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In-Season Prediction of Potential Grain Yield in Winter Wheat Using Canopy Reflectance

William R. Raun,* John B. Solie, Gordon V. Johnson, Marvin L. Stone, Erna V. Lukina,
Wade E. Thomason, and James S. Schepers

ABSTRACT

Nitrogen fertilization rates in cereal production systems are generally determined by subtracting soil test N from a specified N requirement based on the grain yield goal, which represents the best achievable grain yield in the last 4 to 5 yr. If grain yield could be predicted in season, topdress N rates could be adjusted based on projected N removal. Our study was conducted to determine if the potential grain yield of winter wheat (*Triticum aestivum* L.) could be predicted using in-season spectral measurements collected between January and March. The normalized difference vegetation index (NDVI) was determined from reflectance measurements under daytime lighting in the red and near-infrared (NIR) regions of the spectra. In-season estimated yield (EY) was computed using the sum of two postdormancy NDVI measurements (Jan. and Mar.) divided by the cumulative growing degree days (GDD) from the first to second reading. A significant relationship between grain yield and EY was observed ($R^2 = 0.50$, $P > 0.0001$) when combining all nine locations across a 2-yr period. Our estimates of potential grain yield (made in early Mar.) differed from measured grain yield (mid-July) at three sites where yield-altering factors (e.g., late summer rains delayed harvest and increased grain yield loss due to lodging and shattering) were encountered after the final sensing. Evaluating data from six of the nine locations across a 2-yr period, EY values explained 83% of the variability in measured grain yield. Use of EY may assist in refining in-season application of fertilizer N based on predicted potential grain yield.

Historically, grain yield goals have been the most reliable method available for estimating preplant fertilizer N rates. Recent advancements in weather forecasting and crop modeling have enabled the development of technologies for predicting potential grain yields, and thus have allowed for in-season nutrient adjustments to reflect early crop development and growing conditions.

Yield Goals

Crop grain yield may be expressed simply as a function of all conditions of the growing environment, or growth factors, and any preconceived yield goal or limit set by management. In dryland agriculture, it is usually advantageous to set the grain yield goal above that of average yields to fully take advantage of above-average growing conditions (Johnson, 1991). A yield goal was defined by Dahnke et al. (1988) as the "yield per acre you hope to grow." They further noted that what you hope to grow and what you end up with are two different things. Yield goals can vary all the way from past average yield to potential yield (Dahnke et al., 1988). The authors defined potential grain yield as the highest possible yield obtainable with ideal management, soil, and weather. In our work, what they define as potential grain yield would be maximum grain yield because *potential* yield is associated with specific soil and weather conditions that can change annually. For most farmers, North Dakota State University recommends that the grain yield goal is the highest yield attained in the last 4 to 5 yr and is usually 30 to 33% higher than the average yield (R.J. Goos, personal communication, 1998).

Rehm and Schmitt (1989) noted that with favorable soil moisture at planting, it would be smart to aim for a 10 to 20% increase over the recent average when selecting a grain yield goal. They also indicated that if soil moisture is limiting, the use of history and past maximums (used to generate avg.) may not be the best method for setting a grain yield goal for the upcoming crop. The use of farm or county averages was not suggested for progressive farmers concerned with high farm profitability (Rehm and Schmitt, 1989).

Black and Bauer (1988) reported that the grain yield goal should be based on how much water is available to the winter wheat crop from stored soil water to a depth of 1.5 m in the spring plus the anticipated amount of growing-season precipitation. An estimation the N

W.R. Raun, G.V. Johnson, E.V. Lukina, and W.E. Thomason, Dep. of Plant and Soil Sci., Oklahoma State Univ., Stillwater, OK 74078; J.B. Solie and M.L. Stone, Dep. of Biosystems and Agric. Eng., Oklahoma State Univ., Stillwater, OK 74078; and J.S. Schepers, USDA-ARS, Lincoln, NE 68583. Contribution of the Oklahoma Agric. Exp. Stn. Received 19 Jan. 2000. *Corresponding author (wrr@mail.pss.okstate.edu).

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Abbreviations: EY, in-season estimated yield; GDD, growing degree days; NDVI, normalized difference vegetation index; NIR, near infrared; PPNT, preplant NO_3 test; PSNT, presidedress NO_3 test.

fertilization requirements can be achieved by combining the grain yield goal, soil test NO_3–N, and a simple estimate of the N use efficiency. Several states recommend that farmers apply 33 kg N ha^{-1} for every 1 Mg of wheat (2 lb N acre^{-1} for every bushel of wheat) they hope to produce, minus the amount of NO_3–N in the surface (0–15 cm) soil profile (Johnson et al., 1997). Therefore, when grain yield goals are applied, it explicitly places the risk of predicting the environment (good or bad year) on the producer. University extension (e.g., soil testing), fertilizer dealers, and private consulting organizations have historically used grain yield goals due to the lack of a better alternative.

