I. ESTIMATION OF NITROGEN MINERALIZATION IN SOILS FROM LONG-TERM APPLICATION OF FERTILIZER AND ITS EFFECT ON WINTER WHEAT RESPONSE TO TOPDRESS NITROGEN

II. USE OF IN-SEASON SENSOR DERIVED RESPONSE INDICES TO PREDICT THE RESPONSE INDEX AT HARVEST

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Submitted to the Faculty of the
Graduate College of
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 2003

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ACKNOWLEDGEMENTS

First and foremost, I thank God for giving me the strength and wisdom to complete this degree, without His love and guidance this work would not be possible. I would also like to thank my loving wife Mary, for supporting me in my decision to pursue this degree, and always being there no matter how late I got home from work. I am also very grateful to the Department of Plant and Soil Sciences for the opportunity to work and study at Oklahoma State University. Special thanks to the Soil Fertility Project for their continued support and aid in accomplishing my goals and most of all for their friendship. Specifically, I would like to thank the following graduate and undergraduate members of the Soil Fertility Project: Kyle Freeman, Roger Teal, Paul Hodgen, Micah Humphreys, Jagadeesh Mosali, Wade Thomason, Doug Cossey, Kathie Wynn, Shambel Moges, Keri Brixey, Jason Lawles, Kefyalew Girma, Aaron Witt, Kent Martin, Erica Justesen, and Angie Harting. To my committee members, Dr. Gordon Johnson, Dr. Marvin Stone, and Dr. John Solie, I thank you for your encouragement, time, and guidance I received throughout my pursuit of this degree. Finally, heart felt thanks to my major adviser, Dr. Bill Raun, for taking me into the project and allowing me to be a part of something that I feel really makes a difference.

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ESTIMATION OF NITROGEN MINERALIZATION IN SOILS FROM LONG-TERM APPLICATION OF FERTILIZER AND ITS EFFECT ON WINTER WHEAT RESPONSE TO TOPDRESS NITROGEN

ABSTRACT

Currently, nitrogen use efficiency (NUE) of worldwide cereal production is estimated to be 33%. Mineralization of the soil organic N fraction can impact how crops use inorganic fertilizer N additions. Accurate prediction of soil N mineralization is possible under controlled conditions (temperature and moisture), but varies greatly with environmental changes under field conditions. If N mineralization during a growing season could be quantified, in-season adjustment of N could be refined by topdress fertilization. One long-term, continuous winter wheat experiment was chosen for this study that has received fixed rates of N for 30 consecutive years. The main plots were split such that one-third received preplant N, one-third received topdress N, and one-third did not receive N. Preplant and topdress rates were equivalent to historical rates, and the subplots were re-randomized each year for two years (such that each subplot did not receive N for one year). Optical sensor readings were taken from each subplot and the normalized difference vegetative index (NDVI) was calculated. A response index was also calculated for each main plot using both

NDVI and yield measurements. When the amount of N accumulated within the forage from a crop receiving N is equal to or close to the amount of N accumulated within the forage of a crop not receiving N (due to mineralization or N contribution from other sources), topdressing of N does not result in increased yields. This evidence further supports the inclusion of some sort of fertilizer response index (RI) in N management to maximize nitrogen use efficiency and profitability.

INTRODUCTION

Accurate prediction of N mineralization is extremely important to increasing worldwide nitrogen use efficiency (NUE) (Honyecutt, 1999). Currently, N fertilizer rates are based solely on yield goals which are determined from historical performance with credits given to soil inorganic N determined by soil testing. In Oklahoma wheat production, split applications of N between the fall and spring are common. If N mineralization rates between the fall and spring application could be quantified, producers could adjust N management in-season, resulting in higher NUE. This ability to adjust N fertilization rates in-season has significant implications economically and environmentally.

Raun and Johnson (1999) reported worldwide NUE of cereal production to be 33%. This implies that only 33% of N applied as fertilizer is recovered by the grain. A factor which may contribute to this low NUE is unpredictable mineralization of organic matter decreasing or increasing the need for supplemental fertilizer N. For example, a long-term trial established in 1977 shows dramatic changes in check yields (0-N) from year to year, believed to have resulted from N mineralization (Johnson et al., 2000). This indicates that in years of high mineralized N, the yield response to fertilizer N may be small, resulting in low NUE. The economic implications of this are significant. If a producer can determine that N mineralization is high, and thus response to additional N is expected to be low, adjustment of in-season fertilizer N addition could result in less N being applied, while not adversely affecting yields.

The environmental implications are just as significant. Excess N in the soil profile can be subject to several losses that can negatively affect the environment. The major soil N sources of environmental contamination are denitrification (Burford and Bremner, 1975; Olson et al., 1979), leaching (Johnson and Raun, 1995), and runoff. Denitrification of soil nitrate results in nitrous oxide release to the atmosphere which is known to contribute to the greenhouse effect (Beardsley, 1997). Leaching of nitrate to groundwater is an often identified source of environmental contamination from excess fertilizer N (Goss and Goorahoo, 1995; Paramasivam and Alva, 1997). The problem of hypoxia is a result of runoff producing a toxic effect on aquatic organisms (Gascho et al., 1998; Burkart and James, 1999). If producers could make N management decisions based on potential crop response (and that included N mineralization), environmental impacts of N could be minimized.

Because N mineralization is a result of microbial activity, soil environment plays an important role in determining the mineralization rate. Soil temperature, soil moisture, and oxygen supply are all rate controlling factors of microbial activity. Optimum soil temperature for N mineralization ranges from 25 to 35°C (Havlin et al., 1999). Soil moisture content regulates aerobic and anaerobic microbial activity; maximum aerobic activity and resulting N mineralization occur between 50 and 70% water-filled pore space (Havlin et al., 1999).

Numerous methods exist to measure the potential N mineralization of a specific soil (Schepers and Meisinger, 1994). The initial approach was the buried bag method, where a soil sample was placed in a polyethylene bag, returned to the field, and later retrieved for analysis (Eno, 1960). This method did not, however, take into account soil water dynamics (Honeycutt, 1999). Schnabel (1983), in an attempt to overcome the buried bag flaw, suggested placing anion exchange resins at the base of intact soil cores with their tops open to rainfall input and with the base open to allow the water to percolate out. These methods are not easily adapted to producer use. Additionally, the methods defined above do not consider the plant as an integral part of the system. Ultimately, a healthy, growing plant may be the best measure of soil fertility and the best indicator of N mineralization.

Optical sensing technology using canopy reflectance to determine plant health and N uptake have become useful in replacing destructive methods of analysis. Stone et al. (1996) showed that the use of a vegetative index determined using plant reflectance in the red (660 ± 10 nm) and near-infrared (NIR) (780 ± 10 nm) regions of the spectrum could be a reliable predictor of forage N uptake. The reflectance based normalized difference vegetative index (NDVI) is calculated using the equation:

$$NDVI = [(NIR_{ref}) - (Red_{ref})] / [(NIR_{ref}) + (Red_{ref})] \quad [1]$$

where NIR_{ref} and Red_{ref} are the amounts of NIR and red light reflected from the crop canopy, respectively.

A response index ($RI_{Harvest}$) determined using harvested grain yield has been proposed to indicate crop response to applied N (Johnson et al., 2000). The $RI_{Harvest}$ is calculated using the equation:

$$RI_{Harvest} = \text{(grain yield with application of N /grain yield where no N has been applied)} \quad [2]$$

Mullen et al. (2001) evaluated the relationship between $RI_{Harvest}$ and an RI measured in-season using NDVI (RI_{NDVI}) to determine if the response to applied N could be accurately identified mid-season. The RI_{NDVI} is calculated using the equation:

$$RI_{NDVI} = \text{(NDVI with application of N/NDVI where no N has been applied)} \quad [3]$$

The objective of this work is to establish a method to determine N mineralization based on NDVI differences between plots receiving N and those not receiving N, and determine if the addition of topdress N would result in increased yield based on differences in forage N uptake.

MATERIALS AND METHODS

The experimental site was selected in the fall of 2000 at the North Central Experiment Station near Lahoma, Oklahoma (Grant silt loam, fine-silty, mixed, thermic Udic Argiustoll). Treatments were superimposed on a pre-existing long-term winter wheat fertility study known as 502, which was established in 1977. The 502 experiment is laid out in a randomized complete block design with 14 treatments evaluating varying levels of nitrogen, phosphorus, and potassium fertility. Plots with similar P and K fertility but with varying levels of N fertilization were used for the current study. These plots receive ammonium nitrate-N rates of 0, 22, 45, 67, 90, and 112 kg ha^{-1} broadcast applied, preplant, using a dry fertilizer spreader. Initial soil test data is reported in Table 1. Dates of activities are reported in Table 2.

Main plots were divided into 3 subplots, with three different types of N application (preplant, topdress, or 0 N). Main plot size was 4.9 x 18.3 m, and subplot size was 4.9 x 6.1 m. Subplots either received no N or N was applied preplant or as a topdress. Subplot treatments were imposed to evaluate the difference between N mineralization with regard to previous N application rates. Altering the timing of the applications allows for analysis of possible differences in N mineralization due to timing of N applications.

Spectral reflectance was measured using a handheld sensor constructed at Oklahoma State University that included two upward and downward directed photodiode sensors that collected irradiated red (671±6nm) and near-infrared (NIR)(780±6nm) light from the crop canopy (Stone et al., 1996). Reflectance readings were taken three times during the winter months of 2001 and 2002. The winter wheat growth stage when sensor readings were taken generally corresponded to Feekes 3 (tillers formed), 4 (erection of the pseudo-stem, leaf sheaths beginning to lengthen), 5 (pseudo-stem strongly erect) and 6 (first node of stem visible) (Large, 1954). Nitrogen mineralization (N contribution from the soil) was estimated by measuring the amount of N taken up by the check treatment where no N has been applied for the last 30 years. The model used to predict forage N uptake waspresented in Stone et al. (1996).

Winter wheat grain was harvested using a self-propelled combine, removing an area of 2 x 6.1 m from the center of each subplot. A subsample of wheat grain from each subplot was taken for total N analysis using the Carlo-Erba NA-1500 dry combustion analyzer (Schepers et al., 1989).

Response indexes (RI) were calculated in-season using NDVI and at harvest using grain yield as proposed by Johnson et al. (2000) and Mullen et al. (2001). Response indexes were calculated using the average of subplot data so that a RI was calculated within each N rate.

Differences between yield and grain N of subplots was evaluated using ANOVA generated by SAS (SAS, 2000). Regression equations and coefficients of determination (r^2) values were determined using Microsoft Excel and verified using SAS.

RESULTS

Estimated N Mineralized

The amount of N contributed by the soil at Feekes 4 in 2000-2001, determined using the predicted forage N uptake of the check (0 N) treatment, was 15.7 kg N ha^{-1} (Table 3). At this stage of growth, application of N did not increase forage N uptake. This implies that N supplied as preplant fertilizer was unnecessary because the crop did not have an environment conducive to growth beyond what the soil was able to support. At Feekes 5, the predicted forage N uptake of the check treatment, predicted with the model of Stone et al. (1996), was 17.6 kg N ha^{-1} again with no increases in forage N uptake due to application of N (Table 4). The plant had taken up considerably more N at Feekes 6, when the check treatment was predicted to contain 39.2 kg N ha^{-1}, and the 67 kg N ha^{-1} rate resulted in the only response above the check treatment (Table 5). Based on the fact that no significant differences in forage N uptake existed between treatments where N was applied one would not expect any significant differences in grain yield. If the difference between the amount of N accumulated in the plant in an area that has received fertilizer N is small compared to an area that has not received N, the likelihood of observing a response to additional topdress N should be small.

