IMPROVING POTENTIAL YIELD PREDICTION IN WINTER WHEAT USING IN-SEASON SENSOR BASED MEASUREMENTS

By

ERNA VLADISLAVOVNA LUKINA

Bachelor of Science
Tashkent State University
Tashkent, Uzbekistan
1988

Master of Science
Oklahoma State University
Stillwater, Oklahoma
1998

Submited to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 2001

IMPROVING POTENTIAL YIELD PREDICTION IN WINTER WHEAT USING IN-SEASON SENSOR BASED MEASUREMENTS

Thesis Approved:

William Raun

Thesis Advisor

Gordon V. Johnson

John B. Solie

Timothy J. Pettibone

Dean of the Graduate College

ACKNOWLEDGEMENTS

I would like to express my appreciation to the Department of Plant and Soil Sciences of Oklahoma State University for giving me the opportunity to pursue a doctoral degree. Sincere thanks go to my major advisor Dr. William R. Raun for his leadership, guidance, encouragement, and understanding. It has been a privilege to work and learn within the soil fertility project. I would like to extend my gratitude to the many members of the OSU Soil Fertility project, including: Wade Thomason, Robert Mullen, Kyle Freeman, Roger Teal, Kathie Wynn, Jagadeesh Mosali, Shambel Moges for their help, support and friendship. Gratitude is also expressed to Dr. Gordon V. Johnson for his comments and suggestions and to Dr. Marvin L. Stone, Dr. John B. Solie from the Biosystems and Agricultural Engineering Department. My special thanks goes to Mrs. Essie Raun and Dr. Ned Raun for their constant encouragement and support.

Finally, I would like to thank my mother Borisova Lyubov for help and taking care of my kids, my husband Vladimir for his continuous help and support, and my sons Alexander and Maxim for their patience and understanding.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table Page

Chapter I

Chapter II

LIST OF FIGURES

Figure Page

Chapter I

Chapter II

Figure Page

IMPROVING POTENTIAL YIELD PREDICTION IN WINTER WHEAT USING IN-SEASON SENSOR BASED MEASUREMENTS

INTRODUCTION

Efficient use of agricultural inputs is still problematic in food production. One of the most important and commonly applied fertilizers is nitrogen (N) since it is a building block of proteins. Raun and Johnson (1999) reported that efficiency of N utilization by cereals is about one-third of the total amount applied with fertilizers, which in turn highlights the need to develop methods for increasing N fertilizer use efficiency.

Nitrogen use efficiency (NUE) is also complicated by cropland spatial variability that is known to exist at resolutions (field elements) smaller than 1 m^2 (Solie et al., 1996). Variable fertilizer treatment of crops, where each field element is treated separately, can be an effective alternative to the existing uniform fertilizer application practices. Usually, fertilizer rates are defined by a specified yield goal, taking into account available soil N (Raun et al., 2001). Nitrogen fertilizer requirements depend on the potential N uptake by the crop and which is related to overall yield potential. Potential yield is the yield that can be produced on specific soil at a specific location under specific weather conditions that change annually (Raun et al., 2001).

In-season knowledge of potential yield might be the key to successful variable rate fertilizer applications particularly for topdress N in the spring. Raun et al. (2000) demonstrated that the estimated yield (EY) index was a good predictor of grain yield over a wide range of environmental conditions. They further noted that EY could be used to refine in-season fertilizer N based on predicted potential yield.

Kincheloe (1994) wrote that best management practices must be site specific for each field and areas within fields. By "best management practices" he defined those practices that have been tested in research and proven on the farmers' fields as most effective in terms of input efficiency, production potential and environmental protection. Site-specific fertilizer management is largely determined by how well small-scale variability is managed and the time fertilizers are applied. Ground based on-the-go sensing provides a means for topdress N fertilizer application on a fine scale.

Our goal is to refine the relationship between spatial distribution and predicted potential yield to improve efficiency of N fertilizer use.

EVALUATION OF ALTERNATIVE METHODS FOR DETERMINING ESTIMATED YIELD

ABSTRACT

Efficiency of site-specific fertilizer management is largely determined by how well small-scale variability is managed and the time fertilizers are applied. In-season knowledge of yield potential might be the key to successful variable rate fertilizer applications particularly for winter wheat topdress N in the spring. This study was conducted to estimate influence of various climatological inputs such as air temperature, soil type and moisture with a modified in-season estimated yield (INSEY) index to predict grain yield. Spectral measurements in red (671 ± 6 nm) and near infrared ((NIR) 780 ± 6 nm) bandwidths were collected from 23 winter wheat experiments throughout Oklahoma over four growing seasons, 1998, 1999, 2000, and 2001. Different combinations of sensor readings growing degree days (GDD) and number of days from planting to sensing were considered in order to find the best yield predicting function. The best estimation of grain yield was achieved using the INSEY index with only two input variables, NDVI collected once, anywhere from Feekes growth stage 4 to 6, and number of days from planting to sensing date with GDD above zero. The relationship between this index and winter wheat grain yield for 23 locations over 4 years (where growing conditions, varieties, planting dates, harvest dates, and management varied widely) had a coefficient of determination of 0.55. This index is essentially an indicator of growth rate from plating to sensing, and an estimate of health and development of the crop during that time period.

INTRODUCTION

Presence of spatial variability of plant growth in the field is an issue demanding careful consideration for efficient use of fertilizers. One approach to increase fertilizer use efficiency is variable rate technology (VRT). Different methods of VRT include the use of satellite imaging, grid sampling, and high resolution sensing by ground-based sensors. Aerial or satellite remote sensing can provide information on spatial variability of crop nutrient status and can be used to detect N stress for further fertilizer application at variable rates (Ferguson, 1997, Mangold, 1998). Kanemasu et al. (1985) used a radiometer to sense irradiance of spring wheat canopy for the purpose of evaluating leaf area index (LAI), which was used as an input into a growth and yield model. Spectrally-derived LAI showed promising results in wheat growth and yield modeling.

Carr et al. (1991) investigated economic efficiency of uniform fertilizer rates for wheat and barley versus variable rates in accordance with soil units that had different crop yield potential. They showed positive returns of \$21.68 - \$23.51/ac when optimum treatments for a specific soil were applied rather than uniform rates for the whole field. Although soil units and satellite images distinguish field elements by nutrient availability, their separation is rather poor (coarse scale), which results in low efficiency of variable versus uniform application scheme. Also, using satellite images maybe rather difficult to obtain during cloudy weather conditions.

Grid soil sampling is commonly used for fertilizer recommendations. The most common grid size is between 1.2 and 1.6 ha (Ferguson et al., 1997), from which one composite sample is taken. Usually, this type of coarse resolution soil sampling does not take into account the high variability within the field over short distances. Ferguson et al.

(1997) used two sampling densities in an experiment in Nebraska for N recommendations. Both densities were much higher than commonly used. They found that 45 % of the field had discrepancies in N recommendations derived from grids of different density. To increase accuracy of N recommendations based on grid sampling is a difficult task since it is not clear what grid size is acceptable. Evaluating the profitability of site-specific farming, Swinton and Lowenberg-DeBoer (1998) demonstrated no profitability of variable fertilizer rates applied to 0.5-acre grid for winter wheat and barley. In this regard, high-density grid sampling is very costly and time consuming and could offset the benefits of high-density sampling.

High resolution optical sensing on-the-go VRT should be the most effective of the four methods since it allows application of variable rates based on a field element, that could be smaller than 1 m^2 (Raun et al., 1998; Solie et al., 1999). In addition, on-the-go optical sensing can be used for topdress N application to correct deficiencies during the growing season. This approach will likely reduce the chances of losing nutrients applied pre-plant by immobilization, leaching, and volatilization.

The key point of topdress N application is the growth stage of a crop when this application is done. Wheat planted in the fall has active vegetative growth even in mid-winter months. Depending on hibernation conditions different geographical regions could have stable, unstable or no winter dormancy period for wheat (Chirkov, 1979). Oklahoma has unstable winter dormancy period. Utilizing long-term historical weather data and planting date, Klepper et al., (1988) demonstrated that a stage of crop development could be predicted by using growing degree days (GDD). “Degree-days”, “heat units”, and “thermal units” are different terms that have been used by different authors to designate a degree per day of mean temperature above the base temperature (Nuttonson, 1955). Considering that a specific amount of heat is required by each crop to reach mturity, degree-days could be a reliable estimate of environmental conditions for that crop. Nuttonson (1955) demonstrated that base temperatures of 32 and 40° F (0, 4.4° C, respectively) resulted in the lowest coefficient of variation for the various phenological stages of wheat. However, since there is almost no physiological activity below 40° F, this temperature was chosen as a base line for calculation of degree-days. Studying the use of GDD to project sampling dates in cereals, Klepper et al. (1988) developed a sampling program with target cumulative GDD from planting to sampling at desired crop stages for three widely separated sites in Oregon and Washington. They indicated that 150 cumulative GDD were required for wheat emergence from seeding date when planted into soil with adequate moisture.

Dwyer et al. (1999a) and Stewart et al. (1998) used GDD and its 'derivatives' to rate maize maturity. They assumed that phenological development of corn was constant per degree of temperature between 10° C and 30° C (minimum and a maximum threshold air temperature, respectively). They also assumed that development rate beyond this range was zero. They evaluated several indices developed on the basis of GDD. The best predictability of maturity dates was obtained using general thermal index (GTI) based on fitted maize development temperature response functions for the vegetative and grain-filling periods (Dwyer et al., 1999b). Basically, GTI was a sum of polynomial functions of GDD components for these two development periods.

In a historical review of the heat unit approach, Wang (1960) pointed out that it had been in use for over two hundred years. Different researchers tried to develop new equations, which would take into account wind velocity, solar radiation, duration of light, etc. Despite existing limitations, the heat unit approach was widely adopted due to its satisfying practical usage and lack of other systems that take into account environmental conditions, which could effectively replace it.

Moulin and Beckie (1993) studied the predictive ability of CERES (Crop Estimation through Resource and Environment Synthesis) and EPIC (Erosion/Productivity Impact Calculator) models for forecasting spring grain yield over time. The CERES model was based on daily precipitation, maximum and minimum temperature, and solar radiation, while EPIC model required wind speed and relative humidity in addition to the above mentioned variables. Various groups have demonstrated that both models provided accurate estimates of long-term average grain yields, which could be valuable in long-term management decisions. Otter and Ritchie (1985) investigated the CERES-wheat model, and they assembled a data base of 300 crop years from 25 sites around the world with various soil types, weather, and management systems. They also included in the data base information on yield and some phenological stages. They confirmed that CERES model had a wide application range. However Moulin and Beckie (1993) suggested CERES and EPIC simulation models had given poor performance for predicting annual yields, because year-to-year variability of yield was a function of weather.

OBJECTIVES

The objective of this study was to develop an index to allow estimation of grain yield from crop reflectance measurements.

MATERIALS AND METHODS

Spectral measurements were collected from 23 winter wheat experiments scattered throughout Oklahoma over four growing seasons, 1998, 1999, 2000, and 2001. In 1998, spectral readings were taken from areas 0.84 m^2 at three experimental fields at Perkins and Tipton, OK. In 1999, 2000, and 2001, spectral measurements and grain yield were collected from 4.0 m^2 areas. Pre-plant soil test and chemical characteristics, as well as treatment structure for these experiments are reported in Tables 1 and 2, respectively. All experiments employed a randomized complete block experimental design. For all experiments listed in Table 2, N, P and K were applied prior to planting and disk incorporated at the rates reported. Twenty-one experiments were planted at seeding rate of 78 kg ha^{-1} with 0.19 m row spacing, while S&N experiments at Perkins and Tipton in 1998 had various row spacings ranging from 0.15 to 0.30 m with seeding rates ranging from 49 to 99 kg ha^{-1}.

Spectral reflectance measurements from the winter wheat canopy were taken in two bands, RED (671 ± 6 nm) and near infrared ((NIR) 780 ± 6 nm) bandwidths (Stone et al., 1996). The reflectance sensor employed photodiode detectors with interference filters. One pair of filters (up-looking) received incoming light from the sun, and the other pair (down-looking) received light reflected by vegetation and/or soil surface. The sensor used a 16 bit A/D converter that converted the signals from all four photodiode sensors simultaneously. The ratio of readings from down-looking to up-looking photodiodes minimized fluctuation among readings due to differences in atmospheric conditions, and shadows. Three sets of sensor readings were taken during the growing season. Planting, sensing, and harvest dates are reported in Table 3. The normalized difference vegetative index (NDVI) was calculated as:

(1)
$$NDVI = \frac{\left(\frac{NIRref}{NIRinc} - \frac{REDref}{REDinc}\right)}{\left(\frac{NIRref}{NIRinc} + \frac{REDref}{REDinc}\right)},$$

where *ref* and *inc* stand for reflected light and incident light readings.

EY, EY2, EY3 and INSEY indices were also evaluated as follows:

(2)
$$EY = \frac{NDVI_{T_1} + NDVI_{T_2}}{Days\ from\ T_1\ to\ T_2},$$

(3)
$$EY2 = \frac{(NDVI_{T_1} + NDVI_{T_2})}{CGDD\ from\ T_1\ to\ T_2},$$

(4)
$$EY3 = \frac{NDVI\ at\ Feekes5}{CGDD\ from\ planting\ to\ sensing},$$

(5)
$$EY4 = \frac{NDVI\ at\ Feekes5}{Days\ from\ planting\ to\ sensing}.$$

For these equations, T_1 and T_2 were times of the first and second sensor readings, and CGDD was cumulative growing degree-days between two dates. GDD was calculated as follows:

(6)
$$GDD = \left[\frac{TEMPmax + TEMPmin}{2} - 4.4^{\circ}C\right],$$

Daily maximum and minimum temperatures in centigrade were used. CGDD was taken as a sum of the positive daily GDD values between two dates (Rickman et al., 1996). Different combinations of sensor readings taken at three different times were considered in order to find the best time for taking sensor measurements for the sake of predicting yield. EY, EY2 and EY3 computation was based on two sets of sensor readings, while INSEY required only one reading.

$$(7) \qquad INSEY = \frac{NDVI_{T_1}}{DAYS\ from\ planting\ to\ T_1\ GDD > 0}.$$

The advantage of using only one set of readings is that it allows good prediction of grain yield without having to sense a field two times in one season.

RESULTS AND DISCUSSION

Raun et al. (2001) defined measured, potential, and maximum grain yield as follows: grain yield that was harvested in a given year at a given location is measured grain yield; yield predicted in mid growing season for a given year and site, based on the assumption that the level of growth factors responsible for early stages of 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) as potential grain yield; and yield obtained when all manageable growth factors (e.g., nutrients and pests) were non-limiting under ideal environmental conditions as maximum grain yield. Depending on the environment, potential grain yield would always be less then or equal to maximum grain yield.

First approach (Sum of NDVI at two growth stages to predict grain yield)

Past work at Oklahoma State University showed high predictability of wheat biomass and total N uptake by NDVI (Stone et al., 1996, Solie et al., 1996, Sembiring et al., 2000). We took several sensor readings between Feekes growth stages 4 and 6 each year, in order to evaluate the best stage of development for making spectral measurements of the crop.

In the first year, we had three experiments at two locations (Perkins S&N, Perkins N&P, and Tipton S&N). Figure 1 demonstrates that spectral measurements taken at Feekes growth stage 4 and 5 could be used as predictors of grain yield (R^2=0.73 and 0.75, respectively). However, when yield-limiting factors are expressed after the spectral measurements are taken, predictive equations are found to be less accurate. Assuming that growth from planting in October to mid-winter sensing provides a reliable indicator of wheat health and seasonal growth-limiting conditions for that time period, various combinations of NDVI at two growth stages, GDD, and total days between readings were evaluated. The sum of two NDVI values from Feekes growth stage 4 and 5 had even better correlation with grain yield (R^2=0.82) compared to correlation with a single sensor reading (Figure 2).

Second approach (Sum of NDVI at two growth stages and number of days between sensings to predict grain yield)

Single NDVI or sum of NDVI values from two growth stages did not employ a method to account for environmental conditions, which could create a problem when attempting to evaluate predictability of the index for different sites with widely varying environmental conditions. In this regard, the total number of days and/or GDD between two sensing dates were thought to provide a possible adjustment for weather conditions. Indices EY and EY2 (equation 2 and 3, respectively) were developed as alternatives for predicting grain yield. Plotting EY against grain yield from three experiments resulted in improved correlation (R^2=0.88) between these two variables (Figure 3). Six additional experimental locations were evaluated and added to express the function in the next year the of study. Combined data for 9 locations over two years are presented in Figure 4. Those sites where deviation was notable from the trend line could be explained by environmental effects such as: 1) late planting (Nov. 9, 1998) and high rainfall at the end of the season at Efaw AA; 2) delayed grain harvest by 3 - 4 weeks due to rainfall resulting in wheat lodging and shattering, and consequently reduced yield at Experiment 502; and 3) low water holding capacity of the sandy loam soil at Perkins (1999). Removing the three sites mentioned, improved the correlation of EY with final grain yield, and explained 66 % of the variation in grain yield (Figure 5).

Third approach (Sum of NDVI at two growth stages and GDD between sensings to predict grain yield)

Additional locations revealed the deficiency of the existing function. The number of days between sensings as a denominator, needed to be replaced with a more appropriate divisor. The relationship was somewhat improved by using EY2 where GDD between sensings was used as a divisor (Figure 6). Removing problematic sites resulted in greater improvement of the relationship between EY2 and grain yield (R^2=0.69) compared to that with EY (Figures 6 and 7).

When considering the use of two sensor readings, we recognized that those taken at Feekes growth stage 4 characterized establishment and growth from planting to the end of dormancy. The second sensing at Fekees growth stage 5 reflected post dormancy growth over a short period of time.

