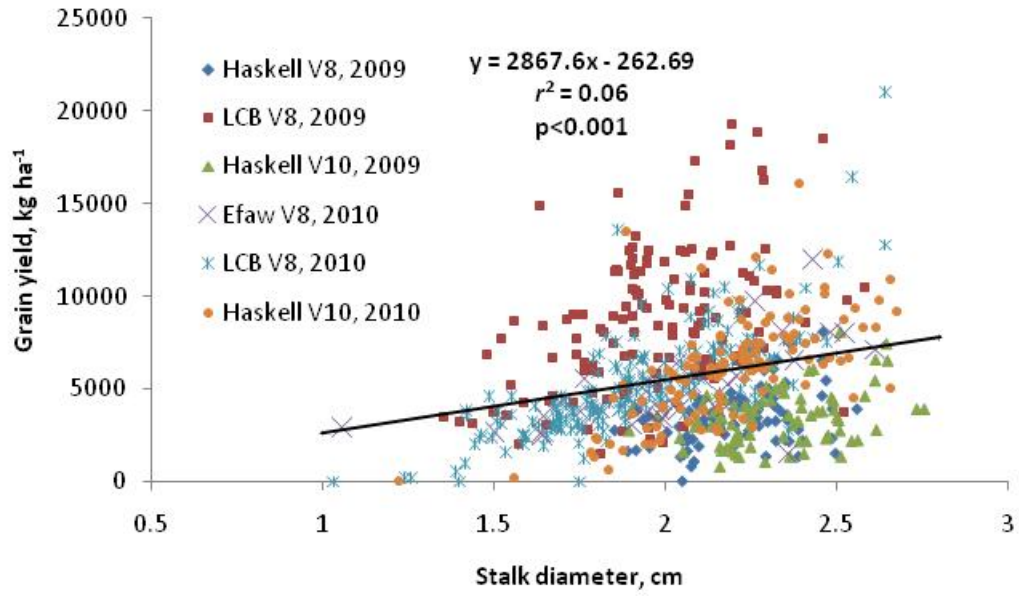
Fig. 3. Relationship between stalk diameter and by-plant corn grain yield, growth stages V8 to V10, Haskell, Lake Carl Blackwell, and Efaw, 2009 and 2010.