In 2001-2002, forage N uptake of the check treatment at Feekes 4 was higher than the previous year (21.2 kg N ha^{-1}), but application of N did not increase forage N uptake (Table 3). At Feekes 5, application of 22 kg N ha^{-1} preplant resulted in the highest forage N uptake of all preplant treatments, while application of topdress N did not increase forage N uptake (Table 4). Some differences in forage N uptake were noted at Feekes 6 when the wheat forage had accumulated considerably more N (Table 5). A linear and quadratic increase in forage N uptake was observed for both preplant and topdress N application, but the same trends were noted for treatments that historically receive N. This is primarily due to the fact that the check plot accumulated significantly less N than the N treatments, which indicates that the response to N was higher the second year of the study. Even though there was a significant response to N, treatments that historically received N showed the same response indicating that even though the experiment was responsive (with respect to the true N check) the environment within each treatment was affected by historical management and not responsive.

Grain Yield

As indicated in the forage N uptake data, yield response to N was low the initial year of the study (Table 6). Although application of either preplant or topdress N did not result in yields above that of the check (0 N), treatment differences were noted. Topdress N was applied rather late in the season primarily due to a late planting date and a cool, dry winter resulting in very little vegetative growth. In 2001, application of N topdress resulted in a linear decrease in grain yield ($p < 0.05$). This is interesting because it elucidates the fact that application of N above what is needed by the plant can cause a decrease in harvested grain whether by lodging or increased water use resulting in late season plant stress. Within rates, differences in timing of N application were noted. No differences in yield were noted between application of topdress N and historical N rate at any rate of application. When N was preplant applied at rates of 45 and 112 kg ha^{-1}, grain yield was increased compared to treatments not receiving N this specific year (historically N has been applied at equivalent rates). At N rates of 67 and 112 kg ha^{-1}, preplant application of N resulted in increased yield compared to topdress treatments.

Since no differences existed in the amount of N taken up in wheat forage at the time of topdressing, the likelihood of observing a response to topdress N was small. This was actually observed by the lack of yield response to topdress N, which is an important point. If producers can identify when the likelihood of a response does or does not exist, N management can be altered to increase profitability and decrease environmental impact.

As indicated by the differences in forage N uptake associated with N treatments, grain yield differences due to application of N did exist with respect to the true N check in 2001-2002. Preplant application of N and where N had historically been applied resulted in a quadratic increase in yield (Table 6). Grain yield was statistically maximized when preplant N was applied at the 22 kg N ha^{-1} rate. As in the first year, differences in NDVI of plots receiving N and plots not receiving N were small resulting in a small response index. Thus the likelihood of observing a response to applied N was small which was noted by the lack of yield response to topdress N. Even though there was a response to applied N (compared to the true N check), the treatment where N had historically been applied did not result in lower grain yields than its corresponding subplots that had received preplant or topdress N. Thus addition of N was not necessary to maximize yield where N had been historically applied. Due to the fact that the plot had historically received N, the need for additional N was diminished even though there was obviously a response to N relative to the check plot.

Grain N

Although grain yield was relatively unaffected by application of N in the initial year of the study, grain N was altered by application of both preplant and topdress N. A linear and quadratic increase in grain N was observed when N was applied preplant, topdress, and based on historical N application (Table 7). Differences in grain N due to timing of N application were also noted at each level of N. Application of preplant N, with the exception of the 45 kg N ha^{-1} rate, resulted in increased grain N compared to treatments where N was historically applied but not in this year. Topdress N application with the exception of the 90 kg N ha^{-1} rate resulted in increased grain N above that of historical N treatments where N was not applied this year. Grain N was also increased at the 90 kg N ha^{-1} rate when N was applied preplant compared to topdress application.

Even though grain yield was unaffected by N application, grain N was quite responsive to additional N. Presently, premiums for high protein grain are not paid to Oklahoma producers, thus application of additional N to improve protein is not economically motivated.

Despite the fact that addition of N did not greatly increase grain yield in 2001-2002, application of N did increase grain N concentration. A linear and quadratic response to applied N (preplant and topdress) and historical N application was noted (Table 7). Application of preplant or topdress N up to 45 kg N ha^{-1} did not increase grain N levels compared to treatments based on historical N application (not receiving N within this year). Application of N above 45 kg N ha^{-1} did result in higher grain N concentrations than historical N treatments. Timing of N application (preplant or topdress) did not have an effect on grain N concentration. As noted for grain yield and estimated N mineralization, the responsiveness of the experiment was apparent (with respect to the true check), but within treatments, historical application of N precluded the need for fertilizer N.

Grain N Uptake and NUE

Because grain N was highly affected by application of N, grain N uptake was also significantly altered due to application of N. A linear trend of increasing grain N uptake was noted for both preplant and topdress application of N with a quadratic trend also noted for preplant treatments (Table 8). Timing of application also resulted in differences in grain N uptake within specific N rates. Application of preplant N at rates of 45 kg ha^{-1} and higher resulted in increased grain N uptake compared to treatments where N was historically applied but not in this year. Topdress N application increased grain N uptake above that of historical treatments at the 45 kg N ha^{-1} rate. At the 67 and 90 kg N ha^{-1} rates, application of preplant N resulted in increased grain N uptake compared to topdress treatments.

Although grain N uptake was significantly affected by application of N, NUE levels never exceeded 20% (data not shown). Thus the amount of fertilizer N utilized by the plant was small and supplementation of N was probably unnecessary. This again illustrates that identifying the responsiveness of the crop for the specific environment is essential to maximize profit and minimize environmental impact.

Contrary to the initial year of the study, grain N uptake was significantly affected by application of N and treatments that historically receive N in 2001-2002 (Table 8). Application of N (preplant and topdress) and historical application of N resulted in a linear and quadratic increase in grain N uptake. At the 45 kg N ha^{-1} rate, application of preplant N increased grain N uptake compared to the historical N treatment. Thus applying N this year did not increase grain N uptake when taking into consideration historical N application (with the exception of the 45 kg N ha^{-1} rate).

Although grain N uptake was significantly increased compared to the true N check treatment, application of N did not result in NUE values greater than 30% when compared to the corresponding historical N treatment. Thus not applying N (where N had historically been applied) was the best option environmentally and economically.

DISCUSSION

It is interesting to note that yield levels varied greatly between the two years of this trial while response to applied N was low each year. Comparison of grain yield between the two years reveals that the amount of N required for maximum yield differed. But based on the lack of response or low response to applied N, the soil was able to contribute enough N via mineralization, rainfall, etc. to provide the majority of N needed to maximize yield.

The ability to recognize the responsiveness of a crop to N is more important than simply quantifying the amount of N mineralized. Lab procedures that provide estimates of N mineralization potentials of soils are really of no practical use in determining N need. Not only because a lab environment can not accurately replicate field conditions, but it also can not identify the N need of the crop within the growing season. Utilizing the crop as an indicator of N mineralization is a more sensible technique because it integrates all soil conditions for both microbial activity and plant growth up to the point when sensor measurements are taken.

CONCLUSIONS

When the amount of N accumulated within the forage from a crop receiving N is equal to or close to the amount of N accumulated within the forage of a crop not receiving N, topdressing of N does not result in increased yields, but may however influence grain N concentration. This evidence further supports the inclusion of some sort of RI in N management to maximize nitrogen use efficiency and profitability. The ability to recognize that application of topdress N will not contribute to higher yields but may result in higher grain protein, provides producers the opportunity to manage N for protein if premiums are available. Using the crop to estimate N mineralized (or N contribution of the environment) with NDVI may prove to be a more reliable method than current lab techniques.

Historical N management also greatly affects crop response within a given year. If producers wish to maximize profit, preplant N rates must be decreased significantly or eliminated. Even N rates as low as 22 kg N ha^{-1}, when applied annually for a number of years, can diminish the need for additional fertilizer N within a given year.

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TABLE 1. Initial soil data from main plots in fall of 1999.

Nitrogen rate	OC	TN	NH_4-N	NO_3-N	P	K	pH
---kg ha^{-1}---	------g kg^{-1}------		-------------------------kg ha^{-1}------------------				
0	7.7	0.9	31.5	10.4	127	1133	5.5
22	7.5	0.9	25.5	7.8	155	1082	5.4
45	7.7	0.9	26.8	14.3	141	1114	5.3
67	7.6	0.9	28.1	19.3	159	1158	5.6
90	7.1	0.8	32.8	19.5	140	1156	5.8
112	7.2	0.9	30.8	22.6	164	1173	5.8

OC-organic carbon, TN-total nitrogen, NH_4-N and NO_3-N-2 M KCl extraction, P and K – Mehlich III extraction, pH-1:1 soil:water

TABLE 2. Fertilization, planting, topdressing, and harvest dates at Lahoma, Oklahoma, 2000-2001 and 2001-2002.

Year	Fertilization	Planting	Topdressing	Harvest
2000-2001	08/09/00	01/12/00	05/04/01	15/06/01
2001-2002	30/08/01	28/11/01	22/03/02	26/06/02

TABLE 3. NDVI and estimated N mineralized based on forage N uptake calculated using NDVI at Feekes 4, 2000-2001 and 2001-2002.

N rate kg ha^{-1}	Timing of N application	NDVI values 2001	NDVI values 2002	Forage N uptake kg ha^{-1} 2001	Forage N uptake kg ha^{-1} 2002
0	---	0.210	0.481	15.7	21.1
22	PP	0.195	0.572	15.6	27.1
	TD	0.183	0.519	15.5	23.0
	NA	0.191	0.554	15.5	25.4
45	PP	0.190	0.436	15.6	19.5
	TD	0.157	0.438	15.4	19.5
	NA	0.157	0.424	15.4	19.0
67	PP	0.252	0.468	16.0	20.5
	TD	0.189	0.507	15.6	22.3
	NA	0.199	0.555	15.6	25.5
90	PP	0.174	0.449	15.5	19.8
	TD	0.140	0.464	15.3	20.4
	NA	0.142	0.398	15.3	18.3
112	PP	0.194	0.407	15.6	18.5
	TD	0.148	0.455	15.4	20.1
	NA	0.136	0.452	15.3	19.9
	SED	0.021	0.042	0.1	2.1
Contrasts					
N rate linear - PP		NS	***	NS	**
N rate quadratic - PP		NS	NS	NS	NS
N rate linear - TD		***	NS	NS	NS
N rate quadratic - TD		NS	NS	NS	NS
N rate linear - NA		***	*	***	NS
N rate quadratic - NA		NS	NS	NS	NS

NA – no N applied, PP – N applied preplant, TD – N applied topdress
*, **, ***, NS - significant at the 0.1, 0.05, and 0.01 confidence level or non-significant (NS)

TABLE 4. NDVI and estimated N mineralized based on forage N uptake calculated using NDVI at Feekes 5, 2000-2001 and 2001-2002.

N rate	Timing of	NDVI values		Forage N uptake kg ha^{-1}	
kg ha^{-1}	N application	2001	2002	2001	2002
0	---	0.370	0.487	17.6	21.4
22	PP	0.302	0.593	16.5	28.9
	TD	0.293	0.542	16.4	24.4
	NA	0.318	0.577	16.8	27.2
45	PP	0.325	0.504	16.8	22.6
	TD	0.254	0.474	16.0	21.4
	NA	0.256	0.465	16.0	20.4
67	PP	0.363	0.521	17.5	23.1
	TD	0.319	0.566	16.7	26.2
	NA	0.331	0.574	16.9	26.9
90	PP	0.317	0.502	16.7	21.9
	TD	0.259	0.507	16.1	22.6
	NA	0.244	0.446	15.9	19.7
112	PP	0.283	0.479	16.3	21.3
	TD	0.247	0.509	15.9	22.8
	NA	0.207	0.494	15.6	21.8
	SED	0.036	0.034	0.6	2.4
Contrasts					
N rate linear - PP		NS	NS	NS	NS
N rate quadratic - PP		NS	NS	NS	NS
N rate linear - TD		***	NS	**	NS
N rate quadratic - TD		NS	NS	NS	NS
N rate linear - NA		***	NS	***	NS
N rate quadratic - NA		NS	NS	NS	NS

NA – no N applied, PP – N applied preplant, TD – N applied topdress

*, **, ***, NS - significant at the 0.1, 0.05, and 0.01 confidence level or non-significant (NS)

TABLE 5. NDVI and estimated N mineralized based on forage N uptake calculated using NDVI at Feekes 6, 2000-2001 and 2001-2002.