In the year 2000, data from 7 other experiments were incorporated in the expected yield function. Fitting all the data to an existing function increased the error in the relationship between EY2 and grain yield. Due to wide variations in environmental conditions among various locations and years, the sum of two NDVI values and GDD between dates of spectral measurements did not provide reliable prediction of yield (Figure 8). Another index, EY3, was tested to evaluate GDD from planting to sensing (Figure 9). We assumed that taking cumulative GDD from planting to sensing could provide a reliable adjustment for readings from different experiments and that could be applied to the same scale. Results from 16 locations over 3 years did not confirm this assumption. Elimination of problematic sites discussed earlier did not improve the relationship. Dwyer et al., (1999b) reported that the GDD concept often overestimates the heat units required for grain filling. They also pointed out that predicting crop maturity using GDD may be off by several hundred heat units which was especially pronounced in colder years. Similar overestimation might be possible in the assessment of vegetation development of the crop. To avoid overestimation, we decided to use the number of days from planting to sensing as a divisor in an EY4 index. The EY4 index was a better predictor of yield, having a coefficient of determination of 0.62 (Figure 10). Data from seven additional experiments were included in the existing index in the fourth year of our study. Figure 11 shows the relationship of EY4 with grain yield obtained from 23 locations over 4 years (R^2=0.50). The number of days from planting to sensing varied considerably depending on the year and/or location (Table 4). For instance, the highest number of days from planting to sensing was observed at the Haskell location, experiment 801 in the year 2001 (191 days). At Perkins (experiment N&P) in 1999, the lowest number of days between these two dates was 122 days (Table 4).

Final approach so far

Considering that the total number of days does not precisely indicate the conditions conducive to biological growth, we decided to take into account the number of days between planting and sensing where GDD was above zero. This assumes that variations in environmental conditions due to weather differences would be accounted for in our calculations. The number of days where conditions were conducive for biological growth ranged from 55 at Lahoma in the year 2001 to 127 at Haskell, in the year 2000 (Table 4). Equation 7 presents the best estimation of yield, which we call the INSEY index. Figure 12 demonstrates the relationship between this index and winter wheat grain yield for 23 locations over 4 years with a coefficient of determination of 0.55, and that encumbered all sites.

The INSEY index gave the best estimation of grain yield using only two variables, which were: NDVI collected once, anywhere from Feekes growth stage 4 to 6, and number of days from planting to sensing date with GDD above zero (Figure 12). It was important to revisit the relationship between one NDVI reading (collected from Feekes 4 and 6) and grain yield (Figure 13). Although this relationship remained significant, dividing by the number of days where GDD>0 (Figure 12) improved correlation and thus the reliability of predicting yield over locations and years where management and inputs varied considerably. In light of the many things that can happen post sensing, it was exciting to find an index that could predict yield 55 % of the time over 23 sites and 4 years.

CONCLUSION

Indirect crop sensing techniques can increase the opportunities that we have to refine inputs in agricultural crop production. Ground-based spectral measurements proved to be an effective management tool in order to predict final grain yield. Comparison of these indices demonstrated that INSEY was the most efficient index in terms of grain yield prediction. This index is essentially an indicator of growth rate from planting to sensing, and an estimate of health and development of the crop during that time period. In many regards, it was exciting to find that grain yield could be predicted using one sensor reading (accounting for the days from planting to sensing where GDD>0) since this proved to be valid over 23 locations and 4 years where growing conditions, varieties, planting dates, harvest dates, and management were drastically different.

REFERENCES

Carr, P.M., G.R. Carlson, J.S. Jacobsen, G.A. Nielsen, and E.O. Skogley. 1991. Farming soils, not fields: a strategy for increasing fertilizer profitability. J. Prod. Agric., 4(1):57-61.

Chirkov Y.I. 1979. The climate of grain crops. p. 145-151. In J. Seemann, Y.I. Chirkov, J. Lomas, B. Primault. Agrometeorology. Springer-Verlag Berlin Heidelberg.

Dwyer, L.M., D.W. Stewart, L. Carrigan, B.L. Ma, P. Neave, and Balchin. 1999b. Guidelines for comparisons among different maize maturity rating systems. Agron. J. 91:946-949.

Dwyer, L.M., D.W. Stewart, L. Carrigan, B.L. Ma, P. Neave, and Balchin. 1999a. A general thermal index for maize. Agron. J. 91:940-946.

Ferguson, R.B., G.W. Hergert, J.S. Schepers. 1997. Strategies for site-specific nitrogen management. p. 387-395. In J.V. Stafford (ed.) Precision agriculture'97: I. Spatial variability in soil and crop.

Kanemasu, E.T., G. Asrar, and M. Fuchs. 1985. Application of remotely sensed data in wheat growth modeling. p. 357-369. In W. Day and R.K. Atkin (ed.) Wheat growth and modelling. Plenum Press, New York, NY.

Kincheloe, S. 1994. Tools to aid management: The use of site specific management. J. Soil Water Conserv., 49(2):43-47.

Klepper, B., R.W. Rickman, J.F. Zuzel, and S.E. Waldman. 1988. Use of growing degree days to project sample dates for cereal crops. Agron. J. 80:85-852.

Large, E.C. 1954. Growth stages in cereals. Plant Pathol. 3:128-129.

Mangold, G. 1998. Crop images. Successful farming. 96(7):44-45.

Moulin A.P., H.J. Beckie. 1993. Evaluation of the CERES and EPIC models for predicting spring wheat grain yield over time. Can. J. Plant Sci. 73:713-719.

Nuttonson, M.Y. 1955. Wheat-climate relationships and the use of phenology in ascertaining the thermal and photo-thermal requirements of wheat. Amer. Inst. Of Crop Ecol. Washington, DC.

Otter, S. and J.T. Ritchie. 1985. Validation of CERES-wheat model in diverse environments. p. 307-310. In W. Day and R.K. Atkin (ed.) Wheat growth and modelling. Plenum Press, New York, NY.

Raun, W. R., and G. V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron J. 91:357-363.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, and W.E. Thomason, and J.S. Shepers. 2001. In-season prediction of yield potential in winter wheat. Agron. J. 93(1):131-138.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Whitney, H.L. Lees, H. Sembiring, and S.B. Philips. 1998. Microvariability in soil test, plant nutrient, and yield parameters in bermudagrass. Soil Sci. Soc. Am. J. 62:683-690.

Rickman, W.R., S.E. Waldman and B. Klepper. 1996. MODWht3: A development-driven wheat growth simulation. Agron. J. 88:176-185.

Sembiring, H., H.L. Lees, W.R. Raun, G.V. Johnson, J.B. Solie, M.L. Stone, M.J. Deleon, E.V. Lukina, D.A. Cossey, J.M. Laruffa, C.W. Woolfolk, S.B. Phillips, and W.E. Thomason. 2000. Effect of growth stage and variety on spectral radiance in winter wheat. J. Plant Nutr. 23:141-149.

Solie, J.B., W.R. Raun, R.W. Whitney, M.L. Stone, J.D. Ringer. 1996. Optical sensor based field element size and sensing strategy for nitrogen application. Trans. ASAE 39(6):1983-1992.

Solie, J.B., W.R. Raun, and M.L. Stone. 1999. Submeter spatial variability of selected soil and bermudagrass production variables. Soil Sci. Soc. Am. J. 63:1724-1733.

Stewart, D.W., Dwyer, L.M., and L.L. Carrigan. 1998. Phenological temperature response of maize. Agron. J. 90:73-79.

Stone, M.L., J.B. Solie, W.R. Raun, R.W. Whitney, S.L. Taylor, and J.D. Ringer. 1996. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. Trans. ASAE. 39(5):1623-1631.

Swinton, S.M. and Lowenberg-DeBoer. 1998. Evaluating the profitability of site-specific farming. J. Prod. Agric. 11:439-446.

Wang, J.Y. 1960. A critique of the heat unit approach to plant response studies. Ecology 41:785-790.

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

Location	N-P-K	pH	NH_4-N	NO_3-N	P	K	Total N	Organic C
	---kg ha^{-1}---		-------------- mg kg^{-1} ---------------				---------- g kg^{-1} -------	
Efaw AA	check	6.0	2.5	11.3	19.9	197	0.94	10.4
Classification:	Easpur loam (fine-loamy, mixed,superactive, thermic Fluventic Haplustoll)							
Efaw SS	check	5.8	6.9	5.0	30.2	16.8	1.06	11.9
Classification:	Norge loam (fine mixed, thermic Udertic Paleustoll)							
Haskell 801	check	5.3	7.4	3.4	8.5	163	0.70	7.4
	112-58-74	4.7		31.7	82	193	0.8	8.0
Classification:	Taloka silt loam (fine, mixed, thermic Mollic Albaqualf)							
Hennessey	check	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	check	5.5	5.3	13.9	39.9	416	0.80	7.4
	90-19-56	5.4			76.0	453	0.90	9.2
Classification:	Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll)							
Perkins N&P	check	5.4	2.6	9.1	16.5	132	0.79	7.0
Classification:	Teller sandy loam (fine-loamy, mixed, thermic Udic Argiustoll)							
Perkins S&N	check	5.4	2.6	9.1	16.5	132	0.79	7.0
Classification:	Teller sandy loam (fine-mixed, thermic Udic Argiustoll)							
Stillwater 222	check	5.9	12.0	8.6	4.9	192	0.96	7.9
	90-29-37	5.5			34.0			1.1
Classification:	Kirkland silt loam (fine, mixed, thermic Udertic Paleustoll)							
Tipton S&N	check	7.4	4.4	8.6	31.8	462	0.86	8.3
Classification	Tipton silt loam (fine-loamy, mixed, thermic Pachic Argiustoll)							

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

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

	Efaw AA[a]	Efaw SS	Haskell 801	Hennessey[a]	Lahoma 502	Perkins N&P	Perkins S&N[a]	Stillwater 222	Tipton S&N
	----------N-P_2O_5-K_2O (kg ha^{-1})----------								
Treatments	0-0-0	0-0-0	0-0-0	0-0-0	0-0-0	0-67-0	0-0-0	0-0-0	0-0-0
	56-0-0-VB[b]	45-0-0	0-134-134	56-0-0	0-45-67	56-67-0	56-0-0	0-67-45	56-0-0
	90-0-0-VB[b]	90-0-0	112-134-134	90-0-0	22-45-67	112-67-0	112-0-0	45-67-45	112-0-0
	123-0-0-VB[b]	179-0-0	112-0-134	123-0-0	45-45-67	168-67-0	168-0-0	90-67-45	168-0-0
	56-0-0-B[c]	269-0-0	112-45-134	(Two application methods)	67-45-67		(at 4 row spacings)	134-67-45	(at 4 row spacings)
	90-0-0-B[c]	538-0-0	112-90-134		90-45-67				
	123-0-0-B[c]		168-134-134		112-45-67				

---

[a] – preplant application of 90 kg ha^{-1} P_2O_5.

[b] – anhydrous ammonia applied by V-blade

[c] – ammonium nitrate applied by barber sprayer

Table 3. Planting, sensor readings, and harvest dates, at Efaw, Haskell, Hennessey, Lahoma, Perkins and Stillwater, OK.

	EfawAA	EfawSS	Haskell 801	Hennessey	Lahoma502	Perkins N&P	Perkins S&N	Stillwater 222	TiptonS&N
				1997-98					
Planting date	-	-	-	-	-	10/21/97	10/21/97		10/07/97
Sensing date at Feekes 4:	-	-	-	-	-	02/24/98	02/24/98		01/27/98
Sensing date at Feekes 5:	-	-	-	-	-	04/02/98	04/06//98		02/26/98
Grain harvest date:	-	-	-	-	-	06/15/98	06/15/98		06/03/98
				1998-1999					
Planting date:	11/09/98	10/15/98	10/16/98	11/25/98	10/09/98	10/12/98	-	10/13/98	-
Sensing date at Feekes 4:	02/19/99	02/19/99	02/16/99	03/05/99	02/10/99	02/12/99	-	01/18/98	-
Sensing date at Feekes 5:	03/24/99	03/24/99	03/23/99	03/25/99	03/05/99	03/04/99	-	02/24/99	-
Grain harvest date:	06/15/99	06/15/99	07/06/99	06/29/99	06/30/99	06/9/99	-	06/15/99	-
				1999-2000					
Planting date:	10/07/99	10/07/99	10/08/99	10/07/99	10/12/99	10/08/99	-	10/07/99	-
Sensing date 1:	01/03/00	01/03/00	01/14/00	01/11/00	01/13/00	12/17/99	-	01/04/00	-
Sensing date 2:	02/10/00	02/10/00	03/14/00	02/15/00	02/15/00	02/08/00	-	02/10/00	-
Sensing date 3:	03/06/00	03/06/00	-	03/13/00	03/13/00	03/07/00	-	03/06/00	-
Grain harvest date:	07/07/00	06/02/00	06/02/00	06/07/00	06/13/00	05/30/00	-	07/06/00	-
				2000-2001					
Planting date:	11/22/00	11/16/00	10/04/00	11/21/00	12/01/00	11/17/00	-	11/20/00	-
Sensing date 1:	03/30/01	03/30/01	04/12/01	04/05/01	04/13/01	04/04/01	-	04/05/01	-
Sensing date 2:	04/23/01	04/23/01	04/24/01	04/13/01	-	04/23/01	-	04/23/01	-
Sensing date 3:	04/30/01	04/30/01	05/03/01	05/10/01	05/10/01	04/30/01	-	04/30/01	-
Grain harvest date:	06/11/01	06/11/01	06/06/01	06/13/01	06/15/01	06/07/01	-	06/12/01	-

MM/DD/YY – month/ day/year

Table 4. GDD and rainfall data for 23 experiments over 4 years.

Sign on graphs	Location/ Experiment	Year	Planting Date	Total number of days from planting to sensing	Number of days from planting to sensing with GDD>0	Rainfall		
						Planting to Maturity	Planting to Feekes 5	Feekes 5 to Harvest
						mm		
△	Tipton S&N	1998	Oct 07, 1997	142	104	415	277	138
■	Perkins S&N	1998	Oct 21, 1997	167	99	638	396	242
◉	Perkins N&P	1998	Oct 21, 1997	163	95	638	396	242
○	Perkins N&P	1999	Oct 12, 1998	142	113	655	244	411
◆	- - - - - - - - -	2000	Oct 08, 1999	122	99	514	203	311
△	- - - - - - - - -	2001	Nov 17, 2000	165	91	444	208	236
△	Stillwater 222	1999	Oct 13, 1998	133	102	759	305	454
◬	- - - - - - - - -	2000	Oct 07, 1999	150	114	810	292	518
◇	- - - - - - - - -	2001	Nov 20, 2000	155	80	341	171	170
○	Stillwater_Efaw 301	1999	Oct 15, 1998	159	122	759	309	450
□	- - - - - - - - -	2000	Oct 07, 1999	150	114	588	292	296
□	- - - - - - - - -	2001	Nov 16, 2000	166	88	341	171	170
◆	Stillwater_Efaw AA	1999	Nov 09,1998	134	96	596	146	450
○	- - - - - - - - -	2000	Oct 07, 1999	150	114	810	292	518
◆	- - - - - - - - -	2001	Nov 22, 2000	160	87	341	171	170
▲	Haskell 801	1999	Oct 16, 1998	157	123	1016	600	416
◇	- - - - - - - - -	2000	Oct 10, 1999	157	127	703	342	361
▨	- - - - - - - - -	2001	Oct 04, 2000	191	115	823	561	262
◇	Lahoma 502	1999	Oct 09, 1998	146	107	882	337	545
▨	- - - - - - - - -	2000	Oct 12, 1999	152	109	536	317	219
◆	- - - - - - - - -	2001	Dec 01, 2000	134	55	362	167	195
○	Hennessey AA	2000	Oct 07, 1999	157	119	603	341	262
▲	- - - - - - - - -	2001	Nov 11, 2000	144	72	387	195	192

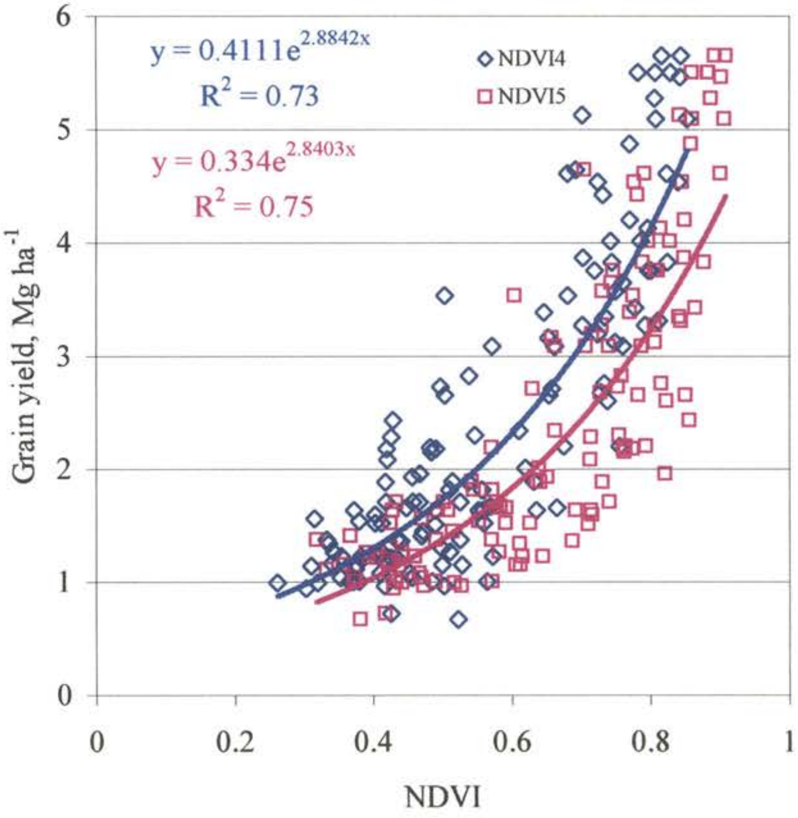

Figure 1. Relationship between grain yield and NDVI readings collected at Feekes growth stage 4 (NDVI4) and growth stage 5 (NDVI5) in three experiments in 1998, Perkins and Tipton, OK.

