In-Season Prediction of Corn Grain Yield Potential Using Normalized Difference Vegetation Index

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ABSTRACT

Drastic increases in the cost of N fertilizer and increased public scrutiny have encouraged development and implementation of improved N management practices. This study evaluated the relationship between corn (*Zea mays* L.) grain yield and early season normalized difference vegetation index (NDVI) sensor readings using the GreenSeeker sensor. The relationships between grain yield and several predictor variables were determined using linear and nonlinear regression analysis. Categorizing NDVI measurement by leaf stage indicated that growth stage was critical for predicting grain yield potential. Poor exponential relationships existed between NDVI from early sensor measurements (V6–V7 leaf stage) and grain yield. By the V8 stage, a strong relationship (R^2 = 0.77) was achieved between NDVI and grain yield. Later sensor measurements (V9 and later) failed to distinguish variation in green biomass as a result of canopy closure. Normalizing the NDVI with GDD (growing degree days) did not significantly improve yield potential prediction (R^2 = 0.73), but broadened the yield potential prediction equation to include temperature and allowed for adaptation into various climates. Sensor measurements at the range of 800 to 1000 GDD resulted in a significant exponential relationship between grain yield and NDVI (R^2 = 0.76) similar to the V8 leaf stage categorization. Categorizing NDVI by GDD (800–1000 GDD) extended the sensing time by two additional leaf stages (V7–V9) to allow a practical window of opportunity for sidedress N applications. This study showed that yield potential in corn could be accurately predicted in season with NDVI measured with the GreenSeeker sensor.

NITROGEN is well documented as a limiting nutrient in crop production and is considered one of the best producer inputs to increase profitability under an appropriate management system. In 2003, about 11.5 million t of N fertilizer were applied to 96% of the total corn acreage in the Great Plains (National Agricultural Statistics Service, 2005). With the present 33% average NUE (N use efficiency) in world cereal crop production (Raun and Johnson, 1999), >6.7 million t of N fertilizer would have been expected to be lost to the environment in the Great Plains for the 2003 crop year at a cost of US$2.3 billion. Improved N management is essential to maintain producers' income and diminish environmental degradation.

Traditionally, N application rates have been made based on grain yield goals determined from a recent 5-yr crop yield average increased typically by 10 to 30% to assure adequate N for above-average growing conditions (Johnson, 1991; Dahnke et al., 1988). Dahnke et al. (1988) defined yield goal as the "yield per acre you hope to grow". Setting unrealistic yield goals and not accounting for yield variation between fields and within a field, however, has led to consistent, excessive N application. As a result, some fields have enough inorganic N in the soil in semiarid regions to supply adequate N for multiple years of cereal crop production. Given the fluctuation of growing conditions annually, the yield goal may vary from past average yield to potential yield (Dahnke et al., 1988).

Several studies improved the use of yield goal in N decision management by taking into account the soil NO_3 level (Johnson et al., 1997). Recommendation guidelines are to apply 33 kg N ha^{-1} for every 1 Mg of wheat (*Triticum aestivum* L., Johnson et al., 1997) and 20 kg N ha^{-1} for every 1 Mg of corn (Schmitt et al., 1998), subtracting the soil NO_3 level. Further research showed that the percentage increase in grain yield goal above the 5-yr average should be based on either the available soil moisture at planting (Rehm and Schmitt, 1989) or the sum of this soil moisture plus the anticipated growing season precipitation (Black and Bauer, 1988) determined at planting. The environment, however, is not controlled by a single growth factor but rather compounded effects of soil fertility, climate, and inputs.

Additional research has focused on determining in-season N need by adjusting either yield goal or N availability. Other research has used PSNT (presidedress soil NO_3 tests) as an indication of available mineralized N and setting N application limits based on NO_3 levels in the soil (Magdoff et al., 1984; Durieux et al., 1995; Spellman et al., 1996). While the PSNT method increased NUE, consistent results were not obtained since sidedress N applications were not adjusted for fluctuating environmental conditions affecting yield goals. In-season N management was developed using chlorophyll meters (SPAD meters) to determine N need based on an N sufficiency index [(as-needed treatment/well-fertilized treatment)100], where N application was recommended when the index value dropped under 95% (Blackmer and Schepers, 1995; Varvel et al., 1997). Indirect in-season chlorophyll content measurement has been successful in determining N need due to the high correlation between chlorophyll content and leaf N concentration (Wolfe et al., 1988; Schepers et al., 1992). A drawback of chlorophyll meter sampling for determining N need is that plant-to-plant variation can range up to 15% (Peterson et al., 1993), requiring many measurements to obtain a representative average. Such N recommendations are similar in principle to the PSNT

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Abbreviations: DFP, days from planting; GDD, growing degree days; INSEY, in-season estimated yield; NDVI, normalized difference vegetation index; NUE, nitrogen use efficiency.

method where N recommendations are based on soil N concentration alone with no consideration of yield potential.