N rate kg ha^{-1}	Timing of N application	NDVI values 2001	NDVI values 2002	Forage N uptake kg ha^{-1} 2001	Forage N uptake kg ha^{-1} 2002
0	---	0.672	0.690	39.2	43.4
22	PP	0.662	0.781	37.9	70.9
	TD	0.665	0.784	38.1	73.0
	NA	0.669	0.772	38.9	67.3
45	PP	0.717	0.766	48.5	64.4
	TD	0.663	0.752	36.9	60.2
	NA	0.675	0.754	39.9	59.4
67	PP	0.727	0.802	51.3	75.1
	TD	0.703	0.795	45.2	73.1
	NA	0.719	0.799	49.3	74.8
90	PP	0.669	0.794	38.4	73.7
	TD	0.657	0.793	37.1	74.3
	NA	0.651	0.760	35.3	61.1
112	PP	0.638	0.759	34.1	61.5
	TD	0.647	0.772	34.9	65.8
	NA	0.608	0.749	30.7	56.7
	SED	0.028	0.017	4.0	5.5
Contrasts					
N rate linear - PP		NS	***	NS	***
N rate quadratic - PP		***	***	***	***
N rate linear - TD		NS	***	NS	***
N rate quadratic - TD		NS	***	NS	***
N rate linear - NA		*	***	NS	***
N rate quadratic - NA		***	***	NS	***

NA – no N applied, PP – N applied preplant, TD – N applied topdress

*, **, ***, NS - significant at the 0.1, 0.05, and 0.01 confidence level or non-significant (NS)

TABLE 6. Effect of N and timing of N application on winter wheat grain yield, 2000-2001 and 2001-2002.

N rate, kg ha^{-1}	Timing of N application	Yield, kg ha^{-1} 2001	Yield, kg ha^{-1} 2002
0	---	1655	2446
22	PP	1356	3145
	TD	1465	3068
	NA	1458	3163
45	PP	1632	3232
	TD	1468	2870
	NA	1336	2693
67	PP	1648	2998
	TD	1443	2821
	NA	1517	3389
90	PP	1517	2859
	TD	1443	3013
	NA	1361	2650
112	PP	1520	2951
	TD	1203	3014
	NA	1247	3015
	SED	120	232
Contrasts			
N rate linear - PP		NS	NS
N rate quadratic - PP		NS	**
N rate linear - TD		***	NS
N rate quadratic - TD		NS	NS
N rate linear - NA		***	NS
N rate quadratic - NA		NS	**

NA – no N applied, PP – N applied preplant, TD – N applied topdress
*, **, ***, NS - significant at the 0.1, 0.05, and 0.01 confidence level or non-significant (NS)

TABLE 7. Effect of N and timing of N application on winter wheat grain N, 2000-2001 and 2001-2002.

N rate, kg ha^{-1}	Timing of N application	Grain N, g kg^{-1} 2001	2002
0	---	18.9	18.7
22	PP	24.7	20.7
	TD	24.2	21.1
	NA	22.7	20.0
45	PP	24.2	22.8
	TD	25.6	23.0
	NA	23.5	23.5
67	PP	25.1	25.0
	TD	24.3	24.7
	NA	23.0	22.9
90	PP	26.4	25.2
	TD	24.6	24.8
	NA	23.5	23.9
112	PP	26.2	25.2
	TD	26.0	25.3
	NA	24.1	23.8
	SED	0.1	0.1
Contrasts			
N rate linear - PP		***	***
N rate quadratic - PP		***	***
N rate linear - TD		***	***
N rate quadratic - TD		***	***
N rate linear - NA		***	***
N rate quadratic - NA		***	**

NA – no N applied, PP – N applied preplant, TD – N applied topdress
*, **, ***, NS - significant at the 0.1, 0.05, and 0.01 confidence level or non-significant (NS)

TABLE 8. Effect of N and timing of N application on winter wheat grain N uptake, 2000-2001 and 2001-2002.

		Grain N uptake, kg ha^{-1}	
N rate, kg ha^{-1}	Timing of N application	2001	2002
0	---	31.5	45.7
22	PP	32.9	65.1
	TD	35.3	64.9
	NA	33.5	63.6
45	PP	39.3	73.5
	TD	37.5	65.6
	NA	31.4	61.7
67	PP	41.3	74.9
	TD	35.0	68.5
	NA	34.9	77.5
90	PP	39.9	72.2
	TD	35.4	75.2
	NA	31.9	62.2
112	PP	39.6	74.4
	TD	31.3	76.4
	NA	30.1	71.9
	SED	2.7	5.8
Contrasts			
N rate linear - PP		***	***
N rate quadratic - PP		**	***
N rate linear - TD		NS	***
N rate quadratic - TD		***	*
N rate linear - NA		NS	***
N rate quadratic - NA		NS	**

NA – no N applied, PP – N applied preplant, TD – N applied topdress
*, **, ***, NS - significant at the 0.1, 0.05, and 0.01 confidence level or non-significant (NS)

APPENDIX

FIGURE 1. Grain yield response to N applied either preplant (PP) or topdress (TD) and response to historical N rate (NA) at Lahoma, Oklahoma, 2000-2001.

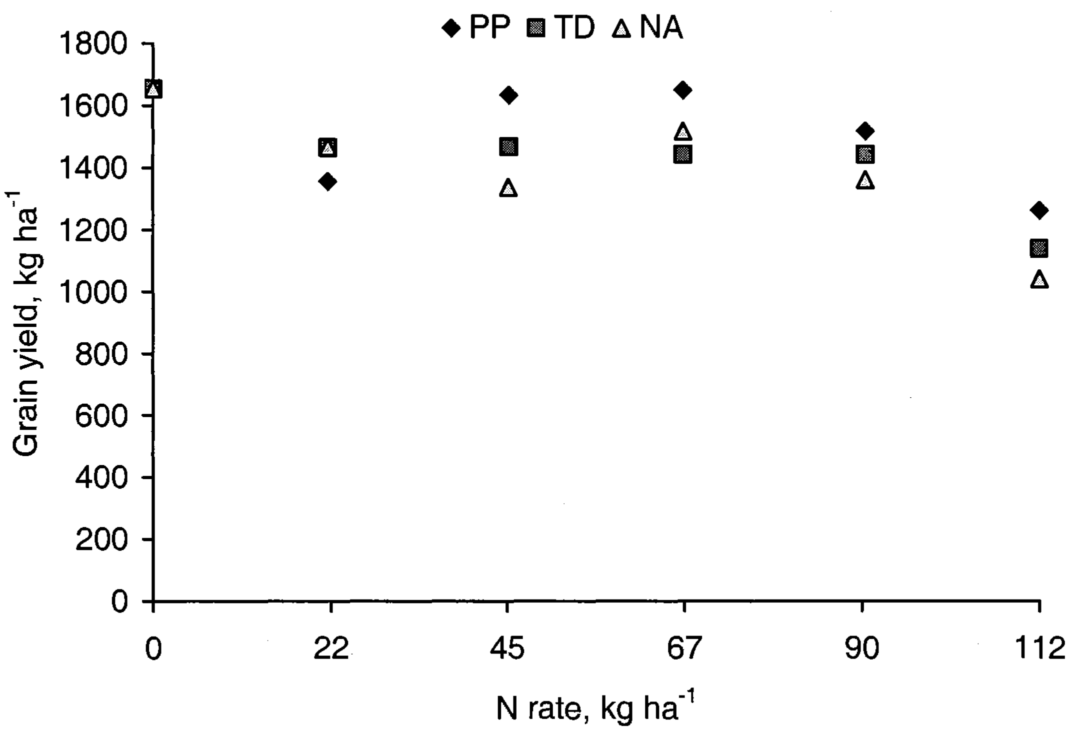


FIGURE 2. Grain N response to N applied either preplant (PP) or topdress (TD) and response to historical N rate (NA) at Lahoma, Oklahoma, 2000-2001.

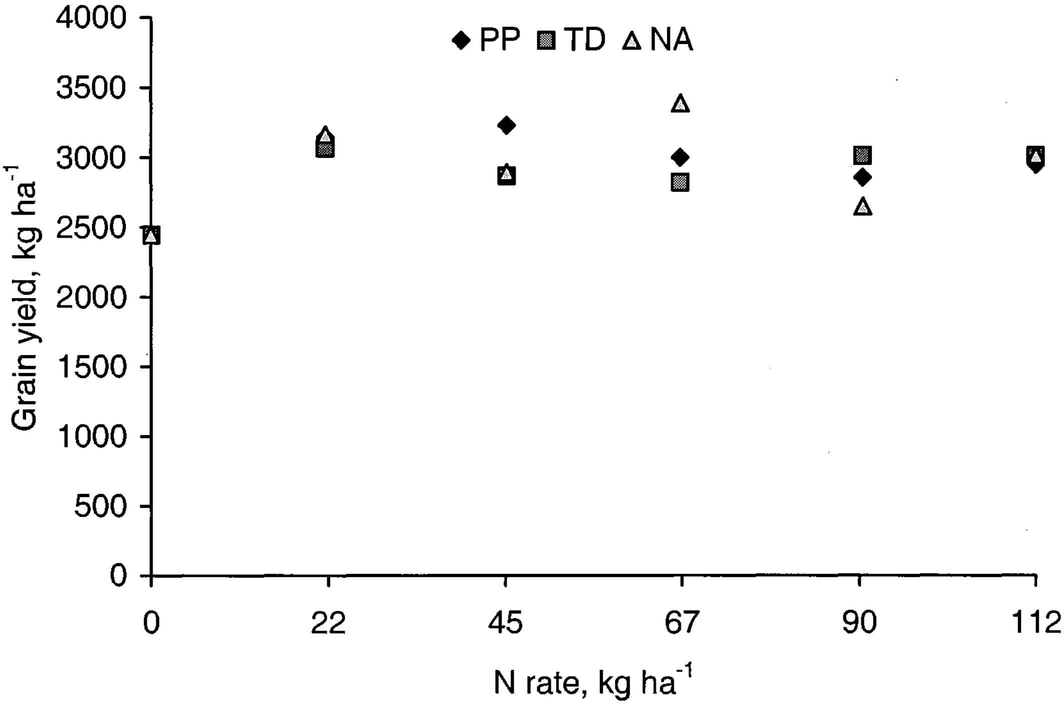


FIGURE 3. Grain N uptake response to N applied either preplant (PP) or topdress (TD) and response to historical N rate (NA) at Lahoma, Oklahoma, 2000-2001.

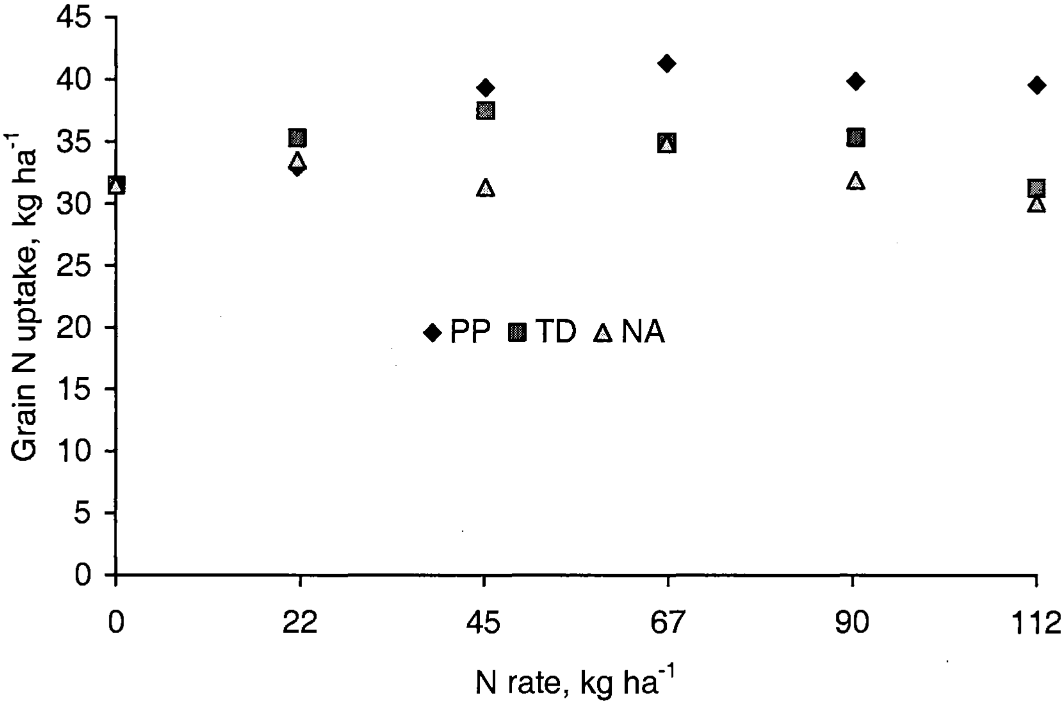


FIGURE 4. Grain yield response to N applied either preplant (PP) or topdress (TD) and response to historical N rate (NA) at Lahoma, Oklahoma, 2001-2002.

