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By-Plant Prediction of Corn (*Zea mays* L.) Grain Yield using Height and Stalk Diameter

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Methods for determining midseason nitrogen (N) rates in corn have used the parameter normalized difference vegetation index (NDVI) and, in some cases, plant height. The objective of this study was to analyze the relationship of stalk diameter along with predictors of yield, including NDVI and plant height with grain yield. Five site-years of data were analyzed, where several rows of corn plants were selected, and yield from plants within the row was recorded individually. Measurements of stalk diameter, plant height, and NDVI were taken from growth stages V8–VT. Using a value of stalk diameter × plant height gave the best correlation with grain yield (r^2 = 0.34, 0.55, 0.67; V8, V10, V12, growth stages respectively). This work showed that stalk diameter × plant height was positively correlated with by-plant corn grain yields, and this parameter could be used for refining midseason fertilizer N rates for growth stages V8–V12.

Keywords By-plant, grain yield, NDVI, stalk diameter

Introduction

It has been estimated that worldwide nitrogen (N)–use efficiency (NUE) of applied N fertilizers is about 33 percent for cereal crops where Raun and Johnson (1999) calculated NUE as

$$\text{NUE} = \big[(\text{total cereal N removed}) - (\text{N coming from the soil} + \text{N deposited in the rainfall})\big] \,/\, (\text{fertilizer N applied to cereals})$$

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 ammonia (NH_3) (Raun and Johnson 1999). 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). By using data available in 1999, Raun and Johnson showed that a 1 percent increase in NUE would be worth $234,658,462. Using their same calculation a 1 percent increase in NUE would be worth $648,617,544 in 2012 ($479 per metric ton of N 1999; $1324 per metric ton (US Department of Agriculture Economic Research Service)).

Because of this extensive inefficient use of N fertilizer, there is a pronounced need in the United States, as well as worldwide, to increase NUE among cereal crops, especially

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corn. Several methods can be used to improve NUE worldwide, including selection of better hybrids or cultivars, conservation tillage, ammonium (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, p. 1). Some of the ways that precision agriculture can help increase NUE is through application resolution and remote sensing.

Application resolution refers to the precision with which N is applied to fields, with a common N-management practice that often implements a field element size of the entire field in question, and N rates are often applied at a flat rate across an entire field. Better practices include using a zone or grid management systems to match N rates to a smaller field element size within the larger field unit, and these zones can range from 0.2 to 4 or more hectares (ha) in size. However, significant soil-test and biomass differences have been detected at resolutions equal to or less than 1 m^2 (Raun and Johnson 1999; Solie et al. 1996). Raun et al. (1998) and Solie, Raun, and Stone (1999) found significant soil-test differences of N, phosphorous (P), and potassium (K) values within resolutions of less than 1 m^2 in 0.3 m × 0.3 m bermudagrass plots.

With these findings of variability within a resolution size often less than 1 m^2, 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 m^2 would be cost-prohibitive; therefore, other methods of determining the amount of fertilizer needed variably across the field 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 (Trimble Navigation, Sunnyvale, CA), have been successfully used to make variable-rate applications of N fertilizer at a resolution of 0.84 m^2 (Tubaña et al. 2008). Teal et al. (2004) noted that NUE can increase by more than 10 percent in corn and 15 percent in winter wheat using midseason N fertilizer rates based on predicted yield potential and a response index system, such as those used by Oklahoma State University.

The resolution of the GreenSeeker sensor could even allow for detecting by-plant differences in corn throughout a row. By-plant variability in corn yields is well documented (Freeman et al. 2007; Martin et al. 2005; Teal et al. 2004), which expresses the need for management of N on a by-plant basis for corn. A study by Freeman et al. (2007) revealed that normalized difference vegetative index (NDVI), along with plant height measurements, could be used to predict by-plant corn forage yield. This study found that an index of NDVI × plant height had a strong relationship ($r^2 = 0.77$) with N uptake from V10 to R1 (Ritchie, Hanway, and Benson 1996) growth stages. Additionally, they 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; Raun et al. 2005; Teal et al. 2004) 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 greatest in corn from growth stages V6 to V8, and lowest from V10 to 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 greater CV of NDVI measurements at these growth stages. However, from V10 to VT, the plants were larger, were 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 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.