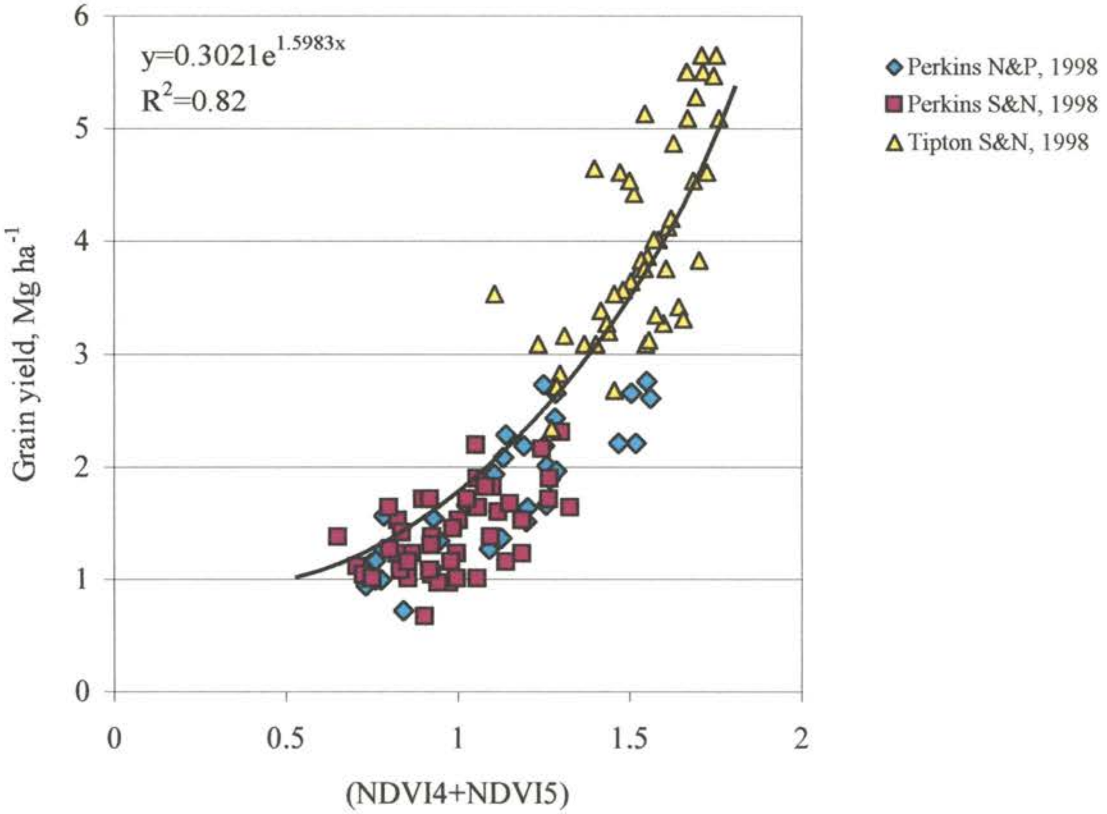

Figure 2. Relationship between grain yield and the sum of NDVI readings (Feekes 4 and 5), at three locations in Oklahoma, 1998.

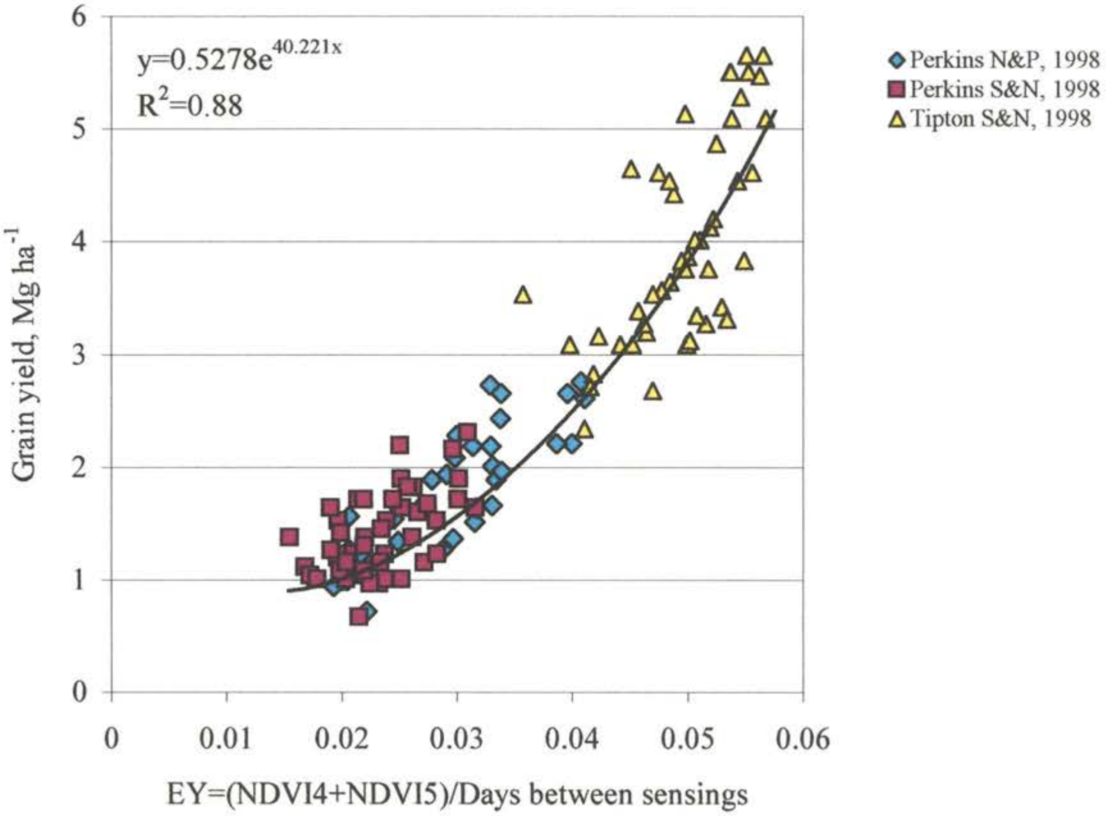

Figure 3. Relationship between grain yield and the sum of NDVI readings (Feekes 4 and 5) divided by days between sensings, at three locations in Oklahoma, 1998.

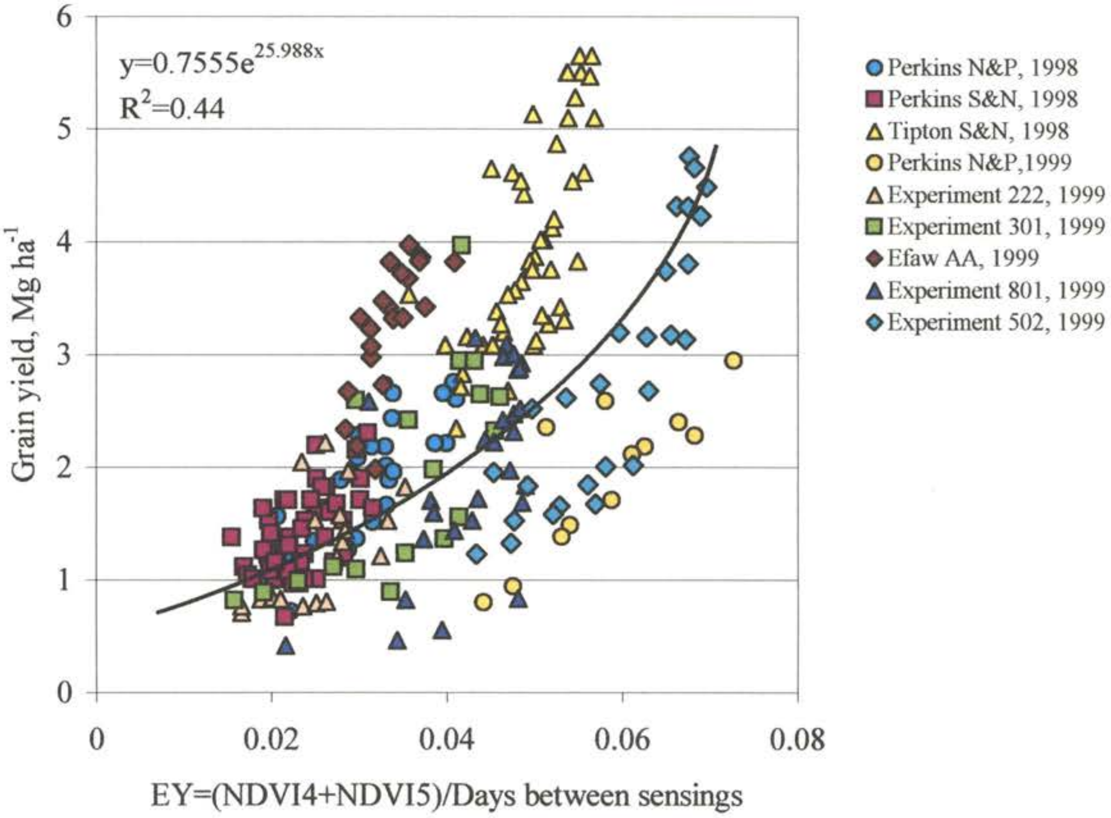

Figure 4. Relationship between grain yield and the sum of NDVI readings (Feekes 4 and 5) divided by days between sensing, at nine locations in Oklahoma, 1998 and 1999.

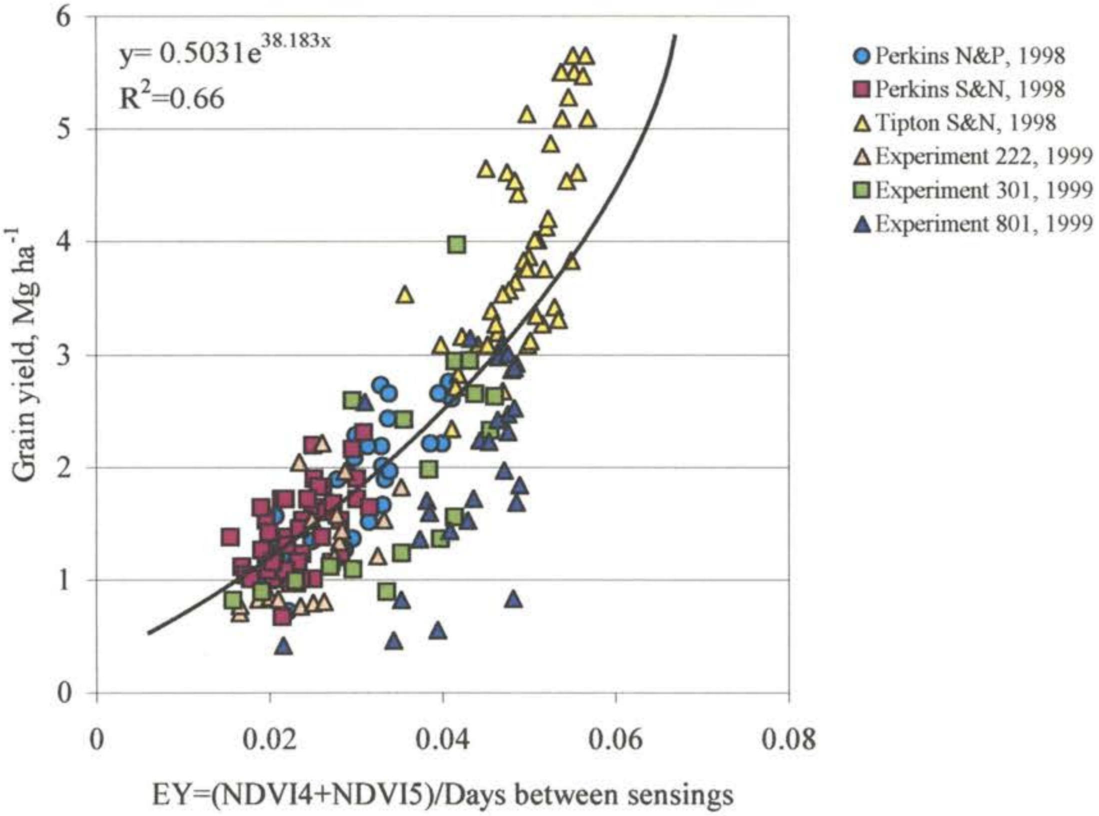

Figure 5. Relationship between grain yield and the sum of NDVI readings (Feekes 4 and 5) divided by days between sensings (excluding three locations) in Oklahoma, 1998 and 1999.

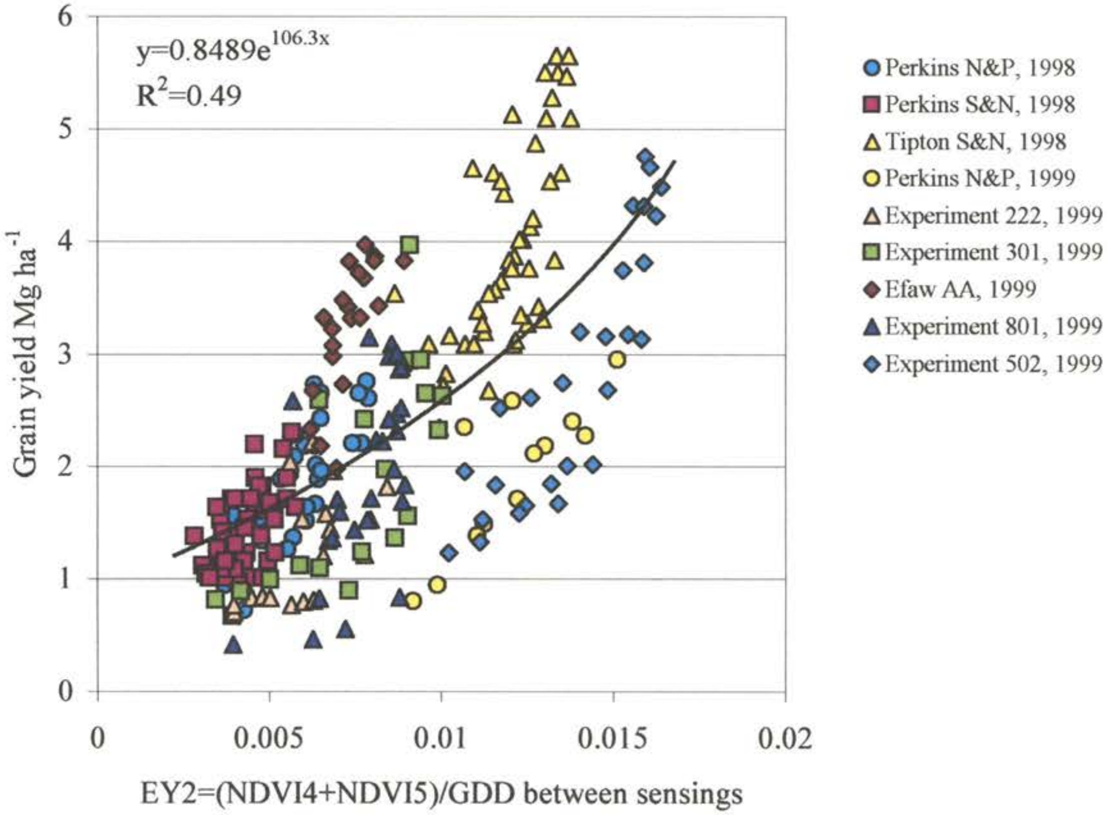

Figure 6. Relationship between grain yield and sum of NDVI readings (Feekes 4 and 5) divided by GDD between sensings at nine locations in Oklahoma, 1998 and 1999.

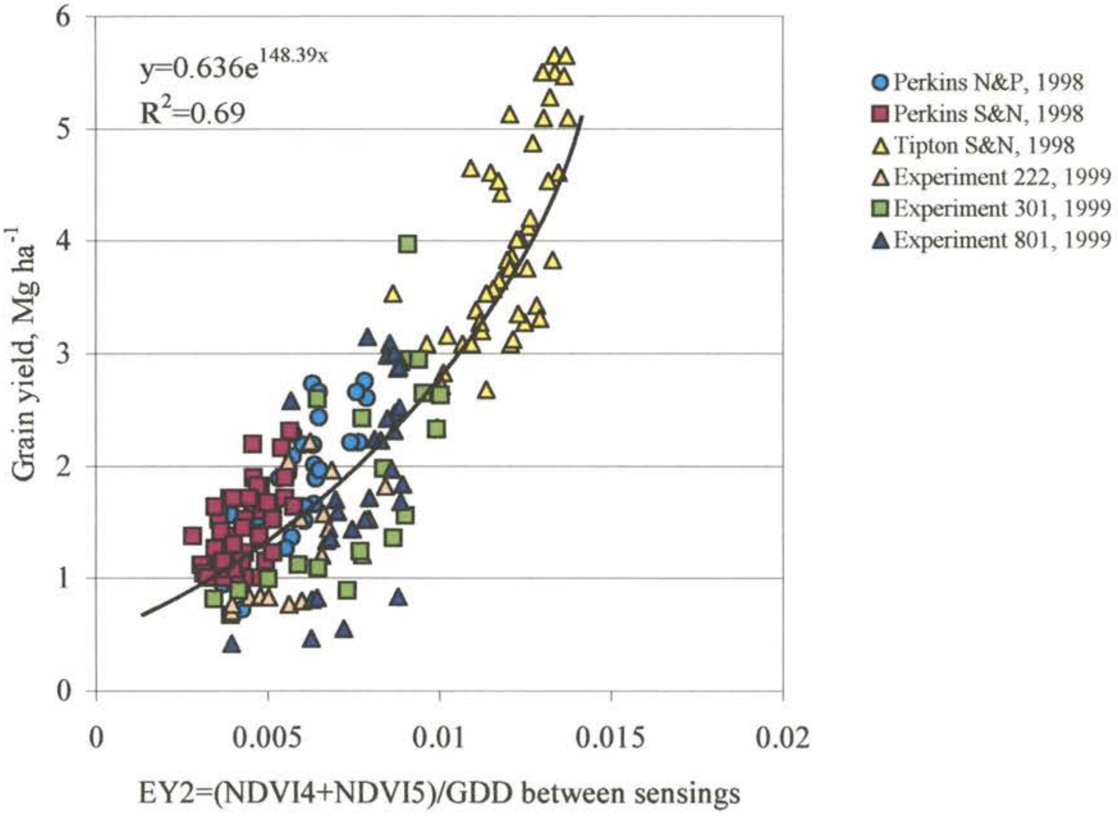

Figure 7. Relationship between grain yield and sum of NDVI readings (Feekes 4 and 5) divided by GDD between sensings at six locations in Oklahoma, 1998 and 1999.