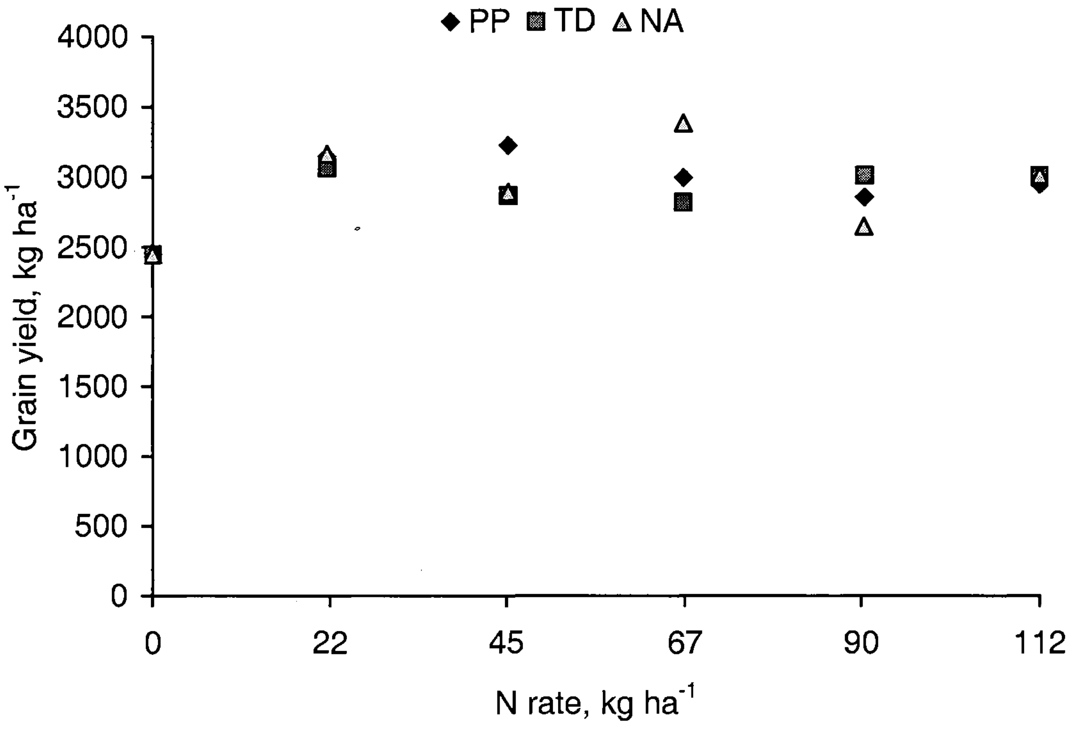


FIGURE 5. Grain N response to N applied either preplant (PP) or topdress (TD) and response to historical N rate (NA) at Lahoma, Oklahoma, 2001-2002.

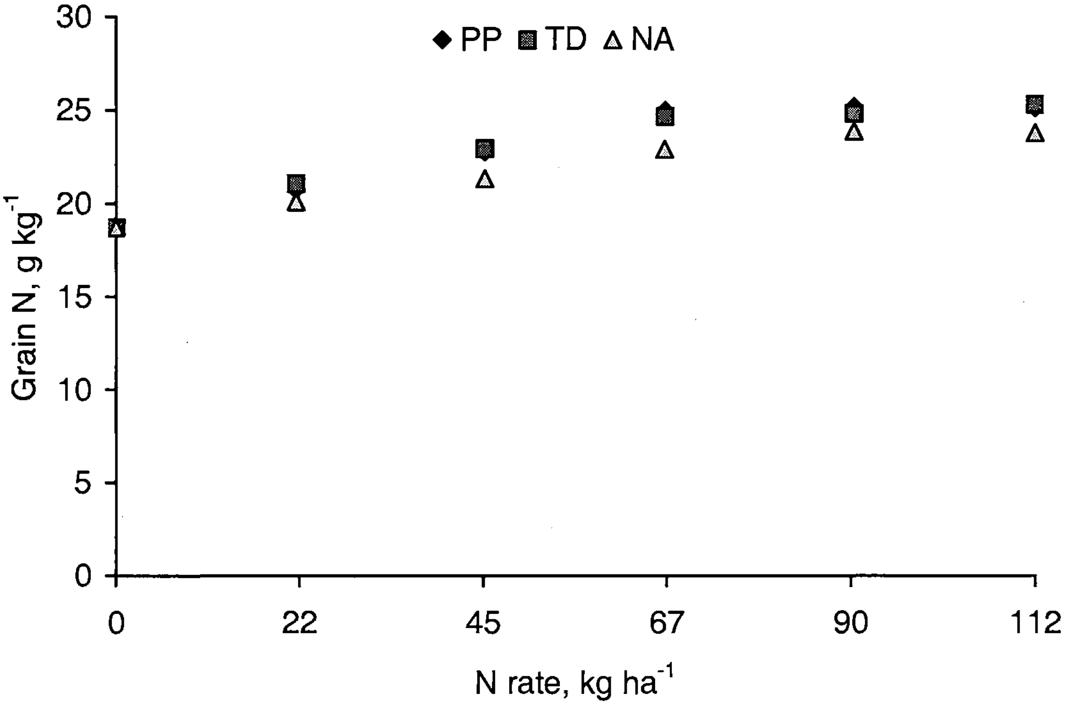
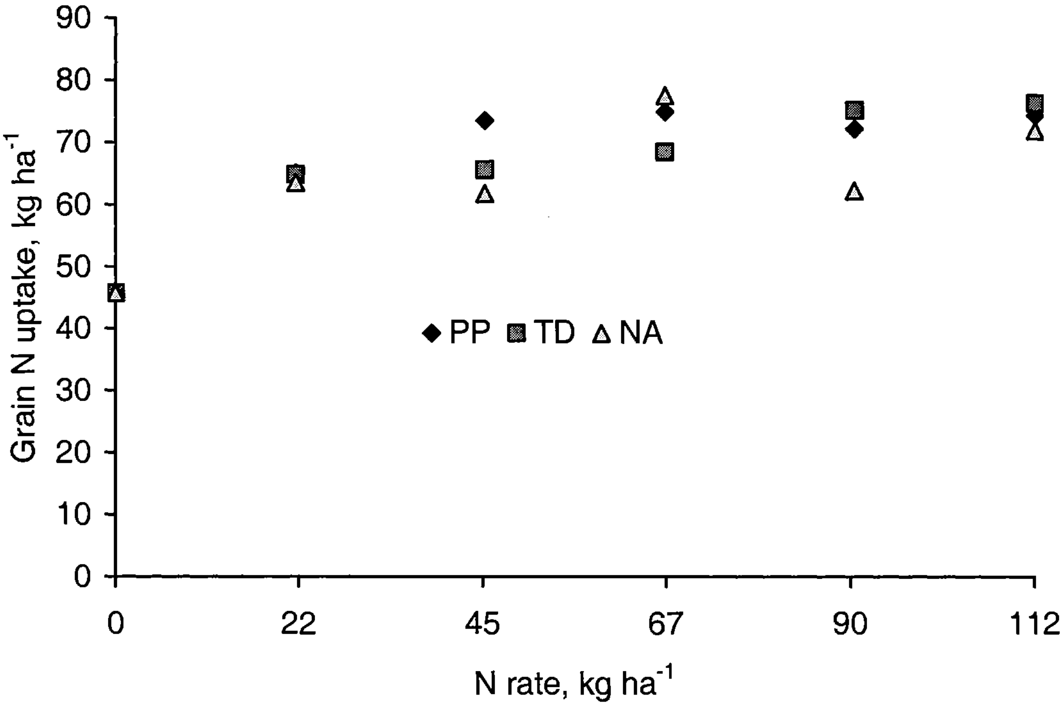


FIGURE 6. Grain N uptake response to N applied either preplant (PP) or topdress (TD) and response to historical N rate (NA) at Lahoma, Oklahoma, 2001-2002.



Response Index

An in-season response index (RI_{NDVI}) was calculated using the average preplant NDVI and the average historical N application NDVI within the subplots as was $RI_{Harvest}$. The correlation between RI_{NDVI} and $RI_{Harvest}$ was relatively good at each stage of growth when sensor readings were taken (r^2>0.69) (Figures 7, 8, and 9). The relationship between RI_{NDVI} and $RI_{Harvest}$ was different for each stage of growth, noted by the change in the regression lines, but appeared to be best at Feekes 5.

The RI calculated using the preplant yield and historical N application yield for each subplot was more related to the unfertilized yield (historical N application) than the fertilized yield (preplant or topdress N) within each year (Figures 10-13). In 2000-2001, the relationship between the RI_{NDVI} and check (0 N) yield was better than the relationship between RI_{NDVI} and fertilized yield (Figures 10 and 11. The same was noted in 2001-2002 but the differences in the relationships were more dramatic (Figures 12 and 13). This elucidates the fact that RI is more a function of check yield than fertilized yield.

FIGURE 7. Relationship between RI_{NDVI} and $RI_{Harvest}$ of subplots at Feekes 4 at Lahoma, Oklahoma, 2000-2001 and 2001-2002.

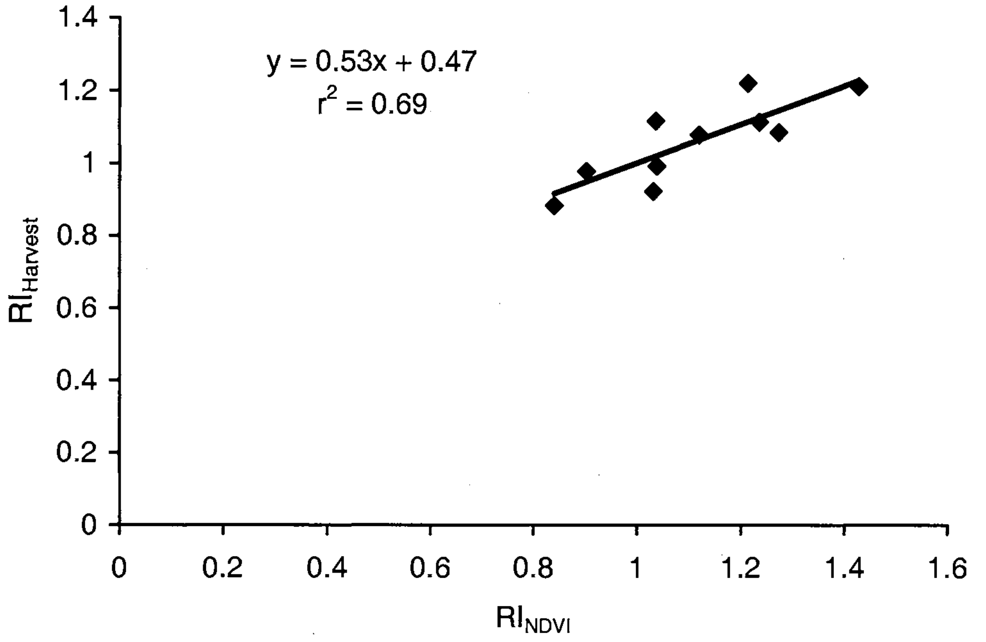


FIGURE 8. Relationship between RI_{NDVI} and $RI_{Harvest}$ of subplots at Feekes 5 at Lahoma, Oklahoma, 2000-2001 and 2001-2002.

