RELATIONSHIP BETWEEN AMMONIUM AND NITRATE IN WHEAT PLANT TISSUE AND ESTIMATED PLANT NITROGEN LOSS

By

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Abstract

Nitrogen (N) is one of the most important elements in the nutrition of higher plants. N fertilizer is one of the most costly inputs in the production of winter wheat in the Great Plains. It ranks second only to precipitation as the most frequent yield limiting factor, and even when N is not the yield limiting factor, wheat is less than 50% efficient at utilizing applied N fertilizer. If N supplied to the crop is not utilized efficiently, it may then be lost from the cropping system to the surrounding environment. Because of the costs associated with N fertilizer and the potential degradation of the environment from inefficient use of N by the soil-plant system, it is imperative to understand the loss mechanisms that cause this inefficiency. The primary objective of this study was to evaluate the relationship between NH_4-N and NO_3-N in wheat tissue and estimated plant N loss. A secondary objective was to evaluate the use of early-season NH_4-N and NO_3-N in wheat tissue to predict late-season N accumulation in the forage and grain. Two experimental sites for this study were selected as subplots located within existing plots in two long-term winter wheat experiments at Stillwater (experiment 222) and Lahoma (experiment 502), Oklahoma. Wheat forage samples were collected at Feekes growth stage 5 (leaf sheath strongly erected) and Feekes growth stage 10.5.2 (flowering complete to top of head). The samples were dried and ground, and total N, NH_4-N and NO_3-N analysis were performed. The relationship between total N, NH_4-N and NO_3-N at both growth stages and estimated plant N loss (plant N uptake at flowering minus total N uptake in the grain plus straw) were evaluated. No linear relationship was found to exist between forage NH_4-N and NO_3-N with estimated plant N loss at either growth stage at either location in either year. Due to cool and moist climatic conditions during late spring

in both years, limited N losses were observed from anthesis to maturity using the method described above. However, NO_3-N at Feekes growth stage 5 did predict N accumulation in the wheat forage at Feekes growth stage 10.5.2 and in the grain at experiment 502 in both years. The same relationship did not exist in either year at experiment 222. Sensor readings (red, NiR, red/NiR, and NDVI) at Feekes 5 showed a significant relationship with Feekes 5 NO_3-N at experiment 502 in 1999. The same relationship was not seen at experiment 222 in 1999. These relationships may assist in refining the methodology associated with mid-season topdress N applications. Although early-season tissue NH_4-N and NO_3-N measurements did not accurately predict estimated plant N loss from flowering to maturity, total N at Feekes 5 was found to be correlated with final grain yield.

Introduction

It is important to understand losses of N that occur in soil-plant systems, and how these losses may effect nitrogen use efficiency. Denitrification, volatilization from the soil surface and leaching are potential sinks of N. Denitrification is the conversion of nitrate nitrogen (NO_3-N) to gaseous forms such as N_2O, NO and N_2. This process occurs in anaerobic conditions, usually at pH < 6.0. In many fertilizer recovery studies, denitrification is often cited as the most significant loss of N. Nitrogen losses due to denitrification of applied fertilizer have been reported as ranging from 9.5% (Aulakh et al., 1982) to 22% (Hilton et al.). Another potential loss is ammonia (NH_3) volatilization from the soil surface. Fertilizer N (especially urea) added to a soil with a pH greater than 7.0 may result in NH_3 volatilization and further loss of fertilizer N. Losses of 55-65% of applied urea have been reported (Al Kanani, 1990, Volk, 1966). This can be significant under certain environmental conditions such as low moisture, high wind velocity and high pH. Nitrogen leaching is the process whereby NO_3-N is translocated by percolation of water through the soil profile. This loss could lead to groundwater contamination. One study reported that 113 kg ha^{-1} of NO_3-N leached below the root zone when two consecutive bean crops were grown (Robbins and Carter, 1980.) Losses such as these account for much of the inefficiency with which wheat uses applied N. Another potential loss is volatile plant loss of N. Tissue analysis has been used to determine nutrient deficiencies in-season and to apply subsequent additions of N fertilizer. It may be possible to use tissue tests at certain stages of growth to estimate the amount (or potential amount) of N being volatilized from the crop canopy.

The relationship between NH_4-N and NO_3-N in wheat tissue has not been evaluated as a tool to predict estimated N loss in winter wheat. Understanding gaseous N loss may be a key to increasing the efficient use of N fertilizers applied to cropping systems. Harper et al. (1987), in an N cycling study, concluded that approximately 11% of N was lost in a 20-day period following fertilization from both soil and plant. The plant loss was attributed to the overloading of plant N as NH_4^+. They considered additional losses of N (9.8%) from the plants between anthesis and maturity. This loss was due almost entirely to plant senescence and inefficient redistribution of N within the plant. Eleven percent of the potential N available for redistribution from the stems and leaves was lost as volatile NH_3. The high N (and therefore, increased NH_4^+) content of the plants lends itself to NH_3 volatilization from the plant to the atmosphere. Francis et al. (1993) in a corn (*Zea maize* L.) study found that N losses from aboveground biomass in a hybrid variety ranged from 45 to 81 kg N ha^{-1}. Also, they reported that 52 to 73% of the unaccounted for fertilizer in

^{15}N balance studies could be attributed to plant N loss. They stated that in the past, studies have listed denitrification as the major gaseous loss of N from the systems. The estimations of denitrification and leaching might have been less if N loss from the plant would have been considered. Papakosta and Gagianas (1991) stated that N loss in wheat from anthesis to maturity depends on the plant N content at anthesis. When N content was high at anthesis (>200 kg ha^{-1}), N losses were inevitable even when yields were high. When N content was lower (150 kg ha^{-1}) at anthesis, N losses were not observed. Between these N contents, N loss was highly correlated with yield, where high yields prevented N loss and low yields caused a net loss of N. Daigger et al. (1976) studying N content in wheat noted that the percent N in plant tissue did not change during a 23-day period preceding maturity. He found, though, that the period between anthesis and maturity netted a total loss of 30% of the applied N, and losses of N increased with increasing N applied. The N loss accounted for 26, 28 and 41% of the anthesis N when 0, 67, and 133 kg of N/ha were applied, respectively. In the above-cited studies the major components of gaseous N loss seem to be the amount of N supplied to the plant and, therefore, the plant content of N at later stages of growth. Because of this, it is important to understand the processes controlling N uptake and assimilation within the growing wheat plants and redistribution of supplied N, especially at later stages of growth.

Chesworth (1998) notes that nitrate (NO_3^-) and ammonium (NH_4^+) are the two inorganic forms of N that are taken up by plants. Nitrate is taken up by the roots of the plant, moved through the xylem, and stored in the vacuoles of plant cells. Nitrate must then be reduced to NH_3 to be incorporated into organic molecules by the plant. Two enzymes catalyze this reduction, nitrate reductase (NR) and nitrite reductase (NiR). The reduction occurs in two steps; conversion of nitrate to nitrite via nitrogen reductase, and conversion of nitrite to ammonia via nitrite reductase. Reduction of NO_3^- may take place in the roots or shoots of growing plants. Up to 80% of the NO_3^- taken up by wheat may pass through the roots without being reduced (Chesworth, 1998). Ammonia is very toxic to most cells and it seems to uncouple the electron transport from ATP production in the mitochondria and chloroplasts. It must be converted into organic compounds as quickly as possible. This conversion of ammonia to glutamine (the most common form of transported N in non-leguminous plants) is accomplished by the action of two enzymes, glutamine synthetase and glutamate synthase. Glutamine can then be used in the biosynthesis of amino acids. As the wheat approaches maturity, the N contained in the roots, shoots and leaves are redistributed to the grain. In the case of cereals, up to 90% of the of the total N in the plant at maturity will be taken up during the first half of its growth cycle and 85% of the N in leaves will be translocated to the grain (Chesworth, 1998). Grain production is greatly affected by NH_4^+ and NO_3^- nutrition. Silberbush and Lips (1991) found that the number of tillers per plant was correlated with dry matter yield. The number of tillers also increased with nitrogen concentration and with NH_4^+/NO_3^- ratio fed to plants. Mean grain weight was negatively correlated with NH_4^+/NO_3^- ratio fed to plants. The number of grains per plant also decreased with increasing NH_4^+/NO_3^- ratio fed to plants. They concluded that plants receiving high NH_4^+ concentrations are stimulated to invest most of their carbohydrate reserves on new tiller formation. Nitrate-fed plants, on the other hand, invest the bulk of the carbohydrates in grain production. In a study by Martin del Molino (1991), he found that grain protein increased linearly with grain yield and above ground plant dry weight at anthesis. Grain yield also increased linearly with leaf N content at anthesis. The study showed, however, that grain protein was more closely related to the aboveground dry weight at anthesis multiplied by the level of N in the two upper most leaves, than either of the components taken separately. Leaf N concentration at anthesis had less of an effect on grain protein and more effect on the production of biomass. Raun and Westerman (1991) found that crown and leaf NO_3^- was correlated with yield when sampled at Feekes growth stages 4 and 5. A linear relationship was established between leaf NO_3^- content and N rate at Feekes 5. Samples taken at Feekes 7 and 10 did not correlate well with yield. Gregory et al. (1981), in a nutrient study found that even when there was limited uptake of N after anthesis, the grain continued to grow and substantial amounts of N were translocated from the leaves and stems. He stated that 23 to 26% of the final amount of N contained in the grain was taken up after anthesis. This was in contrast to the previous year, when uptake of N after anthesis represented 42 to 52% of the total N in the grain. The higher percentages of post anthesis uptake were attributed to higher moisture content in the soil. He concluded that amounts of N and moisture in the soil played a major role in the amount of N translocated from other parts of the plants.