Another approach to improving NUE is to adjust the yield goal midseason by determining yield potential. Johnson (1991) defined yield potential of a crop as a function of the growing condition in the field. Raun et al. (2001) established a nondestructive estimation of yield potential using spectral measurements in winter wheat based on the concept developed by Tucker (1979). This NDVI is highly correlated with total aboveground biomass. Raun et al. (2001) identified critical growth stages between Feekes 4 and 6 at which yield potential could be predicted as a result of the strong relationship between NDVI and grain yield. They further improved the relationship between NDVI and grain yield by normalizing the NDVI. This was done by dividing it by the number of days with average temperatures >4.4°C from planting to sensing (Lukina et al., 2001). Such days are when growth is possible. In-season estimated yield (INSEY), the acronym given to NDVI normalized by the number of days with growth, predicts biomass produced per day of positive growth. In six out of nine locations during a 2-yr period, a strong relationship existed between wheat grain yield and INSEY, with a coefficient of determination of 83% (Raun et al., 2001).

In developing an algorithm for topdress N application in wheat, Raun et al. (2002) combined midseason yield potential prediction, N response using INSEY, and a response index. This response index is calculated by dividing NDVI from a nonlimiting-N strip by NDVI from a parallel strip that represents N availability across the field (Mullen et al., 2003). When combining both midseason yield potential and N response, the NUE of wheat was increased by >15% (Raun et al., 2002). After further evaluation, Raun et al. (2005) reported that the opportunity still existed for their yield potential prediction model to over- or underestimate yield potential. In addition, they stated that to correctly predict yield potential, models should be fitted to grain yields not influenced by adverse conditions from sensing to harvest. Therefore, Raun et al. (2005) adjusted the constant a within their exponential model [$y = a\exp(bx)$] so that the number of observations above the curve was 32% of the total data points. The adjusted curve ($YP_0 + 1$ standard deviation) represented the attainable yield potential in rainfed winter wheat from midseason (February) to harvest based on 6 yr of data collected from 30 sites.

Success of this technology initiated the development of algorithms for other equally important crops such as corn. This study was conducted to determine the most effective growth stages to predict grain yield potential and establish an equation to predict corn yield potential generated from actual yield and early season NDVI measurements.

MATERIALS AND METHODS

Statistical analysis was conducted on experimental data from 21 existing field trials throughout Oklahoma from 2002 to 2005. Soil descriptions for each location are as follow: Eastern Oklahoma Research Station (near Haskell, OK), Taloka silt loam (fine, mixed, active, thermic Mollic Albaqualf); Efaw Research Agronomy Research Farm (Stillwater, OK), Easpur loam (fine-loamy, mixed, superactive, thermic Fluventic Haplustoll); Lake Carl Blackwell Agronomy Research Farm (near Stillwater, OK), Pulaski fine sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvent); and Perkins, Teller sandy loam (fine-loamy, mixed, active, thermic Udic Argiustoll).

All field trials used a randomized complete block design with three replications except for the by-row experiments, which consisted of four random rows, 30 m in length. The other trials' plot size measured 3.0 by 6.1 m and 3.0 by 9.1 m; however, all trials were planted in conventional tillage with 0.76-m row spacing. Each experiment had different specific goals but the same objective of improving NUE. Plots that received only preplant N applications were selected from the different trials for yield potential prediction. Additional experiment information is reported in Table 1.

Using the GreenSeeker hand-held sensor (Ntech Industries, Ukiah, CA), NDVI values were collected from growth stages V6 to V11 with the sensor nadir to the ground and ~0.70 m above the crop canopy. Leaf stage with the corresponding DFP (days from planting) and GDD base 10°C since planting are summarized for all sites in Table 2. As an index used to estimate green biomass (Tucker 1979), NDVI was computed as

$$\mathrm{NDVI} = \frac{\rho\mathrm{NIR} - \rho\mathrm{Red}}{\rho\mathrm{NIR} + \rho\mathrm{Red}}$$

where ρNIR is the fraction of emitted NIR radiation returned from the sensed area (reflectance) and ρRed is the fraction of emitted red radiation returned from the sensed area (reflectance).