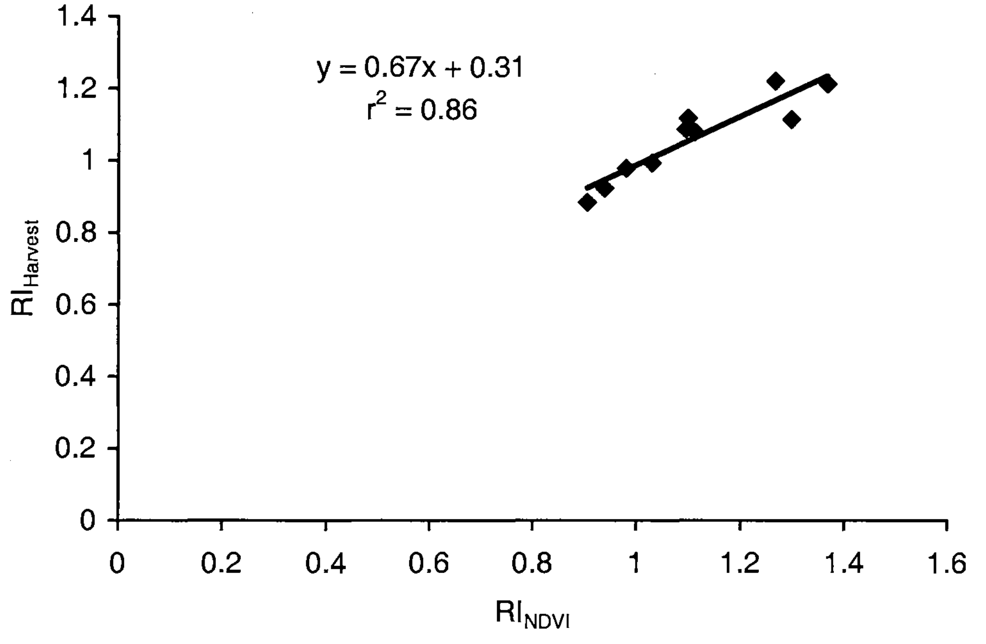


FIGURE 9. Relationship between RI_{NDVI} and $RI_{Harvest}$ of subplots at Feekes 6 at Lahoma, Oklahoma, 2000-2001 and 2001-2002.

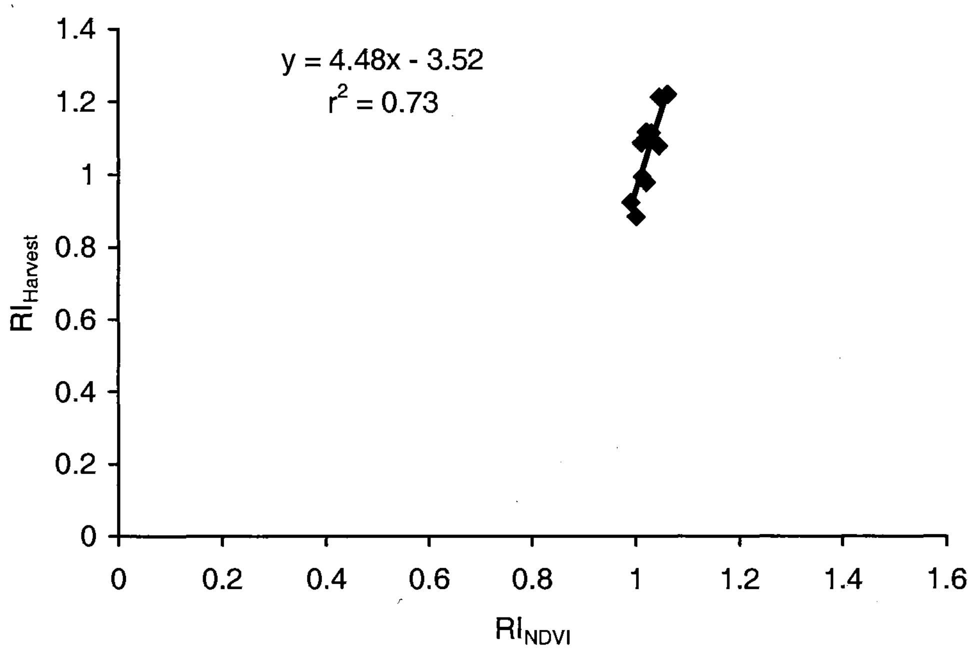


FIGURE 10. Relationship between RI_{NDVI} and the average yield of unfertilized subplots at Lahoma, Oklahoma, 2000-2001.

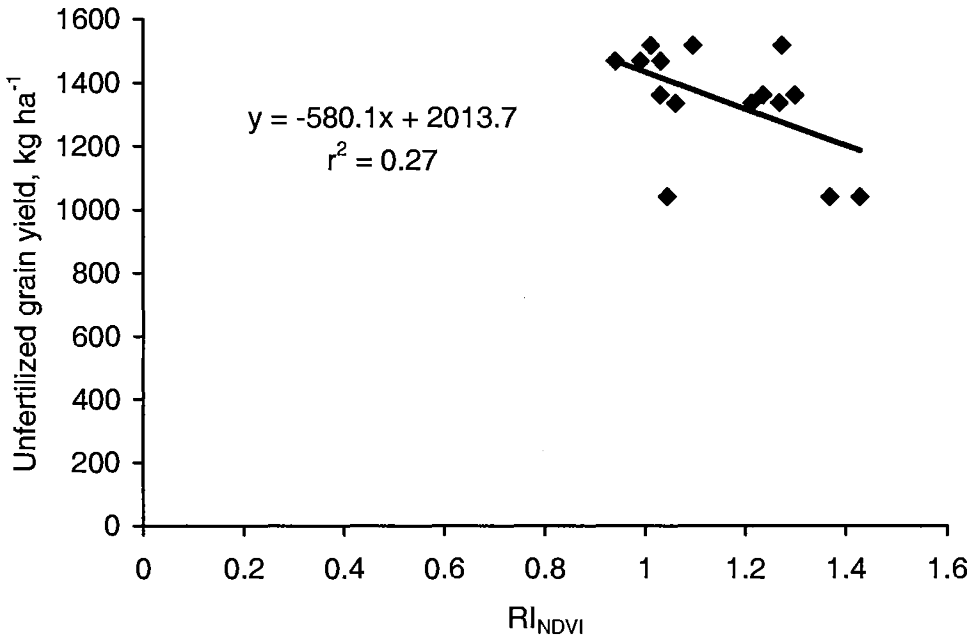


FIGURE 11. Relationship between RI_{NDVI} and the average yield of fertilized subplots at Lahoma, Oklahoma, 2000-2001.

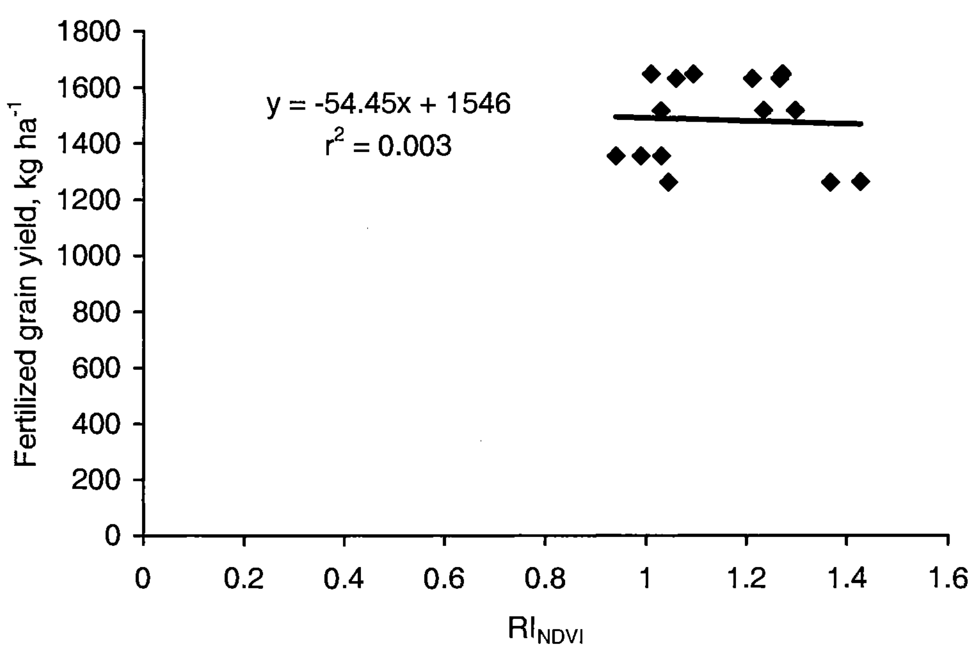


FIGURE 12. Relationship between RI_{NDVI} and the average yield of unfertilized subplots at Lahoma, Oklahoma, 2001-2002.

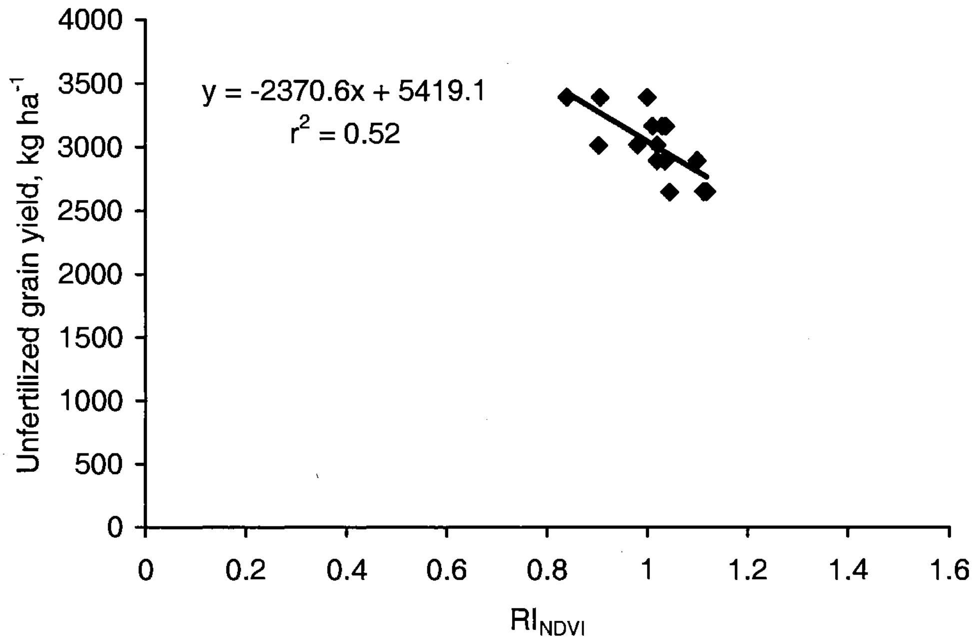
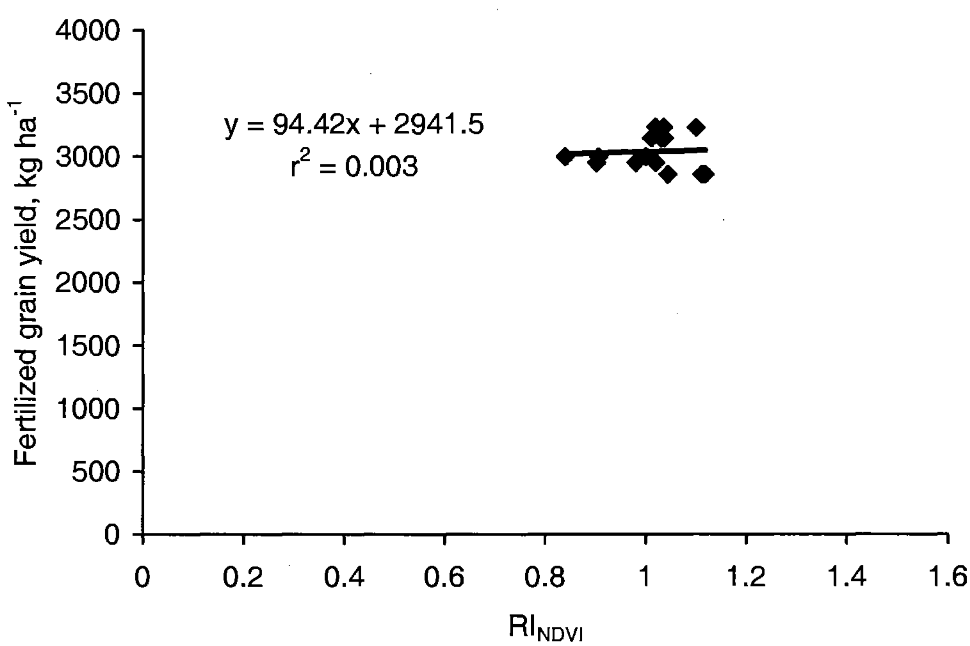


FIGURE 13. Relationship between RI_{NDVI} and the average yield of fertilized subplots at Lahoma, Oklahoma, 2001-2002.