Materials and Methods

Two experimental sites were selected as subplots located within existing plots in two long-term winter wheat experiments at Stillwater (222) and Lahoma (502), Oklahoma. Nitrogen rates have been applied annually since 1969 and 1970 in experiments 222 and 502, respectively. Both experiments employed randomized complete block designs with four replications. Plots were 6.1x18.3 m and 4.9x18.3 m at experiments 222 and 502, respectively. At both sites N was applied preplant incorporated utilizing conventional tillage. N rates were 0, 45, 90, and 134 kg $ha^{-1} yr^{-1}$ at Stillwater and 0, 45, 67, 90, and 112 kg $ha^{-1} yr^{-1}$ at Lahoma. Each year, ammonium nitrate (34-0-0) has been applied broadcast and preplant incorporated at both sites. Phosphorus and potassium as triple superphosphate (0-46-0) and potassium chloride (0-0-62) were applied with nitrogen each year at rates of 29 and 20 kg P ha^{-1} and 38 and 56 kg K ha^{-1} at experiment 222 and 502 Initial soil test data taken from the check plots is shown in Table 1. Each year forage was hand-harvested from plots at Feekes growth stage five (leaf sheath strongly erected) and again at Feekes growth stage 10.5.2 (flowering complete to top of ear) (Large, 1954). Grain was harvested from an area in the center of each plot measuring 6.1x18.3m and 4.9x18.3m at experiment 222 and experiment 502, respectively, with a Massey Ferguson self-propelled combine. Forage and grain samples were dried and ground to pass a 140 mesh (106 um) sieve and lab analysis was completed for both the 1997-98 and 1998-99 crop years. Forage samples were extracted with 0.01 M calcium sulfate and the concentration of NH_4-N and NO_3-N in the extracts was analyzed using flow injection analysis (Lachat, 1989). Each year, forage, straw, and grain samples were analyzed for total N content via dry combustion analysis using a Carlo Erba NA 1500 analyzer (Schepers, 1989). Total N uptake in the forage, grain and straw was calculated as the %N contained in each times the dry matter yield. Plant N loss was calculated as the difference in the total N uptake in the Feekes 10.5.2 forage and the total N uptake in the grain plus straw. Sensor readings in the were taken in the red (670nm) and near infrared (780nm) portions of the spectrum from an area measuring 6.1x18.3m and 4.9x18.3m at experiment

222 and experiment 502, respectively at Feekes 5. The Normalized Difference Vegetative Index was calculated as:

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

where, NIR_{ref} and Red_{ref} is the magnitude of reflected light and NIR_{inc} and Red_{inc} are the magnitude o0f incident light. Statistical analysis was performed using SAS software (SAS Institute, 1985).

Results and Discussion

Analysis of variance and associated treatment means for grain and straw yield are reported in tables 2-5 for experiment 222 and experiment 502 for 1997-98 and 1998-99 Grain yield showed a significant response to increasing N rate at both sites in both years. Similarly, straw yield increased significantly with applied N at each location and each year

With few exceptions, no measurement of tissue N (NH_4-N, NO_3-N and total N) was well correlated with estimated plant N loss. Since estimated plant N loss is calculated as the total N uptake in the tissue at flowering minus the total N uptake at maturity (grain + straw), it is likely that the wheat continued to take assimilate N after flowering, since limited N loss was observed at either site in either year. The increased uptake of N after anthesis could be a direct result of highly favorable environmental conditions in both years during grain fill. In both years, moisture levels were adequate and temperatures were cool during the period between Feekes 10.5.2 and maturity. Because of these conditions, wheat may have continued to assimilate N and redistribute it to the grain, thus limiting N loss observed by others (Kanampiu et al. (1997), Harper et al. (1991), and Diagger et al (1976))

The relationship between NO_3-N at Feekes 5 and total N at Feekes 5 at both locations and both years is reported in Figures 1 and 2. These two parameters were well correlated as could be expected, since the measurements are at the same stage of growth and the two N measurements are interrelated.

Figures 3 and 4 illustrate the relationship between NO_3-N at Feekes 5 and the total N in the forage at Feekes 10.5. Forage NO_3-N at Feekes 5 was a good predictor of total N in the wheat forage at Feekes 10.5, the exception being experiment 222 in 1998. This observation, combined with the ability to predict grain yield and total grain nitrogen, may have further use for precision agriculture, since topdress N is applied at Feekes 5. Early work by Raun and Westerman (1991) showed that grain yield could be reliably predicted using NO_3-N and PO_4-P in the leaves at Feekes 5. However, they noted that this was highly dependent upon environment. Considering new technologies designed to sense plant health at early stages of growth using sensor-based methods, this information could be interlaced within precision agriculture strategies for mid-season nutrient adjustment

The relationship between NO_3-N at Feekes 5 and final grain N was also significantly correlated at experiment 502 in both years, but not at experiment 222 in either year. Graphs for both locations and years are shown in Figures 5 and 6. It was interesting to note that total grain N could be predicted using a forage NO_3-N reading approximately 3 months before the grain was harvested at experiment 502. Similarly, this information may have further use for precision agriculture, since topdress N is applied at Feekes 5, and because NO_3-N could possibly be sensed

The relationship between total N at Feekes 5 and grain yield at both locations and both years is reported in Figures 7 and 8. Total N content of the forage at Feekes 5 was significantly correlated with grain yield. This was the most consistent predictor of grain yield above all other measurements of N (NH_4-N and/or NO_3-N versus grain yield at either location or in either year).

Figure 9 illustrates the relationship between sensor readings (red, NIR, red/ NIR, and NDVI) at Feekes 5 and NO_3-N in the forage at Feekes 5 at experiment 502 in 1999. At this location, early-season sensor readings were not correlated with tissue NO_3-N. However, as Figure 10 illustrates, there was a significant relationship between sensor readings (red, NIR, red/NIR, and NDVI) at Feekes 5 and total N in the forage at Feekes 5 at experiment 502 in 1999. This relationship is important because if total N could be used to estimate yield, and sensor readings could be used to estimate total N, then sensor readings could be used to estimate yield without having to take biological samples.

Figure 11 and 12 illustrate the relationship between Feekes 5 sensor readings (red, NiR, red/NiR, and NDVI) and NO_3-N and total N in the forage at Feekes 5 at experiment 222 in 1999. Some correlation was evident using these indirect measures, but no relationship was likely to be highly reproducible. This could be important in estimating late-season N accumulation thus allowing management decisions to be made on whether or not to apply topdress fertilizer

Conclusions

Tissue concentrations of NH_4-N and NO_3-N, and total N contents in the wheat at Feekes 5 and Feekes 10.5.2 were not good predictors of estimated plant N loss. Many factors could have caused these poor estimates of N loss, including ideal climatic conditions during the period from anthesis to maturity that increased N uptake from flowering to maturity when losses are generally the greatest Combined, these factors increased the error associated with estimated plant N loss.