The majority of the trials were mechanically harvested with a Massey Ferguson 8XP experimental combine and the rest were harvested by hand (Table 1). The experimental combine method consisted of harvesting the two center rows from each plot using a yield-monitoring computer (HarvestMaster, Juniper Systems, Logan, UT) installed on the combine to record grain weight and moisture levels. Corn grain harvested by hand consisted of picking and shucking the two center rows (or a single row for the by-row trials) of each plot separately and recording the total ear weight for each row. From each row, four random ears were collectively weighed, dried in a forced air oven at 66°C, and weighed again to determine moisture levels. The four ears were then shelled using a hand-crank corn sheller (Root-Healey Manufacturing Co., Plymouth, OH) and the grain weight was taken to determine an average grain weight percentage for each row. Finally, grain yield for both harvest methods was determined by adjusting grain weight to 15.5% moisture.

Linear and nonlinear regression models were used to determine the relationships between grain yield and NDVI using Procedures in SAS (SAS Institute, 2002). In addition, an INSEY equation for yield potential prediction was established similar to Raun et al. (2002). Two of the indices evaluated had relatively high combined R^2 values. The DFP INSEY (Raun et al., unpublished data, 2004), was calculated as

$$\mathrm{DFP\ INSEY} = \frac{\mathrm{NDVI}}{\mathrm{DFP}}$$

where DFP includes all days from planting to sensing.

In addition, the GDD INSEY was calculated as

$$\mathrm{GDD\ INSEY} = \frac{\mathrm{NDVI}}{\mathrm{GDD}}$$

Table 1. Field trial information for all experiments evaluated for predicting yield potential, 2002 through 2005.

Experiment†	Location‡	Year	Hybrid relative maturity	Planting date	Harvest date	Harvest method§
OFIT	LCB, OK	2005	113-d	12 Apr.	7 Sept.	combine
OFIT	Efaw, OK	2005	113-d	30 Mar.	27 Aug.	combine
OFIT	Perkins, OK	2005	110-d	28 Mar.	31 Aug.	combine
OFIT	Efaw, OK	2004	113-d	7 Apr.	3 Sept.	combine
OFIT	Perkins, OK	2004	108-d	2 Apr.	1 Sept.	combine
Regional	LCB, OK	2005	113-d¶	15 Apr.	13 Sept.	combine
Catchup	LCB, OK	2005	113-d	12 Apr.	7 Sept.	combine
Catchup	Efaw, OK	2005	113-d	30 Mar.	27 Aug.	combine
Catchup	Haskell, OK	2005	113-d	4 Apr.	28 Aug.	combine
N rate	Haskell, OK	2005	113-d	4 Apr.	28 Aug.	by hand
N rate	LCB, OK	2005	113-d	12 Apr.	14 Sept.	by hand
YP_0	Haskell, OK	2002	105-d 109-d 113-d	18 Apr.	11 Sept.	combine
YP_0	Haskell, OK	2003	104-d 107-d 111-d	3 Apr.	20 Aug.	combine
YP_0	Haskell, OK	2004	99-d 113-d	1 Apr.	31 Aug.	by hand
YP_0	LCB, OK	2002	105-d 109-d 113-d	23 Apr.	28 Aug.	combine
YP_0	LCB, OK	2003	104-d 107-d 111-d	1 Apr.	7 Aug.	combine
YP_0	LCB, OK	2004	99-d 113-d	3 Apr.	28 Aug.	by hand
By-row	Efaw, OK	2003	107-d	31 Mar.	12 Aug.	by hand
By-row	Efaw, OK	2004	113-d	7 Apr.	25 Aug.	by hand
By-row	LCB, OK	2003	111-d	8 Apr.	5 Aug.	by hand
By-row	LCB, OK	2004	113-d	3 Apr.	16 Aug.	by hand

† Standard plot sizes = 3.0 by 6.1 m or 3.0 by 9.1 m; by-row plot size = 1 row by 30 m.
‡ LCB = Lake Carl Blackwell, near Stillwater, OK; Efaw, Efaw Research Agronomy Research Farm near Stillwater, OK.
§ Combine = center two rows harvested with a Massey Ferguson 8XP experimental combine; by hand = center two rows harvested by hand.
¶ Two hybrids of the same maturity evaluated.

where GDD is cumulative growing degree daysfrom planting to sensing and calculated using the "optimum day method" (Barger, 1969). The "optimum day method" was calculated as

$$\mathrm{GDD} = \frac{T_{\max} + T_{\min}}{2} - 10°\mathrm{C}$$

where $T_{\max}$ and $T_{\min}$ denote minimum and maximum temperature, respectively.