In-Season Soil Testing

Initial work by Magdoff et al. (1984) evaluated the use of an in-season NO_3–N soil test for corn (*Zea mays* L.) by sampling soils to 30 cm when plants are 15 to 30 cm tall. This test, which was later referred to as the presidedress NO_3 test (PSNT), was useful for predicting N needs in the northeastern portions of the USA. The benefits of PSNT over yield goals to recommend N for corn was shown by Durieux et al. (1995) where less N was applied with no reduction in grain yield. Sims et al. (1995) indicated that the leaf chlorophyll meter could be an alternative to the PSNT for refining in-season fertilizer N requirements in corn. Spellman et al. (1996) showed that the critical PSNT ranged between 13 and 15 mg N kg^{-1} for the 0- to 30-cm soil sampling depth for irrigated corn grown in a semiarid environment in Colorado—well below the 21 mg N kg^{-1} suggested for humid regions of the USA. Bundy and Andraski (1995) indicated that separating NO_3 test data according to the potential yield of soils (medium and high based on depth of root zone, water holding capacity, and length of growing season) may improve the utility of the preplant NO_3 test (PPNT) and PSNT for making N recommendations for corn when soil test values are in the N responsive region.

Fox et al. (1993) evaluated the PSNT, NIR spectrophotometer reflectance from soil samples taken at planting, and an at-planting soil NO_3 test for use in predicting the grain yield and soil N-supplying capability. These methods did not predict the relative grain yield or the potential to supply N. However, they noted that NIR preplant soil testing did predict whether or not humid-region corn fields would respond to N fertilizer.

Indirect Measures for Grain Yield Prediction

Estimating crop yields is an important application of remote sensing (Lillesand and Kiefer, 1994; Moran et al., 1997). The NDVI, calculated with measurements of reflected light from the red and NIR bands, has long been used as an indirect measure of crop yield, including that of wheat (Tucker et al., 1980; Pinter et al., 1981). Aase and Siddoway (1981) confirmed the relationship of NDVI to wheat grain yield but noted that the relationship deteriorated rapidly as wheat ripened. Soil background, view and solar angles, atmospheric conditions, and crop canopy architecture are also important factors affecting NDVI (Huete, 1987; Jackson and Huete, 1991). Pinter et al. (1981) reported that summing NDVI values from late-season (Feekes 10.5, flowering to grain fill) spectral measurements was useful in predicting the grain yield of wheat. Bartholome (1988) reported that accumulated NDVI was a more stable predictor of millet (*Panicum miliaceum* L.) and sorghum [*Sorghum bicolor* (L.) Moench] grain yields than a single spectral measurement. Rasmussen (1992) calculated a sampling-interval weighted average NDVI by integrating multitemporal spectral measurements with time, which improved the grain yield estimates of millet from a single spectral measurement. Smith et al. (1995) reported that sensing twice and combining NDVI using a linear model improved correlation with wheat grain yield compared with sensing once. Rasmussen (1998) failed to improve the correlation of the NDVI to grain yield by integrating the product of multitemporal NDVI measurements and photosynthetically active radiation.

Definitions of Measured, Potential, and Maximum Grain Yields

Measured grain yield is that which is actually harvested in a given year at a given site (independent of scale). Potential grain yield is that which is predicted for a given year and site, based on the assumption that the level of growth factors that are responsible for the early development of the crop will be maintained (limitations that existed at early stages of growth will continue to similarly influence development to maturity, e.g., N deficiency). Maximum grain yield is that which is achievable when all manageable growth factors (e.g., nutrients, insects, disease, and weeds) are nonlimiting, and the environment is ideal. Depending on the environment, potential grain yield would always be $\leq$ maximum grain yield.

Prediction of Biomass and Percent Coverage

Recent work has shown that NDVI measurements in winter wheat between Feekes Physiological Growth Stages 4 and 5 can provide a reliable prediction of both N uptake and biomass (Stone et al., 1996; Solie et al., 1996). The percentage of soil covered by wheat was highly correlated with NDVI at Feekes Growth Stages 4 and 5, and both NDVI and coverage were correlated with vegetative biomass (Lukina et al., 1999). In these trials, plant coverage was generally $>50\%$ at Feekes 4 and 60% at Feekes 5. Similar work by Reeves et al. (1993) used direct in-season measurements of total N uptake in winter wheat at Feekes Growth Stage 5 to predict grain yield.