The use of early-season N measurements may prove to be effective estimates of late-season N accumulation in wheat. Tissue NO_3-N at Feekes 5 was significantly correlated with total forage N at Feekes 5, however the relationship was not as good as expected. Tissue NO_3-N at Feekes 5 was significantly correlated with total forage N at Feekes 10.5.2. At Lahoma 502, tissue NO_3-N at Feekes 5 was significantly correlated with grain N in both years. This relationship was not observed at Stillwater 222 in either year. However, total N in the forage at Feekes 5 was significantly correlated with grain yield at both sites in both years.

Sensor readings taken at Feekes 5 may be useful in assessing the relationships described above. Non-destructive measures of nutrient status may allow estimations of yield potential, thus improving management decisions regarding topdress N applications

Early-season N measurements may prove useful in the estimation of late-season N accumulation in winter wheat. It may also be used to better understand yield potential. Coupled with precision farming techniques used to predict yield potential, these early season estimates of late-season N accumulation may help refine the techniques used to maximize yield, such as topdress fertilizer application.

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Table 1. Surface soil (0-15 cm) chemical characteristics and classification at Stillwater, (experiment 222) and Lahoma, (experiment 502) OK, 1998.

Location	PH[a]	NH_4-N	NO_3-N	P[b]	K[b]	Total N[c]	Organic C[c]
	mg kg^{-1}					g kg^{-1}	
Stillwater	5.7	4.64	2.3	33	159	0.9	10.6
Classification: Kirkland silt loam (fine-mixed, thermic Udertic Paleustolls)							
	mg kg^{-1}					g kg^{-1}	
Lahoma	5.6	5.60	4.0	77	467	0.9	11.0
Classification: Grant silt loam (fine-silty, thermic Udic Argistolls)							

[a]pH: 1:1 soil:water
[b]P and K: Mehlich III
[c]Organic C and Total N: dry combustion

Table 2. Analysis of variance and associated treatment means for grain yield and straw yield and TN, NH_4-N, and NO_3-N at Feekes 5, Lahoma, OK, 1998.

		Grain yield	Straw yield	TN, g kg^{-1}	NH_4-N, mg kg^{-1}	NO_3-N, mg kg^{-1}
Source of variation	df	--------mean squares, kg ha^{-1}------		-----------------------mean squares--------------------------		
Replication	3	2381017	1944739	186*	294	180239
N rate	4	12190807**	8110119*	361*	2926**	549717**
Residual error	12	7060506	6366672	172	1886	357693
Contrast						
N rate_linear	1	8840876**	6605333**	292**	2322**	522232**
N rate_quadratic	1	306584	69371	39	127	14039
SED		1879	1784	9	31	423
CV		22	47	10	17	74
N Rate, kg ha^{-1}		----------------kg ha^{-1}-------------		-----g kg^{-1}----	----------------------mg kg^{-1}-------------	
0		2112	539	28	94	19
45		3586	1546	36	78	136
67		3665	1196	38	67	207
90		3426	2159	38	74	292
112		4541	2264	41	58	513

TN-total nitrogen, dry combustion.
*, **-significance at the 0.05 and 0.01 probability level, respectively.
SED-standard error of the difference between two equally replicated means.
CV-coefficient of variation, %.

Table 3. Analysis of variance and associated treatment means for grain yield and straw yield and TN, NH_4-N, and NO_3-N at Feekes 5, Lahoma, OK, 1999.

Source of variation	df	Grain yield	Straw yield	TN, g kg^{-1}	NH_4-N, mg kg^{-1}	NO_3-N, mg kg^{-1}
		--------mean squares, kg ha^{-1}------		----------------------mean squares------------------------		
Replication	3	2293635	13181003	321*	2930	142107
N rate	4	38738125**	8687791**	576**	1676	106107
Residual error	12	19643932	14588078	452	7860	2737763
Contrast						
N rate_linear	1	22911017**	863293**	137*	141	39226
N rate_quadratic	1	1840044	356433	24	796	2240
SED		3134	2701	15	63	370
CV		30	60	17	27	130
N Rate, kg ha^{-1}		----------------kg ha^{-1}-------------		-----g kg^{-1}----	---------------------mg kg^{-1}--------------	
0		2181	776	27	75	9
45		2381	1320	26	99	32
67		4496	1526	32	84	166
90		5240	1647	33	84	303
112		5191	2774	39	75	99

TN-total nitrogen, dry combustion.

*, **-significance at the 0.05 and 0.01 probability level, respectively.

SED-standard error of the difference between two equally replicated means.

CV-coefficient of variation, %.

Table 4. Analysis of variance and associated treatment means for grain yield and straw yield and TN, NH_4-N, and NO_3-N at Feekes 5, Stillwater, OK, 1998.

Source of variation	df	Grain yield	Straw yield	TN, g kg^{-1}	NH_4-N, mg kg^{-1}	NO_3-N, mg kg^{-1}
		--------mean squares, kg ha^{-1}------		-----------mean squares-----------		
Replication	3	560861	916404	37	1231	466
N rate	3	1260704*	8271938**	651**	7619*	17204
Residual error	9	728767	2425805	52	6838	22850
Contrast						
N rate_linear	1	1117631**	6269882**	593**	6362**	8825
N rate_quadratic	1	119227	1763714*	53**	634	2389
SED		697	1272	6	68	123
CV		20	29	10	26	124
N Rate, kg ha^{-1}		---------kg ha^{-1}---------		-----g kg^{-1}----	----------mg kg^{-1}----------	
0		983	587	18	130	13
45		1594	2030	21	113	44
90		1593	2262	24	112	13
134		1726	2376	35	70	93

TN-total nitrogen, dry combustion.
*, **-significance at the 0.05 and 0.01 probability level, respectively.
SED-standard error of the difference between two equally replicated means.
CV-coefficient of variation, %.

Table 5. Analysis of variance and associated treatment means for grain yield and straw yield and TN, NH_4-N, and NO_3-N at Feekes 5, Stillwater, OK, 1999.

Source of variation	df	Grain yield	Straw yield	TN, g kg^{-1}	NH_4-N, mg kg^{-1}	NO_3-N, mg kg^{-1}
		--------mean squares, kg ha^{-1}------		----------mean squares----------		
Replication	3	434641	1122969	28	224	3474
N rate	3	6589302**	394323	405**	418	16331*
Residual error	9	3399371	1247177	74	3210	9015
Contrast						
N rate_linear	1	6185363**	291880	380**	165	13493**
N rate_quadratic	1	400475	70950	25	239	2835
SED		1505	912	7	46	78
CV		31	69	10	21	74
N Rate, kg ha^{-1}		----------kg ha^{-1}----------		-----g kg^{-1}----	----------mg kg^{-1}----------	
0		1315	273	21	100	17
45		1529	606	27	88	17
90		2124	608	32	88	42
134		2971	675	34	91	92

TN-total nitrogen, dry combustion.
*, **-significance at the 0.05 and 0.01 probability level, respectively.
SED-standard error of the difference between two equally replicated means.
CV-coefficient of variation, %.

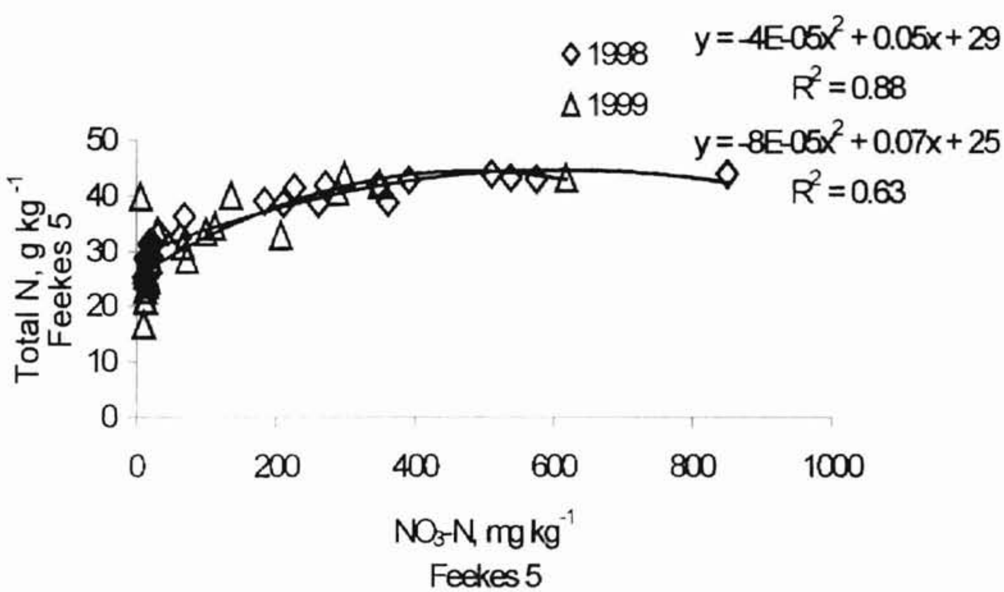

Figure 1 Relationship between NO_3-N at Feekes 5 and total N at Feekes 5 at Lahoma, 1998 and 1999.