The equation resulting from the best line that described the relationship between actual corn grain yield and INSEY (both DFP INSEY and GDD INSEY) was fitted and the equation was used for predicting the yield potential for corn. Also, the yield potential plus one standard deviation method

Table 2. Days from planting (DFP) and cumulative growing degree days (GDD)† categorized by leaf stage‡, 2002 through 2005.

		V6		V7		V8		V9		V10–V11	
Experiment§	Year	DFP	GDD	DFP	GDD	DFP	GDD	DFP	GDD	DFP	GDD
		d		d		d		d		d	
LCB, OK OFIT	2005	37	521	46	732	50	809	53	880		
Efaw, OK OFIT	2005	49	674	52	753	54	808	62	975	69	1107
Perkins, OK, OFIT	2005	56	836	65	1026	68	1028			78	1309
Efaw, OK, OFIT	2004					56	954				
Perkins, OK, OFIT	2004					62	1059				
LCB, OK, Regional	2005	43	703	47	779	49	823				
LCB, OK, Catchup	2005	37	521	46	732	50	809	53	880		
Efaw, OK, Catchup	2005	49	674	52	753	54	808	62	975	69	1107
Haskell, OK, Catchup	2005					59	893			66	1060
Haskell, OK, N rate	2005					59	893			66	1060
LCB, OK, N rate	2005	37	521	46	732	50	809	53	880		
Haskell, OK, YP0	2002							62	1207		
Haskell, OK, YP0	2003	50	775	54	835	58	920			65	1047
Haskell, OK, YP0	2004	52	792			57	920	61	1010		
LCB, OK, YP0	2002					53	952				
LCB, OK, YP0	2003	51	765	54	814	63	987			68	1067
LCB, OK, YP0	2004	46	658	51	798	57	951	60	1015		
Efaw, OK, by-row	2003	39	576			52	998			63	1006
Efaw, OK, by-row	2004	40	621			44	733			49	865
LCB, OK, by-row	2003	43	765			58	1032			66	1201
LCB, OK, by-row	2004	47	714			55	924			67	1196

† GDD calculated = [(maximum daily temperature + minimum daily temperature)/2] – 10°C, with bases of 10°C and 30°C for minimum and maximum temperatures.
‡ Vegetative growth stages (V#) determined by number of collared leaves.
§ LCB = Lake Carl Blackwell, near Stillwater, OK; Efaw, Efaw Research Agronomy Research Farm near Stillwater, OK.

Table 3. Relationship between grain yield and NDVI (normalized difference vegetation index) by leaf stage and GDD (growing degree day) fitted to an exponential regression model, 2002 through 2005. All models were highly significant ($P < 0.001$).

	R^2		
Parameter	**NDVI†**	**DFP INSEY‡**	**GDD INSEY§**
Leaf stage¶			
V6	**0.22**	**0.29**	**0.34**
V7	**0.09**	**0.19**	**0.16**
V8	**0.77**	**0.74**	**0.73**
V9	**0.22**	**0.31**	**0.60**
V10–V11	**0.40**	**0.43**	**0.40**
GDD range			
500–674	**0.33**		**0.33**
675–799	**0.31**		**0.26**
800–1000	**0.76**		**0.75**
1000	**0.16**		**0.32**

† NDVI = (ρNIR – ρRed)/(ρNIR + ρRed), where ρNIR is the fraction of emitted near-infrared radiation returned from the sensed area (reflectance) and ρRed is the fraction of emitted red radiation returned from the sensed area (reflectance).

‡ DFP INSEY = days from planting in-season estimated yield, calculated as NDVI/DFP.

§ GDD INSEY = growing degree day in-season estimate yield, calculated as NDVI/GDD, where GDD is calculated as (maximum daily temperature + minimum daily temperature)/2) – 10°C, with bases of 10°C and 30°C for minimum and maximum temperatures.

¶ Vegetative growth stages determined by number of collared leaves.

(Raun et al., 2005) was used to develop a measurement of yield potential unaffected by adverse environmental conditions.