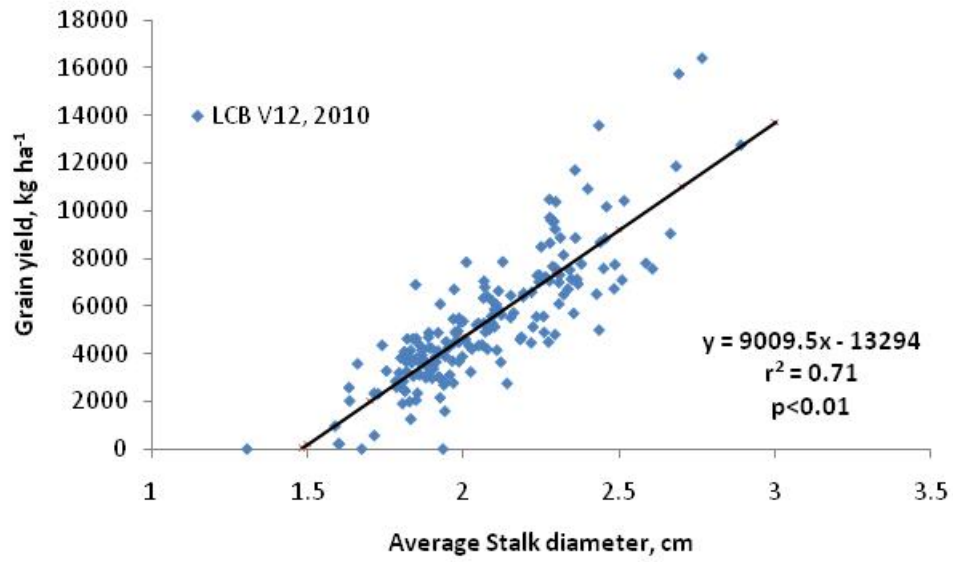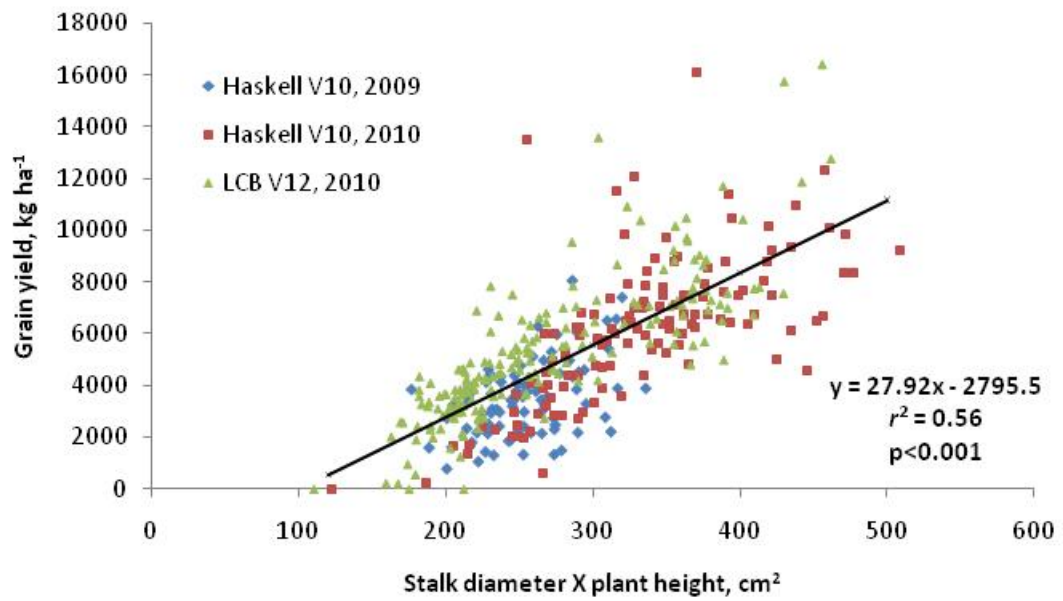
Fig. 4. Relationship between stalk diameter and by-plant corn grain yield at growth stage V12, Lake Carl Blackwell, 2010.