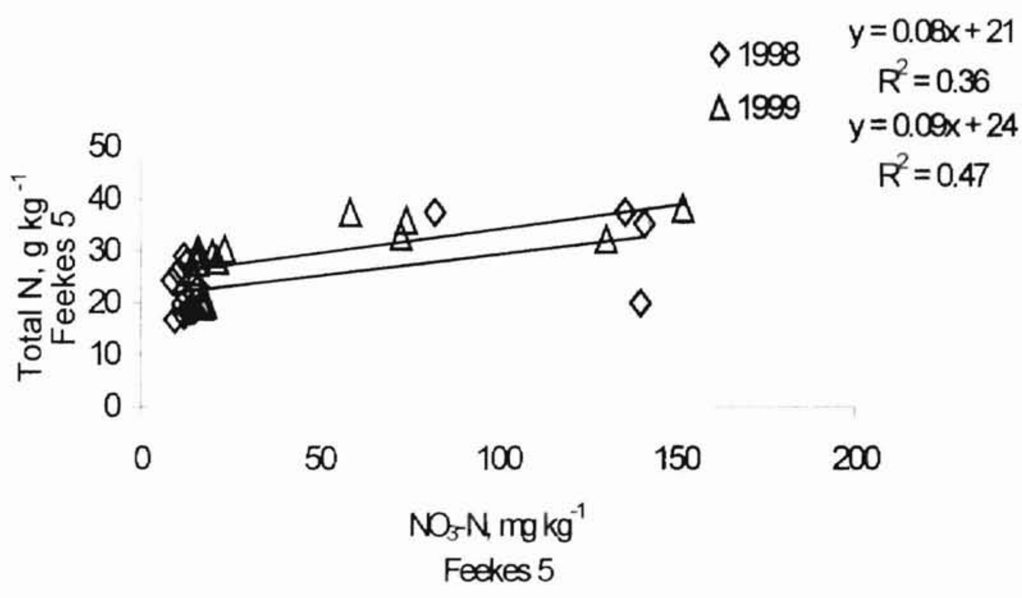

Figure 2. Relationship between NO_3-N at Feekes 5 and total N content at Feekes 5 at Stillwater, 1998 and 1999.

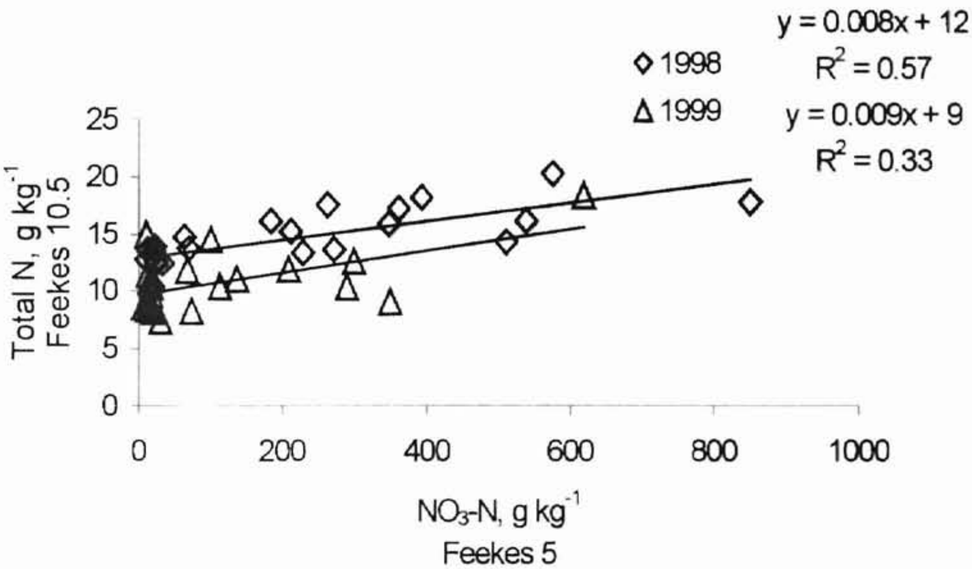

Figure 3. Relationship between NO_3-N at Feekes 5 and total N at Feekes 10.5 at Lahoma, 1998 and 1999.

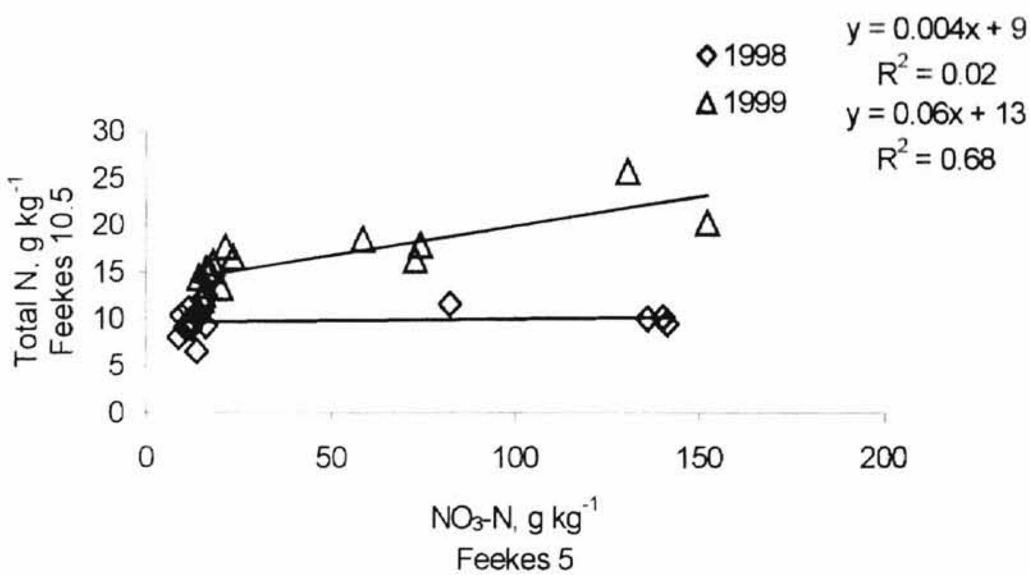

Figure 4. Relationship between NO_3-N at Feekes 5 and total N at Feekes 10.5 at Stillwater, 1998 and 1999.

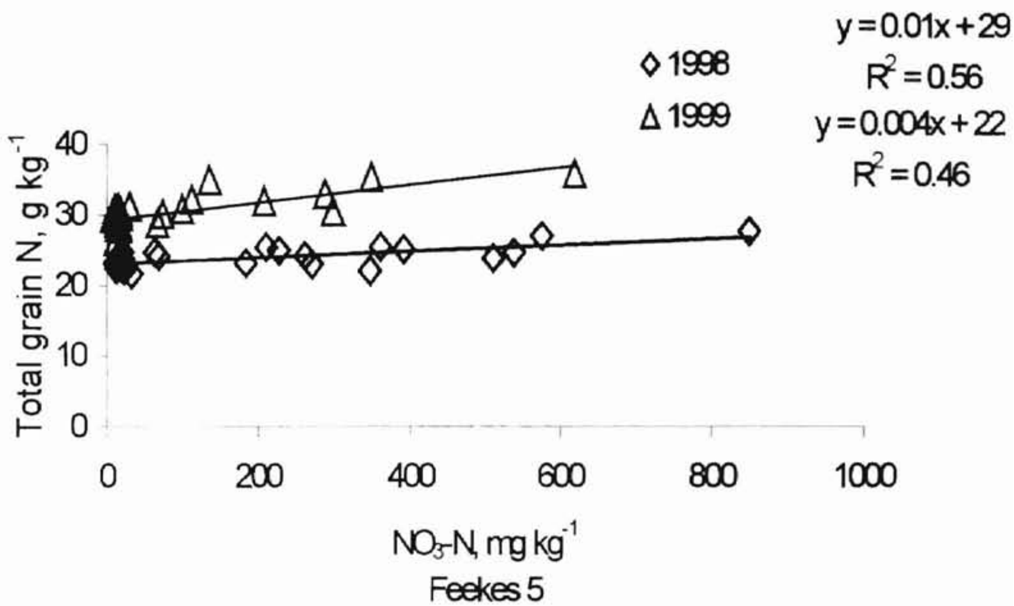

Figure 5. Relationship between NO_3-N at Feekes 5 and total grain N at Lahoma, 1998 and 1999.