RESULTS AND DISCUSSION

Growth stage was a major factor in predicting yield potential. Regression analysis showed that weak exponential relationships occurred between NDVI and grain yield when sensor measurements were categorized by leaf stage from six to seven leaves (Table 3). This was probably a result of the yield potential still developing after NDVI measurement. However, a strong relationship between yield and NDVI was achieved at V8 (Fig. 1), with an R^2 value of 0.77. Later sensor measurement (V9 and later) relationships with grain yield were similar to earlier (before V8) comparisons, where yield potential was not accurately determined (Table 3). As noted by Teal et al. (unpublished data, 2006), due to canopy closure influence on the sensor field of view, the later NDVI readings were unable to distinguish variation, similar to research findings for other remote sensing techniques measuring NDVI (Viña et al., 2004).

Varvel et al. (1997) reported that maximum grain yields in corn could not be realized due to lost yield potential when severe N deficiencies occurred at V8; however, Scharf et al. (2002) found that N applications (no preplant N) could be delayed as late as V11 with no yield loss and only minor yield loss (~3%) when N sidedress was delayed until V12 to V16. Other recent work showed that when preplant N applications (90 kg N ha^{-1}) were applied, maximum yield levels could still be obtained when sidedress was delayed until V10, but delaying sidedress N applications further (VT) or not applying preplant N to responsive sites reduced grain yield (O. Walsh, personal communication, 2006). While the effects of delayed N application on grain yield are highly dependent on available mineralized N and plant demand, this research clearly indicates that predicting the yield potential at V8 is highly desirable for maximum effectiveness of sidedress N application.

As a method of normalizing NDVI measurements across various environmental conditions, the DFP INSEY was used in the initial corn yield prediction equation. The DFP INSEY estimated average biomass produced per day as the determinant of yield prediction. Normalizing the NDVI by DFP and GDD generally improved the yield potential prediction model at most leaf stages (Table 3), but not at V8 (Fig. 2 and 3). Generally, the GGD INSEY model had higher coefficients of determination than the DFP INSEY model, although not significant at most leaf stages (Table 3).

As shown above, sensing time was critical in predicting yield potential; however, trials evaluated in this

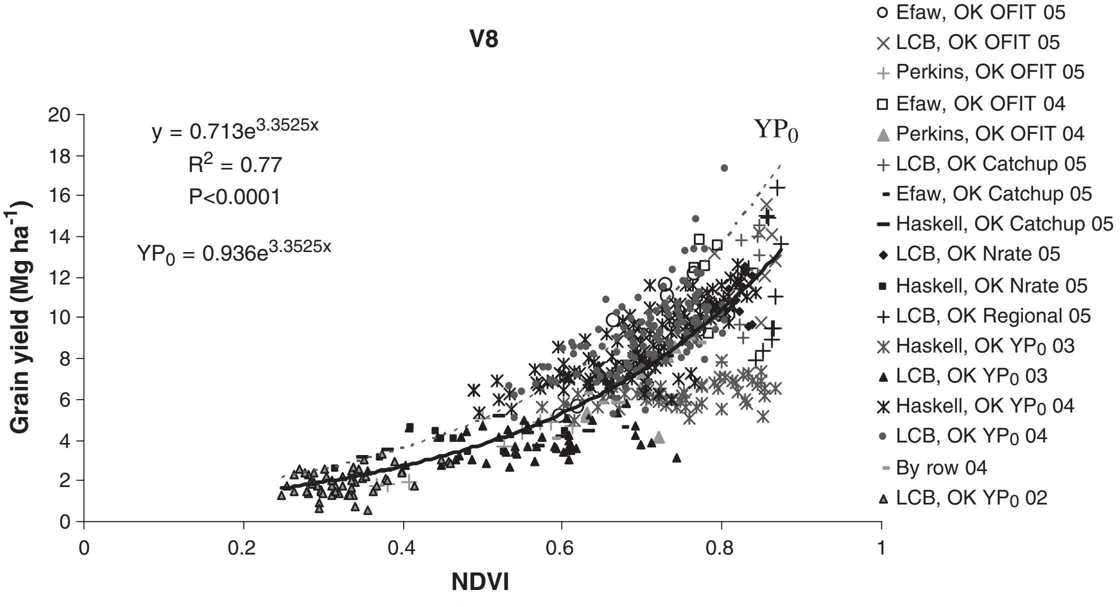

Fig. 1. Relationship between grain yield and NDVI (normalized difference vegetation index) from V8 sensor measurements for 4 yr and 17 locations, 2002 through 2005. YP$_0$ = yield potential; YP$_0$ calculated = mean + one standard deviation.