Much of the work associated with making fertilizer recommendations has not considered the potential for using in-season prediction of potential grain yield. Therefore, the objective of this work was to evaluate the use of early season red and NIR spectral reflectance field measurements of wheat tissue combined with GDD to predict potential grain yield.

Table 1. The location, number of plots, growth stage, and sampling date of experiments where sensor and winter wheat grain yield data were collected.

Experiment	Location	Year sensed	No. of plots	Dates sensed (T1 & T2)	Days T1 to T2†	GDD‡ T1 to T2†	Planting date	Harvest date	Variety	Rainfall planting to maturity	 planting to T2	 T2 to maturity
											mm	
S × N§	Perkins, OK	1998	48	24 Feb. 1998 6 Apr. 1998	42	187	21 Oct. 1997	15 June 1998	Tonkawa	638	396	242
S × N§	Tipton, OK	1998	48	27 Jan. 1998 26 Feb. 1998	31	120	7 Oct. 1997	3 June 1998	Tonkawa	415	277	138
N × P¶	Perkins, OK	1998	36	24 Feb. 1998 2 Apr. 1998	38	154	21 Oct. 1997	15 June 1998	Tonkawa	638	396	242
N × P¶	Perkins, OK	1999	12	12 Feb. 1999 4 Mar. 1999	21	99	12 Oct. 1998	9 June 1999	Tonkawa	655	244	411
Exp. 222	Stillwater, OK	1999	20	18 Jan. 1999 24 Feb. 1999	38	153	13 Oct. 1998	15 June 1999	Tonkawa	759	305	454
Exp. 301	Stillwater, OK	1999	18	19 Feb. 1999 24 Mar. 1999	34	142	15 Oct. 1998	15 June 1999	Tonkawa	759	309	450
Efaw AA	Stillwater-Efaw, OK	1999	21	19 Feb. 1999 24 Mar. 1999	34	142	9 Nov. 1998	15 June 1999	Tonkawa	596	146	450
Exp. 502	Lahoma, OK	1999	28	10 Feb. 1999 5 Mar. 1999	24	96	9 Oct. 1998	30 June 1999	Tonkawa	882	337	545
Exp. 801	Haskell, OK	1999	28	16 Feb. 1999 23 Mar. 1999	36	189	16 Oct. 1998	6 July 1999	2163	1016	600	416

† T1 to T2, Time-1 (Feekes Growth Stage 4) to Time-2 (Feekes Growth Stage 5).

‡ GDD, growing degree days calculated as the daily sum of (Tmin + Tmax)/2 − 4.4°C.

§ S × N, row spacing × N rate experiment.

¶ N × P, N rate × P rate experiment.

MATERIALS AND METHODS

During the winter months of 1998 and 1999, spectral reflectance readings were taken from nine winter wheat experiments. Each experiment was either an ongoing long-term experiment (no. assigned in the 1960s and 1970s as 222, 301, 502, and 801) or a short-term (1–3 yr) field experiment that included the evaluation of preplant N rates. Each of these locations is further defined in Table 1. The soils at each of these locations follow: Perkins, Teller sandy loam (fine-loamy, mixed, thermic Udic Argiustolls); Tipton, Tipton silt loam (fine-loamy, mixed, thermic Pachic Argiustolls); Stillwater, Kirkland silt loam (fine, mixed, thermic Udertic Paleustolls); Stillwater-Efaw, Norge silt loam (fine-silty, mixed, thermic Udic Paleustolls); Lahoma, Grant silt loam (fine-silty, mixed, thermic Udic Argiustolls); and Haskell, Taloka silt loam (fine, mixed, thermic Mollic Albaqualfs). The row spacing × N rate (S × N) and Efaw anhydrous ammonia (AA) experiments were each 1-yr trials. The N rate experiment at Perkins was initiated in 1996. Experiments 222, 301, and 502 were initiated in 1969, 1993, and 1971, respectively, and all three evaluated the annual rates of applied N at constant levels of P and K (Table 1). Winter wheat was planted at a 78 kg ha^{-1} seeding rate using a 0.19-m row spacing, excluding the S N experiment at Perkins (spacing ranged from 0.15–0.30 m).

Spectral reflectance was measured using an instrument that included two upward-directed photodiode sensors that received light through cosine-corrected Teflon windows fitted with red (671 ± 6nm) and NIR (780 ± 6nm) interference filters. The instrument also included two down-looking photodiode sensors that received light through collination and interference filters that were identical to the up-looking sensors. The instrument used a built-in 16 bit A/D converter that simultaneously converted the signals from all four photodiode sensors. The collination was configured to constrain the view of the down-looking sensors to a 0.84 m^2 oblong area at the plant surface. Stability of the sensor was maintained across time through calibration using a barium sulfate ($BaSO_4$) coated Al plate. The reflectance of the barium sulfate coated plate was assumed to be 1.0 for both spectral bands that were investigated.