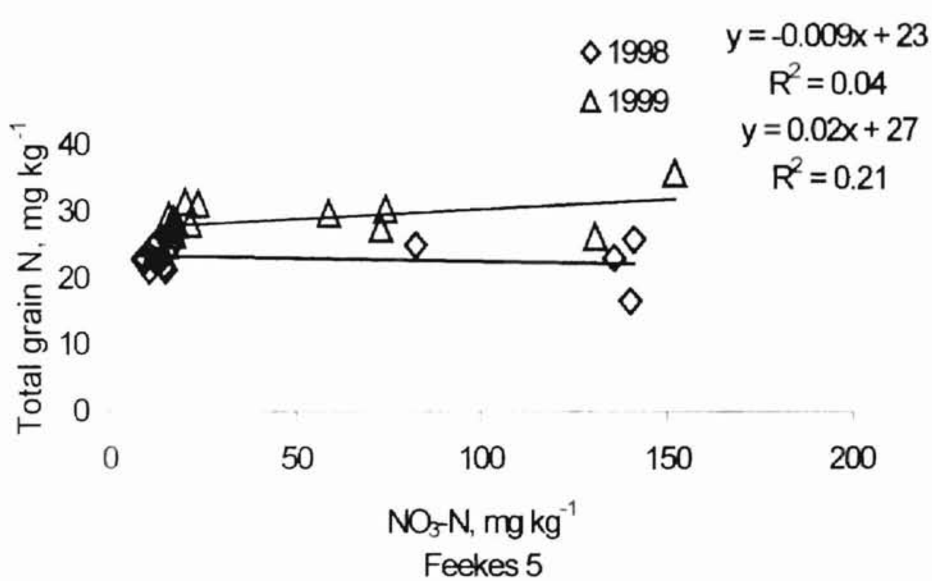

Figure 6. Relationship between NO_3-N at Feekes 5 and total grain N at Stillwater, 1998 and 1999.

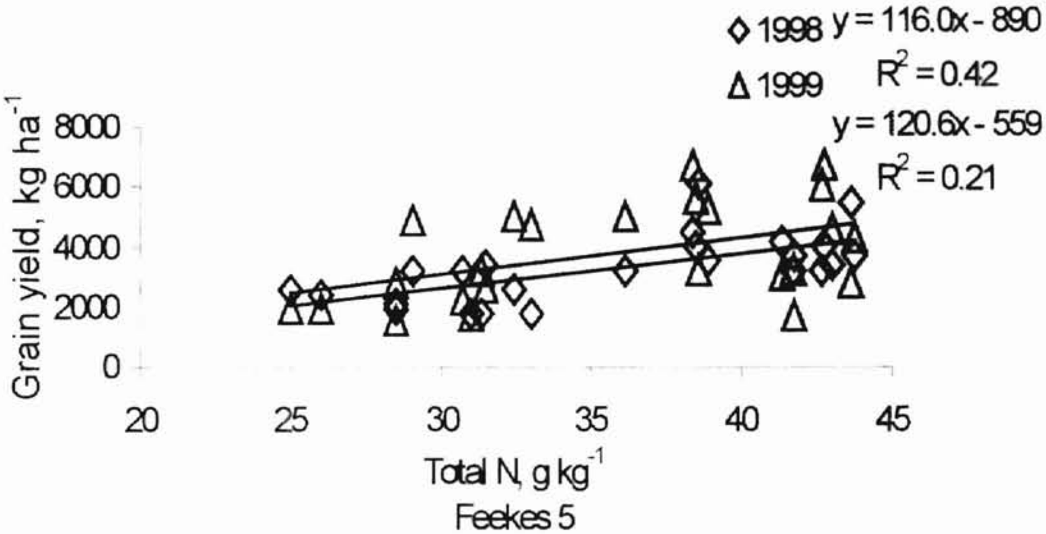

Figure 7. Relationship between total N at Feekes 5 and grain yield at Lahoma, 1998 and 1999.

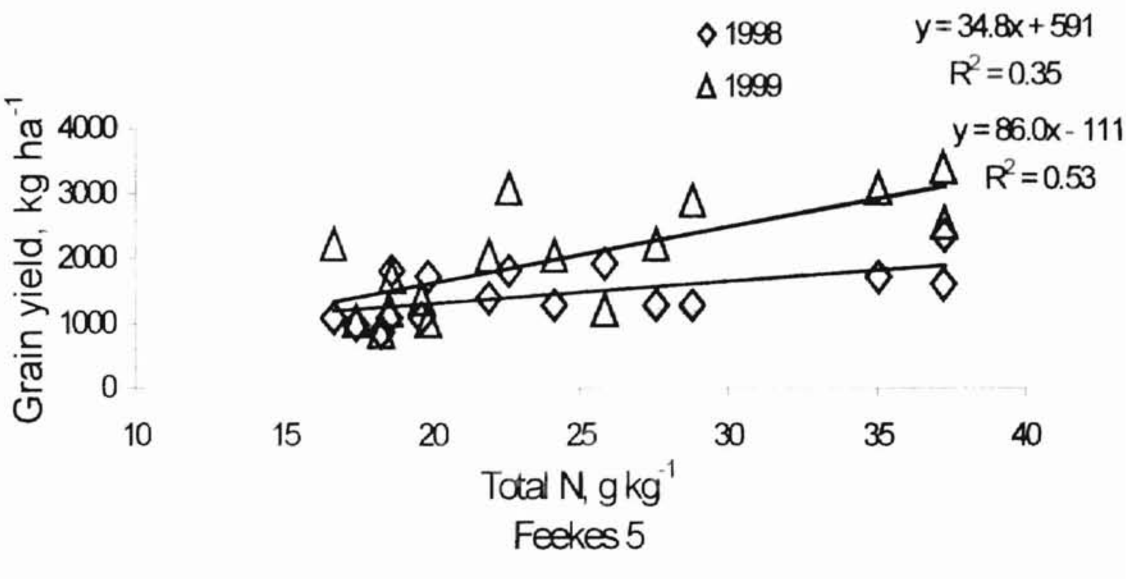

Figure 8. Relationship between total N at Feekes 5 and grain yield at Stillwater, 1998 and 1999.