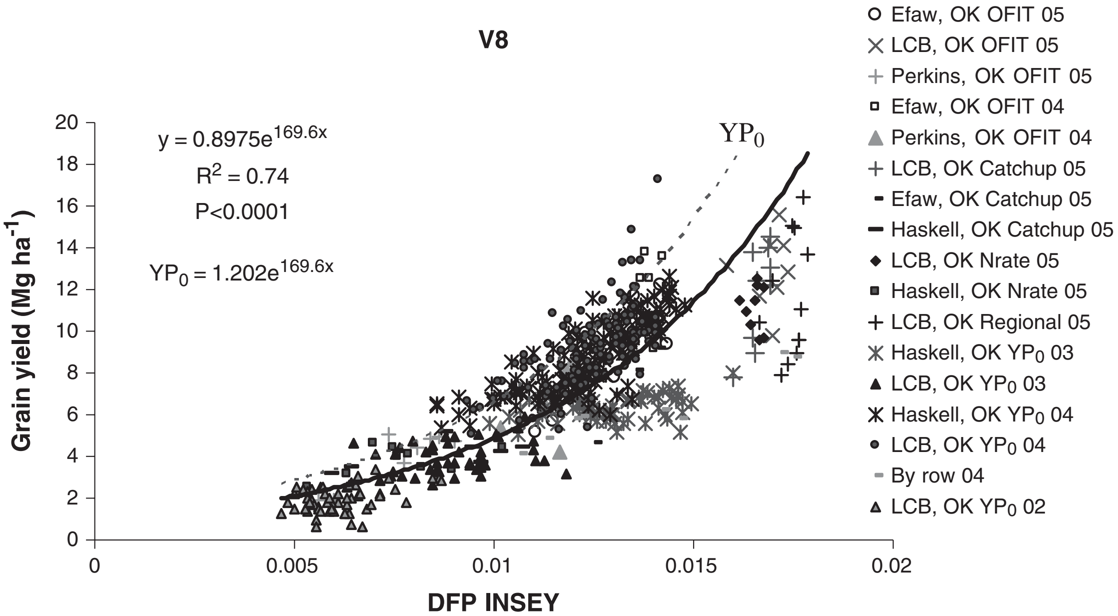

Fig. 2. Relationship between grain yield and DFP INSEY (degrees from planting in-season estimated yield) from V8 growth stage sensor measurements for 4 yr and 17 locations, 2002 through 2005. YP_0 = yield potential; YP_0 calculated = mean + one standard deviation.

study showed DFP to the V8 growth stage and the corresponding GDD varied considerably (Table 2). As a result, setting ranges to identify the leaf stage with these values may not be viable. Temperature has been well documented as the primary factor governing the rate of leaf appearance in corn (Berbecel and Eftimescu, 1972; Coelho and Dale, 1980; Warrington and Kanemasu, 1983). Berbecel and Eftimescu (1972) went further to state that moisture stress reduced the length of the internodes between leaves, but had little effect on the number of leaves set. Swan et al. (1987) reported that no-till production requires greater GDD to reach V6 than conventional tillage, indicating that additional variables are present that influence crop growth and the consistency of GDD at a growth stage. Although the NDVI and DFP INSEY yield potential prediction equations were effective, given that GDD is a measurement of temperature and NDVI is a measurement of green biomass, the use of GDD INSEY should normalize NDVI more consistently across various field conditions and climates.

The equation from the GDD INSEY relationship at V8 can be used to predict corn yield potential; however, there is a narrow range of sensing time at this particular leaf stage. According to our results, the sensing time range at V8 leaf stage falls within 3 to 8 d before reaching leaf stage V9. The duration of the V8 leaf stage varies depending on the growing conditions and there will be a risk