All of the experiments included in this study are described in Table 1. Varietal differences were not targeted in this work because the findings of Sembiring et al. (2000) showed limited differences in postdormancy NDVI readings for common wheat varieties grown in this region. Reflectance readings from all experiments were collected at two postdormancy dates. The two dates (Time-1 and Time-2, respectively) where readings were collected generally corresponded to Feekes Growth Stage 4 (leaf sheaths beginning to lengthen) and 5 (pseudo-stem formed by sheaths of leaves that are strongly erect) (Large, 1954). Due to differences in planting times and growing conditions, spectral reflectance readings were collected between January and March (Table 1). All of the reflectance readings from wheat were taken from a 4.0-m^2 area between 1000 and 1600 h under natural lighting.

Reflectance values (the ratio of incident and reflected values) were used in the NDVI calculation to minimize the error associated with cloud cover, shadows, and sun angle. The modified equation used was

$$\mathrm{NDVI} = [(\mathrm{NIR_{ref}}/\mathrm{NIR_{inc}}) - (\mathrm{Red_{ref}}/\mathrm{Red_{inc}})]/[(\mathrm{NIR_{ref}}/\mathrm{NIR_{inc}}) + (\mathrm{Red_{ref}}/\mathrm{Red_{inc}})]$$

where $\mathrm{NIR_{ref}}$ and $\mathrm{Red_{ref}}$ are the magnitude of reflected light and $\mathrm{NIR_{inc}}$ and $\mathrm{Red_{inc}}$ are the magnitude of incident light.

In both years, grain yield was determined using a self-propelled combine from the same 4.0-m^2 area where spectral reflectance data were collected. We assumed that growth from planting in October to the mid winter months of January and February would provide an excellent indicator of wheat health in each 4.0-m^2 area, and thus the early season growth-limiting conditions for small areas as well. The sum of NDVI at Time-1 and Time-2 divided by GDD between the two dates [GDD = (Tmin + Tmax)/2 − 4.4°C] (Tmin and Tmax recorded from daily data) was computed and evaluated as an index for the in-season prediction of potential grain yield (in-season estimated yield, or EY). Minimum and maximum air temperatures and rainfall data were collected within 1.7 km of the actual experiment at all locations.

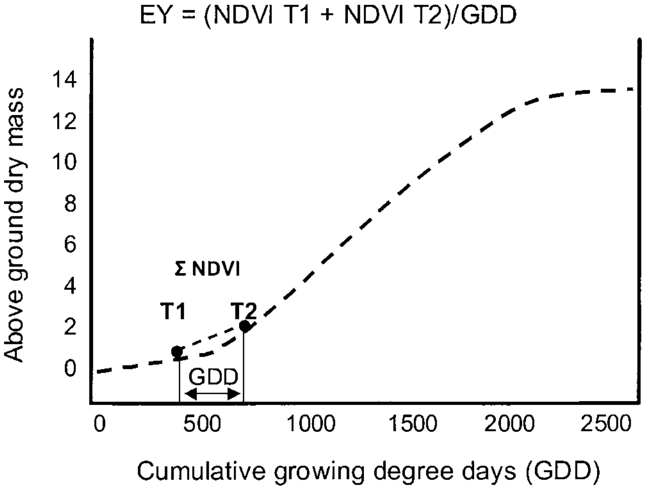

Fig. 1. Schematic relationship (Rickman et al., 1996) between aboveground dry mass (estimated using NDVI) obtained at two stages of growth (T1 and T2) and the cumulative growing degree days (GDD). Calculation of in-season estimated yield (EY) is also shown.

The EY index was one of many indices evaluated that included mathematical combinations of the following: the NDVI at Time-1 and Time-2, GDD and total days from Time-1 to Time-2, GDD and total days from planting to Time-1, and GDD and total days from planting to Time-2. The EY value was expected to reflect a point on the potential growth curve for that season, and thus provide an estimate of potential grain yield based on local growing conditions between planting and the dates of sensing. This index was found to include all sites and had a high combined r^2 when compared with the many other indices tested.

Measured grain yield was considered to be the best available measure of potential grain yield, especially where limited stress occurred after sensor readings in late February and early March. The use of GDD in the computation of EY allowed us to integrate early season growing conditions and growth rate. This approach is consistent with work by Rickman et al. (1996) showing the relationship between aboveground dry mass and cumulative GDD (Fig. 1). Dividing the sum of NDVI at Time-1 and Time-2 by GDD results in a unit of predicted biomass (using NDVI) per GDD.