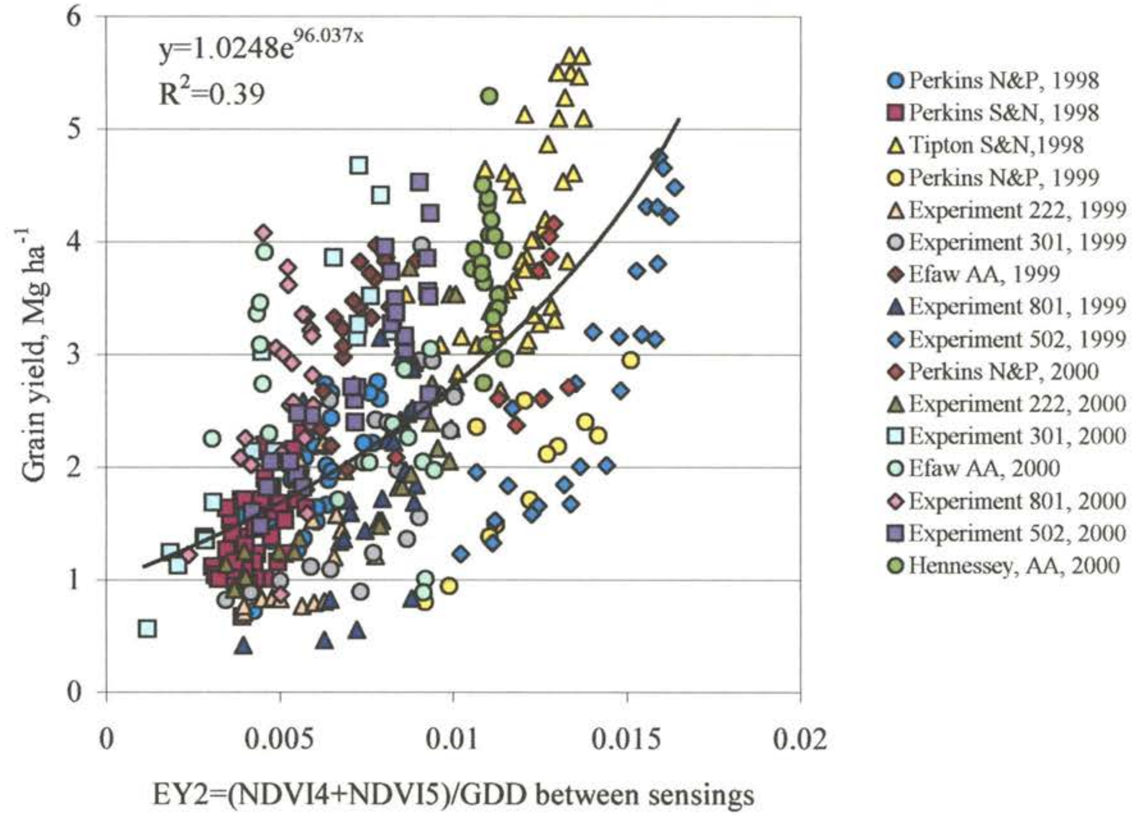

Figure 8. Relationship between grain yield and sum of NDVI readings (Feekes 4 and 5) divided by GDD between sensings at 16 locations in Oklahoma, 1998, 1999, and 2000.

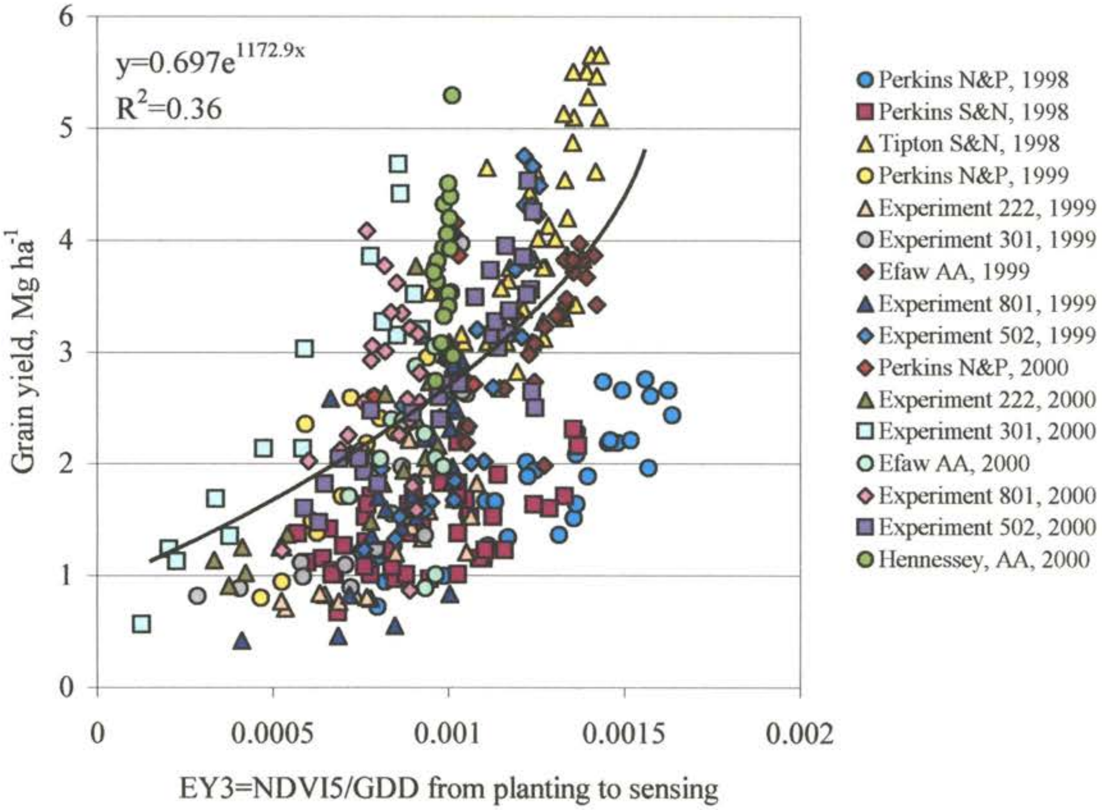

Figure 9. Relationship between grain yield and single NDVI reading (Feekes 5) divided by GDD from planting to sensing at 16 locations in Oklahoma, 1998, 1999, and 2000.

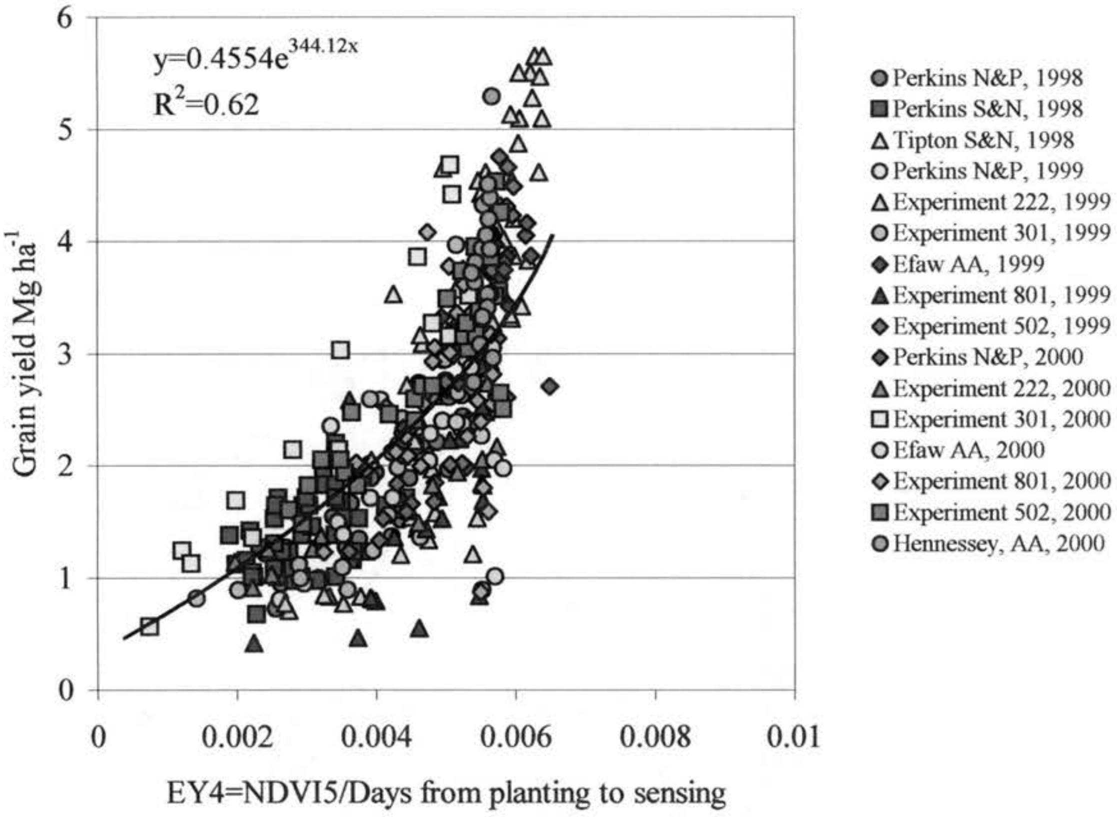

Figure 10. Relationship between grain yield and single NDVI reading (Feekes 5) divided by days from planting to sensing at 16 locations in Oklahoma, 1998, 1999, and 2000.

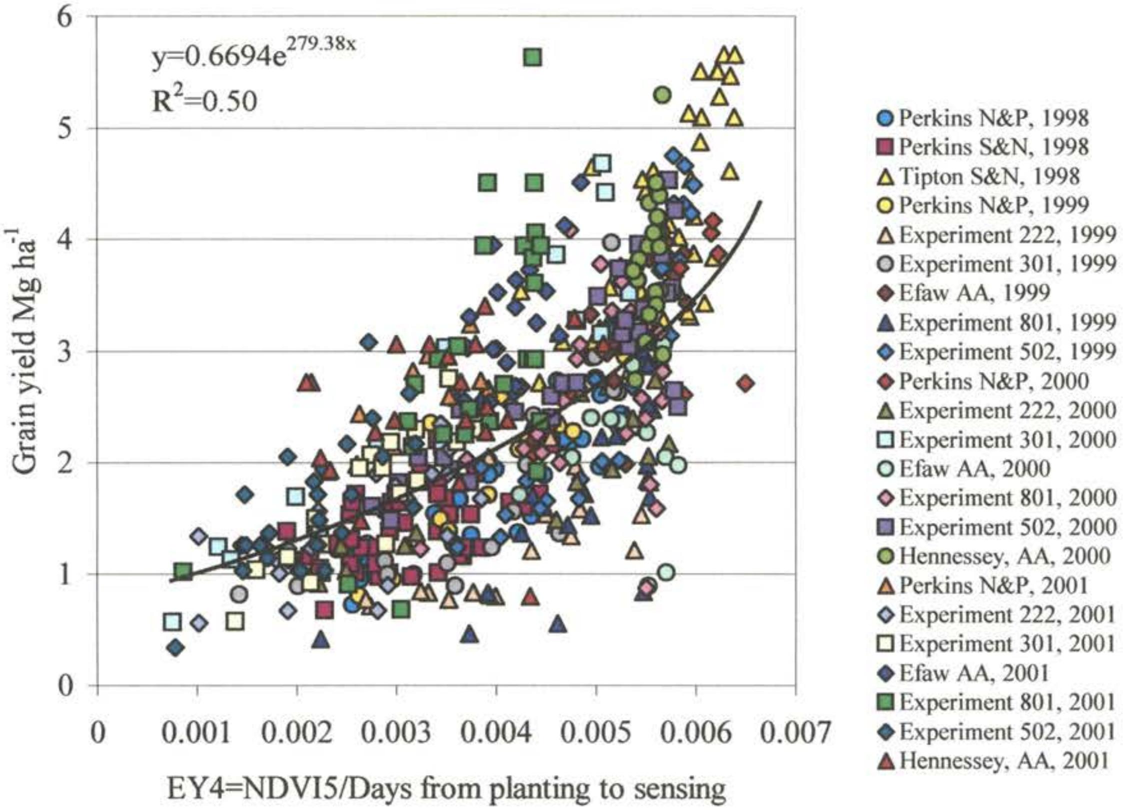

Figure 11. Relationship between grain yield and single NDVI reading (Feekes 5) divided by days from planting to sensing at 23 locations in Oklahoma, 1998, 1999, 2000, and 2001.

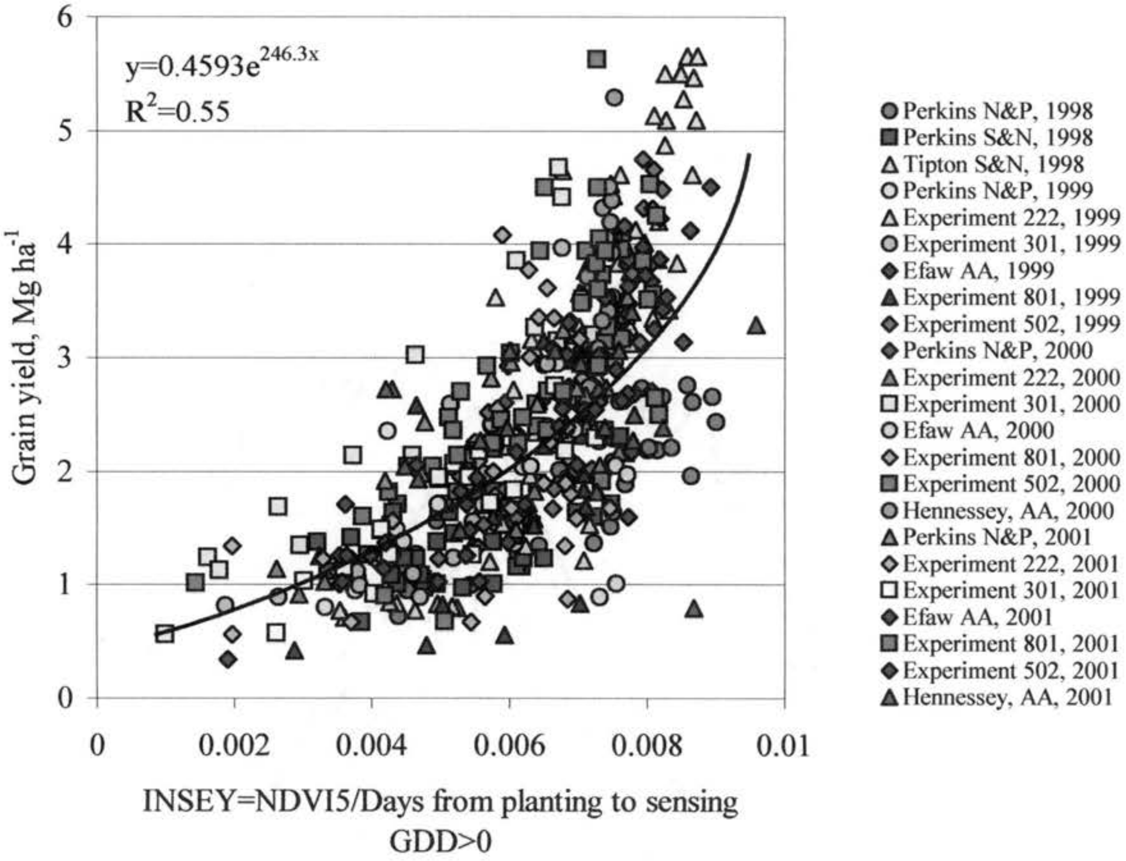

Figure 12. Relationship between grain yield and single NDVI reading (Feekes 5) divided by days from planting to sensing with GDD>0 at 23 locations in Oklahoma, 1998, 1999, 2000, and 2001.