Fig. 5. Relationship between stalk diameter X plant height and by-plant corn grain yield, growth stages V10 to V12, Haskell and Lake Carl Blackwell, 2009 and 2010.
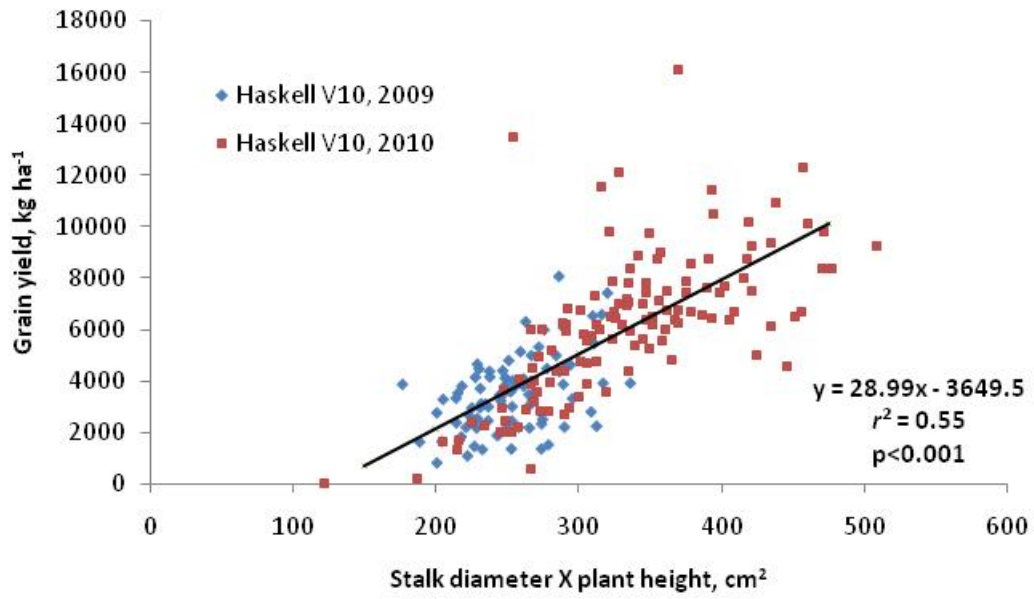
Fig. 6. Relationship between stalk diameter X plant height and by-plant corn grain yield, growth stage V10, Haskell, 2009-2010.