With the findings of Martin et al. (2007) using the CV of NDVI values in corn, and the positive relationship of using a NDVI × plant height index for predicting yield potential as reported by 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 that may be considered include 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. They also reported that both stalk height and diameter were subject to differences among corn varieties. Pordesimo, Edens, and Sokhansanj (2004) showed that regression equations using both stalk diameter and height may be used to predict both fresh and dry weights 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, Lamb, and Butts (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 grain yield. Research has shown that 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 midseason N application.

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, and another location was added for 2010 at the Efaw site of the Stillwater Agronomy Research Station, Stillwater, OK. 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 site at the Eastern Research Station was located on a Taloka silt loam, 1 to 3 percent slope (fine, mixed, active, thermic Mollic Albaqualfs), and the Efaw site was located on a Norge loam, 3 to 5 percent slope, eroded (fine-silty, mixed, active, thermic Udic Paleustolls). 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, whereas the irrigated site at Lake Carl Blackwell was planted at a target population of 85,000 seeds ha^{-1}. Two years of data were taken from the Haskell and the LCB irrigated sites and 1 year at the Efaw site for a total of 5 site-years. Four rows of corn 6.1 m long were selected within existing field trials at each location in Oklahoma with different preplant N rates (no top-dress N applied). The preplant N rates were 0, 45, 90, and 180 kg N ha^{-1}, and these rates were applied merely to effect a change in the measurements taken. Even though this experiment was located inside of a replicated field trial, replications were not considered because each plant was analyzed with yield individually. Phosphorus and potassium (K) 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 midseason application of glyphosate. Within each row, the distance down the row from a predetermined point was recorded, and each plant was tagged with a unique identifying tag. At growth stages V8, V10, V12 (eighth, tenth, and twelfth leaf collar unfolded respectively), and VT (last branch of tassel visible), plant height, NDVI, and stalk diameter were taken from each tagged plant within the selected rows. These growth stages were chosen because most midseason 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 percent 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 an NDVI value for every centimeter of linear distance in the row. The GreenSeeker Hand Held unit measures NDVI in a 0.6 m × 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) wavelengths (Freeman et al. 2007). The GreenSeeker calculates NDVI as follows:

$$\text{NDVI} = (\rho_{\text{NIR}} - \rho_{\text{red}}) / (\rho_{\text{NIR}} + \rho_{\text{red}}) \tag{1}$$

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 rows, while the sensor maintained a position centered over the row at 0.9 m above the crop canopy, travelling parallel with the row. By starting at a predetermined point where each individual corn plant's distance was marked, it was then possible to calculate NDVI for each individual plant. This was accomplished 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 7 days. Corn ears were weighed and then shelled, and the grain was weighed for each individual plant. 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 the standard moisture of 15.5 percent and then expressed as kg ha^{-1}.

Average stalk diameter was calculated by averaging the major and minor axes of the stalk:

$$(\textit{Minor axis} + \textit{Major axis}) / 2 = \text{average stalk diameter} \tag{2}$$

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:

$$\textit{average stalk diameter} \times \textit{height} = \text{normalized data} \tag{3}$$

All data from V8 to VT, at all locations, and across all years, were combined and analyzed. Data were analyzed by each growth stage individually, as well as being divided into three groups for analysis: V8–V10, V10–V12, and V12–VT. An effort was made to look at all groups with sites and years combined to derive a yield prediction equation that would work across sites and years. Simple correlation in SAS (SAS Institute 2003) was used to identify variables highly correlated with grain yield in this study. Using the variables stalk diameter, stalk diameter × height, NDVI, and NDVI × height as independent variables, linear regression was performed with by-plant corn grain yield (kg ha^{-1}) as the dependent variable. The greatest coefficient of determination (r^2) was used to select the models with the best fit to the data.