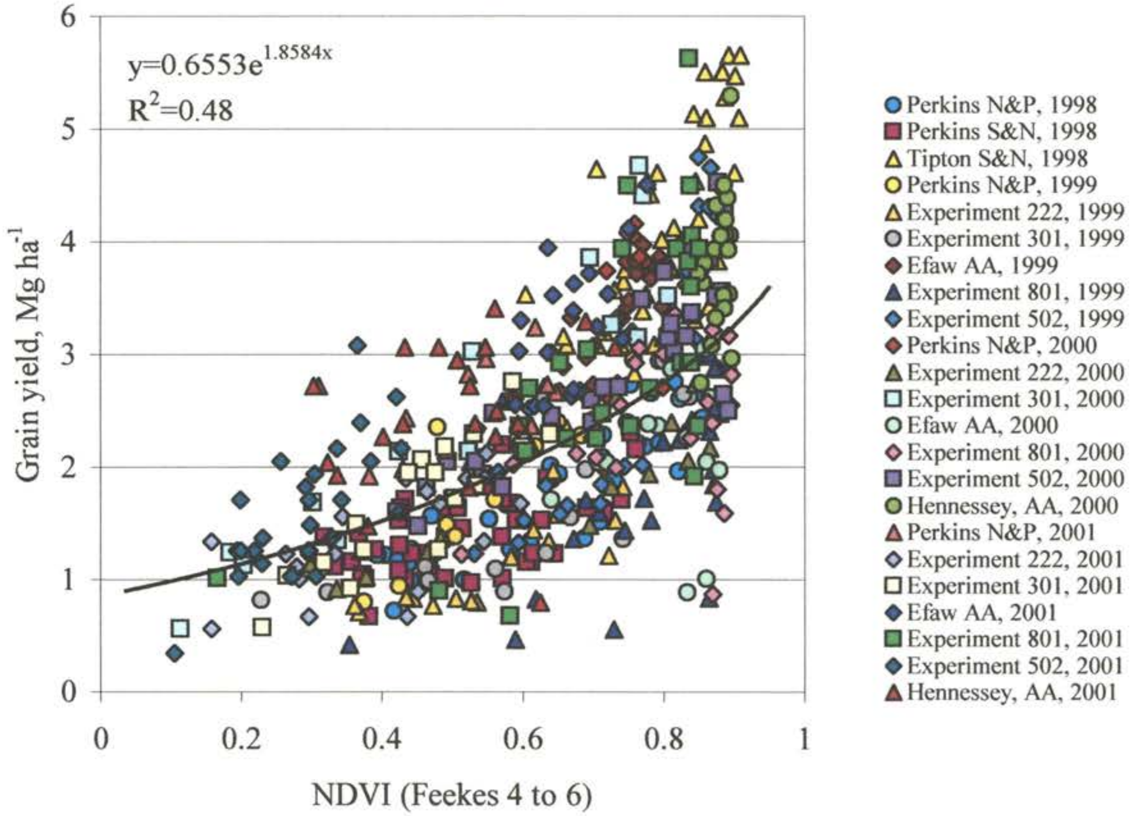

Figure 13. Relationship between grain yield a single NDVI reading (Feekes 4-6) at 23 locations in Oklahoma, 1998, 1999, 2000, and 2001.

USE OF IN-SEASON ESTIMATE OF YIELD FOR TOPDRESS APPLICATIONS OF FERTILIZER NITROGEN IN WINTER WHEAT

ABSTRACT

It is a common practice to apply a uniform N rate consistent with a specified N requirement based on the yield goal adjusted for inorganic N available in the soil. This method does not take into account potential of a particular field to produce a certain yield. Variable fertilizer rates determined using fine-resolution ground-based sensors, should reduce the total field N rate, and optimize nitrogen use efficiency (NUE) due to more effective recognition of spatial variability. These experiments were established to determine if topdress N fertilization rates could be adjusted using in-season estimates of wheat grain yield potential and to compare adjusted N fertilizer rates based on the in-season-estimated-yield (INSEY) index with fixed N rates applied at Feekes 5. Thirteen winter wheat field experiments were conducted from 1999 to 2001. Nitrogen use efficiency of variable topdress rates (prescribed amounts applied to each 1 m^2) was higher compared to the fixed N rates applied in spring. The index INSEY proved to be a reliable predictor of potential yield and could be used for adjustment of in-season N fertilization. Considering that different climatological conditions affect crop growth and development and that they vary widely from year to year at the same location, on-the-go sensing and mid-season fertilizer application should be the best way to correct nutrient deficiencies in order to obtain the best achievable yield.

INTRODUCTION

Uniform N rates consistent with a specified N requirement based on the yield goal, adjusted for inorganic N in the soil is common in cereal crops (Raun et al., 2001). This method does not take into account potential of the particular field to produce a certain yield. Efficient use of fertilizers applied under agricultural crops is dictated by economical and environmental concerns. Often producers apply excessive N for the sake of higher yields, which leads to environmental problems. Schepers et al. (1991) reported that on 14% of the corn production area studied, over application of N exceeded 100 kg ha^{-1}. As a result, groundwater contamination with NO_3^- - N was positively correlated with residual N in the soil surface. Wuest and Cassman (1992) confirmed that pre-plant N application at rates higher than that required for maximum yield did not increase grain N concentration. In their experiment, the highest preplant fertilizer rate was 240 kg N ha^{-1} (twice as high as that needed) but which resulted in protein contents below 12%. They suggested that excess N was lost by conversion to gaseous forms, immobilization, or leaching. Preplant application of recommended and not excessive amounts of N is not enough to avoid financial losses and environmental problems, thus timing of application is very important in terms of efficiency of fertilizer use. Olson and Swallow (1984) demonstrated that spring application of fertilizer resulted in greater N uptake than fall application during the first 4 years of the experiment. They explained the higher efficiency of spring application by immediate uptake of applied N following dormancy and the initiation of rapid growth, leaving less chance for N loss by immobilization, which is most probable with fall applications. However, Olson and Swallow (1984) showed that if the spring application was made too late, utilization of N was lower when compared to fall applications.

Comparing pre-plant N application with applied N at anthesis, Wuest and Cassman (1992) indicated that N recovery in spring wheat production ranged from 30 to 55% and from 55 to 80%, respectively. Accordingly, grain N uptake was increased with N application at anthesis resulting in higher yields due to greater kernel weight. A four-year experiment conducted by Boman et al. (1995) demonstrated that spring applied N (February and March) resulted in the highest grain yield, grain N concentration, and grain N uptake in winter wheat.

Makowski et al. (1999) developed different models for predicting the response to applied N fertilizers and determination of N rates under winter wheat. Optimal N rates were based on prices, field characteristics, yield, grain protein content, and residual mineral N at harvest. They found that model parameter values varied considerably between sites. Models of response to applied N could be very useful for determination of N rate. However, Makowski et al. (2001) stated that in order to find accurate optimal N rates, site-year characteristics must be considered.

Taylor et al. (1998) demonstrated successful use of spectral measurements for N fertilizer adjustments in bermudagrass. They determined variable N rates for each plot using a linear NDVI - N rate scale, where plots with the highest NDVI value received the lowest N rate, while the plots with lowest NDVI values were given the highest N rate. A good separation of spectral signatures for wheat canopy reflectance under various rates of N fertilization was reported by Serrano et al. (2000). They presented spectral measurements taken at the elongation stage, which corresponded to 158 days after planting. At this stage, the maximum contrast was observed in the NIR bandwidth range. Raun et al. (1998) emphasized that sensor based spectral readings could reliably provide measurements equivalent to on-the-go chemical analyses. Therefore, variable fertilizer rates determined using ground-based sensors have the potential to reduce the total field N rate, and optimize NUE due to fine resolution of N application.

OBJECTIVES

The objectives of this experiment were to determine if topdress N fertilization rates could be adjusted using in-season estimates of wheat grain yield potential and to compare adjusted N fertilizer rates based on the in-season-estimated-yield (INSEY) index with fixed N rates applied at Feekes 5.

MATERIALS AND METODS

In the first year of study, 1999-2000 crop year, eight winter wheat experiments were established in order to evaluate the use of an estimated yield (EY) index (Raun et al., 2001). As a result of on-going research on yield potential estimates, a better index, in-season estimated yield (INSEY), was developed and implemented in 2000 – 2001 crop years. In the second year of study, five new experiments were planted in order to assess INSEY as a key input in deciding how much in-season N fertilizer should be applied to each 1m^2 area. Soil classification is presented in Table 1. All experiments used a randomized complete block design where different rates of fixed pre-plant N and fixed or variable topdress applications ranged from 0 to 90 kg N ha^{-1} (Table 2). Each treatment was replicated 4 times. The size of each plot was 6×4 m. Spectral measurements were collected from each 1 m^2 within specific treatments (6, 7, and 8) where N was applied at variable rates. Field plot activities as well as climatological observations for each experiment where N was applied based on EY or INSEY are reported in Tables 3 and 4.

The relationship between EY and potential yield (Raun et al., 2001) was demonstrated using spectral reflectance. Spectral reflectance was measured using an instrument described in chapter 1. Several reflectance readings from all experiments were collected at post-dormancy growth stages. Spectral readings were collected between Feekes growth stage 4 (leaf sheaths beginning to lengthen) and Feekes 6 (first node of stem visible) (Large, 1954). Due to differences in planting times and growing conditions, spectral reflectance measurements were taken between January and April (Tables 3 and 4). Reflectance readings from 1.0 m^2 surface area from wheat canopy were taken within the hours of 10 a.m. and 4 p.m. under natural lighting.

Reflectance values (the ratio of incident and reflected values) were used in the normalized difference vegetative index (NDVI) calculation (Raun et al., 2001).

First year of study

The EY and INSEY values were expected to reflect a point on the potential growth curve for the season, thus providing an estimate of potential yield based on local growing conditions between planting and the dates of sensing (Raun et al., 2001). Growing degree days (GDD) were incorporated in the computation of EY to integrate early-season growing conditions and growth rate. This approach was consistent with work showing the relationship between above ground dry weight and cumulative growing degree days (Rickman et al., 1996). Dividing the sum of NDVI values (Time-1 and

Time-2) by GDD resulted in a unit of predicted biomass (using NDVI) per growing degree day. The ratio of NDVI at Feekes growth stage 5 to number of days from planting to sensing with GDD above zero gives an estimate of biomass per day with biologically active air temperature.

Topdress N rates were determined using a nitrogen fertilization optimization algorithm (NFOA) developed at Oklahoma State University (Lukina et al., 2001). In particular, the N rate for each square meter (treatments 6, 7, and 8) was calculated as the difference between predicted grain N uptake and predicted forage N uptake. These values were then divided by an efficiency factor of 0.4 in the first year of the study. The NFOA for the first year included the following steps:

1. Predicted grain yield (PGY) = $572\times e^{150.2EY}$;
2. Predicted N uptake by vegetation (PFNU) = $3.205\times e^{3.8774\times NDVI}{}_{T2}$;
3. Predicted grain N concentration (PGN) = $5.0E\text{-}08\times PGY^2-0.0004\times PGY+3.0851$;
4. Predicted grain N uptake (PGNU) = PGY×PGN;
5. Topdress N rate = (PGNU-PFNU)/0.4.

Nitrogen use efficiency was determined by subtracting total grain N uptake in the unfertilized check from grain N uptake in the fertilized plots, and then divided by the rate applied.

Second year of study

The NFOA differed from that used in 2000, utilizing the INSEY index instead of EY employed in the first year of study and incorporating the concept of response index (RI). In-season estimated yield was determined by dividing NDVI collected anywhere from Feekes 4 to Fekees 6 by the number of days from planting where GDD>0. The other major difference in the NFOA was that RI was used for site-specific adjustments of topdress N calculations. RI_{NDVI} was calculated by dividing the highest NDVI value of N fertilized plots by the NDVI value of unfertilized control plots (Table 8). Incorporation of RI_{NDVI} into the algorithm allowed us to determine the magnitude of the response to N fertilization, specific for each field in each year. Since more data were available, the functions used in the algorithm were also different from those of the first year of the investigation.

1. Predicted potential grain yield (YP_0) = $0.77944+0.08481\times e^{451.28\times INSEY}$;
2. Predicted grain yield with additional N (YP_N) = $YP_0\times RI_{NDVI}$;
3. PFNU = $14.67+0.7758\times e^{5.468\times NDVI}$;
4. PGN = $0.703\times YP_N^2-0.5298YP_N+3.106$;
6. PGNU = $PGN\times YP_N/1000$;
5. Topdress N rate = (PGNU-PFNU)/0.7.

Topdress N in form of ammonium nitrate was applied within seven days of sensing (Tables 3 and 4).

Grain yield was determined using a self-propelled combine from the same area where spectral reflectance data were collected in both years. 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 1.0 m^2 area and thus the early-season growth-limiting conditions for small areas. Minimum and maximum temperatures, and rainfall data were collected within 1.7 km of the actual experiment at all locations.

RESULTS

The two years of study (1999-2000 and 2000-2001) differed widely in weather patterns (Tables 3 and 4). Experiments at Blackwell, Lahoma, and Perkins locations were planted late due to dry conditions in the fall of 2000 (Table 4).

Analysis of variance (AOV) and treatment means by year and location for grain yield and grain N uptake are reported in Tables 5 - 8. Single-degree-of-freedom contrasts are also included in each AOV table. Grain yield and grain N uptake showed a significant linear response (at 0.05 probability level) to N rate at Covington, Drummond, Lahoma-S, Perkins and Medford locations in the first year. In the second year, grain yield and grain N uptake had a significant response (0.05 probability level) to N rate at Covington and Lahoma, while at Chickasha only N uptake by grain had a significant linear response to N rate.

Statistical comparison of the flat topdress N rate versus a flat preplant rate (both at 90 kg N ha^{-1} TD90 versus PP90) is reported in Tables 5 and 6. Significant differences in N uptake by grain were observed at three locations (Lahoma, Perkins, and Perry) in the first year of study, TD90 resulted in higher N uptake (Table 7). Thus, topdress N was better utilized by the crop, leaving less chance for N to be lost by microbiological processes or leaching that take place when N was applied preplant. In the second year, results were inconsistent with those of the first year, in fact, N uptake for preplant N application was higher at all five locations. The same pattern was observed for grain yield in the second year (Table 6). Low grain yield could be due to the delayed planting in the fall of 2000, late vegetation development and late topdress N application. This agrees with the findings of Olson and Swallow (1984) that late spring fertilizer application results in lower utilization of N compared to that of fall application. Years when grain yield response to applied N was less likely, topdress N applications resulted in significant increases in grain N uptake, but not necessarily grain yield. Alternatively, years where RI is high, are also those years likely to show a better response to preplant N applications. If RI is high, the environment was not conducive to mineralization of soil organic matter. In summary, NUE from topdress N is likely to be higher in years where RI is high and lower when RI value are small.

At Drummond in the first year of study, observed grain yield for treatments with 90 kg ha^{-1} of N applied by different methods ranged from 2985 to 3062, with N uptake exceeding 71 kg ha^{-1} (Table 7). For PP45-TD-NFOA (45 kg of N per ha applied at planting and 15.5 kg N ha^{-1} topdress) 70 kg N ha^{-1} was taken up in the grain, at a much lower total N rate. Similar results were observed at Lahoma, Orlando, and Perry experiments (Figures 2 – 5). At Covington, Perkins, and Medford in the first year, and 3 locations in the second year, higher rates were applied for PP45-TD-NFOA but that generally resulted in increased yields (Tables 7, 8, 9, and Figures 6 - 12). At Chickasha in 2001, 61 kg N ha^{-1} was used to produce more than the 90 kg N ha^{-1} preplant rate. The ability to maximize grain yield and N uptake for PP45-TD-NFOA was due to preplant application of N for wheat establishment, with small amounts applied topdress.

Comparison of fixed (45 and 90 kg ha^{-1}) topdress N rates with rates based on NFOA (Tables 5 and 6) showed limited differences in grain yield and N uptake at 11 locations over 2 years. However, the NFOA - based N rate (Table 9) resulted in significantly higher grain yields versus that obtained at fixed 45 kg ha^{-1} topdress N at Covington location in 2001 (Tables 6 and 8). Alternatively, N uptake was higher for the high fixed topdress N rate (90 kg ha^{-1}) versus uptake from NFOA – based rates (Table 9) at Perkins, 2000 (Tables 5 and 7). Significantly higher grain yields and N uptake were observed for PP45-TD-NFOA (45 kg ha^{-1} of N preplant plus topdress rate from NFOA) compared to PP45-TD45 with fixed preplant and topdress rates of 45 kg ha^{-1} N at

Covington in the second year (Table 6 and 8). All other locations showed no significant differences between these two treatments over 2 years of the experiment (Tables 5-8).

Figures 6 – 12 clearly demonstrate the savings in N fertilizer when comparing TD45 (fixed rate of 45 kg of N ha^{-1}) versus TD-1/2NFOA (1/2 of NFOA based topdress N rate). In general, TD-1/2NFOA used less than 45 kg of N per ha, while resulting in the same or higher grain yield and N uptake compared to TD45. Blackwell in 2001 and Lahoma-S in 2000 were exceptions where no response to either rate or method of N was found, largely due to severe weed pressure.

In general, NUE was in the same range or lower for PP45-TD-NFOA compared to any other treatments during the first year (Table 10). In 2001 higher NUE at Chickasha for PP45-TD-NFOA was seen compared to TD90, PP45-TD45, and PP90, even though these treatments had similar average N rates. At Covington and Lahoma (Figures 14 and 15, respectively) NUE for TD90, PP45-TD90, PP90, and PP45-TD-NFOA was in the same range regardless the fact that PP45-TD-NFOA had a much higher N rate. The key factor for NUE is the time and method of N application. Since PP45-TD-NFOA had 45 kg ha^{-1} of N applied preplant and the rest applied based on NFOA and topdressed at Feekes 5, recovery rate of the fertilizer was much higher.

DISCUSSION

The efficiency of variable rates of topdress N based on NFOA was higher compared to the fixed N rates applied in spring. Both indices, EY and INSEY proved to be reliable predictors of potential yield and could be used for adjustment of in-season N fertilization rates. However, the use of RI_{NDVI} in the second year proved to be an important input in the NFOA in order to increase NUE. Johnson et al. (2000) noted that NUE decreases with increased N application rates due to the inability of the soil-plant system to use excessive N. They pointed out that the ability of soil-plant system to utilize higher N rates is directly related to yield potential and $RI_{HARVEST}$ of the field. Nevertheless, in the second year of our experiment PP45-TD-NFOA at Covington received the highest average N rate (104.3, Table 9) while the NUE for that treatment was 24 % (Table 10) in the same range as that for treatments with fixed N rates (TD45, TD90, PP45-TD45). However, it must be noted that at this site, the NFOA accurately predicted that more N was required and that resulted in significantly greater yields. Since NDVI is a reliable predictor of plant N status, the ability of the soil plant system to utilize the higher amount of N can be explained by the use of RI_{NDVI}.

The overall comparison of results from two years of investigation showed that efficiency of NFOA was better in the second year compared to that of the first year probably because no field specific adjustments were implemented in the first year based on RI. In the ensuing year, RI played a significant role for adjusting mid-season fertilizer N rates. The highest grain yield was observed for PP45-TD-NFOA treatment at Covington (2001), and it was significantly different from PP45-TD45. The same tendency was observed at Chickasha (2001). Grain yield for the PP45-TD-NFOA treatment at Lahoma (2001) and Perry (2001) was in the same range as for treatments with 90 kg of N per ha^{-1} applied by different methods.