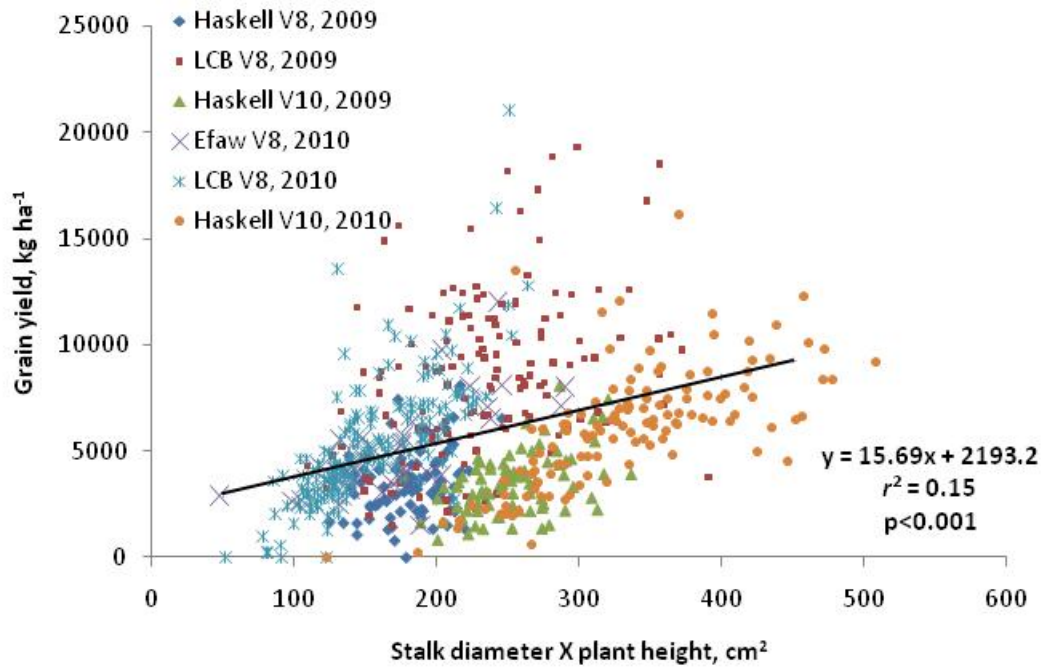
Fig. 7. Relationship between stalk diameter X plant height and by-plant corn grain yield, growth stages V8 to V10, Efaw, Lake Carl Blackwell, and Haskell, 2009 and 2010.
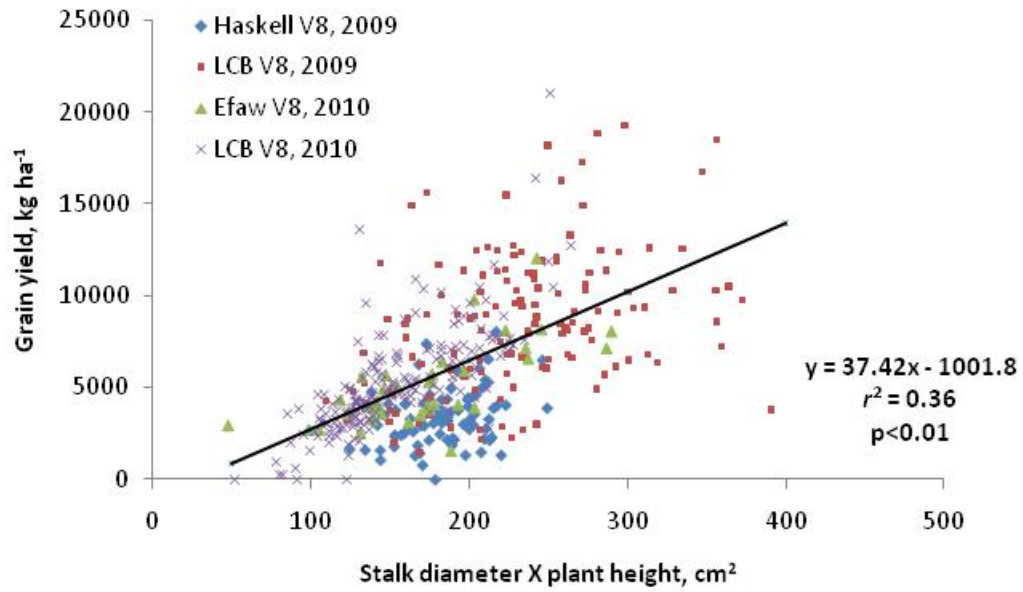
Fig. 8. Relationship between stalk diameter X plant height and by-plant corn grain yield, growth stage V8, Haskell, Lake Carl Blackwell, and Efaw, 2009 and 2010.