Results

Table 1 reports summary statistics of the data collected including the minimum, maximum, mean, standard deviation, and coefficient of variation for each growth stage averaged across sites and years.

Stalk Diameter

Stalk diameter was significantly correlated with by-plant corn grain yield, especially at growth stages V10 to V12. 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. Table 2 includes the coefficient of

Table 1

Summary statistics for plant height,[a] stalk diameter,[a] 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

[a]Reported in centimeters.

Table 2
Relationship of NDVI × plant height, plant height, stalk diameter, stalk diameter × 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 × HT	HT	SD	SD × 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**

Notes. NDVI, normalized difference vegetation index; HT, plant height; SD, stalk diameter. r^2 denotes the proportion of variability in the dependent variable explained by the independent variable by the selected model. V8, eight fully collared leaves; V10, ten fully collared leaves; V12, twelve fully collared leaves; and VT, corn tasseling.
*Model significant at the 0.05 level of probability.
**Model significant at the 0.01 level of probability.

determination for simple linear regression for V8, V10, V10, and combinations of growth stages for stalk diameter and grain yield. Additionally, Table 2 includes the correlation between the stalk diameter × height index.

NDVI × Plant Height Index

When examined for this study, NDVI × 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 2), for sites and years combined. When the growth stages were grouped together, the r^2 values were 0.13, 0.39, and 0.43, for growth stage groups V8–V10, V10–V12, and V12-VT, respectively. Table 2 also compares the correlations of the NDVI × height index to other measurements taken in this experiment.

Discussion

Stalk Diameter

Even though stalk diameter was significantly correlated with grain yield at V10–V12, when sites and years were combined for the earlier growth stages V8 to V10, the r^2 value was much lower at 0.06 (Figure 1). 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. 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 (Figure 2).

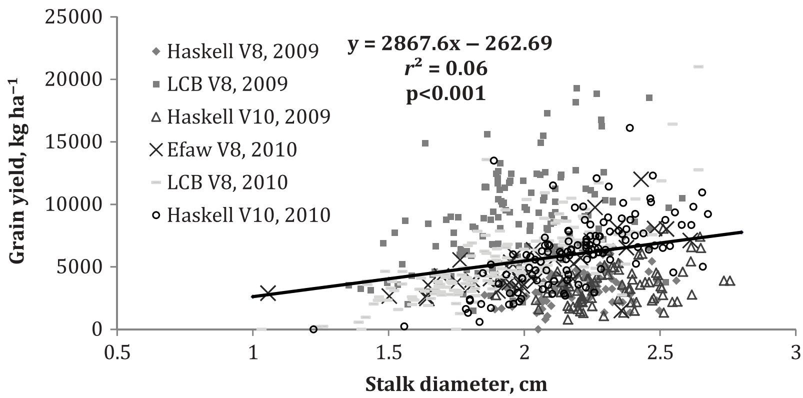

Figure 1. Relationship between stalk diameter and by-plant corn grain yield, growth stages V8 to V10, Haskell, Lake Carl Blackwell, and Efaw, 2009 and 2010.

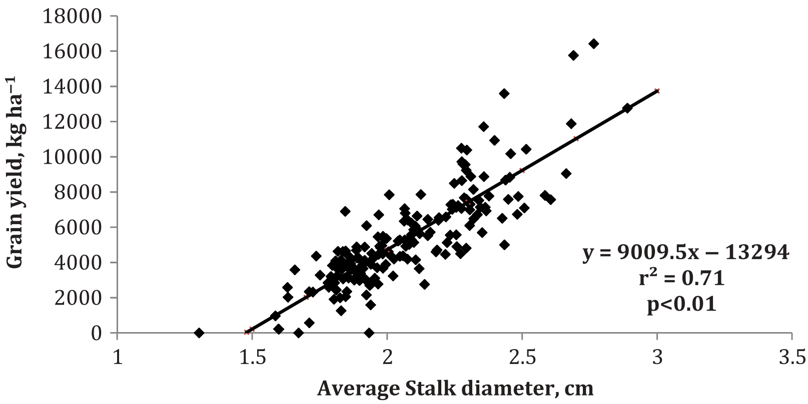

Figure 2. Relationship between stalk diameter and by-plant corn grain yield at growth stage V12, Lake Carl Blackwell, 2010.

