COMMUNICATIONS IN SOIL SCIENCE AND PLANT ANALYSIS
Vol. 34, Nos. 13 & 14, pp. 1837–1852, 2003

# Late-Season Prediction of Wheat Grain Yield and Grain Protein[#]

**K. W. Freeman,[1] W. R. Raun,[1,*] G. V. Johnson,[1] R. W. Mullen,[1] M. L. Stone,[2] and J. B. Solie[2]**

[1]Department of Plant and Soil Sciences and [2]Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, Oklahoma, USA

## ABSTRACT

Pre-harvest prediction of winter wheat (*Triticum aestivum* L.) grain yield and/or protein could assist farmers in generating yield maps and reliable product marketing. This study was conducted to determine the relationship between spectral measurements (taken from Feekes growth stage 8 to physiological maturity) and grain yield and grain protein. Spectral measurements were taken using photodiode detectors and interference filters for near-infrared (NIR) and red spectral bands. The study was conducted over 2 years at seven locations where existing field experiments were already in place across Oklahoma. Spectral readings were taken at Feekes growth stages 8, 9, 10.5, 11.2, and 11.4. The normalized difference vegetative index (NDVI) was calculated. In both

[#]Contribution of the Oklahoma Agricultural Experiment Station.
[*]Correspondence: W. R. Raun, Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078, USA; E-mail: wrr@mail.pss.okstate.edu.



DOI: 10.1081/CSS-120023219 0010-3624 (Print); 1532-2416 (Online)

cropping cycles, NDVI was well correlated with grain yield, grain N uptake, straw N uptake, and total N uptake at Feekes growth stages 9 and 10.5 ($R^2 > 0.5$). However, by Feekes 11.2 no relationship between NDVI and grain yield or N uptake was observed. In 1999–2000 at Feekes 11.4 (harvest), NDVI and grain yield were poorly correlated. Across locations and years, no consistent relationship existed between NDVI and grain N or straw N at any stage of growth. Grain N and straw N could not be reliably predicted using NDVI at any stage of growth.

## INTRODUCTION

Sensor-based variable rate technologies (s-VRT) are continuing to receive attention as a means for precision management of N inputs in winter wheat (*Triticum aestivum* L.) production. Some of this work has been directed at estimating N uptake of winter wheat during early vegetative growth and later correlated with final grain yield. This study focuses on predicting the final yield and/or grain protein of winter wheat at late growth stages using sensors. Pre-harvest prediction of wheat yield and/or protein could assist producers in generating yield maps and allow for reliable means of product marketing.

## LITERATURE REVIEW

### Predicting Grain Yield

Lukina et al.[1] describes advancements in precision agriculture technology (PAT) as decreasing inputs while maintaining yield or supplying the same inputs but achieving higher yields through more efficient crops. Araus[2] reported that methods based on red/near infrared ratios can yield estimates of leaf area index (LAI), green biomass, crop yield, and canopy photosynthetic capacity. In fact, green leaves are strong absorbers in the red, but highly reflected in the near infrared. Mahey et al.[3] found NDVI and wheat grain yield to be highly correlated, establishing the potential to predict grain yield of wheat with remote sensed data. They also noted that the strongest correlation occurred between 75 and 104 days after planting. Also, NDVI has been found to be highly correlated with yield and biomass in barley (*Horduem vulgare* L.).[4] According to work using satellite imagery by Quarmby et al.,[5] wheat yield estimates during the early part of the growing season change rapidly. However, 50 to 100 days prior to harvest, yield estimates stabilize. These results indicate accurate yield estimates may be made two months prior to harvest.

As noted by Filella et al.,[6] remote sensing could provide inexpensive, large-area estimates of N status in wheat. They further reported that the use of reflectance at 430, 550, 680 nm, and red edge wavelengths offers potential for assessing N status of wheat. Work by Kleman and Fagerlund[7] studied different ratios of red, NIR, and infrared (IR) and concluded that IR/red was related to the biomass and grain yield of spring barley (*Hordeum distichum* L.). Stone et al.[8] demonstrated that N uptake and NDVI are highly correlated. Raun et al.[9] showed that the sum of two NDVI readings taken at Feekes[10] growth stages 4 and 5 divided by the growing degree days (GDD) between these readings was a reliable predictor of final grain yield at six of nine sites. However, this work required two post dormancy readings. Ensuing work by Lukina et al.[1] showed a stronger correlation between yield and one NDVI reading collected at Feekes growth stage 5 divided by the total number of days from planting.

## Field Resolution and Mapping

As precision farming becomes adapted and accepted, delineating the proper field element size becomes more important. Solie et al.[11] defines field element size as the area that provides the most precise measure of the available nutrient and where the level of that nutrient changes with distance. This work went on to identify that the fundamental field element size averages 1.5 m. A microvariability study by Raun et al.[12] found significant differences in surface soil test analyses when samples were $<1$m apart for both mobile and immobile nutrients. Solie et al.[13] stated that in order to describe the variability encountered in field experiments soil, plant, and indirect measurements should be made at the meter or submeter level.