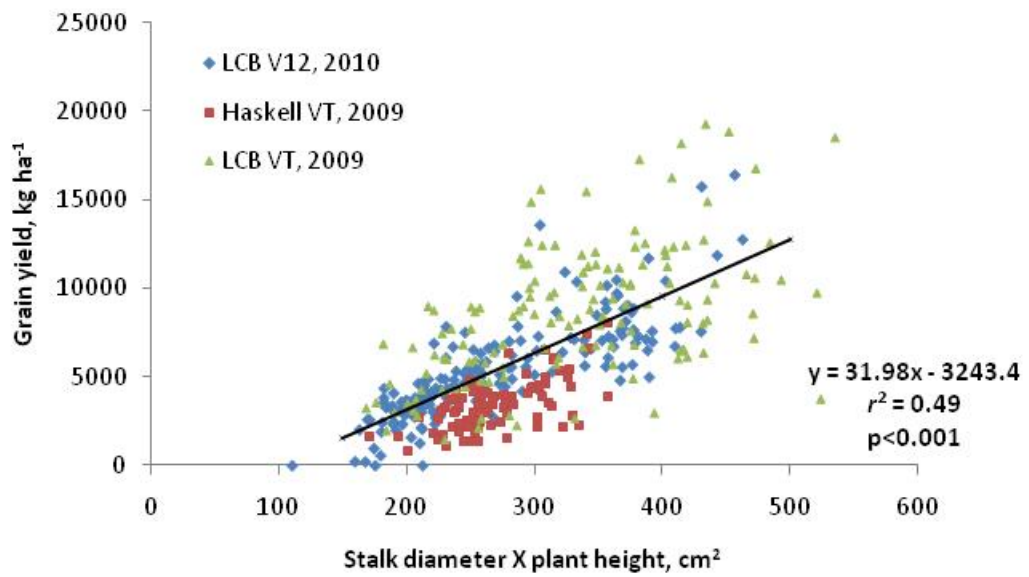
Fig. 9. Relationship between stalk diameter X plant height and by-plant corn grain yield, growth stages V12 to VT, Haskell and Lake Carl Blackwell, 2009 and 2010.
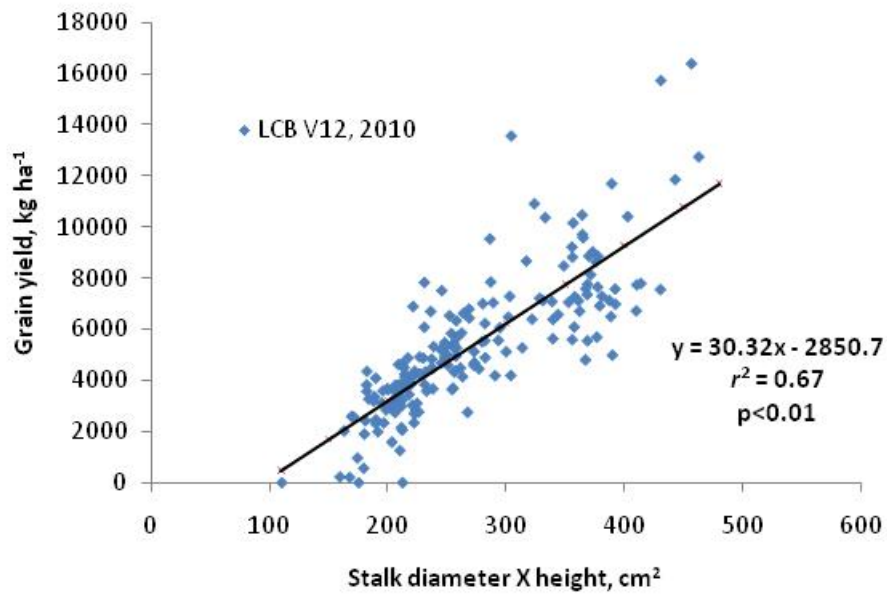
Fig. 10. Relationship between stalk diameter X height