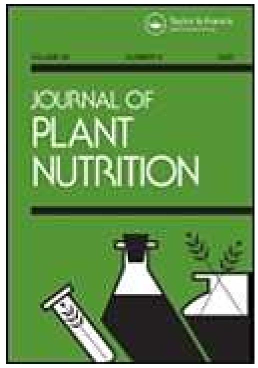

By-Plant Prediction of Corn Grain Yield Using Optical Sensor Readings and Measured Plant Height

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Spatial and temporal variability in optimal nitrogen (N) rates can be attributed largely to soil interactions, management practices, and weather (Blackmer et al., 1997). Within-field yield variation is typically attributed to variability in soil texture, changes in landscape position, cropping history, soil physical and chemical properties, and nutrient availability across fields (Wibawa et al., 1993; Penny 1996). However, these generalizations regarding the source of variability are not always supported by other research. Machado et al. (2002) found that variability in grain yield does not always follow the patterns of soil chemical and physical characteristics. Schepers et al. (2004) showed that using management zones for variable rate inputs like N only worked in three of five seasons. Furthermore, they realized that temporal variability can greatly alter the spatial variability, even in irrigated fields. Likewise, Schmidt et al. (2002) found that a highly variable amount of N was required to bring any given subplot of corn within a farmer’s field to maximum yield. Therefore, quantifying the variability in corn growth and development and the factors causing that variability could be the key to correcting the deficiencies in N. Two difficulties in addressing this variability are: (1) identifying the variability both temporally and spatially and (2) identifying the scale at which the variability exists.

Currently, the use of remote sensors has allowed some issues of spatial and temporal variability to be addressed. Remote sensors can be used to estimate crop yield potential (Lillesand and Kiefer, 1994), defined by Evans and Fisher (1999) as the yield of a cultivar grown in environments to which it is adapted with nutrients, water, and stresses effectively controlled. Rouse et al. (1973) established the foundation for this technology by developing an index called the normalized difference vegetation index (NDVI), which is used to estimate green biomass. This index is calculated as follows:

$$NDVI = \frac{\rho_{NIR} - \rho_{\mathrm{Re}\,d}}{\rho_{NIR} + \rho_{\mathrm{Re}\,d}} \qquad [1]$$

Where:

ρ_{NIR} – Fraction of emitted near infrared radiation returned from the sensed area

ρ_{Red} – Fraction of emitted red radiation returned from the sensed area

Filella et al. (1995) stated that the use of remote sensors in the appropriate reflectance spectrum is a useful tool for monitoring the N status of a crop and can be used to determine the N fertilizer requirement of a crop. Raun et al. (2002) used NDVI to estimate yield potential in winter wheat (*Triticum aestivum* L.) during the growing season (Feekes 4 to 6) with the in-season estimated yield (INSEY) index, calculated as follows:

$$INSEY = \frac{NDVI}{GDD > 0} \qquad [2]$$

Where:

$GDD > 0$ is the days from planting to sensing for which growing degree days (GDD) are > 0

Furthermore, Raun et al. (2002) used the INSEY equation at various resolutions and found that when INSEY was used to calculate N fertilization rates at 1 m^2 resolution, a significant increase in nitrogen use efficiency (NUE) occurred in winter wheat.

Later, Raun et al. (unpublished data, 2004) developed the days from planting (DFP) INSEY for corn based on the concept of INSEY in wheat. The DFP INSEY calculation simply divided NDVI by DFP, which included all days from planting to sensing. Teal et al. (2006) later used the DFP INSEY to successfully predict corn grain yield in whole plot research.

Raun et al. (2005) demonstrated the ability of the GreenSeeker[1] (NTech Industries, Ukiah, Ca) handheld sensor to detect individual plant differences in terms of NDVI. The ability to detect these differences was greatest at the V8 physiological growth stage and diminished at the V10 growth stage. Martin et al. (2007) and Freeman et al. (2007) found similar results and noted that NDVI was highly related to both corn grain and biomass yield.

Data collected by Martin et al. (2005) from locations in Argentina, Mexico, Iowa, Nebraska, Ohio, Virginia, and Oklahoma showed that regardless of location, plant-to-plant variability in corn grain yield averaged more than 2765 kg ha^{-1} over sites and years. They further noted that plant-to-plant variability in corn grain yield can be expected in virtually all production environments.