Linear, quadratic, logarithmic, and exponential models that included all locations and data subsets were evaluated using various indices to predict measured grain yield. In addition, confidence limits were established for point estimates about regression lines for those models that best fit the data.

RESULTS

It is important to note that grain yield limiting factors associated with post Feekes 5 environments can cause measured grain yields to differ from predicted potential grain yields. Therefore, it was critical to identify those sites where obvious yield-limiting or yield-enhancing factors were present following the final sensor measurement. In this regard, we recognized that it would be extremely difficult to identify an index that would reliably predict measured grain yield across nine locations where planting date, harvest date, sensor dates, rain, and GDD differed.

Although many indices were evaluated that included NDVI at Times 1 and 2 (e.g., GDD from planting to Time-1 and Time-2, days from Time-1 and Time-2, and days from planting), the EY index proved to account for more of the variability in measured grain yield, especially when sites where postsensing grain yield limiting factors were considered. It was not until GDD was used as a divisor (combined with mid-winter sensor data) that we found models that included the majority of the nine sites studied. Therefore, regression analysis reported in this paper focuses on results from EY that included GDD in its calculation.

Estimated Yield vs. Grain Yield (All Nine Locations)

The relationship between measured grain yield and EY for all nine locations is illustrated in Fig. 2. Although definite differences were noted between the nine experiments included in this work, quadratic and exponential models for the entire data set resulted in coefficients of determination (r^2) > 0.50 and were highly significant ($P > 0.0001$).

Three sites exhibited responses that were markedly different from the rest of the experiments: Experiment 502 in 1999, N × P Perkins in 1999, and Efaw AA in 1999. When compared with the remaining six locations, Experiment 502 in 1999 and N × P Perkins in 1999 had lower-than-expected grain yields and high EY values (Fig. 2). Combined data for these two sites alone still showed a good relationship between the EY and grain yield ($r^2 = 0.78$). Plant stands were excellent following planting at all sites, a result of timely but not excessive rain, and growing conditions were near ideal before sensing. However, at Experiment 502 in 1999, excessive rain delayed grain harvest to 30 June 1999 (3–4 wk later than normal) and consequently reduced grain yields because of lodging and shattering. Had grain harvest taken place on time, we believe that yields would have been much higher and likely similar to the S × N Tipton data in 1998 (Fig. 2).

Grain yields were much lower than predicted by EY for the N × P Perkins experiment in 1999. Although EY values reflected a much higher potential grain yield, yields were characteristically lower at this site. Forage growth was excellent early in the season as was the plant development up to flowering. However, without timely rain, the sandy loam soil at this site dries out quickly, and the lower moisture storage becomes more yield-limiting than the silt loam and clay loam soils at other sites. As a result, measured grain yields were lower than what would have been predicted using EY even though plant stands and growth up to late February were indicative of a higher yielding crop.

Measured grain yields at the Efaw AA experiment in 1999 were higher than what would have been expected using EY. This experiment was located on an alluvial portion of the landscape and received added moisture via runoff from adjoining slopes. Forage growth was abnormally low at this site due to the late (9 Nov.) planting date (Table 1). As a result, the potential grain yields that were estimated using EY were low because wheat plants were small when sensed in