There was a wide range in the values for stalk diameter (Table 1), and this range may suggest potential differences in sampling procedures among people and differences of whether the lowermost leaf was still attached to the stalk. While data were collected as uniformly as possible, these potential errors could influence the data, especially in the later growth stages, when the lowermost leaf began to senesce and fall off of the stalk. If occurred, it may have affected the stalk diameter measurement, because this leaf sheath would have been attached to the first internodal area where the stalk diameter measurements were taken.

NDVI × Plant Height Index

Freeman et al. (2007) found that the index NDVI × 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. Although we found that the NDVI × height index demonstrated strong r^2 values, other measurements, such as height, and stalk diameter × height, consistently provided better relationships with final by-plant corn grain yield.

Stalk Diameter × Plant Height

Across years and locations, when stalk diameter was multiplied by plant height, the relationship between this index and by-plant corn grain yield was much improved (Table 2). When stalk diameter × 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 × plant height and yield as compared to the other growth stages. This is consistent with the work by Freeman et al. (2007), where NDVI was multiplied with plant height to create a NDVI × plant height index, which proved to be a good predictor of by-plant forage yields. As is reported in Table 2, the r^2 values of stalk diameter × 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 × 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 (Figure 3). When the data were evaluated separately, the relationship between stalk diameter × 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 (Figure 4) for stalk diameter × plant height and grain yield. However, our purpose was to create a more robust equation that would work across sites and years.

To see the relationship between stalk diameter × plant height in comparison to NDVI, these parameters were plotted by row (distance) of corn (Figures 5 and 6). Figure 5 shows these data for Lake Carl Blackwell at growth stage V8, and Figure 6 shows these data for Haskell at V10. Stalk diameter × plant height shows more variability down the row and more closely 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 for Figures 5 and 6, the CV is greater for the stalk diameter × height measurement than the NDVI measurement in both instances, indicating

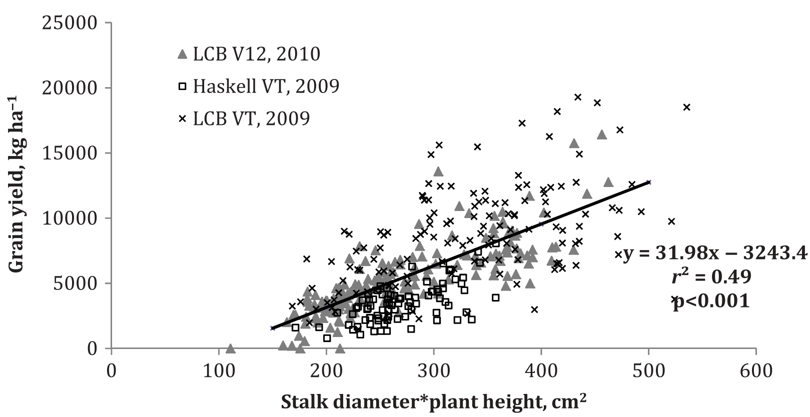

Figure 3. Relationship between stalk diameter × plant height and by-plant corn grain yield, growth stages V12 to VT, Haskell and Lake Carl Blackwell, 2009 and 2010.