Evaluation of individual plants for characteristics related to yield has not been well studied. With the improvement of on-the-go sensor technology, the ability to manage individual plants has become much more realistic. The objective of this study was to develop a functional algorithm to estimate corn grain yield of each corn plant from optical sensor measurements, distance between plants, and plant height.

[1] Mention of trademarked instruments does not imply endorsement by authors.

Materials and Methods

This study was conducted at the Stillwater EFAW Research Station (Easpur loam) at Stillwater, OK, and the Lake Carl Blackwell Research Station (Port-oscar silt loam) west of Stillwater, OK, in 2004 and 2005 and at the Hajek farm in Hennessey, OK (Shellabarger sandy loam) in 2004. The Lake Carl Blackwell 2005 site was irrigated (i.e., it received limited supplemental water); the other sites were rainfed. All sites were conventionally tilled with no fertilizer application and had atrazine 4L herbicide (2-chloro-4 ethylamino-6-isopropylamino-s-triazine) applied for preemergence weed control. Plant population, planting dates, and maturities are reported in Table 1 for all sites.

After emergence, four corn rows were randomly chosen from a larger area of 70 to 100 rows at each site. Once a row was selected, the starting point was always >20 m into the row to exclude end row and border effects. Each corn plant was tagged at the base and numbered sequentially from the beginning of each row, and the distance from the front of the row to each plant was measured and recorded. Knowing the location of each plant, the area occupied by each plant was calculated by assuming that each plant occupied half the distance from it to its nearest neighbor (Eq. [3]).

$$D = \left[\frac{d_i - d_{i-1}}{2} + \frac{d_{i+1} - d_i}{2} \right] \quad [3]$$

Where:

D is the linear distance occupied by the ith plant (cm)

d_{i-1}, d_i, *and* d_{i+1} are the distances to the i-1, i, and i+1 plants (cm)

A GreenSeeker sensor was used to collect NDVI measurements for each plant. The sensor used for this study was a reprogrammed version of the commercially available sensor from NTech Industries Inc. (Ukiah, CA). The reprogrammed sensor averaged NDVI measurements when a signal was sent to the sensor. A conventional bicycle was used as the platform because it would both hold the sensor and collect NDVI as a function of distance. An adjustable pole was mounted to the area where the seat was once attached, and the sensor was mounted 38 cm from the center of the pole on a horizontal bar (Fig. 1) to ensure that the bicycle tire was not in the view of the sensor. This allowed the sensor to be adjustable in height (the sensor was consistently set at 92 cm above the crop canopy for this experiment) and positioned directly over the crop canopy while the sensor head remained parallel to the row of corn.

At the beginning and end of each row (the exact location that was used in the measurements prior to sensing), a dull white cardboard strip was placed on the ground perpendicular to the row. When the sensor measured NDVI on the white surface, values were near zero; when the sensor collected values over the soil surface or plant material, values were greater than 0.20. Using this method, the exact start and end point of each row was identified by the NDVI values. The bicycle was then pushed through the field, and NDVI measurements were collected in 1.2-cm increments along the row of corn with a shaft encoder that was installed on the back tire of the bicycle. With each revolution of the bicycle tire, the shaft encoder sent a fixed number of electric pulses to the sensor processor, causing an NDVI value to be sent to a handheld computer for data collection. After data were collected, NDVI values were averaged for each plant on the basis of linear distance calculated using the half distance concept as described in Eq. [3].

Individual plant height was measured from the soil surface to the tip of the uppermost fully developed leaf extended vertically for each plant at the time of sensing. Measurements of these parameters were done at the V8 growth stage (growth stages were identified in accordance with Iowa State University, 1993).

At physiological maturity, each ear(s) from each corn plant was hand harvested, dried at 66° C for 48 h, and weighed before and after shelling. The weight taken from the dry, shelled corn was the final grain weight used for grain yield prediction.