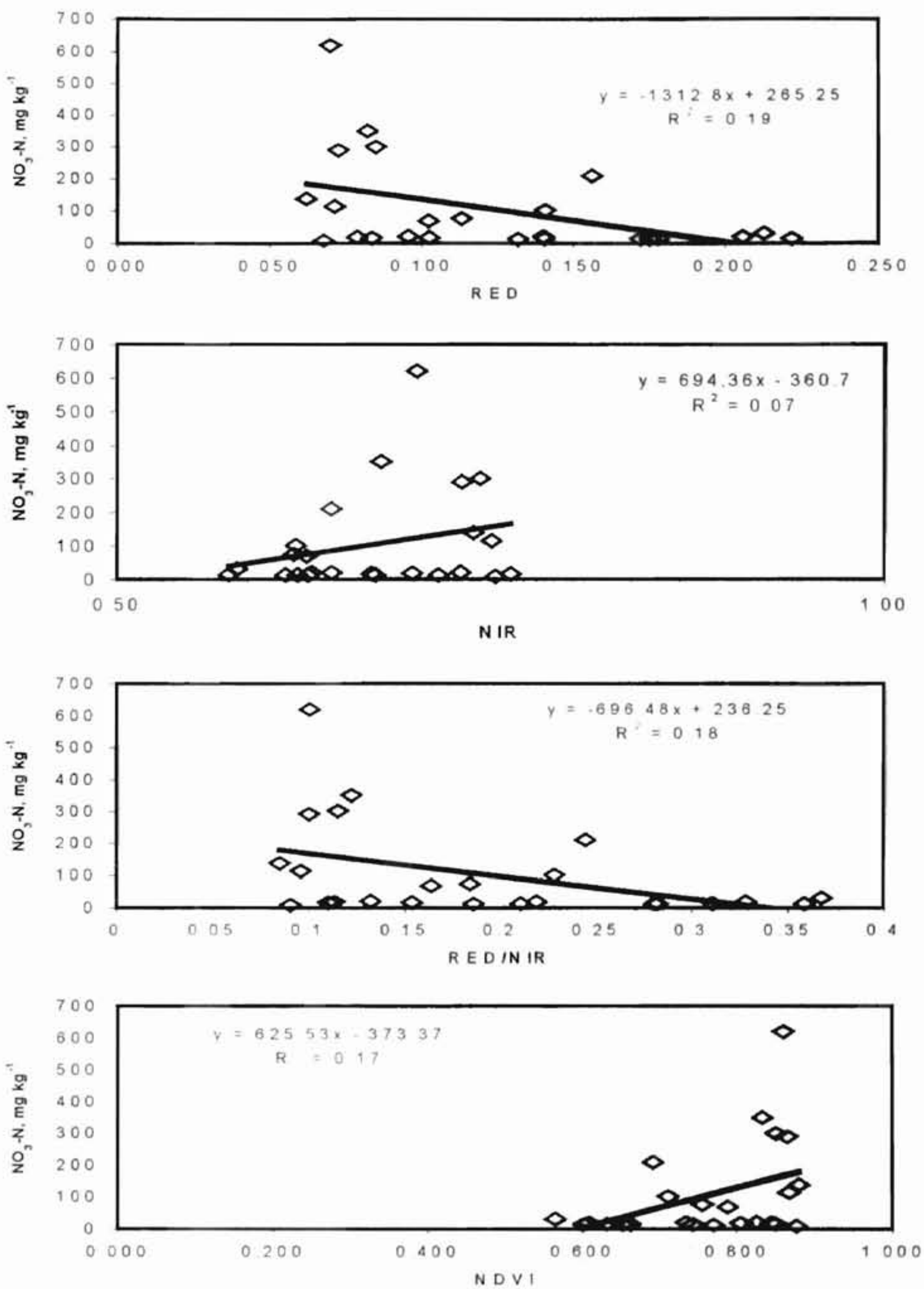

Figure 9. Relationship between Feekes 5 NO_3-N and various sensor readings, Lahoma 502, 1999.

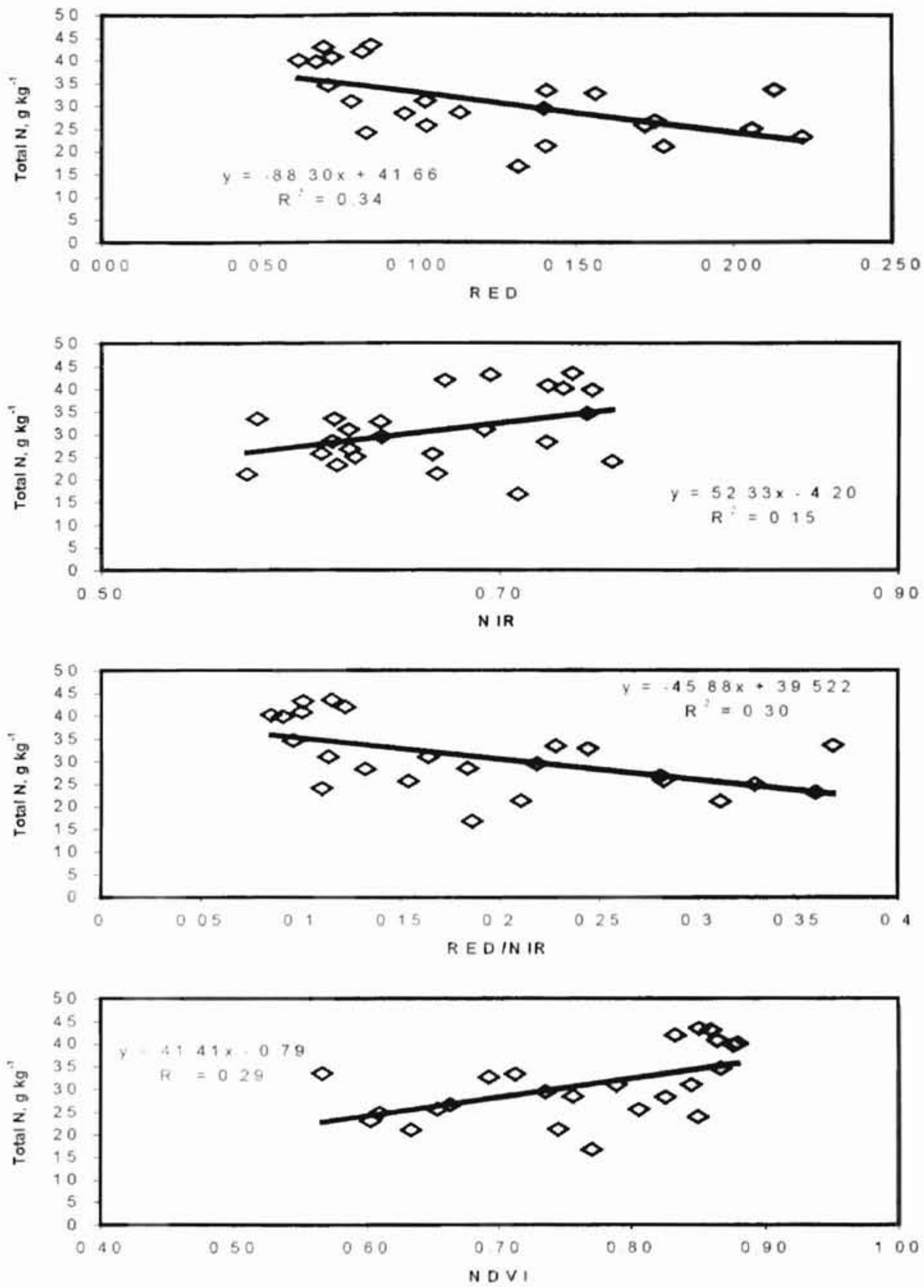

Figure 10. Relationship between total N at Feekes 5 and various sensor readings, Lahoma 502, 1999.