and by-plant corn grain yield, growth stage V12, Lake Carl Blackwell, 2010.
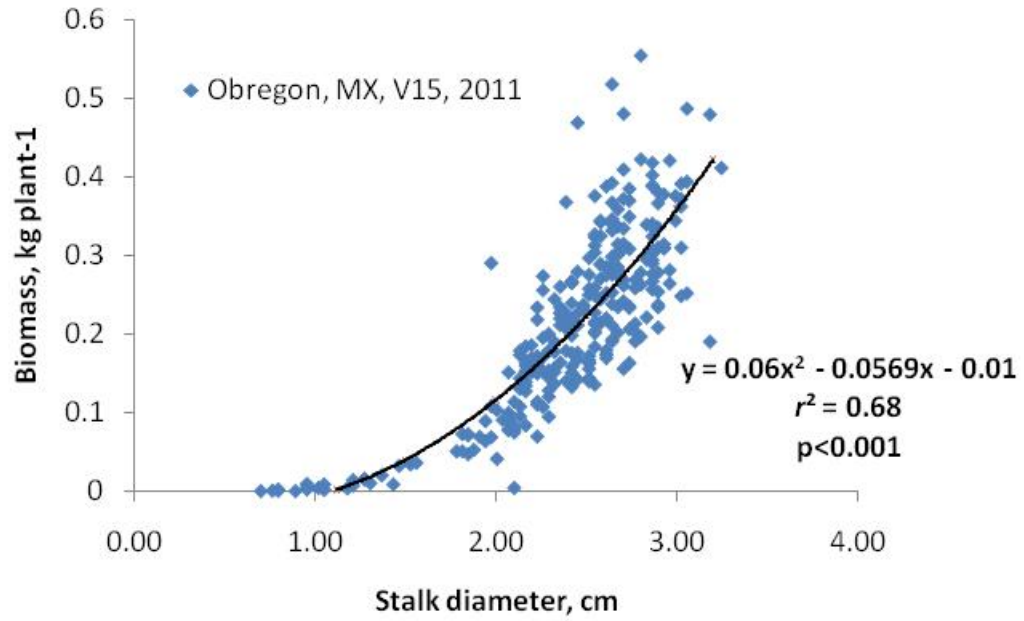
Fig. 11. Relationship between stalk diameter and by-plant corn biomass, growth stage V15, Ciudad Obregon, Mexico, 2011.
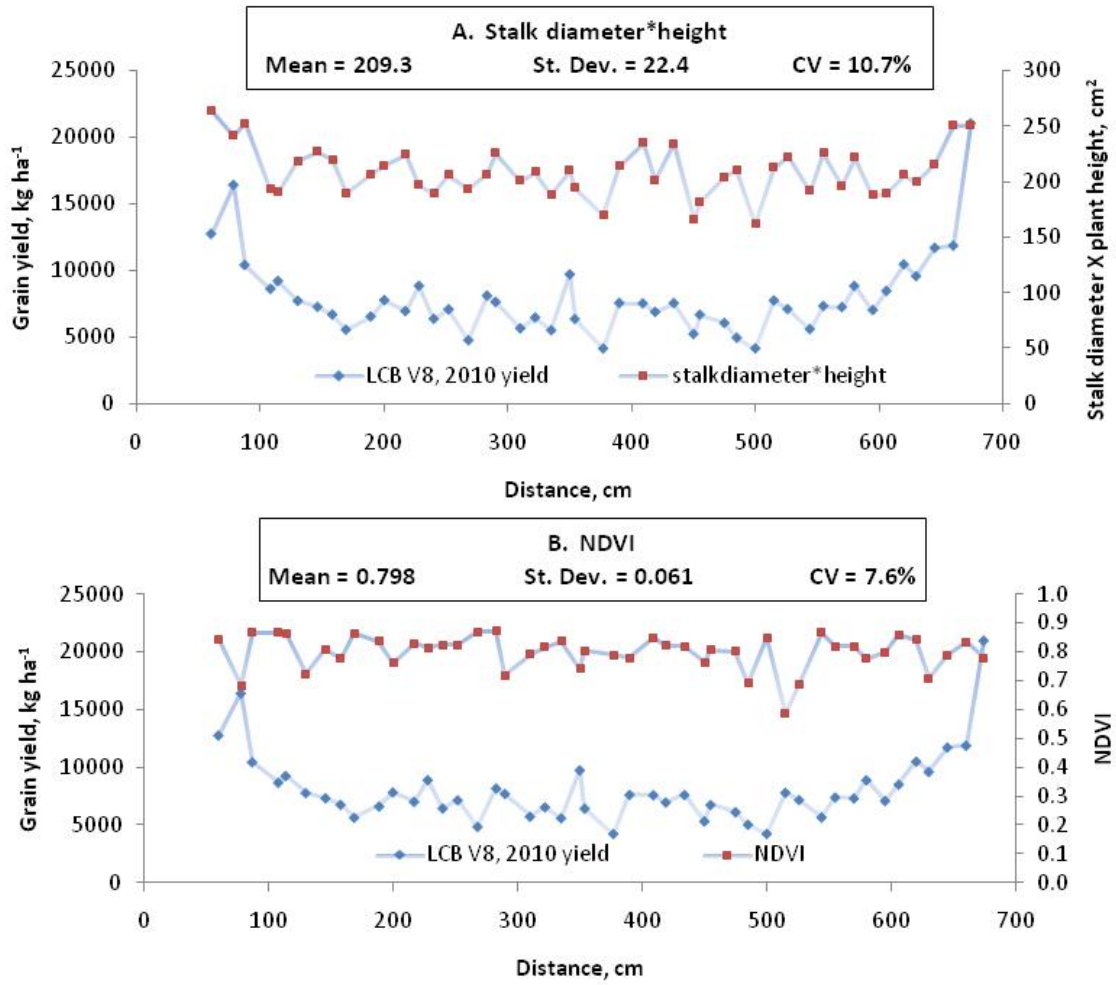
Fig. 12. Stalk diameter X plant height (A) and NDVI (B), as compared to