Willis et al.[14] defined yield maps as tools used by producers to look for general patterns and trends, such as unusually high or low yielding areas. They go on to state that many errors are associated with yield monitor data that could be corrected for by integrating remotely sensed data to the yield maps. Blackmore and Marshall[15] describe these errors as: 1) the time lag of crop from machine intake to yield sensor, 2) yield sensor calibration, 3) GPS accuracy, 4) uncertain crop width entering the header, 5) surging grain, and 6) grain losses. Considering the range of errors that can be encountered with yield monitor data, interest in the development of alternative "yield sensing" methods has increased.

### Predicting Grain Protein

Stone et al.[16] demonstrated a high correlation between the plant nitrogen spectral index (PNSI), the reciprocal of NDVI, and the total N uptake of wheat forage. This work showed that sensors were reliable indicators of the plant N status. According to Wuest and Cassman,[17] early-season N environment has a large influence on N partitioning at maturity. The ability to determine the N status of wheat and relate it to N accumulation in the grain opens the possibility to indirectly predict wheat grain protein using remotely sensed data. The objective of this study was to determine the relationship between spectral measurements taken from Feekes growth stage 8 to physiological maturity and grain yield, grain protein, and total N uptake.

## MATERIALS AND METHODS

This study was conducted at seven locations within existing field experiments. Locations included long-term N and P fertility studies across Oklahoma at Stillwater, Lahoma, Perkins, and Haskell, and additional locations included anhydrous ammonia (AA) experiments at Hennessey and Stillwater, and a sewage sludge loading experiment near Stillwater (Table 1). Two meter by two meter plots were established within plots of differing N rates (Table 2). Spectral reflectance readings were taken using a photodiode-based sensor with interference filters for red at $671 \pm 6$ and near infrared (NIR) at $780 \pm 6$ nm wavelengths, developed by Stone et al.[8] The normalized difference vegetative index (NDVI) was calculated in accordance with the equation $\text{NDVI} = (\text{NIR}_{\text{ref}} - \text{red}_{\text{ref}})/(\text{NIR}_{\text{ref}} + \text{red}_{\text{ref}})$. Red reflectance ($\text{Red}_{\text{ref}}$) is calculated by dividing red reflected light by red incident light, and NIR reflectance ($\text{NIR}_{\text{ref}}$) is calculated by dividing NIR reflected light by NIR incident light. Spectral readings were taken at Feekes growth stages 9 (ligule of last leaf visible), 10.5 (flowering), 11.2 (mealy ripe, contents of kernel soft but dry), and 11.4 (ripe for harvest, straw dead).[10] Sensing, planting, and harvest dates and varieties are reported in Table 3.

Each location was harvested using a self-propelled Massey Ferguson 8XP combine. The entire $4\text{m}^2$ area was harvested and grain weight and moisture were recorded at that time. Straw was collected for calculation of total N uptake using a straw and chaff collector placed under the combine. Straw weights for each plot were recorded and a sample was taken for analysis. Grain and straw samples were then ground to pass a 120-mesh screen and analyzed for total nitrogen using a Carlo Erba 1500 dry combustion analyzer.[18] Statistical analysis was performed using SAS.[19]

*Table 1.* Initial surface (0–15 cm) soil chemical characteristics and classification at Haskell, Hennessey, Lahoma, Perkins, Stillwater, and Tipton, OK.

| Location | pH (mg kg$^{-1}$) | $NH_4$-N (mg kg$^{-1}$) | $NO_3$-N (mg kg$^{-1}$) | P (mg kg$^{-1}$) | K (mg kg$^{-1}$) | Total N (g kg$^{-1}$) | Organic C (g kg$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Stillwater AA | 6.0 | 2.5 | 11.3 | 19.9 | 197 | 0.94 | 10.4 |
| Classification: Easpur loam (fine-loamy, mixed, superactive, thermic Fluventic Haplustoll) | | | | | | | |
| Stillwater SS | 5.8 | 6.9 | 5.0 | 30.2 | 16.8 | 1.06 | 11.9 |
| Classification: Norge loam (fine mixed, thermic Udertic Paleustoll) | | | | | | | |
| Haskell 801 | 5.3 | 7.4 | 3.4 | 8.5 | 163 | 0.7 | 7.4 |
| Classification: Taloka silt loam (fine, mixed, thermic Mollic Albaqualf) | | | | | | | |
| Hennessey AA | 5.6 | 19.3 | 14.5 | 95.6 | 558 | 1.05 | 11.9 |
| Classification: Shellabarger sandy loam (fine-loamy, mixed, thermic Udic Argiustoll) | | | | | | | |
| Lahoma 502 | 5.5 | 5.3 | 13.9 | 39.9 | 416 | 0.8 | 7.4 |
| Classification: Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll) | | | | | | | |
| Perkins N&P | 5.4 | 2.6 | 9.1 | 16.5 | 132 | 0.79 | 7.0 |
| Classification: Teller sandy loam (fine-loamy, mixed, thermic Udic Argiustoll) | | | | | | | |
| Stillwater 222 | 5.9 | 12.0 | 8.6 | 4.9 | 192 | 0.96 | 7.9 |
| Classification: Kirkland silt loam (fine, mixed, thermic Udertic Paleustoll) | | | | | | | |

pH—1:1 soil:water, K and P—Mehlich III, Organic C and Total N–dry combustion.