Results and Discussion

Data Quality

When NDVI values were collected every 1.2 cm at the V8 growth stage, NDVI values were expected to define the space between plants by decreasing to NDVI values near 0.2 (NDVI of bare soil background). If these interplant spaces could be defined in this manner, NDVI values from those spaces would not be used for the individual plant analysis. However, as illustrated in Fig. 2, NDVI values did not consistently decrease to define the plant area because of plant proximity and leaf overlap. Therefore, the NDVI data used were based on Eq. [3]. Figure 2 also shows plant location and height. From the level of NDVI around each plant, it is clear that NDVI was influenced more by plant characteristics than by the interplant spaces. Furthermore, statistical analysis of the data presented in Fig. 2 revealed that the regression of plant height and NDVI collected directly above each plant are not related ($P = 0.40$, Proc Reg, SAS Inst., 2007). This supports the conclusion that factors in addition to plant spacing and plant height affect NDVI.

The NDVI data were also collected two times within 10 min on one plot to evaluate the consistency of the individual NDVI measurements in the row (Fig. 3). The relationship of the two lines in Fig. 3 had an R^2 of 0.42 and was statistically significant at all levels of alpha (Proc Reg, SAS Inst., 2007). These data show that the equipment used to collect NDVI in this study was consistent and that positioning of the NDVI values in relation to the plant location was very good.

Yield Prediction

Measurements collected at the V8 growth stage were used to generate grain yield prediction equations, which were evaluated several ways. First, single parameters including NDVI, plant height, and coefficient of variation (CV) of NDVI were used to estimate grain yield. Naturally, these parameters were expected to generate linear or exponential relationships with grain yield; thus, linear and exponential models were tested (Table 2). All single parameters (NDVI, plant height, and CV) were significantly linearly and exponentially related to grain yield but were characterized by low R^2 (Table 2). This showed that multiple parameters were needed to accurately estimate the yield of individual plants. Following methods described by Teal et al. (2006), two new estimators were evaluated as a combination of NDVI and GDD. The DFP INSEY calculation was regressed against grain yield and showed a significant relationship ($P < 0.001$) and an improvement in the R^2 for both linear and exponential models (Table 2). Furthermore, calculating INSEY with cumulative growing degree days (GDD INSEY) was accomplished by using the following equation (Teal et al., 2006):

$$GDD\ INSEY = \frac{NDVI}{GDD} \qquad [4]$$

Where:

GDD INSEY is the in-season estimated yield

Like the DFP INSEY, when GDD INSEY was regressed against grain yield, it produced a significant linear and exponential relationship and further increased the R^2 to 0.22 for both linear and exponential equations (Table 2).

Although there was continual improvement in model strength with the addition of each parameter or combination of parameters, the best model still had a weak relationship (low R^2) with grain yield. This indicated that additional measurements that encompass more plant characteristics needed to be integrated to accurately estimate yield.

Maddonni and Otegui (2004) noted competition between corn plants and that differences in estimated plant biomass between stand densities were detected as early as V6. They reported that plant population and row spacing treatments alone did not modify the onset of the hierarchical growth among plants. Therefore, height was included as a means of assessing this successive competition of the neighboring corn plants in this study. This assumes that the neighboring plants on both sides of the plant in question will compete for resources. Hence, the height of neighboring plants was compared with the height of the plant in question by using the following equation:

$$C_{adj} = \left[\frac{Ht_{pq}}{\left(\left[\frac{Ht_{pq-1}}{(Ht_{pq-2} + Ht_{pq})/2} \right] + \left[\frac{Ht_{pq+1}}{(Ht_{pq} + Ht_{pq+2})/2} \right] \right) / 2} \right] \quad [5]$$

Where:

C_{adj} is the competition adjustment factor for height of the plant in question

Ht_{pq} is the height of the plant in question

Ht_{pq-2}, Ht_{pq-1}, Ht_{pq+1}, and Ht_{pq+2} are the heights of the pq-2, pq-1, pq+1, and pq+2 plants, respectively

In a series of five plants, the heights of plants 2 and 4 are compared with the average height of their neighbors to assess the competitive ability of plants 2 and 4 as compared with that of the plant in question, plant 3. Series of three and seven plants were evaluated in a similar fashion but did not improve yield prediction. The value generated from the first step of this process (weighted average value of plant 2 and 4 in the series) was then compared with the actual height of plant 3, resulting in a weighted comparison of the competitive ability of plant 3 relative to its neighbors. This competition adjustment factor was then used in combination with the linear distance each plant occupied within a row and DFP INSEY to estimate final grain yield by using the following equation:

$$GY_{est} = \frac{\mathrm{C_{adj}}}{\mathrm{D}} \times (DFP\ \mathrm{INSEY}) \qquad [6]$$