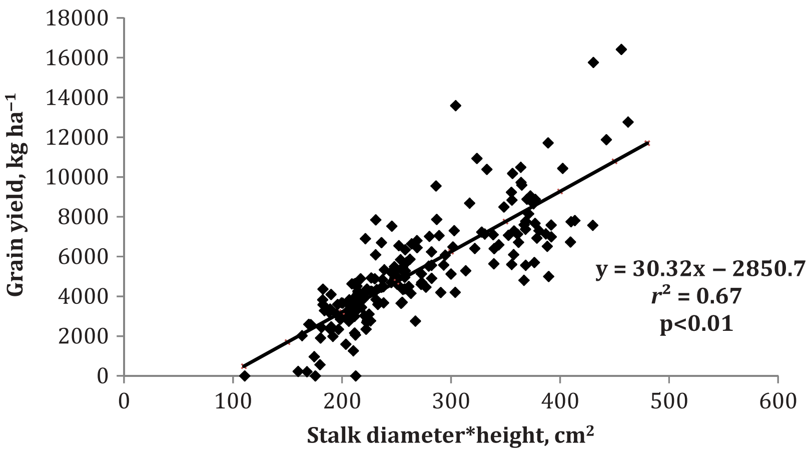

Figure 4. Relationship between stalk diameter × height and by-plant corn grain yield, growth stage V12, Lake Carl Blackwell, 2010.

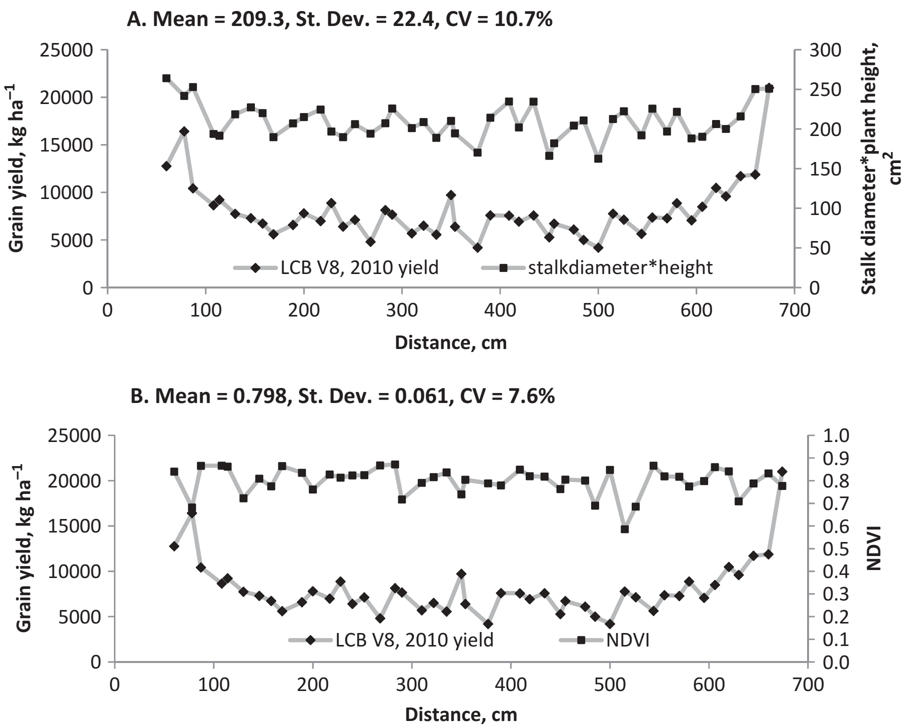

Figure 5. Stalk diameter × plant height (A) and NDVI (B), compared to by-plant corn grain yield by distance down the row. LCB, growth stage V8, 2010.

more variability in the values of stalk diameter × height. At growth stage V8, the CV is 10.7% for stalk diameter × height, as compared to only 7.6 percent for NDVI (Figure 5). At the later growth stages, such as at V10 in Figure 6, the difference in CVs are more easily seen, with a CV of 17.2% for stalk diameter × height and 5.6% CV for NDVI. This