***Table 2.*** Treatment structure at Haskell, Hennessey, Lahoma, Perkins and Stillwater, OK.

| | Stillwater AA, N–P–K ($kg\,ha^{-1}$) | Stillwater SS, N–P–K ($kg\,ha^{-1}$) | Haskell 801, N–P–K ($kg\,ha^{-1}$) | Hennessey AA, N–P–K ($kg\,ha^{-1}$) | Lahoma 502, N–P–K ($kg\,ha^{-1}$) | Perkins N & P, N–P–K ($kg\,ha^{-1}$) | Stillwater 222, N–P–K ($kg\,ha^{-1}$) |
|---|---|---|---|---|---|---|---|
| Treatments | 0-0-0 | 0-0-0 | 0-0-0 | 0-0-0 | 0-0-0 | 0-0-0 | 0-0-0 |
| | 56-0-0 | 45-0-0 | 0-58-111 | 56-0-0 | 0-19-56 | 56-29-0 | 0-29-37 |
| | 90-0-0 | 90-0-0 | 112-58-111 | 90-0-0 | 22-19-56 | 112-29-0 | 45-29-37 |
| | 123-0-0 | 179-0-0 | 112-0-111 | 123-0-0 | 45-19-56 | 168-29-0 | 90-29-37 |
| | (Two application methods) | 269-0-0 | 112-19-111 | (Two application methods) | 67-19-56 | | 134-29-37[a] |
| | | 538-0-0 | 112-39-111 | | 90-19-56 | | |
| | | | 168-58-111 | | 112-19-56 | | |

[a] Split application of N.

*Table 3.* Planting, sensor readings, and harvest dates at Haskell, Hennessey, Lahoma, Perkins and Stillwater, OK for 1999–2000.

| | | | | Date sensed | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Experiment | Location | Year sensed | No. of plots | Feekes 8 | Feekes 9 | Feekes 10.5 | Feekes 11.2 | Feekes 11.4 | Planting date | Harvest date | Variety |
| Exp. 222 | Stillwater, OK | 2000 | 20 | — | 30/03/00 | 24/04/00 | 22/05/00 | 06/07/00 | 07/10/99 | 6/07/00 | Custer |
| | | 2001 | | 23/04/01 | 30/04/01 | 10/05/01 | 24/05/01 | — | 20/11/00 | 12/06/01 | Custer |
| Exp. 301 | Stillwater, OK | 2000 | 18 | — | 04/04/00 | 24/04/00 | 22/05/00 | 15/06/00 | 07/10/99 | 15/06/00 | Custer |
| | | 2001 | | 23/04/01 | 30/04/01 | 10/05/01 | 24/05/01 | — | 16/11/00 | 11/06/01 | Custer |
| Exp. 502 | Lahoma, OK | 2000 | 28 | — | 28/03/00 | 20/04/00 | 15/05/00 | 13/06/00 | 12/10/99 | 13/06/00 | Custer |
| | | 2001 | | 13/04/01 | — | 10/05/01 | 24/05/01 | — | | 15/06/01 | Custer |
| Exp. 801 | Haskell, OK | 2000 | 28 | — | 14/03/00 | 25/04/00 | 16/05/00 | — | 08/10/99 | 2/06/00 | 2137 |
| | | 2001 | | 24/04/01 | 03/05/01 | 14/05/01 | — | — | | 6/06/01 | 2137 |
| N*P | Perkins, OK | 2000 | 12 | — | 04/04/00 | 24/04/00 | 22/05/00 | 30/05/00 | 08/10/99 | 30/05/00 | Custer |
| | | 2001 | | 23/04/01 | 30/04/01 | 09/05/01 | 24/05/01 | — | 17/11/00 | 7/06/01 | Custer |
| AA NUE | Hennessey | 2000 | 21 | — | 28/03/00 | 27/04/00 | 22/05/00 | 07/06/00 | 07/10/99 | 07/06/00 | Custer |
| | | 2001 | | 13/04/01 | — | 10/05/01 | 24/05/01 | — | 21/11/00 | 13/06/01 | Custer |
| AA NUE | Stillwater, OK | 2000 | 21 | — | 04/04/00 | 24/04/00 | 22/05/00 | 07/07/00 | 07/10/99 | 07/07/00 | Custer |
| | | 2001 | | 23/04/01 | 30/04/01 | 10/05/01 | 24/05/01 | — | 22/11/00 | 11/06/01 | Custer |