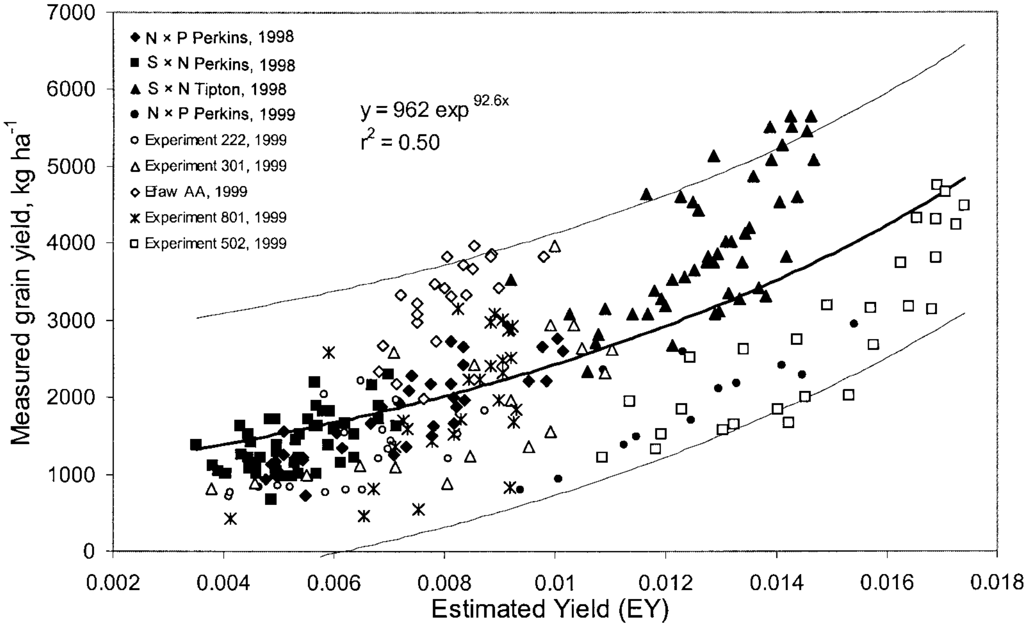

Fig. 2. Relationship between in-season estimated grain yield (EY) computed from two postdormancy NDVI readings divided by the cumulative growing degree days (GDD) (from Time-1 to Time-2) and measured grain yield in nine winter wheat experiments, 1998 and 1999 (confidence limits for point estimates about the exponential model).

February and March. However, forage growth improved significantly later in the season. Late-season wheat growth benefitted from the added moisture received via runoff and a soil profile that provided ample water during grain fill. We believe these factors caused potential grain yields to be underestimated using EY.

Estimated Yield vs. Grain Yield (Six Locations)

When data were removed for the three sites where grain yield was strongly influenced by abnormal post-sensing conditions (N × P Perkins, 1999; Efaw AA, 1999; and Experiment 502, 1999), the relationship between measured grain yield and EY improved (Fig. 3). Including data obtained from these six locations across a 2-yr period, EY values explained 83% of the variability in grain yield ($P > 0.0001$). Two of the six experiments included in this data set were 450 km apart, and rain from planting to harvest ranged from 645 (S × N Tipton, 1998) to 1016 mm (Experiment 801, 1999). Considering the range of factors that affect the final grain yield, and the influence of environment from Time-2 to maturity, we considered it important to find an index that closely predicted potential grain yield.

In our work, all data were combined in an attempt to derive a single standard curve to predict the potential grain yield for the purpose of variably applying N fertilizer. This is noteworthy considering the wide range in NDVI values that were found at all locations at Feekes Growth Stages 4 and 5 (Table 2). The only adjustment to the sum of the NDVI values from Feekes Growth Stage 4 to 5 was the division of this sum by GDD between the two measurements. This divisor was expected to partially account for the growing conditions when combining sites and years. Considering the many noncontrollable environmental factors that can influence final grain yield (after spectral data were acquired), we were willing to tolerate some error if it would enable using a single curve to estimate potential grain yield across a range of conditions. This is important if algorithms are to be developed that minimize the need to recalibrate the sensor or fertilizer controller for changing conditions within a field or between fields. The predicted mean grain yield of the six experiments used to develop the standard curve in Fig. 3 fell within ±14% of the average measured grain yields (Table 3). Linear regression of predicted mean grain yield on measured mean grain yield for the subset of six locations discussed previously and all nine locations had r^2 of 0.98 ($P > 0.01$) and 0.33 ($P > 0.10$), respectively. For these same models, slopes were not significantly different from 1, and intercepts were not different from 0. We believe these errors are tolerable in estimating the potential grain yield if the benefits of variably applying topdress N fertilizer can still be obtained. Experience may identify sites where the sensor consistently overestimates or underestimates potential grain yield, and the calibration can be reliably adjusted.

DISCUSSION

It is important to note that the sum and not the difference in NDVI from Time-1 to Time-2 was used because the sum would reflect the average while the difference (NDVI at Time-2 minus NDVI at Time-1) would theoretically take into account growth rate. Although we were interested in growth from Time-1 to Time-2, the difference in NDVI from Time-1 to Time-2 was inconsistent because some measurements resulted in negative values. This was a biological possibility in winter wheat, especially considering what can happen in terms of