Differences in grain yield between NFOA and 1/2NFOA treatments was insignificant compared to that for 90 kg of N per ha^{-1} treatments, however, NFOA treatments required less N fertilizer.

CONCLUSIONS

Application of N fertilizers applied to each square meter accounting for yield potential, and an in-season response index can result in maximized yields at lower fertilizer rates. Yield potential – based in-season N fertilization should increase grain yield, N uptake, and NUE. Considering that different climatological conditions affect crop growth and development and may vary widely from year to year at the same location, on-the-go sensing and topdress fertilizer application should be the best way to correct nutrient deficiencies in order to obtain the best achievable yield.

REFERENCES

Boman, R.K., R.L. Westerman, W.R. Raun, and M.E. Jojola. 1995. Time of nitrogen application: Effects on winter wheat and residual soil nitrate. Soil Sci. Soc. Am. J. 59:1364-1369.

Johnson, G.V., W.R. Raun, and R.W. Mullen. 2000. Nitrogen use efficiency as influenced by crop response index. p.291. *In* Agronomy Abstracts. ASA, Madison, WI.

Large, E.C. 1954. Growth stages in cereals. Plant Pathol. 3:128-129.

Lukina, E.V., K.W. Freeman, K.J. Wynn, W.E. Thomason, R.W. Mullen, M.L. Stone, J.B. Solie, A.R. Klatt, G.V. Johnson, R.L. Elliot, and W.R. Raun. 2001. Nitrogen fertilization optimazation algorithm based on in-season estimates of yield and plant nitrogen uptake. J. Plant Nutr. 24: 885-898.

Makowski, D., D. Wallach, and Jean-Marc Meynard. 1999. Models of yield, grain protein, and residual mineral nitrogen responses to applied nitrogen for winter wheat. Agron J. 91:377-385.

Makowski, D., D. Wallach, and Jean-Marc Meynard. 2001. Statistical methods for predicting responses to applied nitrogen and calculating optimal nitrogen rates. Agron J. 93:531-539.

Olson, R.V. and C.W. Swallow. 1984. Fate of labeled nitrogen fertilizer applied to winter wheat for five year. Soil Sci. Soc. Am. J. 48:583-586.

Raun, W.R., G.V. Johnson, H. Sembiring, E.V. Lukina, J.M. LaRuffa, W.E. Thomason, S.B. Phillips, J.B. Solie, M.L. Stone, and R.W. Whitney. 1998. Inderect measures of plant nutrients. Commun. Soil Sci. Plant Anal. 29:1571-1581.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, and W.E. Thomason, and J.S. Shepers. 2001. In-season prediction of yield potential in winter wheat. Agron. J. 93:131-138.

Rickman, W.R., S.E. Waldman and B. Klepper. 1996. MODWht3: A development-driven wheat growth simulation. Agron. J. 88:176-185.

Schepers, J.S., M.G. Moravek, E.E. Alberts, and K.D. Frank. 1991. Maize production impacts on groundwater Quality. J. Environ. Qual. 20:12-16.

Serrano, L., I. Filella, J. Panuelas. 2000. Remote sensing of biomass and yield of winter wheat under different nitrogen supplies. Crop Sci. 40:723-731.

Taylor, S.L., W.R. Raun, J.B. Solie, G.V. Johnson, M.L. Stone, and R.W. Whitney. 1998. Use of spectral radiance for correcting nitrogen deficiencies and estimating soil test variability in an established bermudagrass pasture. J. Plant Nutr. 21:2287-2302.

Wuest, S.B. and K.G. Cassman. 1992. Fertilizer-nitrogen use efficiency of irrigated wheat: I. Uptake efficiency of preplant versus late-season application. Agron. J. 84:682-688.

Table 1. Soil classification for on farm INSEY trials.

Location	Soil classification
Blackwell	Norge loam (fine-silty, mixed termic Udic Paleustoll)
Chickasha	Dale silt loam (fine-silty, mixed superactive, thermic Udic Argiustoll)
Covington	Renfrow silt loam (fine, mixed, thermic Vertic Paleustoll)
Drummond	Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll)
Lahoma	Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll)
Medford	Kirkland silt loam (fine, mixed, thermic Udertic Paleustoll)
Orlando	Chickasha loam (fine-loamy, mixed, thermic Udic Argiustolls)
Perkins	Teller sandy loam (fine-loamy, mixed, thermic Udic Argiustoll)
Perry	Renfrow silty clay loam (fine, mixed, thermic Vertic Paleustoll)

Table 2. Treatment structure of on farm INSEY trials for winter wheat experiments employing INSEY and NFOA.

No.		Pre-plant N kg ha^{-1}	Topdress N kg ha^{-1}	Yield Potential Index	Fertilizer Application Resolution
1.	Check	0	0	N	-
2.	TD45	0	45	N	24m^2
3.	TD90	0	90	N	24m^2
4.	PP45-TD45	45	45	N	24m^2
5.	PP90	90	0	N	24m^2
6.	TD-NFOA	0	NFOA	Y	1m^2
7.	TD-1/2NFOA	0	NFOA-1/2	Y	1m^2
8.	PP45-TD-NFOA	45	NFOA	Y	1m^2

NFOA – topdress N rates determined employing estimated yield potential using the nitrogen fertilization optimization algorithm.

Pre-plant N – N applied preplant and disk incorporated prior to planting.

Topdress N – N applied in the spring without incorporation.

Table 3. Field plot activities and climatological observations for experiments where N was applied based on the nitrogen fertilization optimization algorithm (NFOA) at eight locations, 1999-2000.

Plot Activity	Covington	Drummond	Lahoma-E	Lahoma-S	Orlando	Perkins	Perry	Medford
planting date	10/13/00	11/4/99	10/26/99	10/28/99	10/30/99	10/7/99	10/29/99	11/9/99
variety	Custer	Custer	Custer	Custer	Custer	Custer	Custer	Custer
seeding rate, kg ha^{-1}	67	76	84	76	76	76	76	76
T1 sensor date	2/21/00	2/15/00	2/15/00	3/13/00	2/21/00	12/21/99	2/21/00	3/28/00
T2 sensor date	3/6/00	3/13/00	3/13/00	3/28/00	3/6/00	2/8/00	3/6/00	4/6/00
GDD, T1 to T2	129.4	167.8	167.8	120.9	127.0	197.8	127.5	89.1
preplant fertilization date	9/3/99	11/4/99	10/26/99	10/26/99	9/3/99	10/7/99	9/3/99	9/27/99
topdress fertilization date	3/13/00	3/21/00	3/21/00	3/31/00	3/15/00	3/14/00	3/15/00	4/6/00
harvest date	7/5/00	6/8/00	6/8/00	6/8/00	6/06/00	6/06/00	5/29/00	6/23/00
Seasonal Rainfall (mm)	750	463	532	532	559	519	673	623
Rainfall from Planting to Sensing (mm)	311	248	317	400	271	203	331	385
Rainfall from Sensing to Harvest (mm)	439	215	215	132	288	316	342	238
soil pH	6.1	5.3	5.4	7.6	5.1	5.9	5.1	5.7
organic C, g kg^{-1}	9.91	8.31	7.79	7.96	9.67	7.00	7.51	9.40
total N, g kg^{-1}	1.05	0.89	0.84	0.71	0.95	0.67	0.81	0.99
P, mg kg^{-1}	19	32	26	8	38	8	71	7
K, mg kg^{-1}	181	337	346	373	198	193	194	336
NH_4-N, mg kg^{-1}	6.1	5.0	4.3	8.6	5.4	2.6	25.5	7.9
NO_3-N, mg kg^{-1}	1.4	7.4	4.6	2.5	12.4	2.7	2.4	1.9
Preplant P fertilizer applied, kg P, ha^{-1}	8	0	8	16	0	16	0	16

MM/DD/YY – month/day/year

Table.4. Field plot activities and climatological observations for experiments where N was applied based on the nitrogen fertilization optimization algorithm (NFOA) at five locations, 2000-2001.

Plot Activity	Chickasha	Perkins	Covington	Lahoma	Blackwell
planting date	10/03/00	11/17/00	10/01/00	11/27/00	12/01/00
variety	Custer	Custer	Custer	Custer	Custer
seeding rate, kg ha^{-1}	67	76	54	76	76
Sensor date	03/06/01	04/16/01	02/16/01	04/13/01	04/09/01
Days from Planting to Sensing	153	149	137	136	128
Days from Planting to Sensing (GDD>0)	116	76	69	60	61
RI_{NDVI}	1.27	1.48	1.39	2.22	1.27
RI_{SV}	1.40	1.57	1.39	2.84	1.44
preplant fertilization date	10/02/00	11/16/00	09/13/00	11/27/00	09/13/00
topdress fertilization date	03/13/01	04/18/01	02/22/01	04/19/01	04/12/01
harvest date	06/05/01	06/07/01	06/13/01	06/14/01	06/18/01
Seasonal Rainfall (mm)	719	551	362	445	365
Rainfall from Planting to Sensing (mm)	552	266	167	200	174
Rainfall from Sensing to Harvest (mm)	167	285	195	245	191
soil pH	7.1	5.9	6.1	5.6	6.8
organic C, g kg^{-1}	12.3	7	9.91	8.64	6.11
total N, g kg^{-1}	1.1	0.67	1.05	0.92	0.62
P, mg kg^{-1}	66	19	21	45	22
K, mg kg^{-1}	443	181	345	410	205
NH_4-N, mg kg^{-1}	18.5	2.6	6.1	3.8	14.3
NO_3-N, mg kg^{-1}	9.2	2.7	1.4	2.8	18.2
Preplant P fertilizer applied, kg P, ha^{-1}	--	--	8	--	--

MM/DD/YY – month/day/year

Table 5. Analysis of variance and single-degree-of-freedom-contrasts for, total N uptake, and grain yield at eight locations, 1999-2000 crop year.

Source of Variation	df	Covington		Drummond		Lahoma-E		Lahoma-S		Orlando		Perkins		Perry		Medford	
		Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take
										$kg\ ha^{-1}$							
										mean squares							
Rep	3	145223	54	346784*	543**	764100	438*	101070**	19	172252	319**	37439	28	5681454**	2048**	45118*	72**
N rate	7	681907**	256**	161147	265*	298172	105	273826**	237**	11724	38	168338	218	144734	113	49468*	38*
Residual	21	170767	66	131408	115	284463	106	20639	16	59159	43	134540	93	151070	80	13954	11
Contrast:																	
N rate linear	1	**	**	*	**	ns	ns	**	**	ns	ns	*	**	ns	ns	**	**
N rate quadratic	1	ns	ns	ns	ns	ns	ns	**	**	ns	ns	ns	ns	ns	ns	ns	ns
TD90 vs PP45-TD45	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TD90 vs PP90	1	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	*	ns	*	ns	ns
PP45-TD45 vs PP90	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
TD45 vs TD-NFOA	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TD90 vs TD-NFOA	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns
TD45 vs TD-1/2NFOA	1	ns	ns	ns	ns	ns	ns	**	*	ns	ns	ns	ns	ns	ns	ns	ns
PP45-TD45 vs PP45-TD-NFOA	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns, *, ** - not significant, significant at 0.05, and 0.01 probability levels, respectively. PP, TD - preplant and topdress application of N, respectively.

Table 6. Analysis of variance and single-degree-of-freedom-contrasts for, total N uptake, and grain yield at five locations, 2000-01 crop year.

Source of Variation	df	Chickasha		Perkins		Covington		Lahoma		Blackwell	
		Grain Yield	N uptake	Grain Yield	N uptake	Grain Yield	N uptake	Grain Yield	N uptake	Grain Yield	N uptake
						kg ha^{-1}					
		----------	----------	----------	----------	mean squares	----------	----------	----------	----------	----------
Rep	2	837165**	191*	33178	11	1219404**	141	56924	74	47508	73
N rate	7	219865	85	48379	31	1112862**	430**	381837**	308**	127105	62
Residual	21	64965	37	38485	19	91806	54	80099	66	181454	79
Contrast:											
N rate linear	1	ns	*	ns	ns	**	**	*	*	ns	ns
N rate quadratic	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TD90 vs PP45-TD45	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TD90 vs PP90	1	ns	ns	ns	ns	ns	ns	*	*	ns	ns
PP45-TD45 vs PP90	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TD45 vs TD-NFOA	1	ns	ns	ns	ns	*	ns	ns	ns	ns	ns
TD90 vs TD-NFOA	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TD45 vs TD-1/2NFOA	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PP45-TD45 vs PP45-TD-NFOA	1	ns	ns	ns	ns	*	*	ns	ns	ns	ns

ns, *, ** - not significant, significant at 0.05, and 0.01 probability levels, respectively. PP, TD - preplant and topdress application of N, respectively.

Table 7. Wheat grain yield and N uptake response to applied N at fixed rates and rates based on the nitrogen fertilization optimization algorithm (NFOA) at eight locations, 1999-2000.

Trt	N rate		Covington		Drummond		Lahoma-E		Lahoma-S		Orlando		Perkins		Perry		Medford	
			Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take	Grain Yield	N up-take
	kg ha^{-1}	Method	kg ha^{-1}															
1	0	check	1602	30	2614	59	1961	37	2318	40	3031	64	2242	46	1940	40	634	15
2	45	TD45	2426	46	2845	68	2317	45	2889	60	2993	67	2621	54	2126	47	762	19
3	90	TD90	2788	53	3062	78	2234	43	2936	66	2993	70	2868	70	1989	51	908	25
4	90	PP45-TD45	2717	51	3126	77	2402	47	3019	63	2991	65	2639	57	1992	43	840	22
5	90	PP90	2779	51	2985	71	1937	36	2983	60	3040	61	2452	53	1746	37	1014	24
6	(†)	TD-NFOA	2317 (84.1)	42	2932 (20.8)	71	2145 (53.9)	42	3093(57.0)	66	2916(24.5)	63	2643 (61.4)	56	1947 (38.3)	41	787 (54.0)	21
7	(†)	TD-1/2NFOA	2154 (44.5)	40	2828 (10.8)	62	1235 (27.8)	23	2559 (31.0)	53	3087 (13.1)	65	2296 (31.8)	49	1897 (20.0)	39	780 (25.9)	19
8	45+(†)	PP45-TD-NFOA	2725 (74.2)	52	3038 (15.5)	70	2232 (43.2)	44	2855 (41.6)	60	3071 (27.4)	61	2609 (64.4)	58	2395 (39.1)	50	829 (56.2)	21
Response Index ($RI_{HARVEST}$)			1.73		1.14		0.99		1.29		1.02		1.09		0.90		1.60	
SED			369	5.8	264	7.6	251	7.3	97	2.8	171	4.6	253	6.8	294	6.3	79	2.4

SED-standard error of the difference between two equally replicated means. RI computed by dividing the yield from plots with the highest preplant N rate by the yield of unfertilized control plots (G.V. Johnson, personal communication, 2001). †-average N rate applied over all locations and years. PP, TD - preplant and topdress application of N, respectively.

Table 8. Wheat grain yield and total N uptake response to applied N at fixed rates and rates based on the nitrogen fertilization optimization algorithm (NFOA) at five locations, 2000-2001.

Trt: N rate			Chickasha		Perkins		Covington		Lahoma		Blackwell	
			Grain Yield	N uptake	Grain Yield	N uptake	Grain Yield	N uptake	Grain Yield	N uptake	Grain Yield	N uptake
	kg ha^{-1}	Method	kg ha^{-1}									
1	0	check	1033	22	1274	26	1563	20	951	21	2387	48
2	45	TD45	1381	32	1353	32	1995	29	1313	34	1898	39
3	90	TD90	1438	34	1367	31	2462	36	1533	37	1860	37
4	90	PP45-TD45	1677	33	1608	32	2744	41	1894	48	2102	39
5	90	PP90	1776	37	1593	35	2330	33	2084	52	2092	44
6	(†)	TD-NFOA	1410 (19.8)	31	1246 (64.1)	26	2554 (58.6)	40	1543 (48.5)	41	1976 (129.0)	38
7	(†)	TD-1/2NFOA	1197 (9.9)	25	1396 (31.5)	29	1966 (33.8)	30	1697 (24.1)	41	2242 (64.9)	44
8	45+(†)	PP45-TD-NFOA	1784 (16.0)	35	1519 (96.7)	31	3269 (104.3)	55	1824 (71.9)	49	1981 (158.7)	38
Response Index ($RI_{HARVEST}$)			1.72		1.25		1.49		2.19		0.88	
Response Index (RI_{NDVI})			1.27		1.48		1.39		2.22		1.27	
SED			179	4.3	138	3.1	207	5.2	200	5.7	301	6.5

SED-standard error of the difference between two equally replicated means. $RI_{HARVEST}$ computed by dividing the yield from plots with the highest preplant N rate by the yield of unfertilized control plots (G.V. Johnson, personal communication, 2001), and RI_{NDVI} computed by dividing the highest NDVI of N fertilized plots by the NDVI of unfertilized control plots. †-average N rate applied over all locations and years. PP, TD - preplant and topdress application of N, respectively.

Table 9. Average, minimum and maximum topdress N rates applied for three treatments employing the nitrogen fertilization optimization algorithm (NFOA) at eight locations in 1999-2000, and five locations in 2000-2001.