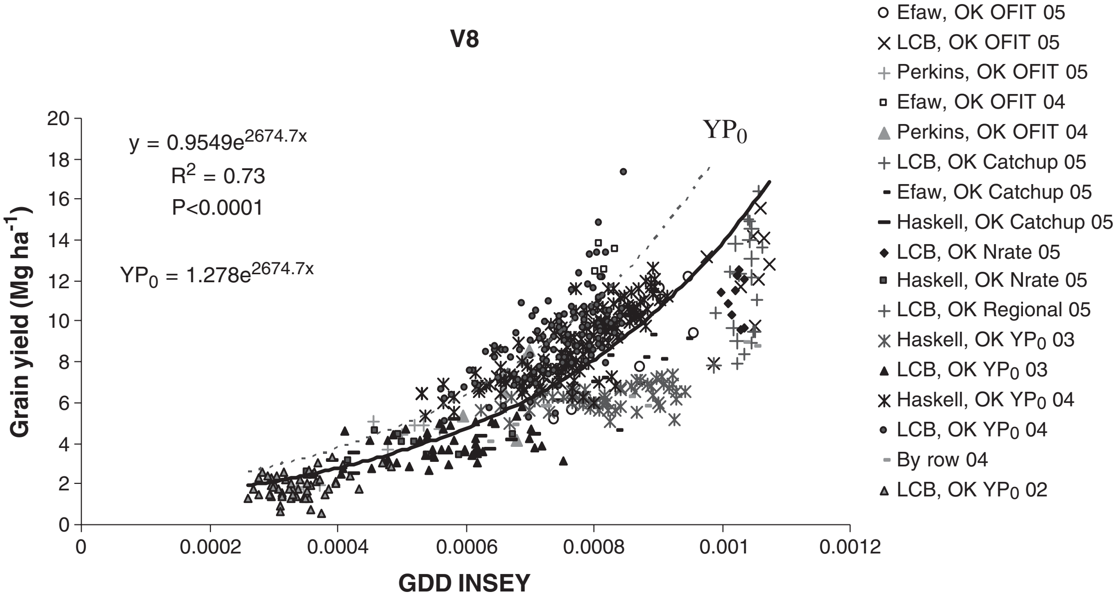

Fig. 3. Relationship between grain yield and GDD INSEY (growing degree day in-season yield potential) from V8 growth stage sensor measurements for 4 yr and 17 locations, 2002 through 2005. YP_0 = yield potential; YP_0 calculated = mean + one standard deviation.

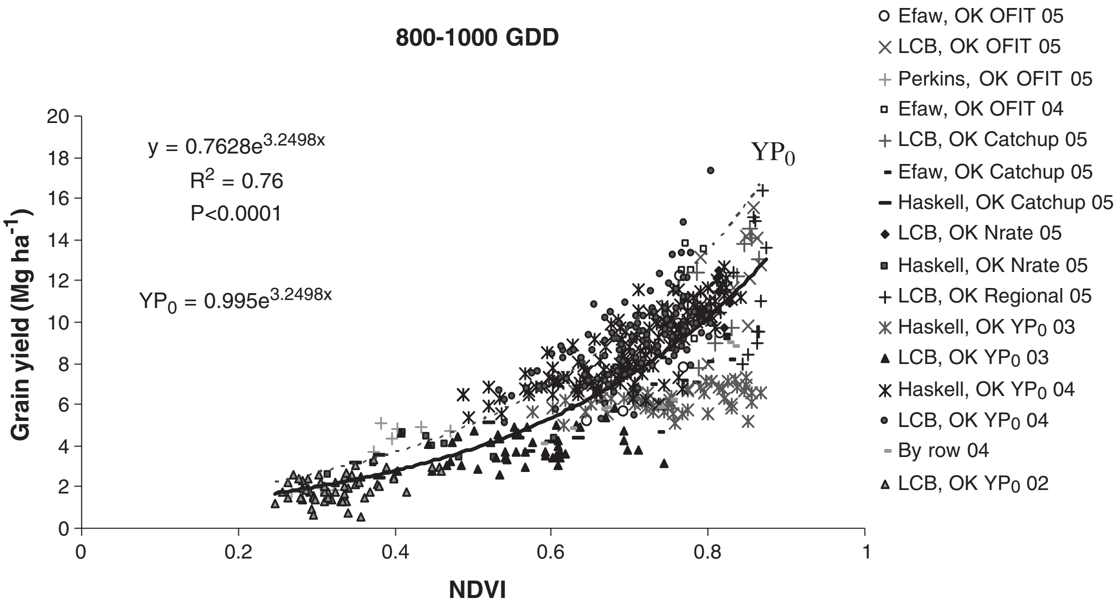

Fig. 4. Relationship between grain yield and NDVI (normalized difference vegetation index) from sensor measurements ranging from 800 to 1000 GDD (growing degree days) for 4 yr and 17 locations, 2002 through 2005. YP_0 = yield potential; YP_0 calculated = mean + one standard deviation.

of failing to measure NDVI within this leaf stage as a result of unavoidable circumstances such as bad weather. To address this limitation, sensor measurements were categorized by GDD. This approach used absolute values to create the category before identifying at which GDD range the best relationship between actual yield and GDD INSEY could be drawn. Further, GDD can be predetermined by DFP, providing a rough indication when sensing time based on GDD is approaching.