Where:

GY_{est} is the estimated grain yield

C_{adj} is the competition adjustment factor generated from Eq. [4]

D is the linear distance occupied by each plant from Eq. [3]

This method of estimating grain yield was significant at all levels of alpha (SAS Inst., 2007) and increased the R^2 to 0.48 (Table 2) for both linear and exponential models (Fig. 4). The resulting equation, which best predicted final grain yield in this study, was:

$$Grain\ Yield = 15083 * GY_{est} + 3315 \qquad [7]$$

Conclusions

Corn production is an integral part of agriculture. The potential benefits, both agronomic and environmental, of predicting corn grain yield on a small scale could be significant. Combining height, distance, and DFP INSEY provided the tools needed to generate such an index.

Teal et al. (2006) was able to predict yield using several methods, none of which included plant height. Because this study targeted a much higher resolution, additional information was needed to predict yield on an individual plant basis, which proved to be successful. However, much more research, particularly on on-the-go height detection, needs to be conducted before this system is ready for implementation in the field. The improved integration of NDVI, height, and distance between plants must continue before an automated system can be implemented.

A specific yield prediction equation was an important outcome of this study; it indicates that by-plant yields could be predicted from mid-season sensing, distance between plants, and plant height. An estimate of plant competition based on five-plant sequences was also needed to refine by-plant yield prediction.

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Figure 3. NDVI of one row of corn collected two times to illustrate consistency of high-resolution NDVI data collection.

Figure 4. By-plant prediction of corn grain yield using optical sensor readings and measured plant height.

Table 1. Planting date, plant population, and days to maturity of corn at each location in 2004 and 2005.

Location	Planting date	Plant population (plants ha^{-1})	Maturity
EFAW, OK	7 Apr. 2004	68000	108 d
EFAW, OK	7 Apr. 2004	37000	108 d
Lake Carl Blackwell, OK	3 Apr. 2004	60000	108 d
Lake Carl Blackwell, OK	3 Apr. 2004	36000	108 d
Hennessey, OK	27 Apr. 2004	36000	113 d
EFAW, OK	7 Apr. 2005	57000	108 d
Lake Carl Blackwell, OK	18 Apr. 2005	70000	108 d

Table 2. Relationship between grain yield and plant parameters collected at the V8 growth stage in corn over all locations and years fitted to both linear and exponential models (SAS Inst., 2007). All models were highly significant ($P < 0.001$).

	Linear		Exponential	
Parameter (X)	Equation	R^2	Equation	R^2
NDVI	$Y = 2781 + 8164*X$	0.07	$Y = 17865 - 44848X + 44310X^2$	0.11
CV	$Y = 10079 - 87 *X$	0.03	$Y = 11725 - 342X + 7X^2$	0.06
Height	$Y = 4005 + 35 *X$	0.06	$Y = 3361 + 45X - 0.0X^2$	0.06
INSEY DFP	$Y = 935 + 539010 *X$	0.16	$Y = 5563 - 223015X + 29582341X^2$	0.17
GDD INSEY	$Y = 1056 + 8485808 *X$	0.22	$Y = 1186 + 8145520X + 207864841X^2$	0.22
GY_{est}	$Y = 3315 + 15083 *X$	0.48	$Y = 2857 + 18746X - 3345X^2$	0.48

NDVI, normalized difference vevetation index; CV, coefficient of variation; INSEY DFP, in-season estimated yield using days from planting; GDD INSEY, in-season estimated yield using cumulative growing degree days; GY_{est}, grain yield estimate.