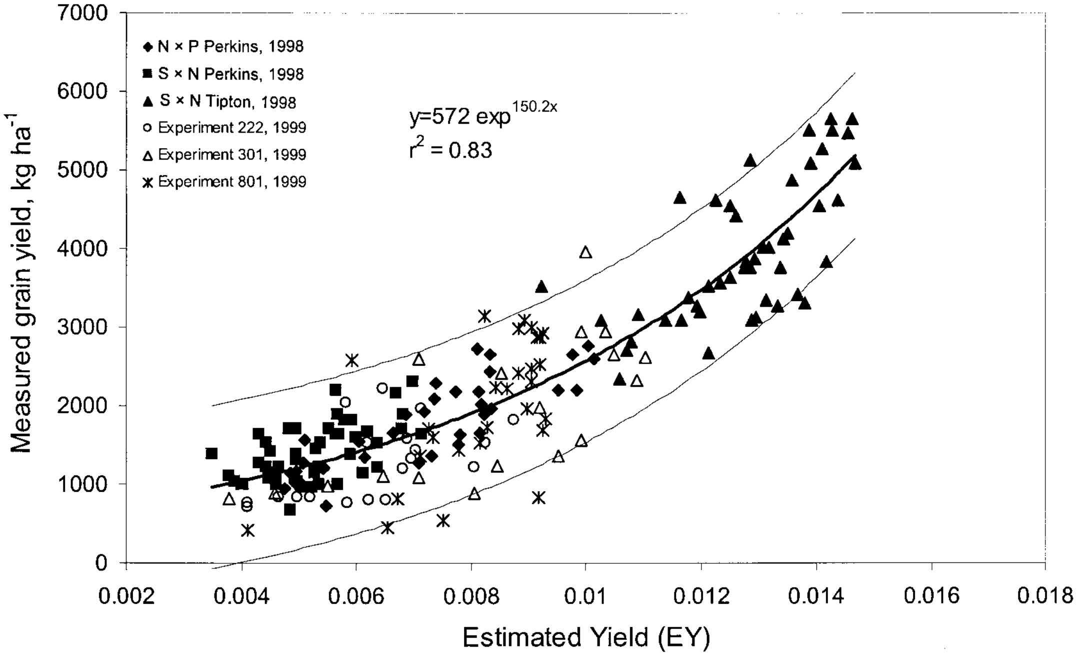

Fig. 3. Relationship between in-season estimated grain yield (EY) computed from two postdormancy NDVI readings divided by the cumulative growing degree days (GDD) (from Time-1 to Time-2) and measured grain yield in six of nine winter wheat experiments, 1998 and 1999 (confidence limits for point estimates about the exponential model).

weather from January to February and its effect on wheat foliage. This is in addition to other factors affecting optical measurements enumerated by Huete (1987) and Jackson and Huete (1991). The sum of NDVI at Time-1 and Time-2 was used because the initial prediction of biomass (Time-1) integrated growing conditions and plant health (stand density, vigor, and N uptake) from planting until the first winter spectral reading. Also, adding the two NDVI readings (estimates of biomass) assisted in removing some of the variability in radiometric data collected from the same 1-m^2 area at different times that would be influenced by changing soil moisture (reduced NIR and increased red reflectance). Pinter et al. (1981) reported that summing NDVI values assisted in predicting grain yield; however, their work employed spectral readings that were first collected at flowering (Feekes 10.5) and proceeded to senescence. Our approach was to collect sufficient information before Feekes 5 (60–90 d before flowering) that could be used to predict potential grain yields, and in time to apply fertilizer N without damaging the crop.

Data collected in the 1998 and 1999 growing seasons were unique because adequate moisture was present at planting and continued throughout each growing season. Only limited moisture stress was present, and all sites received timely rain near flowering. For this reason, measured grain yield and potential grain yield were expected to be similar for 1998 and 1999, and we believe this contributed strongly to our finding a high correlation of EY with measured grain yield at six locations. We would not expect EY to be highly correlated with measured grain yield in all growing seasons because so many things can happen to the wheat crop from postdormancy to maturity (e.g., frost, disease, and drought). However, our interest was in developing a yield parameter that was seasonal sensitive, intrinsic, and would reflect the potential grain yield likely to be realized in that season more than traditional yield goal

Table 2. Minimum, maximum, and mean values for NDVI collected at Feekes Growth Stages 4 and 5, and in-season estimated yield (EY) from nine experiments.

			NDVI Feekes 4			NDVI Feekes 5			EY†		
Exp.	Location	Year	min.	max.	mean	min.	max.	mean	min.	max.	mean
S × N‡	Perkins, OK	1998	0.33	0.64	0.47	0.32	0.76	0.52	0.0035	0.0071	0.0053
S × N‡	Tipton, OK	1998	0.50	0.85	0.74	0.60	0.91	0.80	0.0092	0.0146	0.0128
N × P§	Perkins, OK	1998	0.26	0.76	0.47	0.39	0.86	0.63	0.0047	0.0101	0.0071
N × P§	Perkins, OK	1999	0.55	0.77	0.66	0.37	0.76	0.56	0.0094	0.0154	0.0123
Exp. 222	Stillwater, OK	1999	0.14	0.60	0.39	0.12	0.74	0.54	0.0041	0.0087	0.0063
Exp. 301	Stillwater, OK	1999	0.31	0.74	0.55	0.23	0.84	0.64	0.0038	0.0110	0.0084
Efaw AA	Stillwater-Efaw, OK	1999	0.33	0.62	0.41	0.59	0.80	0.72	0.0068	0.0098	0.0080
Exp. 502	Lahoma, OK	1999	0.40	0.79	0.66	0.41	0.88	0.73	0.0085	0.0174	0.0145
Exp. 801	Haskell, OK	1999	0.42	0.89	0.77	0.35	0.89	0.78	0.0041	0.0093	0.0082