## RESULTS AND DISCUSSION

### Grain Yield

The relationship between grain yield and NDVI when sensor readings were taken at Feekes growth stages 8, 9, and 10.5 are reported in Figs. 1–3. NDVI was a good predictor of wheat grain yield (sensor readings taken from the same 4 $m^2$ area where grain yield was later determined) ($R^2 > 0.54$). No relationship was observed at Feekes 11.2 and 11.4 growth stages. At both Experiment 502 and 222 in 1999–2000, a wide range of NDVI values corresponded with a wide range in wheat grain yield, thus on a by-site basis, correlation was improved. At Efaw AA, and Hennessey AA, plant coverage was good within the entire experiment, and thus, the range in NDVI values was relatively small. Even though the range in wheat grain yields was wide (1000 to 4500 kg $ha^{-1}$) for these sites, red adsorption peaked as expected (due to the excellent coverage) and differences in yield potential were more difficult to detect. This calls further attention to the deficiencies of the NDVI index in being able to assess differences in yield potential where soil plant coverage is good and where plot differences in early biomass production are small. In 2000–2001, delayed fall planting due to wet conditions decreased tillering and coverage resulting in a good range of NDVI values, excluding

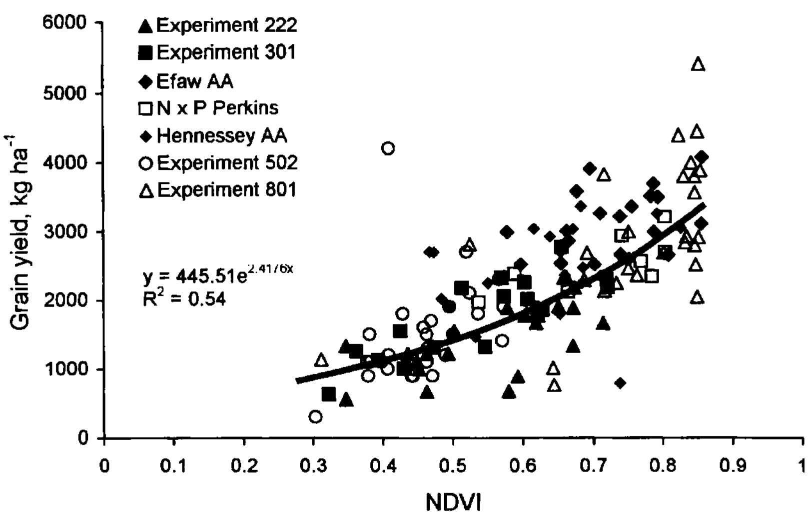


***Figure 1.*** Relationship between NDVI and grain yield at Feekes growth stage 8 at seven locations in crop year 2000–2001.

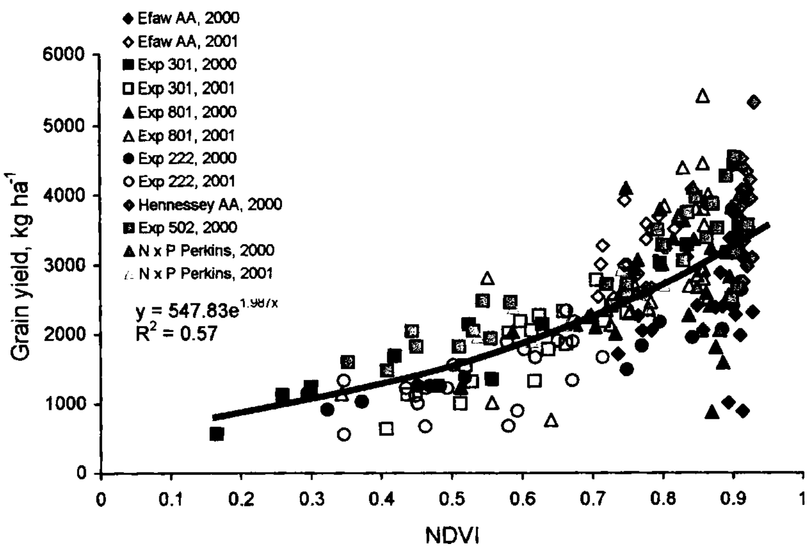


*Figure 2.* Relationship between NDVI and grain yield at Feekes growth stage 9 at twelve locations over two crop years 1999–2000 and 2000–2001.