CHAPTER II

USE OF IN-SEASON SENSOR DERIVED RESPONSE INDICES TO PREDICT THE RESPONSE INDEX AT HARVEST

ABSTRACT

Current nitrogen use efficiency (NUE) of cereal crop production is estimated to be near 33%, indicating that much of the applied fertilizer nitrogen (N) is not utilized by the plant and is susceptible to loss from the soil-plant system. Supplying fertilizer N only when a crop response is expected may improve use efficiency and profitability. A response index using harvest data was recently proposed that indicates the actual crop response to additional N within a given year. This response index, $RI_{Harvest}$, is calculated by dividing the average grain yield of the highest yielding treatment receiving preplant N by the average yield of a check treatment (0 N). Although theoretically useful, $RI_{Harvest}$ does not allow for in-season adjustment of N application. The objective of this work was to determine the relationship between $RI_{Harvest}$ and the response index measured in-season (RI_{NDVI}) using the normalized difference vegetative index (NDVI). Research was conducted in thirty existing field experiments in Oklahoma. Each field experiment evaluated crop response to varying levels of preplant N. At Feekes growth stages 5, 9, and 10.5, $RI_{Harvest}$ was accurately predicted using RI_{NDVI} ($r^2 > 0.64$). These results indicated that the in-season response index

based on sensor readings is a viable method for identifying environments (i.e. fields) where the potential to respond to additional N exists.

INTRODUCTION

Raun and Johnson (1999) estimated current nitrogen use efficiency (NUE) of worldwide cereal production to be near 33%, which suggests that current N strategies are extremely inefficient. Current Oklahoma N fertilizer recommendations are calculated using the equation, N_{rec} = yield goal (kg ha^{-1})*0.033, where the yield goal is based on the average wheat yield for the past 5 years and, on average, 33 kg of N is needed to produce 1000 kg of grain. Typically, all N is injected preplant as anhydrous ammonia between mid-August and mid-September. Avoiding excess application of N fertilizers in crop production is one way to increase NUE (Kanampiu et al., 1997). Application methods which avoid applying large amounts of N at any one time can also increase NUE (Wuest and Cassman, 1992). The soil/plant system is capable of loss via denitrification (Burford and Bremner, 1975; Olson et al., 1979, Burkart and James, 1999), runoff (Gascho et al., 1998; Burkart and James, 1999), or leaching (Goss and Goorahoo, 1995; Paramasivam and Alva, 1997). Thus, there is more N available for loss at any given time during the growing season if N is applied only once per season. Multiple timely applications of N during the growing season, while potentially costly, could significantly increase NUE.

Alternative methods of determining fertilizer N rates for winter wheat using early-season estimates of N uptake and potential yield determined from in-season spectral measurements collected between January and April have been developed (Lukina et al., 2001; Raun et al., 2002). Using a modified daytime-lighting reflectance-sensor, early-season plant N uptake between Feekes physiological stages 4 (leaf sheaths lengthen) and 6 (first node of stem visible) (Large, 1954) has been found to be highly correlated with NDVI (Stone et al., 1996; Solie et al., 1996). Reflectance based NDVI was calculated using the following equation:

$$NDVI = [(NIR_{ref}/NIR_{inc}) - (Red_{ref}/Red_{inc})] / [(NIR_{ref}/NIR_{inc}) + (Red_{ref}/Red_{inc})] \quad [1]$$

where NIR_{ref} and Red_{ref} are the near-infrared and red reflected radiance of the crop, respectively, and NIR_{inc} and Red_{inc} are the near-infrared and red incident radiance, respectively. Further analyses showed that a reliable in-season estimate of yield (INSEY) could be obtained from dividing NDVI by the days from planting to sensing date (where growing degree days > 0) (Raun et al., 2002). This INSEY was subsequently used to estimate N uptake in the grain based on a predicted yield level. Finally, using predicted wheat N uptake (measured by NDVI) and projected grain N uptake from estimated yield (INSEY), topdress fertilizer N rates were adjusted based on the difference (grain N uptake minus early season plant N uptake) (Lukina et al., 2001).

Recently, a response index ($RI_{Harvest}$) was proposed that indicates the actual crop response to applied N (Johnson et al., 2000). The $RI_{Harvest}$ is calculated using the following equation:

$RI_{Harvest}$ = (highest mean yield N-treatment)/(mean yield check treatment) [2]

Freeman et al. (2000) showed that when $RI_{Harvest}$ was greater than 1.5, the correlation of INSEY, determined at Feekes 5, and final grain yield was improved. This suggests that when differences in wheat forage exist at Feekes 5, due to applied N, the ability to accurately predict final grain yield is enhanced. Increased non-fertilizer N contribution via mineralization or rainfall are the most likely reasons for low $RI_{Harvest}$. The use of $RI_{Harvest}$ does not allow for in-season adjustment of N, thus its practical value to N management is minimal.

In-season sensor measurements of NDVI as an indicator of wheat N uptake between plots receiving N and those not receiving N can be used in the same way using the following equation:

RI_{NDVI} = (highest mean NDVI N treatment)/(mean NDVI check treatment) [3]

Basing fertilizer rates on in-season estimate of yield (INSEY) and RI_{NDVI} may help optimize in-season fertilizer application which in turn could increase NUE and yield. The objective of this work was to determine if RI_{NDVI} could accurately predict $RI_{Harvest}$ at Feekes growth stages 5, 9, 10.5, and 11.2.

MATERIALS AND METHODS

Research was conducted at either an on-going long-term experiment (numbers assigned in the 1960's, 1970's, and 1990's as experiments 222, 301, 502, and 801), or a short-term (1-3 years) field experiment that included the evaluation of preplant N rates (Tables 1 and 2). The soils at each of these locations follow; Perkins, Teller sandy loam (fine-loamy, mixed, thermic Udic Argiustoll); Hennessey, Shellabarger sandy loam (fine-loamy, mixed, thermic Udic Argiustoll); Stillwater, Kirkland silt loam (fine, mixed, thermic Udertic Paleustoll); Stillwater-Efaw, Norge silt loam (fine-silty, mixed, thermic Udic Paleustoll); Lahoma, Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll); Haskell, Taloka silt loam (fine, mixed, thermic Mollic Albaqualf); and Tipton, Tipton silt loam (fine-loamy, mixed, thermic Pachic argiusoll). The anhydrous ammonia (AA) nitrogen use efficiency (NUE) experiments were initiated in 1999. The N rate by P rate (N*P) experiment at Perkins was initiated in 1996. Experiments 222, 301, 502, and 801 were initiated in 1969, 1993, 1971, and 1977, respectively, and all four evaluate annual rates of applied N as ammonium nitrate at constant levels of P and K (Table 1). Winter wheat was planted at a 78 kg ha^{-1} seeding rate using a 0.19 m row spacing. All field experiments where sensor and yield data were collected employed randomized complete block designs with 3 to 4 replications (depending on site).

During the winter months of 1998, 1999, 2000, 2001, and 2002 spectral reflectance readings at Feekes (Large, 1954) growth stage 5 were taken from thirty existing winter wheat experiments. Sensor measurements were taken from treatments with varying levels of N nutrition within each replication. Additionally, spectral reflectance readings were taken at Feekes growth stages 9, 10.5, and 11.2 from fourteen existing winter wheat experiments during 2000 and 2001. Spectral reflectance was measured using a handheld sensor constructed at

Oklahoma State University that included two upward and downward directed photodiode sensors that received irradiated red (671±6nm) and near-infrared (NIR)(780±6nm) light from the crop canopy (Stone et al., 1996). The sensor was placed approximately 1.5 m above the crop for all readings, and approximately 10 readings were collected per second resulting in approximately 40 readings taken per plot. Reflectance readings from all plots at each experiment were collected at one post-dormancy date in 1998, 1999, and 2002 and four post-dormancy dates in 2000 and 2001. The date when readings were collected generally corresponded to Feekes growth stages 5 (pseudo-stem, formed by sheaths of leaves strongly erect), 9 (ligule of last leaf just visible), 10.5 (flowering), and 11.2 (mealy ripe, contents of kernel soft but dry) (Large, 1954). Consistent with different planting times and growing conditions, spectral reflectance readings were collected between January and May (Table 2). All reflectance readings from wheat were taken from a 4.0 m^2 area (same area as that harvested for grain yield) between 10 a.m. and 4 p.m. under natural light.

After NDVI values were calculated using equation [1], RI_{NDVI} was computed using equation [2]. Grain yield was determined using a self propelled combine which harvested the same 4.0 m^2 area where spectral reflectance data were collected. From the yield data, $RI_{Harvest}$ was calculated using equation [3]. Linear and quadratic models were used to determine the relationships between $RI_{Harvest}$ and RI_{NDVI} using SAS PROC REG (SAS Insitute, 2000).

RESULTS AND DISCUSSION

$RI_{Harvest}$ vs RI_{NDVI} at Feekes 5

Average yield and NDVI values used in RI_{NDVI} and $RI_{Harvest}$ calculations are reported in Table 3. In these experiments RI_{NDVI} measured at Feekes 5 was highly correlated to $RI_{Harvest}$ ($R^2 = 0.64$, $P<0.001$) (Figure 1). In this work, we recognize that yield enhancing and limiting factors can occur after sensor readings are collected that can result in $RI_{Harvest}$ being underestimated or overestimated by RI_{NDVI}. For example, in 1999, early spring rains after a dry fall planting period improved growing conditions after the sensing dates. This may have resulted in an increased response to N in fertilized plots causing a larger $RI_{Harvest}$ than would have been predicted by RI_{NDVI}. As a result, RI_{NDVI} measured closer to harvest (Feekes 9 and 10.5) should be a better predictor of $RI_{Harvest}$.

$RI_{Harvest}$ vs RI_{NDVI} at Feekes 9, 10.5, and 11.2

The relationships between RI_{NDVI} and $RI_{Harvest}$ measured at Feekes growth stages 5 (Figure 1), 9 (Figure 2), and 10.5 (Figure 3) were similar. Prediction of $RI_{Harvest}$ at Feekes 11.2 was poor, primarily due to early maturation of the check (0-N) plots relative to plots receiving N (Figure 4). It is important to note that sensor readings taken at later stages of growth (near maturation) would most likely result in overestimation of $RI_{Harvest}$ due to early maturation of check (0-N) plots resulting in low NDVI values, thus decreasing the value of the denominator in the calculation of RI_{NDVI}.

The ability to predict whether a response to applied N can be expected is important. If a response to N is expected, then N management strategies can be altered to apply N based on responsiveness. To date, many researchers have struggled to develop indices that assess N mineralization potential. The basic concept is that if N mineralization potential could be determined, N recommendations could be refined.