† EY = (NDVI Feekes 4 + NDVI Feekes 5)/growing degree days from Feekes 4 to Feekes 5.
‡ S × N, row spacing × N rate experiment.
§ N × P, N rate × P rate experiment.

Table 3. Predicted, measured, and percent of measured mean winter wheat grain yield from nine experiments.

Experiment	Location	Year	Measured mean grain yield	Predicted mean grain yield†	Percent of measured mean grain yield
			kg ha^{-1}	kg ha^{-1}	
S × N‡	Perkins, OK	1998	1409	1212	86.0
S × N‡	Tipton, OK	1998	3999	3911	97.8
N × P§	Perkins, OK	1998	1752	1654	94.4
N × P§	Perkins, OK	1999	1932	3622	187.4
Exp. 222	Stillwater, OK	1999	1274	1438	112.8
Exp. 301	Stillwater, OK	1999	1909	2042	106.9
Efaw AA	Stillwater-Efaw, OK	1999	3247	1846	56.8
Exp. 502	Lahoma, OK	1999	2822	5426	192.3
Exp. 801	Haskell, OK	1999	1985	1916	96.5

† Predicted mean grain yield using an exponential model of yield on the in-season estimated yield (EY) reported in Fig. 3.
‡ S × N, row spacing × N rate experiment.
§ N × P, rate × P rate experiment.

estimates. If growth was poor from planting to Time-2, it is unlikely that a high potential grain yield would be realized. Similarly, if growth was excellent from planting to postdormancy, but declined from the first to second reading (e.g., Time-1 to Time-2, drought, and frost damage), potential grain yield would be expected to be lower.

The 10- to 40-d period immediately following dormancy is critical in terms of the resulting grain yield. Obtaining two sensor readings during this period provides a measure of crop development and growing conditions. Unlike growth models that rely on various inputs to predict plant growth, optical sensing uses the plant as the indicator. The first reading establishes a base measurement of crop condition, and the second reading assesses postdormancy change across a short, measured time period. Combined, these two readings and the adjustment for GDD should provide a reasonable indication of the potential grain yield. Typically, information on the early season growing conditions is accessed by the first reading in late February. The period from planting (mid-Oct.) to the end of dormancy (late February) represents more than half of the growing season and provides information on the potential grain yield. Once potential yield is determined, topdress N rates could be adjusted based on projected grain N removal. Sensing beyond Feekes Physiological Stage 5 (Time-2) is not practical for winter wheat grown in the United States because significant stand damage is encountered when topdress equipment is used for N applications following this time.

When spatially precise estimates of potential grain yield are made, these estimates will be determined at the finest resolutions (1 m^2) where differences in soil test parameters are found (Solie et al., 1996; Solie et al., 1999). At coarser resolutions ($>$30 m), the variation in the potential grain yield will be masked by averaging, and benefits that may have been realized in treating the variability can be lost. Thus, one of the reasons why we found such good correlation between EY and measured grain yield (or potential grain yield) was because we were operating at a resolution of 4 m^2. In this regard, topdress N rates based on an in-season prediction of potential grain yield must take place at the same resolution where spatial variability is encountered.

CONCLUSIONS

We propose the use of two postdormancy spectral reflectance readings (NDVI collected at or near Feekes Growth Stage 4 and again at Feekes Growth Stage 5) to assess the initial status of plant growth from planting to the end of dormancy and to assess postdormancy growth across a short time period (Jan. to Mar.). Adding these two NDVI readings and dividing by the GDD between readings provides an indication of what potential grain yield should be for a wide range of growing conditions, planting times, and sensing dates. For the 2 yr evaluated, measured grain yield and estimated potential grain yield, or EY, were expected to be similar because the dryland growing conditions were near ideal throughout the season. Including data obtained from six locations for a 2-yr period, EY values explained 83% of the variability in the grain yield, and thus were an early season indication of potential grain yield (measured grain yield used as the indicator variable) across a range of growing environments.

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