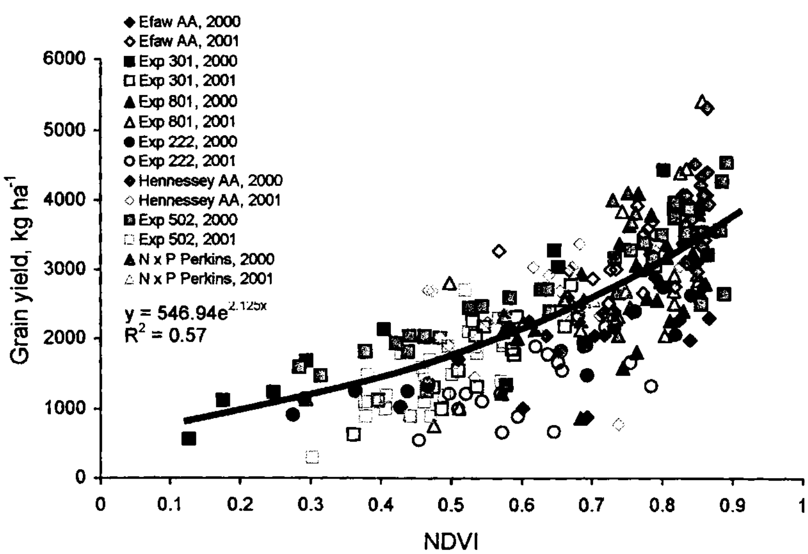


*Figure 3.* Relationship between NDVI and grain yield at Feekes growth stage 10.5 at fourteen locations over two crop years 1999–2000 and 2000–2001.

experiment 801. Due to the poor coverage at most sites at Feekes 8 and 9, maximum adsorption of the red portion of the spectrum was generally not observed, (exception, Experiment 801). This is illustrated by the range of grain yield levels observed near NDVI values of 0.85.

The relationship between NDVI and wheat grain yield at Feekes 11.2 was dramatically different from that observed at earlier stages of growth (data not reported). Feekes 11.2 corresponds with the kernels being mealy ripe, soft, but dry. In 1999–2000, at this stage of growth, a slight trend for yields to increase with increasing NDVI was present. However in 2000–2001, thin wheat stands due to late planting and increased weed pressure inflated NDVI values without increasing harvested grain. By Feekes 11.4 (ripe for cutting, straw dead), wheat grain yields decreased with increasing NDVI (data not reported). At Feekes 11.4, only very limited absorbance of red is encountered, due to the rapid disappearance of chlorophyll (green) with the onset of senescence.

## Grain Nitrogen

The average grain N concentration across all experiments in both years was $24.6\,\mathrm{g\,kg^{-1}}$ and ranged from 18.3 to $38.1\,\mathrm{g\,kg^{-1}}$. No consistent relationship between NDVI and grain N was found at any stage of growth. There was, however, a trend for increased grain N with increasing NDVI at Experiment 801 at Feekes growth stage 9 (data not reported).

## Straw Nitrogen

For the fourteen sites sampled over two years, no distinct relationship between NDVI and straw N was observed. There was, however, a trend for decreased straw N with increasing NDVI when readings were collected on the actual day of harvest in 1999–2000.

## Grain Nitrogen Uptake

Similar to results reported for the relationship between NDVI and grain yield, correlation of NDVI and grain N uptake was significant. However, consistent with data reported by Stone et al.,[16] improved correlation was found at all stages of growth for grain N uptake versus NDVI, as compared to grain yield and NDVI ($R^2 = 0.57, 0.60, 0.62$, for growth stages 8, 9, and 10.5, respectively). The improved $R^2$ (grain N uptake and NDVI vs. grain yield and NDVI) would tend to indicate that either the red or near infrared bands were sensitive to N as chlorophyll in the plant tissue, and that would not be a direct component of grain yield.

## Straw Nitrogen Uptake

Over the fourteen locations included in this work, straw N uptake as a function of NDVI is plotted in Figs. 4 and 5 for the different stages of growth sampled. Straw N uptake and NDVI were well correlated at Feekes growth stages 9 and 10.5 but not at other stages (Figs. 4 and 5). Consistent with observations for NDVI and grain N uptake, correlation was poor at Feekes growth stage 11.2, but that improved (although changing to a negative slope) at the final stage of growth. This poor correlation was expected considering the loss of green color (chlorophyll) during senescence. Furthermore, differences in plant health and physiological development would likely fluctuate as a function of spatial variability. At this time period, younger tillers are still green while main stems are fully senesced. Sloughing of upper leaves would also aid in observing differences in the lower canopy at later stages of growth.