Location	6, topdress -NFOA			7, topdress, ½ NFOA			8, 45 kg N ha^{-1} + topdress-NFOA		
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
	kg ha^{-1}								
				1999-2000					
Covington	84.1	0.0	115.6	44.5	22.7	67.9	74.2	32.4	121.6
Drummond	20.8	0.0	71.8	10.8	0.0	38.7	15.5	0.0	67.6
Lahoma-E	53.9	0.1	75.4	27.8	0	42.2	43.2	0	76.3
Lahoma-S	57.0	27.2	81.1	31.0	10.7	38.6	41.6	15.9	71.4
Orlando	24.5	6.9	42.4	13.1	0.0	22.6	27.4	10.1	40.5
Perkins	61.4	38.0	91.3	31.8	19.4	46.2	64.4	42.0	83.0
Perry	38.3	17.4	45.2	20.0	15.0	22.7	39.1	19.4	43.5
Medford	54.0	40.5	92.8	25.9	18.4	30.7	56.2	41.7	86.5
				2000-2001					
Chickasha	19.8	10.8	22.0	9.9	7.2	10.9	16.0	0.02	21.9
Perkins	64.1	31.9	86.9	31.5	17.3	43.4	69.7	32.8	86.9
Covington	58.6	32.4	102.8	33.8	14.6	70.0	104.3	36.1	233.5
Lahoma	48.5	38.4	75.9	24.1	20.6	36.6	71.9	44.8	109.2
Blackwell	129.0	28.5	241.3	64.9	16.3	120.4	158.7	29.9	241.1

Table 10. Nitrogen use efficiency (NUE) at thirteen locations in Oklahoma, 1999-2000 and 2000-2001 crop cycles.

	Treatment (N rate) and method of application						
Location	TD45	TD90	PP45-TD45	PP90	TD-NFOA	TD-1/2NFOA	PP45-TD-NFOA
	NUE, %						
				1999-2000			
Covington	36	26	23	23	14	23	19
Drummond	20	21	20	13	58	28	18
Lahoma-E	18	7	11	0	9	0	8
Lahoma-S	44	29	26	22	46	42	23
Medford	9	11	8	10	11	15	6
Orlando	7	7	1	0	8	8	0
Perkins	18	27	12	8	16	9	11
Perry	16	12	3	0	3	0	12
Average	21	18	13	9.5	21	16	12
				2000-2001			
Chickasha	23	13	12	17	45	34	22
Covington	21	19	24	15	34	30	24
Lahoma-S	30	18	31	35	40	85	25
Perkins	22	10	11	14	6	19	8
Blackwell*							
Average	24	15	20	20	31	42	20

* - grain N uptake in check plots exceeded that of fertilized plots.

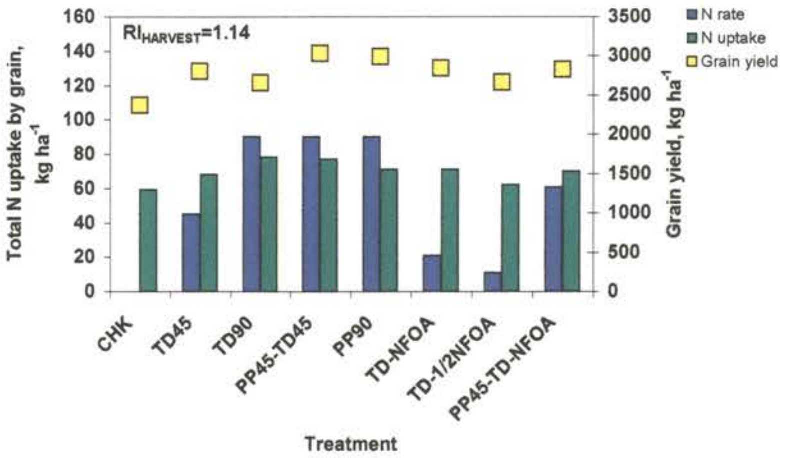

Figure 1. Nitrogen uptake, N rate, and grain yield vs treatment at Drummond, 2000.

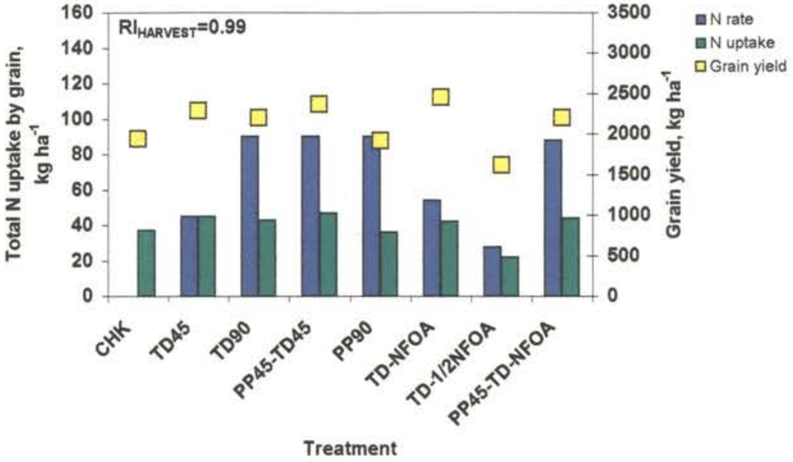

Figure 2. Nitrogen uptake, N rate, and grain yield vs treatment at Lahoma_E, 2000.

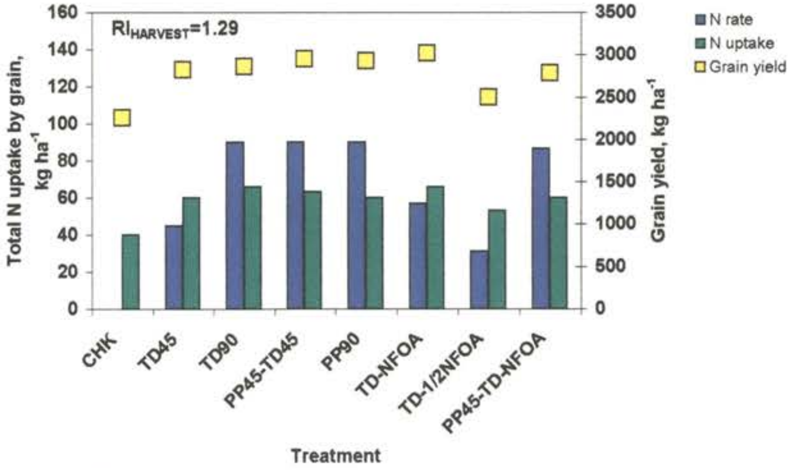

Figure 3. Nitrogen uptake, N rate, and grain yield vs treatment at Lahoma_S, 2000.

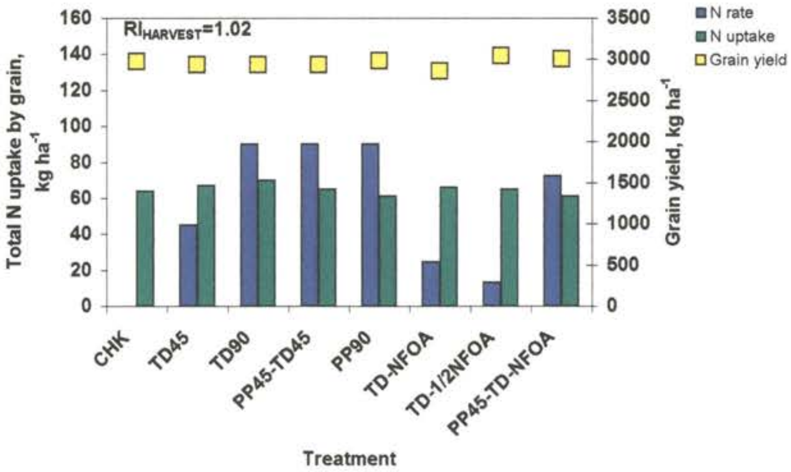

Figure 4. Nitrogen uptake, N rate, and grain yield vs treatment at Orlando, 2000.

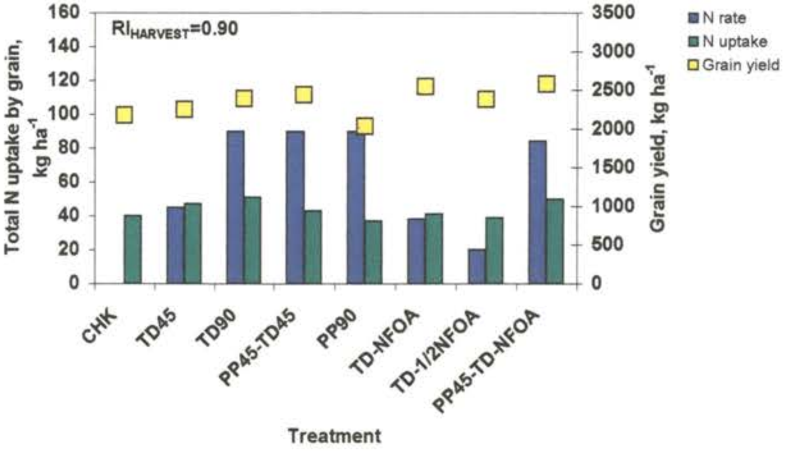

Figure 5. Nitrogen uptake, N rate, and grain yield vs treatment at Perry, 2000.

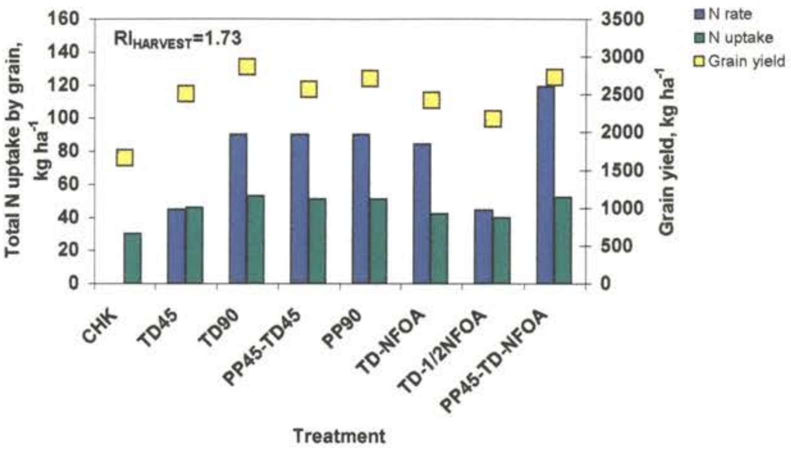

Figure 6. Nitrogen uptake, N rate, and grain yield vs treatment at Covington, 2000.

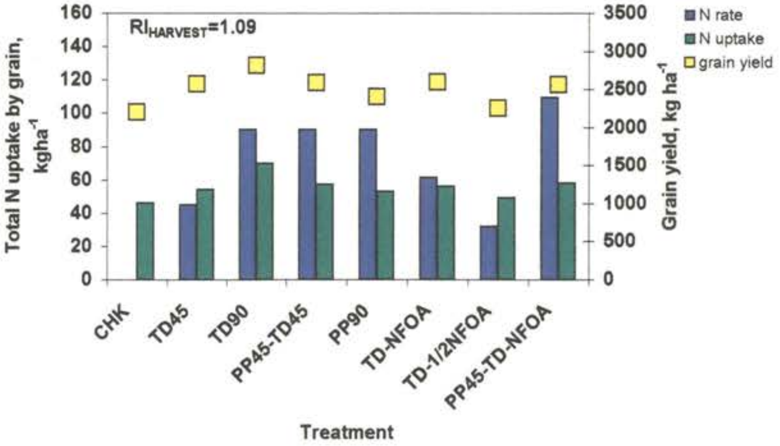

Figure 7. Nitrogen uptake, N rate, and grain yield vs treatment at Perkins, 2000.

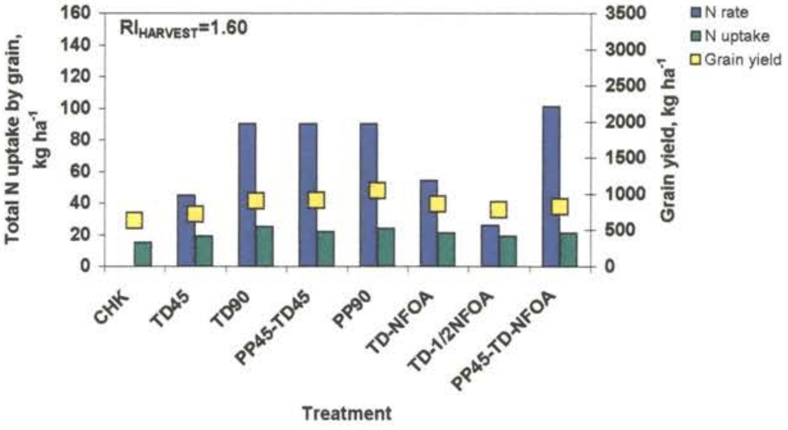

Figure 8. Nitrogen uptake, N rate, and grain yield vs treatment at Medford, 2000.

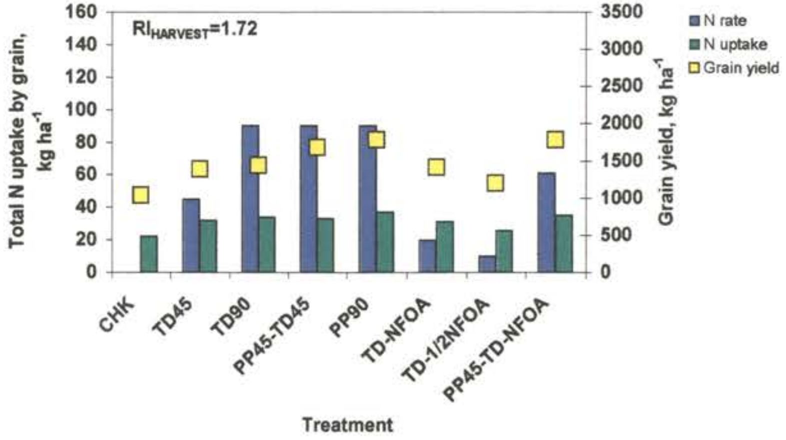

Figure 9. Nitrogen uptake, N rate, and grain yield vs treatment at Chickasha, 2001.

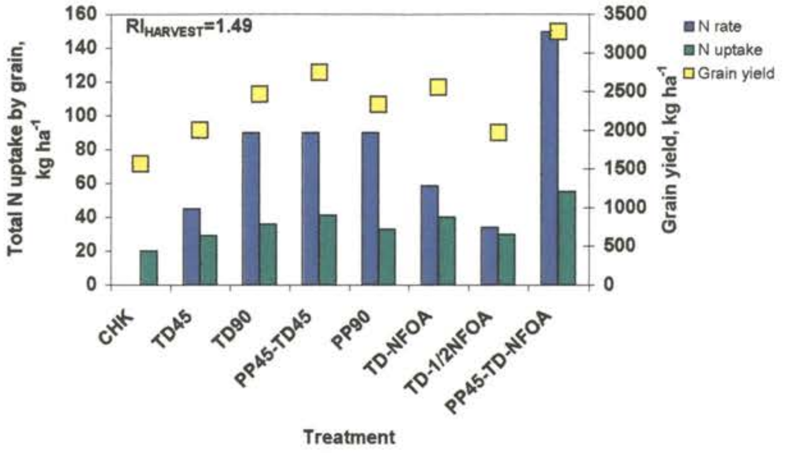

Figure 10. Nitrogen uptake, N rate, and grain yield vs treatment at Covington, 2001.

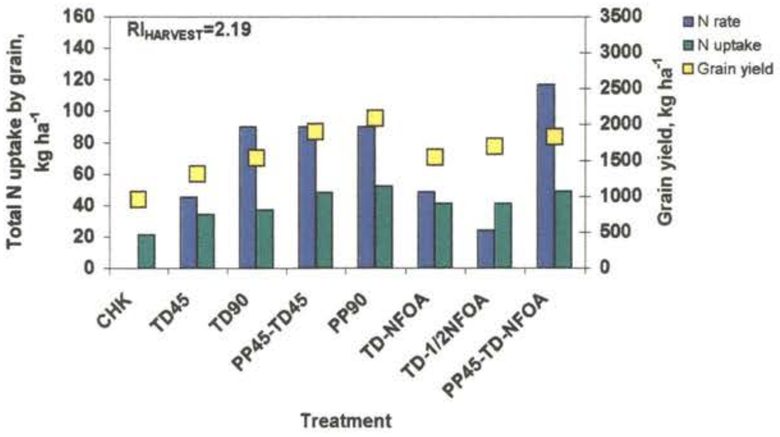

Figure 11. Nitrogen uptake, N rate, and grain yield vs treatment at Lahoma_S, 2001.

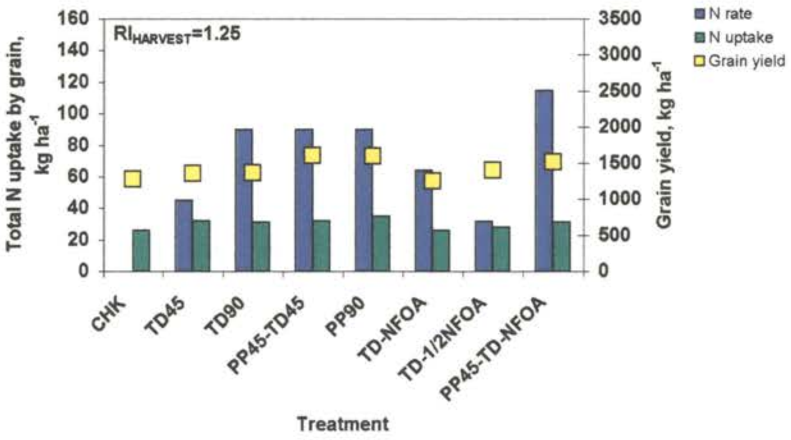

Figure 12. Nitrogen uptake, N rate, and grain yield vs treatment at Perkins, 2001.

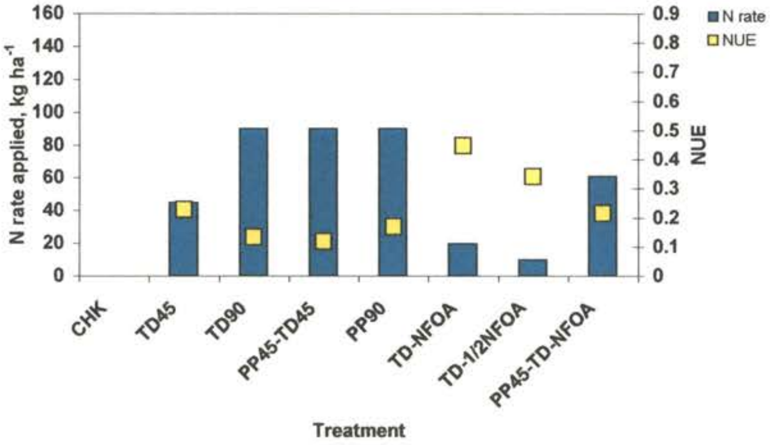

Figure 13. Nitrogen rate and NUE vs treatment at Chickasha, 2001.