Utilizing the crop to assess N contribution from the soil without N fertilization within the growing season, whether by increased rainfall N or mineralization, is novel. The higher the yield level the soil will support without N fertilization (low RI_{NDVI}), in general, the lower the amounts of fertilizer N that will be needed to reach maximum yields. This is not to say that soil testing for ammonium and/or nitrate before fertilizer application is not a reliable tool for assessing N need, but rather that the soil test information determined at a point in time is static and provides no prediction of mineralization and/or immobilization which can occur throughout the growing season.

The importance of determining RI using in-season measurements of NDVI can be summarized in the following scenarios. First, if RI_{NDVI} for a location is relatively low (RI<1.1) meaning that the check (0-N) NDVI and NDVI from N fertilized treatments are similar, the probability of a response to additional N will be low, and thus little, if any, fertilizer N is required. Conversely, if the NDVI of the check treatment is low and the NDVI of N fertilized treatments is high resulting in a high RI_{NDVI} (RI>1.1), the probability of a response to additional N is good, and thus additional fertilizer should be applied. Considering that final grain yield differences due to applied N are being predicted from mid-winter readings at Feekes 5, this information becomes increasingly useful.

The ability of sensors to accurately quantify differences in wheat NDVI between treatments receiving N and those not receiving N at such a high resolution (4 m^2) is an exciting prospect. Demonstrated spatial variability within a field shows that differences in moisture holding capacity, soil test P, organic C, nitrate, and ammonium can exist at resolutions of 1 m^2 (Raun et al., 1998). Determination of RI_{NDVI} for a specific environment (i.e. field) will be computed using a high N strip on a field-size scale and determination of yield potential using INSEY could be used in conjunction to determine N requirement on a 1 m^2 basis.

Current research from Nebraska uses chlorophyll meter readings to calculate a sufficiency index determined by dividing an as-needed N treatment by a well-fertilized treatment (Varvel et al., 1997). Their reference is a well-fertilized treatment and not a check treatment as suggested in this paper. Mathematically, the response index is simply the inverse of the sufficiency index, but theoretically the concepts are different. Utilizing the sufficiency concept, one applies N fertilizer in an attempt to match the tissue N concentration of a well fertilized strip (assumed to be 100% sufficient) without recognizing yield potential. Our approach has been to first recognize yield potential and then to fertilize based on the likelihood of obtaining a response (Raun et al., 2002). The response index is indicative of the % increase in yield that could be obtained via N fertilization, but by itself says nothing about what N rate should be applied, whereas the sufficiency concept is bound directly to an actual fertilizer N rate. Our approach partitions the response index and an estimate of yield potential (Lukina et al., 2001) into two separate components. The first step is to predict potential yield with no added N fertilizer, and then determine N removal (potential yield multiplied times average percent N in the grain, e.g., 2.35 for winter wheat in the central Great Plains). With the prediction of potential yield with no N fertilization (YP_0), the response index allows us to project the potential yield that could be achieved with added N fertilization (YP_N), multiplying YP_0 times RI. In any given year, fertilizer N requirements are determined by subtracting grain N uptake at YP_0 from grain N uptake at YP_N, and dividing by a theoretical maximum use efficiency of topdress N of 0.70.

CONCLUSION

Based on analysis of thirty winter wheat experiments conducted from 1998 to 2002 under different growing conditions RI_{NDVI} was found to provide good prediction of $RI_{Harvest}$ at Feekes growth stages 5, 9, and 10.5. This ability to determine the responsiveness of the crop to additional N at early stages of growth (i.e. Feekes 5) allows altering of N management schemes to potentially increase yield and NUE. Application of the response index strategy may prevent over application of fertilizer N when yield increases are not likely, thus increasing returns to producers while decreasing environmental risk.

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TABLE 1. Fertilizer rates of N, P, and K at Haskell, Hennessey, Lahoma, Perkins and Stillwater, OK.

Stillwater AA	Stillwater 301†	Haskell 801	Hennessey AA	Lahoma 502	Perkins N & P	Stillwater 222
----------	----------	----------	-N-P-K (kg ha^{-1})-	----------	----------	----------
0-0-0*	0-0-0*	0-58-111	0-0-0*	0-19-56	0-29-0**	0-29-37
56-0-0	45-0-0	112-58-111	56-0-0	22-19-56	56-29-0	45-29-37
90-0-0	90-0-0	112-39-111	90-0-0	45-19-56	112-29-0	90-29-37
123-0-0	179-0-0	168-58-111	123-0-0	67-19-56	168-29-0	
				90-19-56		
				112-19-56		

*-Blanket application of P and K to 100% sufficiency
**-Blanket application of K to 100% sufficiency
† - ammonium nitrate was the N source, excluding AA experiments.

TABLE 2. Experiments where sensor and winter wheat grain yield data were collected, location, activity dates, and variety.

Experiment	Location	Year	Planting date	Sensing date	Days from planting to sensing	Harvest date	Variety
N*P[¶]	Perkins, OK	1998	21/10/97	02/04/98[†]	163	16/06/98	Tonkawa
N*S[@]	Perkins, OK	1998	21/10/97	02/04/98[†]	163	16/06/98	Tonkawa
N*P[¶]	Tipton, OK	1998	10/10/97	01/03/98[†]	142	03/06/98	Tonkawa
N*P[¶]	Perkins, OK	1999	12/10/98	04/03/99[†]	143	09/06/99	Tonkawa
Experiment 222	Stillwater, OK	1999	13/10/98	24/02/99[†]	134	15/06/99	Tonkawa
Experiment 301	Stillwater, OK	1999	15/10/98	24/03/99[†]	160	15/06/99	Tonkawa
Efaw AA	Stillwater, OK	1999	09/11/98	24/03/99[†]	135	15/06/99	Tonkawa
Experiment 502	Lahoma, OK	1999	09/10/98	05/03/99[†]	147	30/06/99	Tonkawa
Experiment 801	Haskell, OK	1999	16/10/98	23/03/99[†]	158	06/07/99	2163
N*P[¶]	Perkins, OK	2000	08/10/99	08/02/00[†]	123	30/05/00	Custer
				04/04/00[‡]	179		
				24/04/00[*]	199		
				22/05/00[+]	227		
Experiment 301	Stillwater, OK	2000	07/10/99	10/02/00[†]	126	15/06/00	Custer
				04/04/00[‡]	180		
				24/04/00[*]	200		
				22/05/00[+]	228		
Experiment 222	Stillwater, OK	2000	07/10/99	10/02/00[†]	126	06/07/00	Custer
				30/03/00[‡]	175		
				24/04/00[*]	200		
				22/05/00[+]	228		
Efaw AA	Stillwater, OK	2000	07/10/99	15/02/00[†]	126	07/07/00	Custer
				04/04/00[‡]	180		
				24/04/00[*]	200		
				22/05/00[+]	228		
Experiment 502	Lahoma, OK	2000	12/10/99	15/02/00[†]	126	13/06/00	Custer
				28/03/00[‡]	168		
				27/04/00[*]	198		
				22/05/00[+]	223		
Experiment 801	Haskell, OK	2000	08/10/99	14/03/00[†]	158	02/06/00	2137
				02/04/00[‡]	177		
				25/04/00[*]	200		
				16/05/00[+]	221		
Hennessey AA	Hennessey, OK	2000	07/10/99	15/02/00[†]	131	07/06/00	Custer
				28/03/00[‡]	173		
				27/04/00[*]	203		
				22/05/00[+]	228		

N*P[¶]	Perkins, OK	2001	17/11/00	13/04/01[†]	148	07/06/01	Custer
				30/04/01[‡]	165		
				10/05/01[*]	175		
				24/05/01[+]	189		
Experiment 301	Stillwater, OK	2001	16/11/00	13/04/01[†]	149	11/06/01	Custer
				30/04/01[‡]	164		
				10/05/01[*]	174		
				24/05/01[+]	188		
Experiment 222	Stillwater, OK	2001	20/11/00	13/04/01[†]	145	12/06/01	Custer
				30/04/01[‡]	162		
				10/05/01[*]	172		
				24/05/01[+]	186		
Efaw AA	Stillwater, OK	2001	22/11/00	13/04/01[†]	143	11/06/01	Custer
				30/04/01[‡]	160		
				10/05/01[*]	170		
				24/05/01[+]	184		
Experiment 502	Lahoma, OK	2001	01/12/00	13/04/01[†]	133	15/06/01	Custer
				28/04/01[‡]	148		
				10/05/01[*]	160		
				24/05/01[+]	174		
Experiment 801	Haskell, OK	2001	04/10/00	15/04/01[†]	187	06/06/01	2137
				29/04/01[‡]	201		
				10/05/01[*]	212		
				24/05/01[+]	226		
Hennessey AA	Hennessey, OK	2001	21/11/00	13/04/01[†]	144	13/06/01	Custer
				30/04/01[‡]	163		
				10/05/01[*]	173		
				24/05/01[+]	187		
N*P[¶]	Perkins, OK	2002	16/10/01	27/02/02[†]	98		Custer
Experiment 222	Stillwater, OK	2002	10/10/01	27/02/02[†]	104		Tonkawa
Experiment 301	Stillwater, OK	2002	12/10/01	27/02/02[†]	92		Tonkawa
Efaw AA	Stillwater, OK	2002	04/10/01	27/02/02[†]	97		Tonkawa
Experiment 502	Lahoma, OK	2002	28/11/01	29/03/02[†]	66		Tonkawa
Experiment 801	Haskell, OK	2002	19/10/01	13/03/02[†]	97		2137
Hennessey AA	Hennessey, OK	2002	03/10/01	26/03/02[†]	93		Custer

[¶]N*P-N rate by P rate experiment.

[@]N*S-N rate by spacing experiment.

[†, ‡, *, +] - corresponds to Feekes growth stages 5, 9, 10.5, and 11.2, respectively.

TABLE 3. Mean NDVI values and yield levels of check treatments and treatments receiving preplant N for 30 winter wheat experiments.

Experiment	Year	Check NDVI (0-N)	NDVI N-fertilized	Check NDVI (0-N)	NDVI N-fertilized	Check NDVI (0-N)	NDVI N-fertilized	Check Yield (0 N)	Maximum Yield N-fertilized
		-----------Feekes 5-----------		-----------Feekes 9----------		---------Feekes 10.5--------		------------kg ha^{-1}----------	
Perkins N*S‡	1998	0.56	0.77	----	----	----	----	1332	2375
Perkins N*P†	1998	0.43	0.64	----	----	----	----	1214	1921
Tipton N*S‡	1998	0.74	0.89	----	----	----	----	3285	5466
Efaw AA*	1999	0.63	0.78	----	----	----	----	2169	3708
Efaw 301	1999	0.34	0.78	----	----	----	----	939	2662
Haskell 801	1999	0.72	0.87	----	----	----	----	1990	2600
Lahoma 502	1999	0.62	0.87	----	----	----	----	1680	4443
Perkins N*P†	1999	0.43	0.63	----	----	----	----	1077	2568
Stillwater 222	1999	0.54	0.66	----	----	----	----	926	1724
Efaw AA*	2000	0.77	0.86	0.82	0.91	0.71	0.80	2184	3053
Efaw 301	2000	0.17	0.65	0.23	0.90	0.19	0.80	975	3382
Haskell 801	2000	0.73	0.88	0.73	0.88	0.65	0.81	2399	3070
Hennessey AA*	2000	0.86	0.89	0.91	0.93	0.84	0.86	3800	4064
Lahoma 502	2000	0.52	0.89	0.49	0.90	0.42	0.88	1954	3543
Perkins N*P†	2000	0.52	0.71	0.73	0.87	0.59	0.74	2605	3898
Stillwater 222	2000	0.45	0.81	0.48	0.90	0.41	0.81	1282	2450
Efaw AA*	2001	0.51	0.69	0.64	0.70	0.55	0.69	2693	3488
Efaw 301	2001	0.20	0.45	0.28	0.50	0.24	0.43	922	2096
Haskell 801	2001	0.65	0.78	0.65	0.77	0.61	0.76	3695	4200
Hennessey AA*	2001	0.39	0.60	----	----	0.47	0.62	1905	2952
Lahoma 502	2001	0.34	0.33	----	----	0.56	0.60	821	946
Perkins N*P†	2001	0.62	0.60	0.55	0.55	0.49	0.51	2751	2498
Stillwater 222	2001	0.35	0.55	0.45	0.58	0.41	0.54	1165	1944
Efaw AA*	2002	0.57	0.73	----	----	----	----	1812	4201
Efaw 301	2002	0.37	0.55	----	----	----	----	732	3276
Haskell 801	2002	0.61	0.73	----	----	----	----	2752	3008

Hennessey AA*	2002	0.46	0.52	----	----	----	----	2886	3165
Lahoma 502	2002	0.37	0.49	----	----	----	----	2324	2733
Perkins N*P†	2002	0.68	0.73	----	----	----	----	2926	3252
Stillwater 222	2002	0.36	0.68	----	----	----	----	2423	1040

†N*S-N rate by spacing experiment; ‡N*P-N rate by P rate experiment; *AA-anhydrous ammonia experiment; [a]NUE-nitrogen use efficiency

FIGURE 1. Relationship between RI_{NDVI} and $RI_{Harvest}$ at Feekes 5 across 29 locations in Oklahoma, 1998-2002.