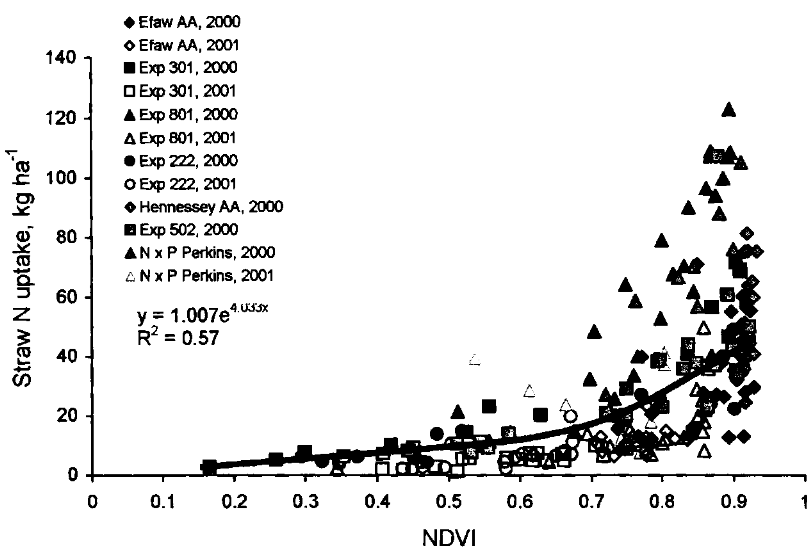


*Figure 4.* Relationship between NDVI and straw N uptake at Feekes growth stage 9 at twelve locations over two crop years 1999–2000 and 2000–2001.

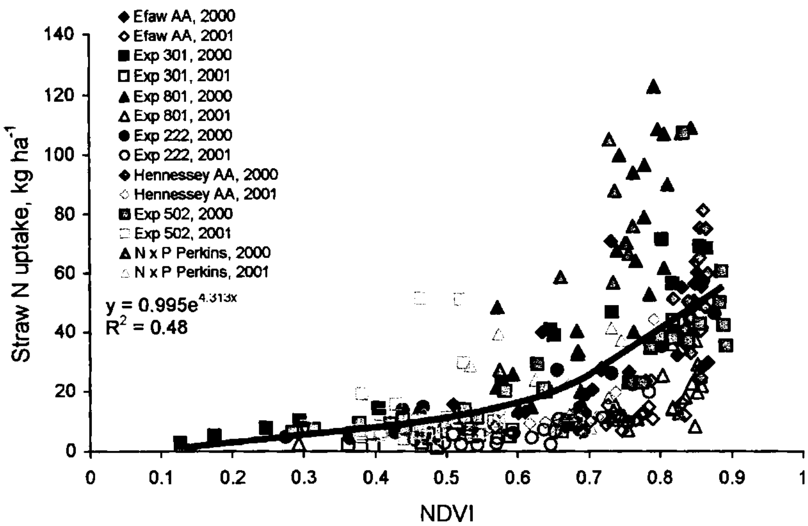


*Figure 5.* Relationship between NDVI and straw N uptake at Feekes growth stage 10.5 at fourteen locations over two crop years, 1999–2000 and 2000–2001.

In 2000–2001, at Perkins N and P, the measured straw N uptake was high, largely due to contamination of the plots by the presence of Italian ryegrass (*Lolium multiflorum* L.), which resulted in higher biomass and N concentrations. Similarly, at Experiment 502 high straw N uptakes were measured due to an infestation of crabgrass in certain plots, which accounted for an increase in biomass and N concentration.

## Total Nitrogen Uptake

Total N uptake (straw + grain) is plotted against NDVI in Figs. 6–8 at Feekes 8, 9, 10.5 stages of growth. No relationship between total N uptake and NDVI was observed at Feekes 11.2 and 11.4. A trend for improved correlation of NDVI with total N uptake was observed, compared to that found for grain N uptake and/or straw N uptake. This is not surprising considering that total N uptake includes both grain and straw components and accounts for all N in the above ground biomass of the plant. It must also be emphasized that the early readings (Feekes 8, 9, and 10.5) were far superior for predicting total N uptake than the later readings. This suggests the importance of collecting red and near infrared readings during vegetative stages of growth where the sensitivity

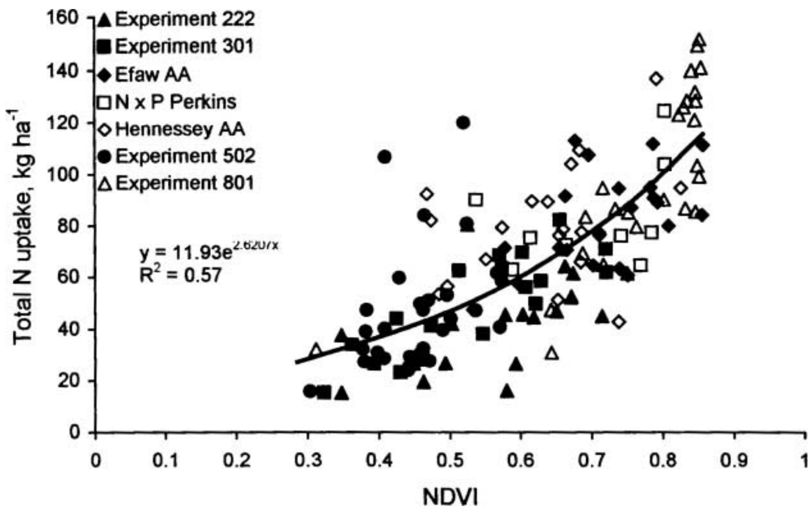


*Figure 6.* Relationship between NDVI and total (grain + straw) N uptake at Feekes growth stage 8 at seven locations in crop year 2000–2001.