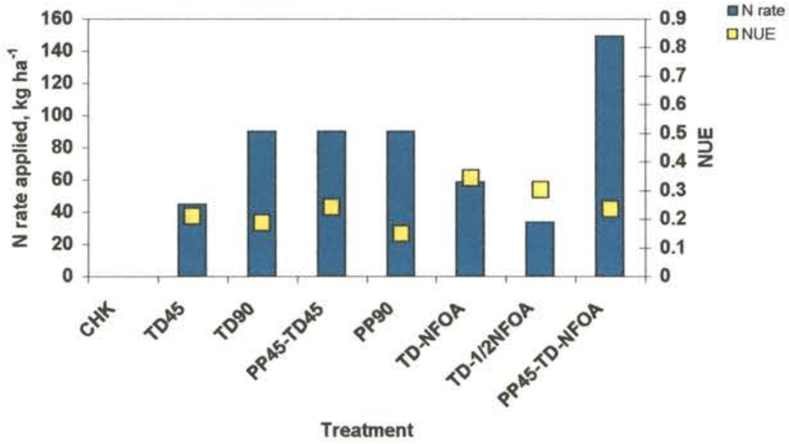

Figure 14. Nitrogen rate and NUE vs treatment at Covington, 2001.

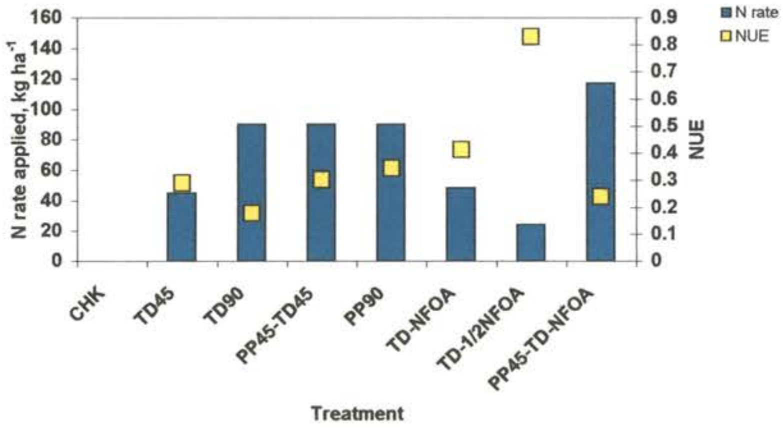

Figure 15. Nitrogen rate and NUE vs treatment at Lahoma_S, 2001.

APPENDIX

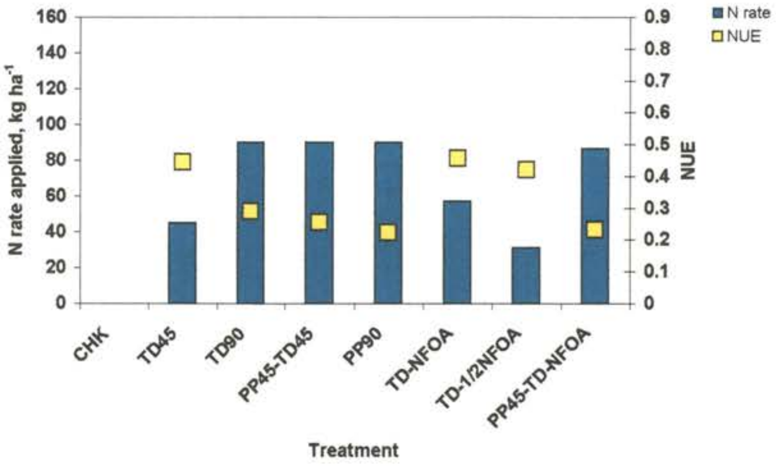

Figure 1. Nitrogen rate and NUE vs treatment at Lahoma_S, 2000.

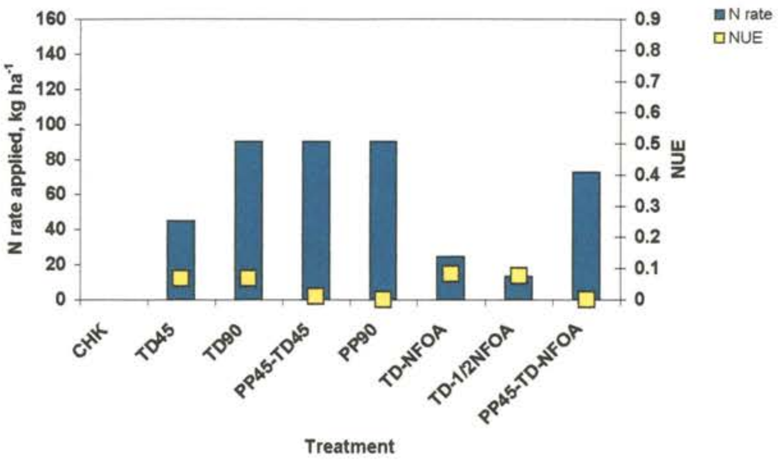

Figure 3. Nitrogen rate and NUE vs treatment at Orlando, 2000.

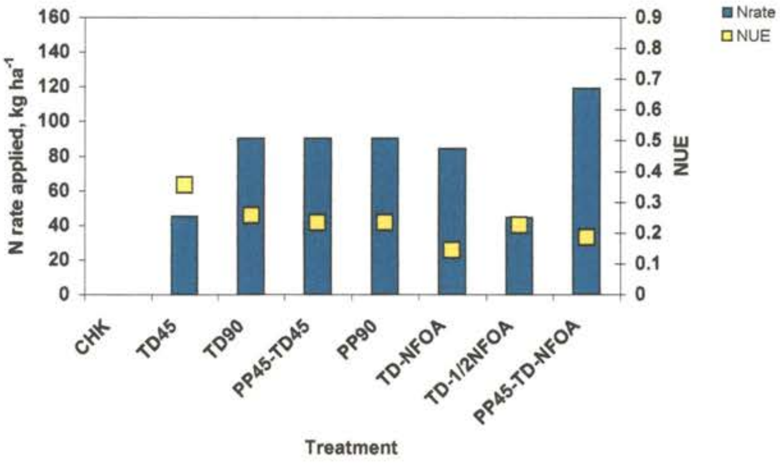

Figure 2. Nitrogen rate and NUE vs treatment at Covington, 2000.

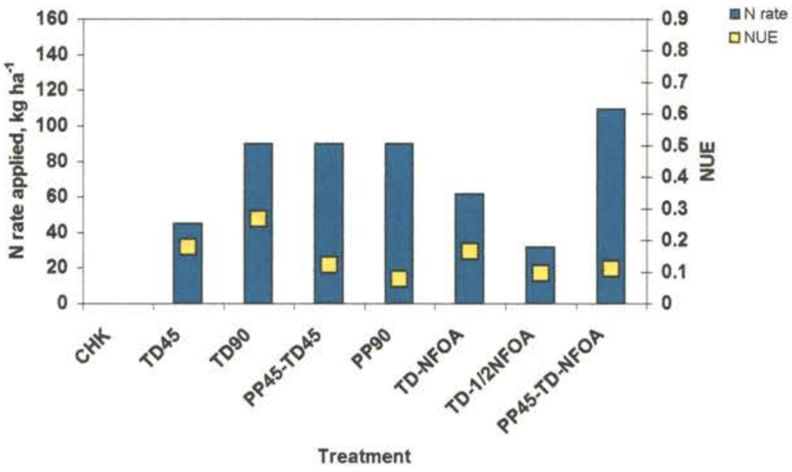

Figure 4. Nitrogen rate and NUE vs treatment at Perkins, 2000.

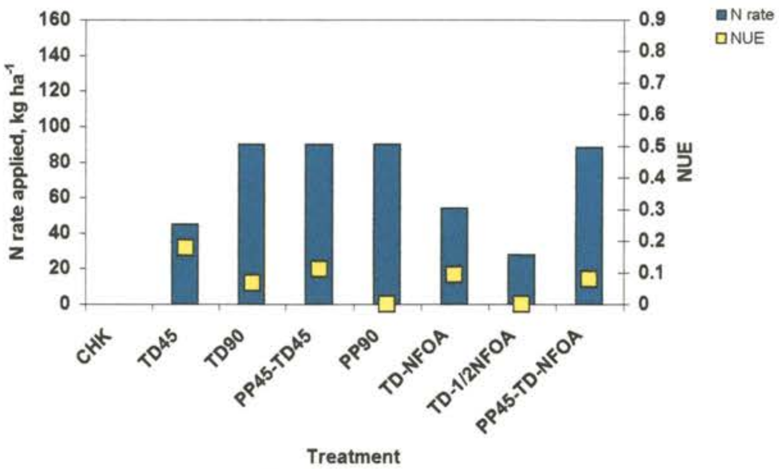

Figure 5. Nitrogen rate and NUE vs treatment at Lahoma_E, 2000.

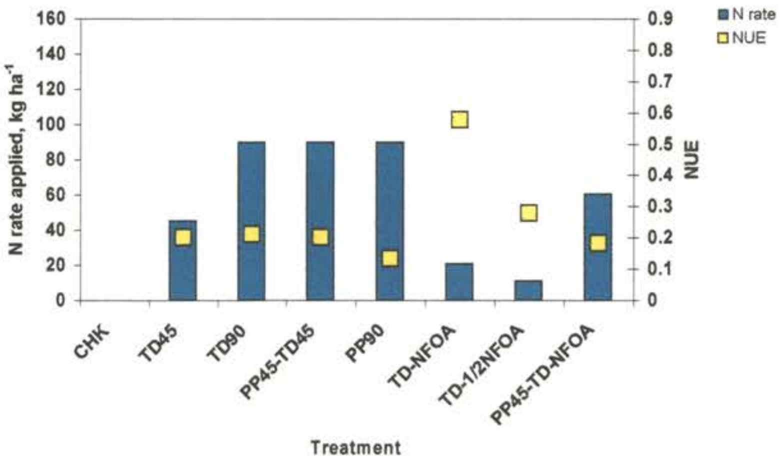

Figure 6. Nitrogen rate and NUE vs treatment at Drummond, 2000.

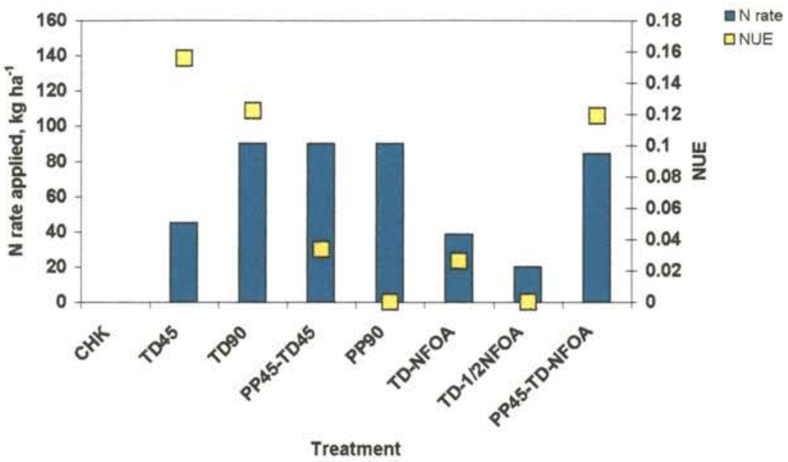

Figure 7. Nitrogen rate and fertilizer N recovery rate vs treatment at Perry, 2000.

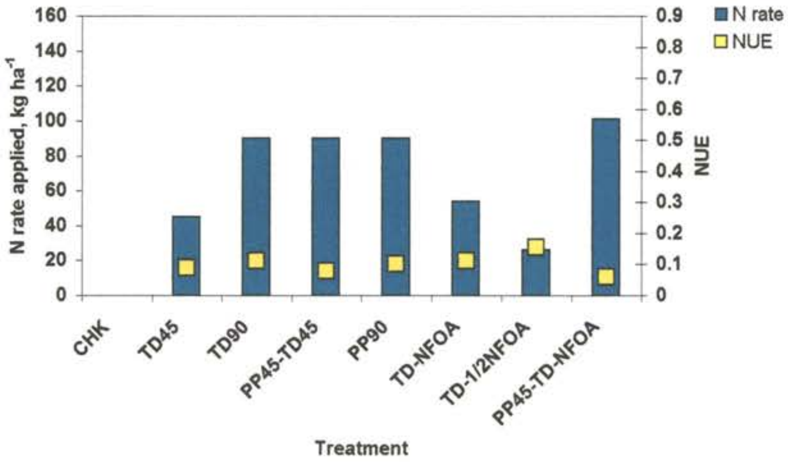

Figure 8. Nitrogen rate and NUE vs treatment at Medford, 2000.

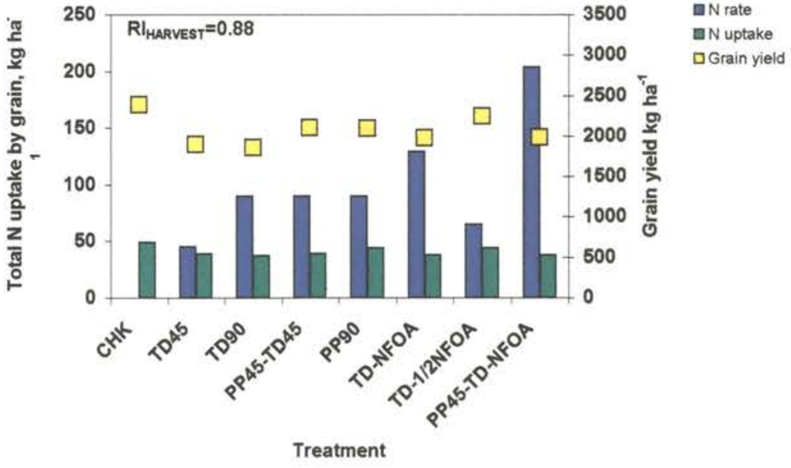

Figure 9. Nitrogen uptake, N rate, and grain yield vs treatment at Blackwell, 2001.

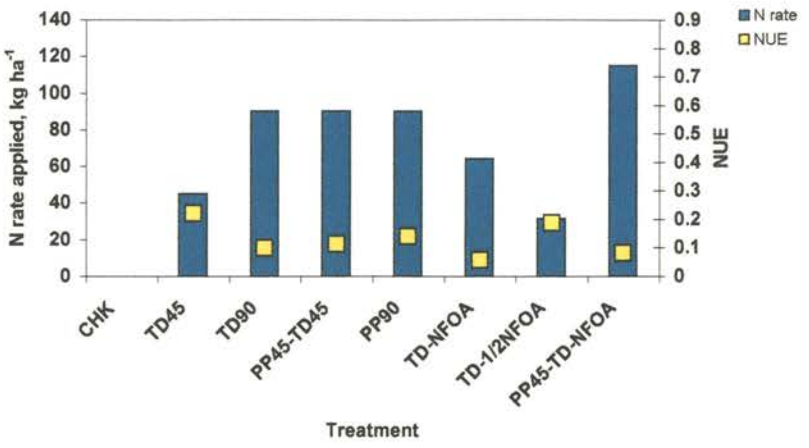

Figure 10. Nitrogen rate and NUE vs treatment at Perkins, 2001.

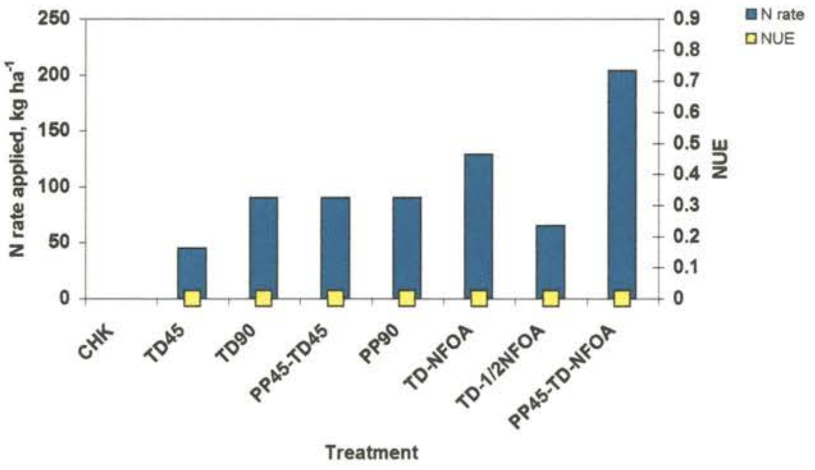

Figure 11. Nitrogen rate and NUE vs treatment at Blackwell, 2001.

2

VITA

Erna Vladislavovna Lukina

Candidate for the Degree of

Doctor of Philosophy

Thesis: IMPROVING POTENTIAL YIELD PREDICTION IN WINTER WHEAT USING IN-SEASON SENSOR BASED MEASUREMENTS

Major Field: Soil Science

Biographical:

Education: Graduated from Secondary School named after Lomonosov, Akkurgan, Uzbekistan in June 1983; received Bachelor of Science degree in Soil Sciences from Tashkent State University, Tashkent, Uzbekistan in July 1988. Received Master of Science degree in Plant and Soil Sciences from Oklahoma State University in December 1998. Completed the requirements for the Doctor of Philosophy degree in Plant and Soil Sciences from Oklahoma State University in December 2001.

Experience: Employed by Oklahoma State University, Department of Plant and Soil Sciences as a graduate research assistant in the soil Fertility Project, August 1996 to present.

Professional Memberships: Soil Science Society of America.