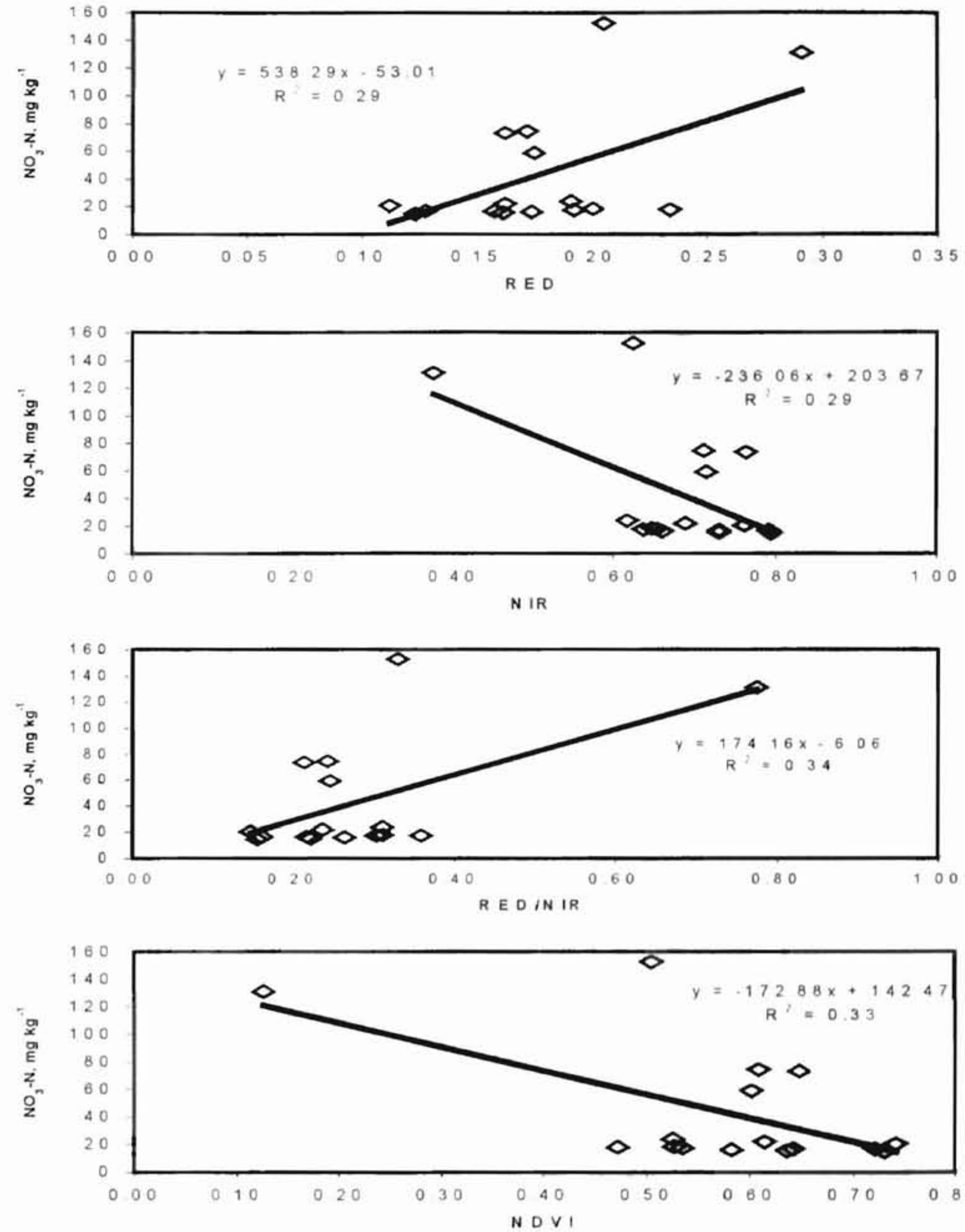

Figure 11 Relationship between Feekes 5 NO_3-N and various sensor readings, Stillwater 222, 1999.

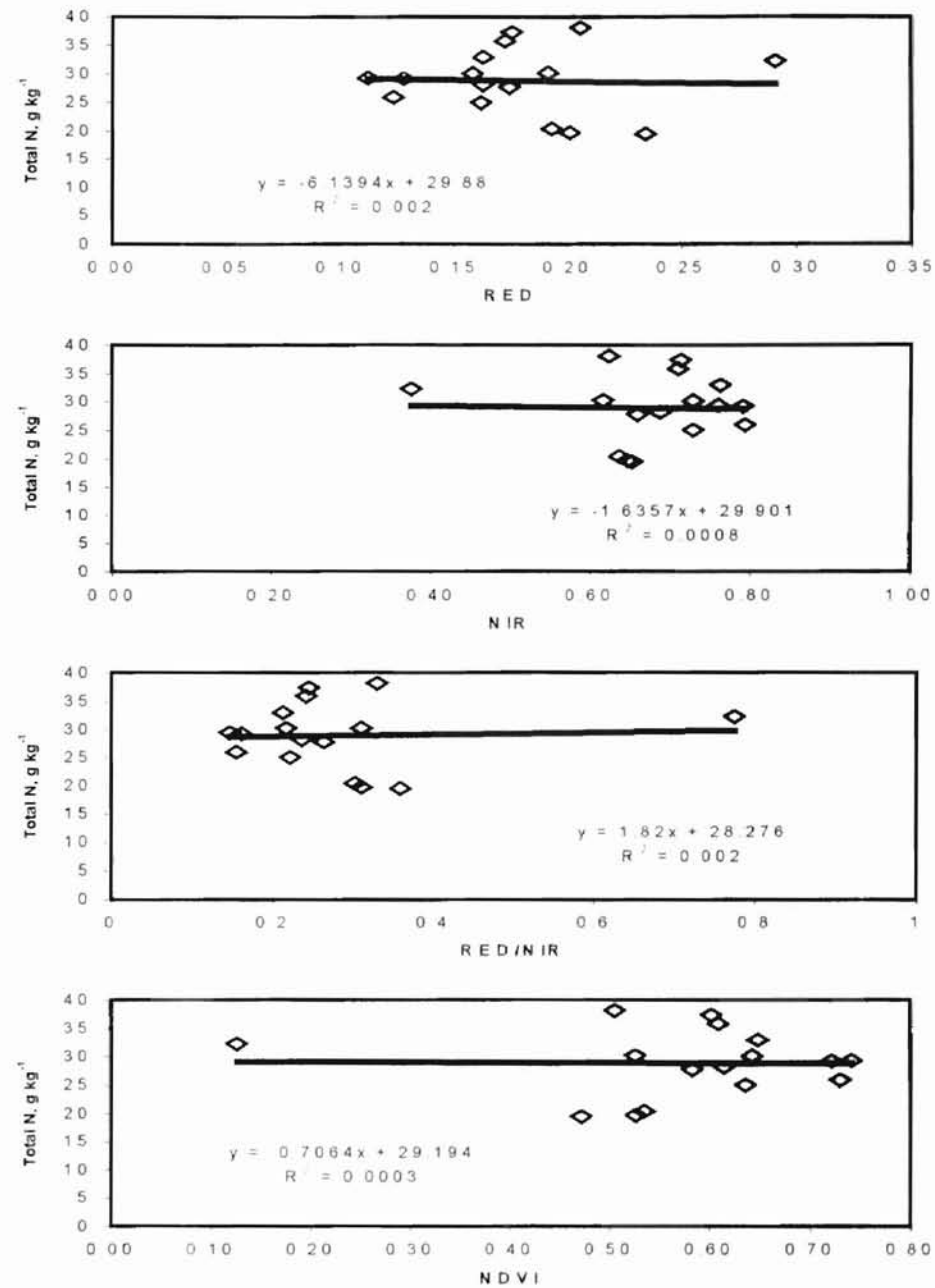

Figure 12. Relationship between total N at Feekes 5 and various sensor readings, Stillwater 222, 1999.

APPENDIX

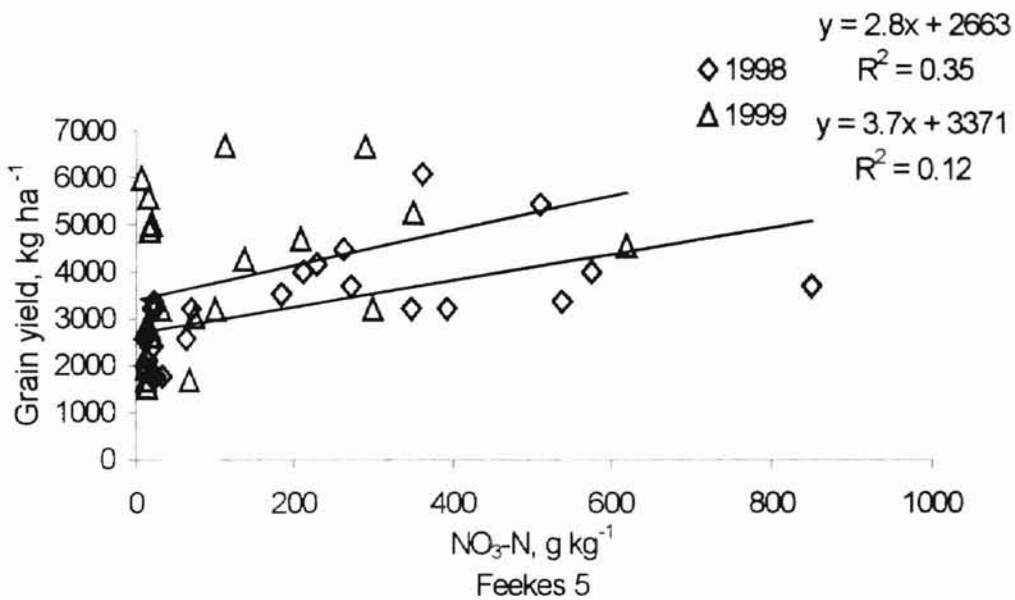

Figure 13 . Relationship between NO_3-N at Feekes 5 and grain yield at Lahoma, 1998 and 1999.