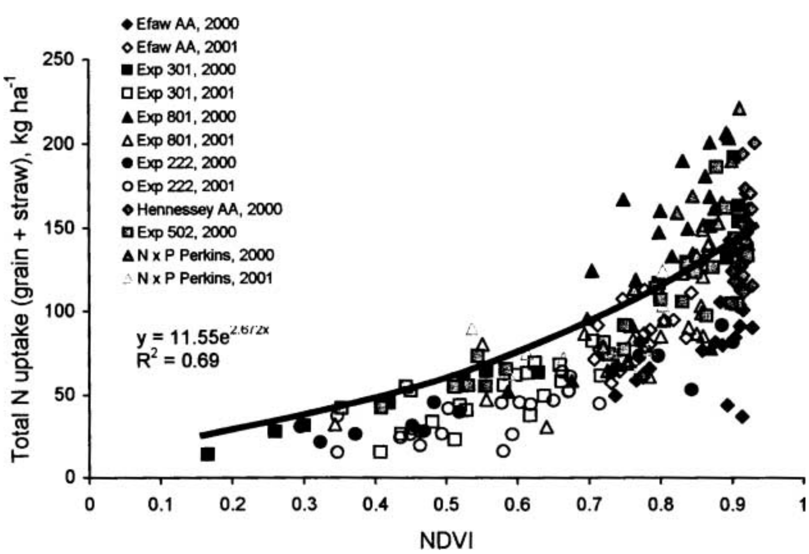


*Figure 7.* Relationship between NDVI and total N uptake (grain + straw) at Feekes growth stage 9 at twelve locations over two crop years 1999–2000 and 2000–2001.

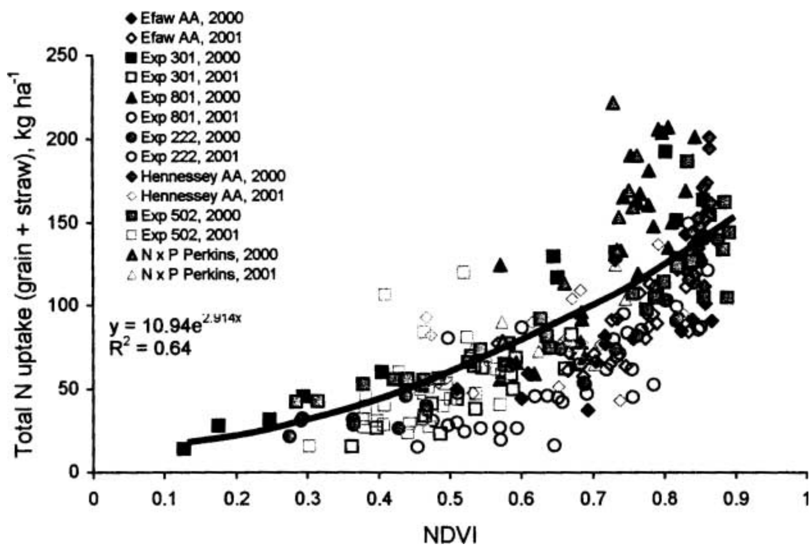


*Figure 8.* Relationship between NDVI and total N uptake (grain + straw) at Feekes growth stage 10.5 at fourteen locations over two crop years, 1999–2000 and 2000–2001.

to green and/or chlorophyll concentrations would be higher. Although correlation remained significant at the final stage of growth, it was significantly diminished.

## CONCLUSIONS

Over two cropping cycles and seven locations, NDVI calculated using red and NIR bands proved to be relatively well correlated with grain yield, grain N uptake, straw N uptake, and total N uptake on sensor measurements observed up through anthesis. Under high plant coverage, associated with good growing conditions and adequate fertility, peak adsorption of the red portion of the spectrum does occur. When red adsorption peaks, the two-dimensional NDVI readings become relatively insensitive to the changes in total biomass, and are later reflected in grain yield (i.e., when NDVI values are high, the range in grain yield at a specific NDVI value can be large). Small ranges in NDVI reduce the ability of the sensor to accurately predict grain yield, grain N uptake, straw N uptake, and total N uptake, especially when ground cover is good at early stages of growth.

Grain N and straw N could not be reliably predicted using NDVI at any stage of growth. This can partially be explained by knowing that there is no way for NDVI to detect how efficiently the plant will translocate N into the grain, and how much of the N will be lost through various pathways, each of which result in relatively constant tissue N in grain and straw at harvest.

Over locations and years, NDVI measurements collected at Feekes growth stage 9 provided reliable estimates of grain yield, grain N uptake, and total N uptake. This vegetative stage of growth that takes place 40 to 60 days before harvest may be an ideal time for collecting aerial images that could later be used for estimating potential yield levels on a by-field basis.