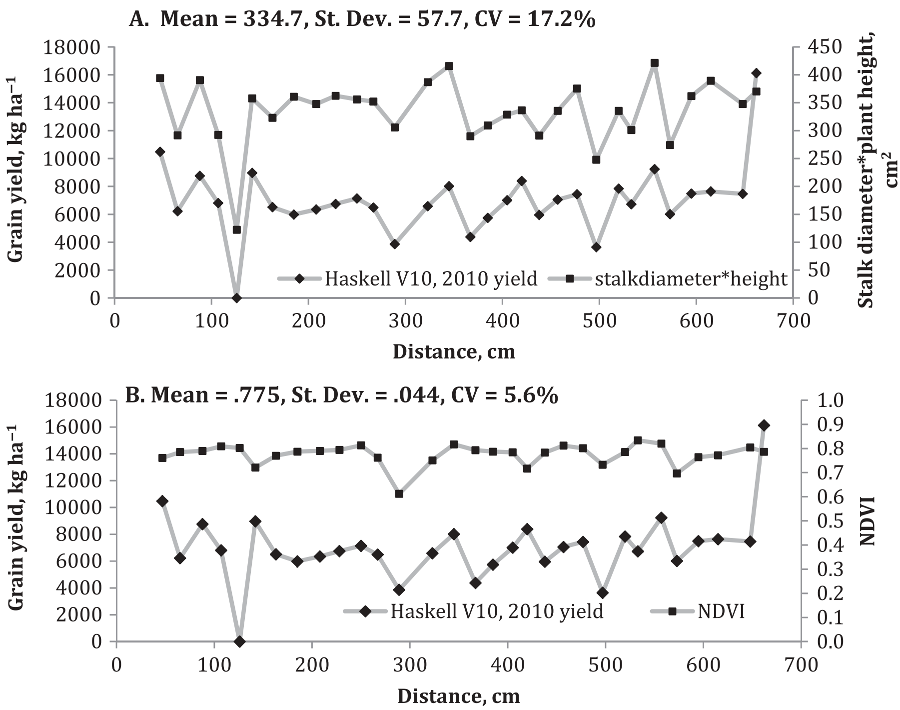

Figure 6. Stalk diameter × plant height (A), and NDVI (B), compared to by-plant corn grain yield by distance down the row. Haskell, growth stage V10, 2010.

suggests that stalk diameter × plant height can be a more accurate indicator of individual corn plant yield than NDVI, by individually diagnosing each plant whereas with NDVI the canopy is diagnosed. This probably results in reading overlapping 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 6, which had no measurable yield. The stalk diameter × plant height measurement was able to capture the difference in yield, but NDVI did not. Most likely, the two larger neighboring corn plants kept that middle corn plant from being able to be "seen" by the GreenSeeker sensor. Based on the correlations, our data suggests that NDVI may not be the most accurate variable for predicting by-plant corn yield.

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 midseason stalk diameter and plant height measurements. Multiplying stalk diameter times plant height (stalk diameter × 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 NDVI in determining yield potential as stalk diameter × plant height and NDVI × plant height consistently resulted in better correlations than NDVI alone. This information will ultimately be used to help make midseason fertilizer N recommendations by refining current algorithms so that they utilize some of the parameters we explored. Further data collection should occur to help refine the models ability for more precise yield prediction using the stalk diameter × height method, especially at different N and seeding populations as there might be interacting factors. Future studies using the stalk diameter × height measurement will also explore how to implement this strategy for N management within a corn field. A possible solution will be to compare stalk diameter × height measurements from the majority of a field to the N-rich strip (Johnson and Raun 2003). An N-rich strip is a non-N-limiting area of the field. 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. This method could even alleviate some of the problems that we encountered with combining sites as each field could be evaluated separately. The need for more precisely placed N fertilizer, even down to the by-plant level, could be more easily achieved using methods such as stalk diameter × plant height indices for midseason N applications. This could lead to an increase in NUE in corn production in the United States as well as worldwide.

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