Similar to categorizing sensor measurements by leaf stage, regression analysis showed weak exponential relationships between NDVI and grain yield when sensor measurements were categorized by GDD ranging from 500 to 799 (Table 3). The NDVI measurements that fall between 800 and 1000 GDD and corresponding grain yields had a significant exponential relationship (Fig. 4), similar to V8 from the leaf stage category (Fig. 3). Note that this GDD range includes data from V7 to V9 growth stages (Table 2). The exponential relationship implies that 76% of the variation in actual grain yield can be explained by NDVI measured and grain yield then can be computed using the equation: grain yield = 0.76exp(3.2498NDVI). Later sensor measurement (>1000 GDD) relationships with grain yield were similar to the earlier (<800 GDD) comparisons, where yield potential was not accurately determined (Table 3).

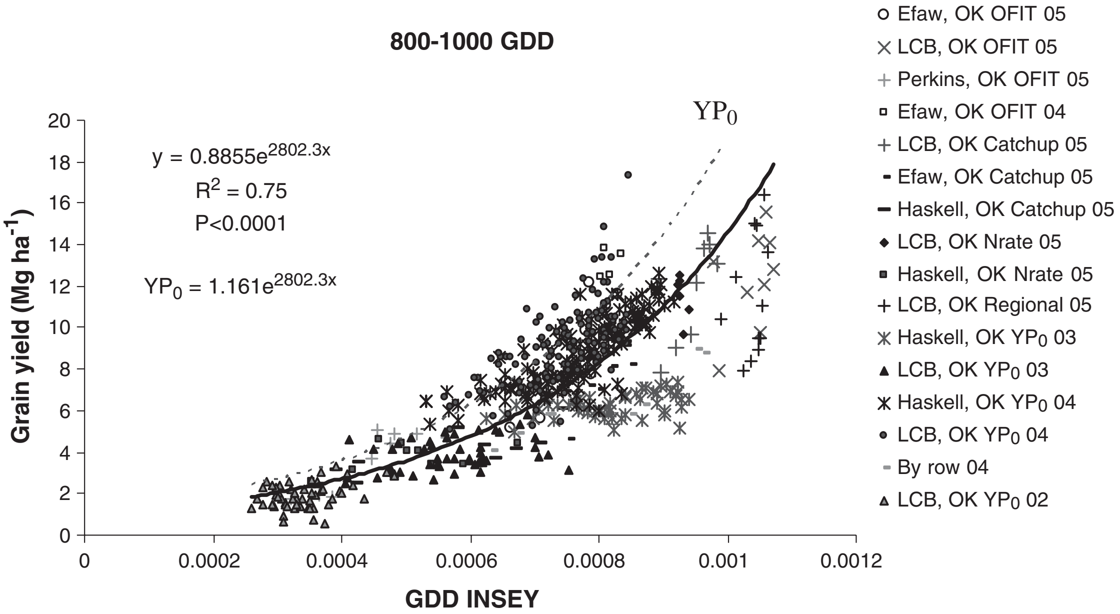

Fig. 5. Relationship between grain yield and GDD INSEY (growing degree day in-season yield potential) from sensor measurements ranging from 800 to 1000 GDD for 4 yr and 17 locations, 2002 through 2005. YP_0 = yield potential; YP_0 calculated = mean + one standard deviation.

Using GDD INSEY in the yield prediction model did not significantly improve the relationship ($R^2 = 0.75$) with grain yield (Fig. 5), but gives an additional factor to normalize the data for ambient temperature. Categorizing the sensor measurements by GDD actually improved the relationship between grain yield and GDD INSEY ($R^2 = 0.73$–0.75) over the leaf stage method, but moreover extended viable yield potential prediction two leaf stages, broadening the critical sensing window to a practical time frame.

CONCLUSIONS

Corn grain yield potential was predicted to within 23% using NDVI at the V8 growth stage for 4 yr of data. Categorizing sensor data by GDD, however, while not improving the accuracy of yield potential prediction with NDVI, extended the critical sensing window two leaf stages. Normalizing NDVI with GDD (using GDD INSEY) did not significantly improve yield potential prediction, but broadened the yield potential prediction equation to include temperature and allowed for adaptation to various climates. Exponential equations accurately defining the relationship between GDD INSEY and actual grain yield were established at V8 ($R^2 = 0.73$) and for GDD ranging from 800 to 1000 GDD ($R^2 = 0.75$). Both equations were capable of approximating corn yield potential at the same level of accuracy except that categorizing sensor data by GDD offered an advantage by extending the critical sensing window two additional leaf stages (V7–V9) and gave an absolute value to determine proper sensing time when using the GreenSeeker sensor.

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