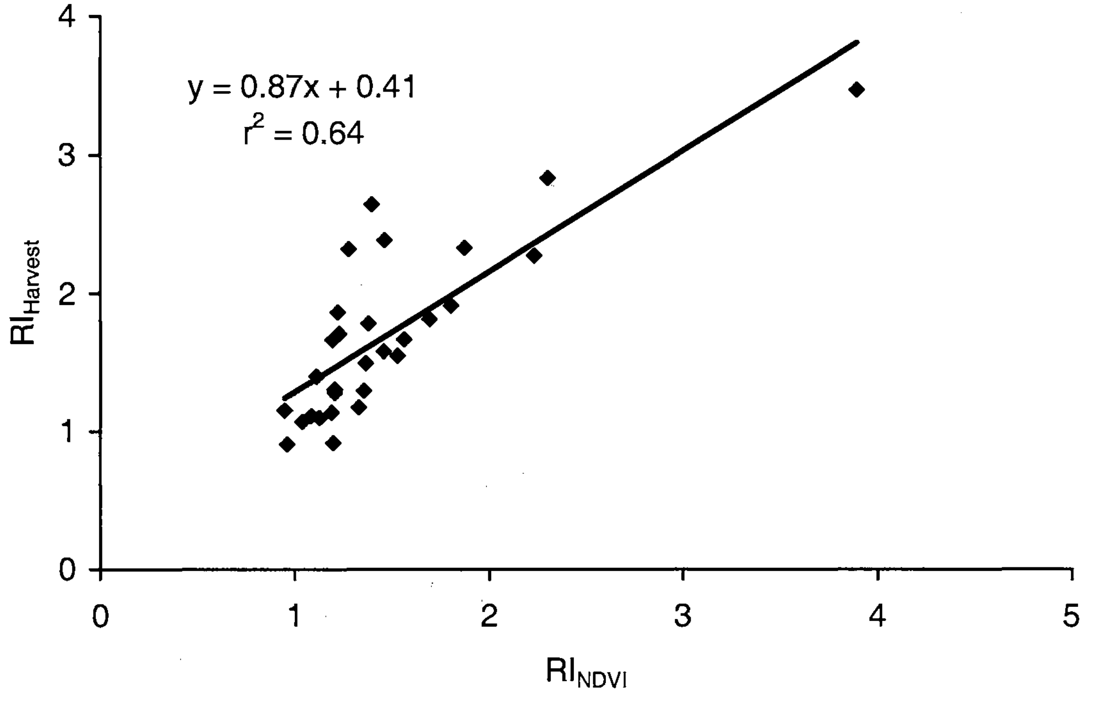


FIGURE 2. Relationship between RI_{NDVI} and $RI_{Harvset}$ at Feekes 9 across 12 locations, 2000-2001.

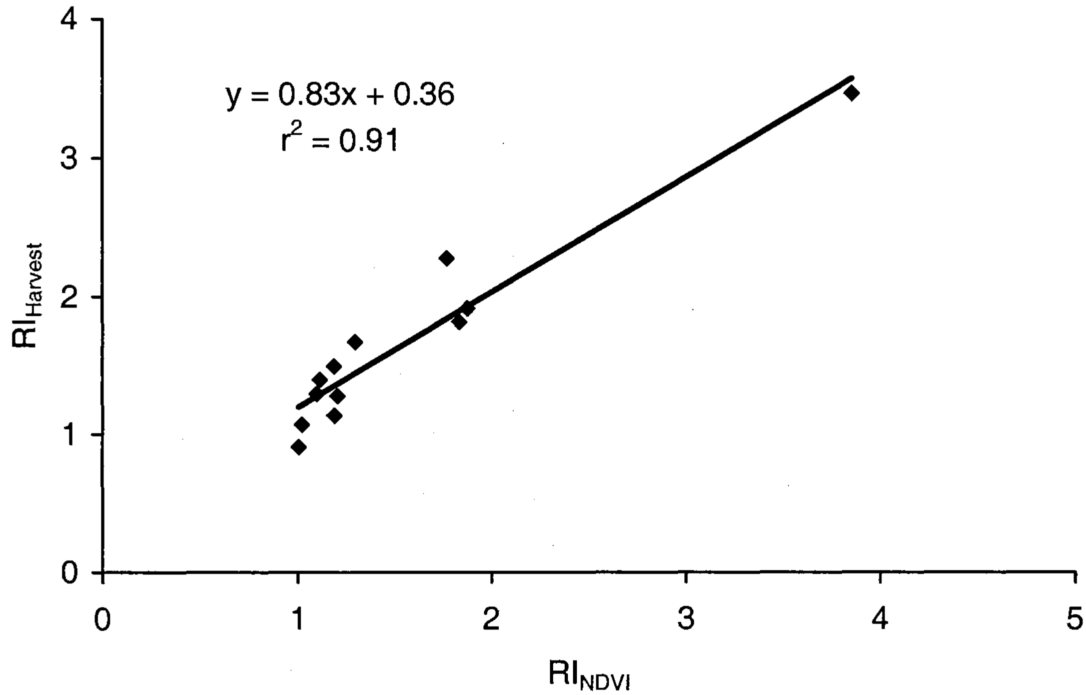


FIGURE 3. Relationship between RI_{NDVI} and $RI_{Harvset}$ at Feekes 10.5 across 13 locations, 2000-2001.

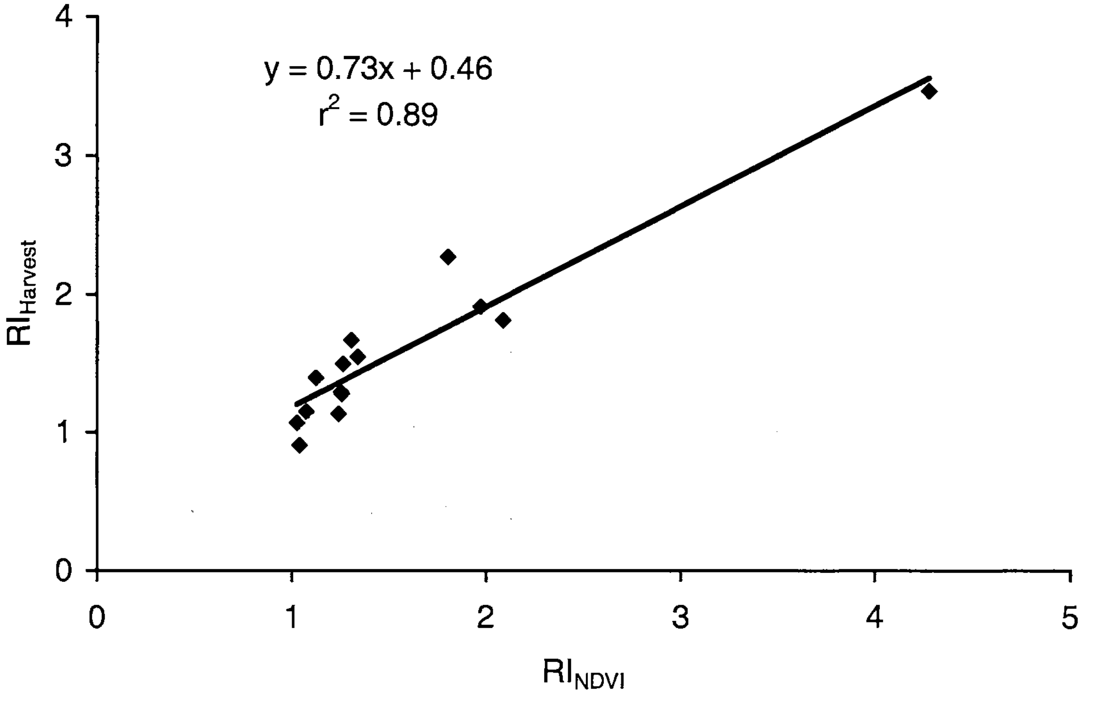
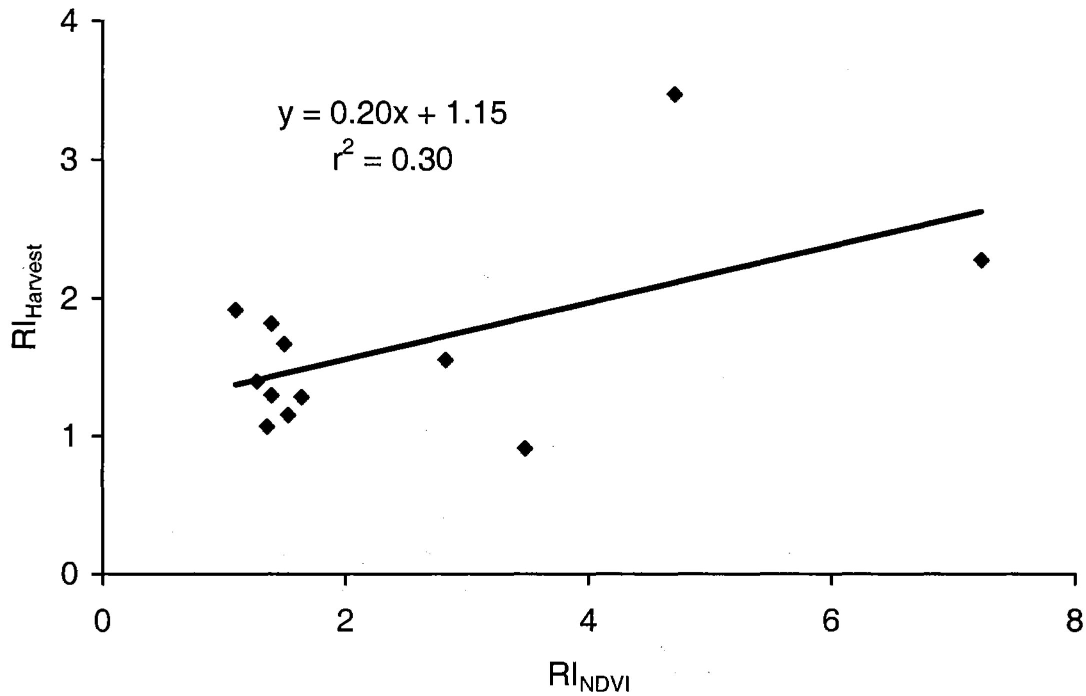


FIGURE 4. Relationship between RI_{NDVI} and $RI_{Harvset}$ at Feekes 11.2 across 13 locations, 2000-2001.



VITA 2

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Doctor of Philosophy

Thesis: I. ESTIMATION OF NITROGEN MINERALIZATION IN SOILS FROM LONG-TERM APPLICATION OF FERTILIZER AND ITS EFFECT ON WINTER WHEAT RESPONSE TO TOPDRESS NITROGEN

II. USE OF IN-SEASON RESPONSE INDICES TO PREDICT RESPONSE INDEX AT HARVEST

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