by-plant corn grain yield by distance down the row. Lake Carl Blackwell, growth stage V8, 2010.
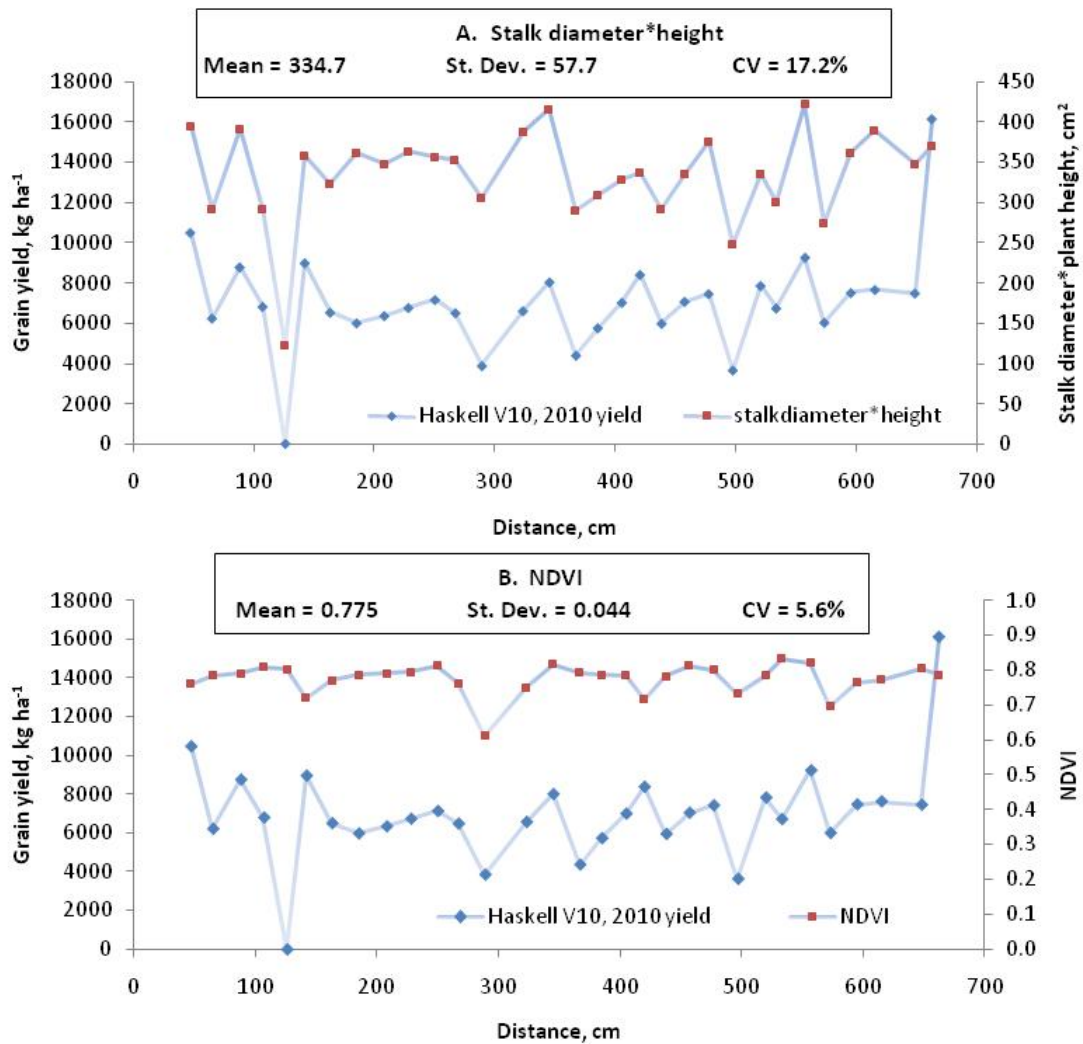
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Fig. 13. Stalk diameter X plant height (A), and NDVI (B), as compared to by-plant corn grain yield by distance down the row. Haskell, growth stage V10, 2010.