The ability to reliably predict grain yield in-season using spectral reflectance can be implemented into any variable rate technology program. This information can be used for producing field maps at the sub-meter level versus current maps at a resolution of 900 square feet. Additionally, the ability of producers to predict wheat yields while their crop is still in the field could assist in more strategic marketing plans and more accurate insurance estimates.

## REFERENCES

1. Lukina, E.V.; Freeman, K.W.; Wynn, K.J.; Thomason, W.E.; Mullen, R.W.; Klatt, A.R.; Johnson, G.V.; Elliot, R.L.; Stone, M.L.; Solie, J.B.; Raun, W.R. Nitrogen fertilization optimization algorithm based on in-season estimates of yield and nitrogen uptake. J. Plant Nutr. **2000**, *24*, 885–898.
2. Araus, J.L. Integrated physiological criteria associated with yield potential. In *Increasing Yield Potential in Wheat: Breaking the Barriers*; Reynolds, M.P., Rajaram, S., McNab, A., Eds.; CIMMYT: Mexico, D.F, 1996; 150–156.
3. Mahey, R.K.; Singh, R.; Sidhu, S.S.; Narang, R.S. The use of remote sensing to assess the effects of water stress on wheat. Exp. Agric. **1991**, *27*, 423–429.
4. Penualas, J.; Isla, I.; Filella, I.; Araus, J.L. Visible and near-infrared reflectance assessment of salinity effects on barley. Crop Sci. **1997**, *37*, 198–202.
5. Quarmby, N.A.; Milnes, M.; Hindle, T.L.; Silleos, N. The use of multi-temporal NDVI measurements from AVHRR data for crop yield estimation and prediction. Int. J. Remote Sensing **1993**, *14*, 199–210.

6. Filella, I.; Serrano, L.; Serra, J.; Penuelas, J. Evaluating wheat nitrogen status with canopy reflectance indices and discriminant analysis. Crop Sci. **1995**, *35*, 1400–1405.
7. Kleman, J.; Fagerlund, E. Influence of different nitrogen and irrigation treatments of the spectral reflectance of barley. Remote Sens. Environ. **1987**, *21*, 1–14.
8. Stone, M.L.; Solie, J.B.; Whitney, R.W.; Raun, W.R.; Lees, H.L. *Sensors for the Detection of Nitrogen in Winter Wheat*; SAE Paper No. 961757; SAE: Warrendale PA, 1996.
9. Raun, W.R.; Johnson, G.V.; Stone, M.L.; Solie, J.B.; Lukina, E.V.; Thomason, W.E.; Schepers, J.S. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. **2001**, *93*, 131–138.
10. Large, E.C. Growth stages in cereals. Plant Pathol. **1954**, *3*, 128–129.
11. Solie, J.B.; Raun, W.R.; Whitney, R.W.; Stone, M.L.; Ringer, J.D. Optical sensor based field element size and sensing strategy for nitrogen application. Trans. ASAE **1996**, *39*, 1983–1992.
12. Raun, W.R.; Solie, J.B.; Johnson, G.V.; Stone, M.L.; Whitney, R.W.; Lees, H.L.; Sembiring, H.; Phillips, S.B. Micro-variability in soil test, plant nutrient and yield parameters in bermudagrass. Soil Sci. Am. J. **1998**, *62*, 683–690.
13. Solie, J.B.; Raun, W.R.; Stone, M.L. Submeter spatial variability of selected soil and plant variables. Soil Sci. Soc. Am. J. **1999**, *63*, 1724–1733.
14. Willis, P.R.; Carter, P.G.; Johanannsen, C.J. Assessing yield parameters by remote sensing techniques. In *Proc. of the 4th Int. Conf. on Precision Agriculture*, St. Paul, MN, July 19–22, 1998; 1465–1473.
15. Blackmore, B.S.; Marshall, C.J. Yield mapping: errors and algorithms. In *Proc. of the 3rd Int. Conf. on Precision Agriculture*, Minneapolis, MN June 23–26, 1996, 403–415.
16. Stone, M.L.; Solie, J.B.; Raun, W.R.; Whitney, R.W.; Taylor, S.L.; Ringer, J.D. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. Trans. ASAE **1996**, *39*, 1623–1631.
17. Wuest, S.B.; Cassman, K.G. Fertilizer-nitrogen use efficiency of irrigated wheat II: Partitioning efficiency of preplant versus late-season application. Agron. J. **1992**, *84*, 689–694.
18. Schepers, J.S.; Francis, D.D.; Thompson, M.T. Simultaneous determination of total C, total N and 15N on soil and plant material. Commun. Soil Sci. Plant Anal. **1989**, *20*, 949–959.
19. SAS Institute. *SAS/STAT User's Guide*; Release 8.1 Ed. SAS Inst.: Cary, NC, 2000.