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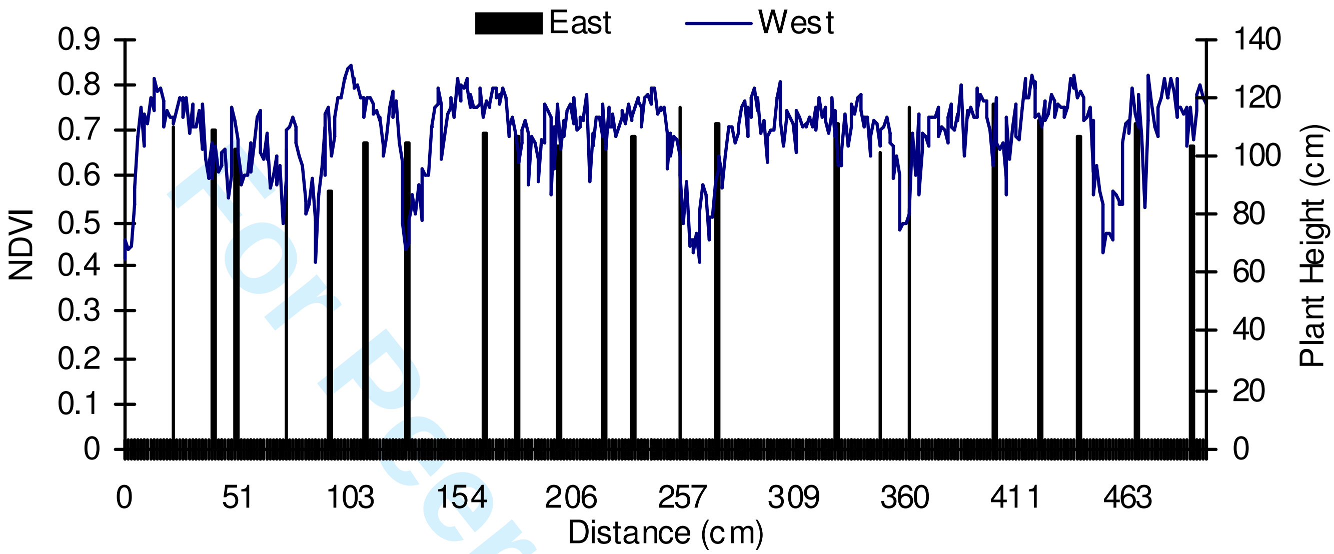

Figure 3. NDVI from one row of corn collected two times to illustrate consistency of high-resolution NDVI data

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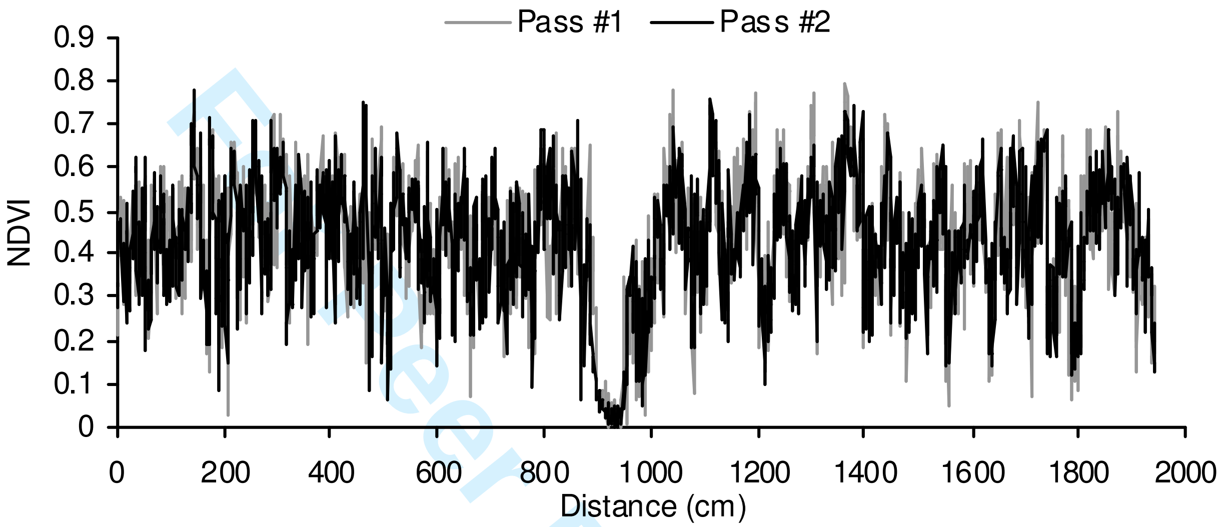

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