VITA

Jonathan Perry Kelly

Candidate for the Degree of

Master of Science

Thesis: BY PLANT PREDICTION OF CORN (Zea mays L.) GRAIN YIELD USING HEIGHT AND STALK DIAMETER

Major Field: Plant and Soil Sciences

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Personal Data: Born in Altus, OK, on February 21, 1986, the son of Joe and Marsha Kelly.

Education: Graduated Valedictorian from Altus High School, Altus, OK, in 2004. Graduated Summa Cum Laude from Western Oklahoma State College with an Associate of Art in 2006. Graduated Summa Cum Laude with a Bachelor of Science in Natural Resource Ecology and Management and Plant and Soil Sciences at Oklahoma State University, Stillwater, OK in 2009. Completed the requirements for the Master of Science in Plant and Soil Sciences at Oklahoma State University, Stillwater, Oklahoma in May, 2011.

Experience: Raised on a cotton and wheat farming operation in Southwest Oklahoma, where employed as a summer-time farm laborer. Employed by Oklahoma State University Department of Natural Resource Ecology and Management for two summers, 2007-2008, as an undergraduate research assistant. Worked as an undergraduate research assistant in the Department of Plant and Soil Sciences under Dr. Bill Raun starting December 2008, and became a graduate research assistant in May 2009. Presently working as Senior Agriculturalist, Soil Fertility Project, Department of Plant and Soil Sciences, since August 2009.

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Name: Jonathan Perry Kelly   Date of Degree: May 2011

Institution: Oklahoma State University   Location: Stillwater, Oklahoma

Title of Study: BY PLANT PREDICTION OF CORN (Zea mays L.) GRAIN YIELD
          USING HEIGHT AND STALK DIAMETER

Pages in Study: 36   Candidate for the Degree of Master of Science

Major Field: Plant and Soil Sciences

Scope and Method of Study: Current methodologies for determining midseason nitrogen
          (N) rates in corn have used Normalized Difference Vegetation Index (NDVI), and
          in some cases, plant height and intra-specific plant competition.   Another
          parameter that can be linked to potential yield is stalk diameter; thus incorporating
          collectively the parameters of NDVI, plant height, and stalk diameter should
          result in a better prediction of yield potential. This could lead to more efficient
          methods of midseason fertilizer N applications. The objective of this study is to
          analyze the relationship of stalk diameter, as well as plant height and NDVI, with
          final grain yield, and to refine the method of predicting yield potential using a
          combination of these factors. In this 2-year study at 4 locations, several rows of
          corn plants were selected, each with varying amounts of pre-plant nitrogen
          fertilizer, from 0 to 145 kg ha^{-1}, with no additional nitrogen inputs throughout the
          growing season. Measurements on plant spacing, stalk diameter, plant height, and
          NDVI were taken from growth stages V8 (eight fully collared leaves) to VT (corn
          tasselling), and all corn plants were harvested by-plant to determine grain yield or
          dry biomass.

Findings and Conclusions: Individual plant height measurements proved to be a good
          predictor of by-plant grain yield ($r^2 = 0.52$, 0.53; V10, V12, respectively). Using
          a value of stalk diameter X plant height gave the best correlation with grain yield
          on an area basis ($r^2 = 0.34$, 0.55, 0.67; V8, V10, V12, respectively). By-plant
          biomass was also predicted well by stalk diameter, with an r^2 value of 0.68 at
          growth stage V15, using a polynomial function. This research indicates that other
          factors besides NDVI can be used to predict by-plant corn grain yields, and stalk
          diameter X plant height may be the best method to use for refining midseason
          fertilizer N rates at growth stages V8 to V12.

ADVISER'S APPROVAL: Dr. William Raun