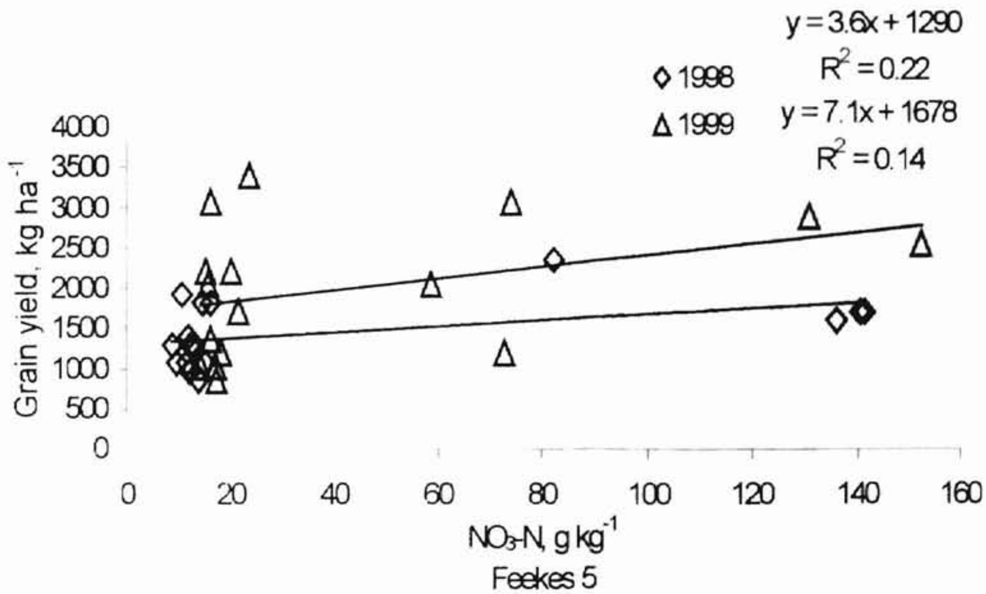

Figure 14. Relationship between NO_3-N at Feekes 5 and grain yield at Stillwater, 1998 and 1999

Table 5. Analysis of variance and treatment means for the total N uptake and ratios between total N uptake at Feekes 5, Feekes 10.5, and in the grain at harvest, Lahoma, OK 1998.

		TNUP_5	TNUP_10.5	TNUP_G	R10.5_G	R5_10.5	R5_G
Source of Variation	df	---------- mean squares, kg ha^{-1} --------			-------------mean squares-------------		
Replication	3	1339	1749	1044	0.27	0.77	0.54
N Rate	4	4453*	10324**	9218**	0.45	4.67**	0.80
Residual Error	12	3951	2167	4594	0.47	3.04	1.41
Contrasts							
N rate_linear	1	4204**	10289**	7204**	0.29**	4.69**	0.04
N rate_quadratic	1	249	24	22	0.004	0.01	0.39
SED		44	33	48	0.48	1.23	0.83
CV		19	23	23	29	26	29
N Rate, kg ha^{-1}		-------------------kg ha^{-1}----------------			------------------ratio-----------------		
0		70	27	49	0.58	2.59	1.52
45		86	40	84	0.46	2.33	1.02
67		99	57	87	0.66	1.84	1.17
90		106	72	83	0.88	1.51	1.30
112		110	90	117	0.81	1.28	1.09

TNUP_5-total N uptake at Feekes 5.
TNUP_10.5-total N uptake at Feekes 10.5.
TNUP_G-total N uptake in grain at harvest.
R10.5_G-total N uptake F10.5/total N uptake grain.
R5_10.5-total N uptake F5/total N uptake F10.5.
R5_G-total N uptake F5/total N uptake grain.
*, **-significance at the 0.05 and 0.01 probability level, respectively.
SED-standard error of the difference between two equally replicated means.
CV-coefficient of variation, %.

Table 6. Analysis of variance and treatment means for the total N uptake and ratios between total N uptake at Feekes 5, Feekes 10.5, and in the grain at harvest, Lahoma, OK 1999.

		TNUP_5	TNUP_10.5	TNUP_G	R10.5_G	R5_10.5	R5_G
Source of Variation	df	--------- mean squares, kg ha^{-1} --------			------------mean squares------------		
Replication	3	22301	5169	4359	0.20	11.72	0.62
N Rate	4	21608	4926	42096**	0.43	27.29	3.09
Residual Error	12	57926	9130	15573	1.09	80.43	6.49
Contrasts							
N rate_linear	1	15151	4437*	37590**	0.01	0.36	0.20
N rate_quadratic	1	2295	156	686	0.09	17.31	0.19
SED		170	78	102	0.70	6.34	1.80
CV		65	55	30	6	94	74
N Rate, kg ha^{-1}		------------------kg ha^{-1} ----------------			----------------ratio----------------		
0		50	30	62	0.49	1.58	0.12
45		112	42	69	0.67	2.61	1.18
67		97	39	140	0.24	4.98	0.06
90		145	61	162	0.37	2.55	0.90
112		130	73	169	0.55	2.09	0.35

TNUP_5-total N uptake at Feekes 5.
TNUP_10.5-total N uptake at Feekes 10.5.
TNUP_G-total N uptake in grain at harvest.
R10.5_G-total N uptake F10.5/total N uptake grain.
R5_10.5-total N uptake F5/total N uptake F10.5.
R5_G-total N uptake F5/total N uptake grain.
*, **-significance at the 0.05 and 0.01 probability level, respectively.
SED-standard error of the difference between two equally replicated means.
CV-coefficient of variation, %.

Taable 7. Analysis of variance and treatment means for the total N uptake and ratios between total N uptake at Feekes 5, Feekes 10.5, and in the grain at harvest, Stillwater, OK 1998.

		TNUP_5	TNUP_10.5	TNUP_G	R10.5_G	R5_10.5	R5_G
Source of Variation	df	---------- mean squares, kg ha^{-1}		--------	------------mean squares		-------------
Replication	3	537*	265**	310	0.48**	0.92	1.91*
N Rate	3	4225**	1466**	973**	0.45**	1.54	1.49*
Residual Error	9	375	47	292	0.12	1.70	0.73
Contrasts							
N rate_linear	1	4092**	1219**	958**	0.22	0.44	1.30**
N rate_quadratic	1	18	211**	15	0.20	1.09*	0.001
SED		16	6	13	0.28	1.07	0.69
CV		19	10	17	17	28	28
N Rate, kg ha^{-1}		-------------------kg ha^{-1}		-----------------	------------------	ratio	-----------------
0		13	13	22	0.60	1.58	0.12
45		30	16	31	0.56	2.61	1.18
90		38	20	38	0.54	4.98	0.06
134		59	38	43	0.95	2.55	0.90

TNUP_5-total N uptake at Feekes 5.
TNUP_10.5-total N uptake at Feekes 10.5.
TNUP_G-total N uptake in grain at harvest.
R10.5_G-total N uptake F10.5/total N uptake grain.
R5_10.5-total N uptake F5/total N uptake F10.5.
R5_G-total N uptake F5/total N uptake grain.
*, **-significance at the 0.05 and 0.01 probability level, respectively.
SED-standard error of the difference between two equally replicated means.
CV-coefficient of variation, %.

Table 8. Analysis of variance and treatment means for the total N uptake and ratios between total N uptake at Feekes 5, Feekes 10.5, and in the grain at harvest, Stillwater, OK 1999.

		TNUP_5	TNUP_10.5	TNUP_G	R10.5_G	R5_10.5	R5_G
Source of Variation	df	---------- mean squares, kg ha^{-1} ---------			------------mean squares------------		
Replication	3	1010	749	52	0.03	0.95	2.02
N Rate	3	7567**	3315**	1647**	0.05	2.34*	1.61
Residual Error	9	2162	1156	267	0.34	1.72	2.07
Contrasts							
N rate_linear	1	7074**	1600**	1567**	0.007	0.34	0.21
N rate_quadratic	1	491	1204**	34	0.2	2.00**	1.38*
SED		38	28	13	0.47	1.07	1.18
CV		27	22	18	34	24	46
N Rate, kg ha^{-1}		-------------------kg ha^{-1}-----------------			-------------------ratio-----------------		
0		35	31	19	0.58	1.63	0.92
45		42	48	22	0.57	2.20	1.35
90		62	72	35	0.64	2.09	1.33
134		91	53	43	0.49	1.24	0.59

TNUP_5-total N uptake at Feekes 5.
TNUP_10.5-total N uptake at Feekes 10.5.
TNUP_G-total N uptake in grain at harvest.
R10.5_G-total N uptake F10.5/total N uptake grain.
R5_10.5-total N uptake F5/total N uptake F10.5.
R5_G-total N uptake F5/total N uptake grain.
*, **-significance at the 0.05 and 0.01 probability level, respectively.
SED-standard error of the difference between two equally replicated means.
CV-coefficient of variation, %.

VITA

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Master of Science

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