MANAGEMENT OF NITROGEN AND PHOSPHORUS EXPERIMENTS USING SPECTRAL RADIANCE AND SOIL N MINERALIZATION IN WINTER WHEAT AND BERMUDAGRASS

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TABLE OF CONTENTS

LIST OF TABLES

Page

CHAPTER I

CHAPTER II

CHAPTER III

CHAPTER IV

LIST OF FIGURES

Page

CHAPTER II

CHAPTER III

CHAPTER IV

INTRODUCTION

This dissertation consists of four chapters, each summarizing research problems conducted separately during my doctoral program. Each chapter is presented in a format suitable for publication in professional journals. Some materials related to chapter II and III are presented in appendix A and B, respectively.

CHAPTER I

DETECTION OF NITROGEN AND PHOSPHORUS NUTRIENT STATUS IN WINTER WHEAT (*TRITICUM AESTIVUM* L.) USING SPECTRAL RADIANCE

ABSTRACT

Nitrogen (N) and phosphorus (P) are major limiting nutrients for crop production and continued interest lies in improving their use efficiency. Spectral radiance measurements were evaluated to identify optimum wavelengths for dual detection of N and P status in winter wheat (*Triticum aestivum* L.). A factorial treatment arrangement of N and P (0, 56, 112 and 168 kg N ha^{-1} and 0, 14.5 and 29 kg P ha^{-1}) was used to further study N and P uptake and associated spectral properties at Perkins and Tipton, Oklahoma. A wide range of spectral radiance measurements (345-1145 nm) were obtained from each plot using a PSD1000 ocean fiber optic spectrometer. At each reading date, 78 bands and 40 combination indices were generated to test for correlation with forage biomass and N and P uptake. Additional spectral radiance readings were collected using an integrated sensor which has photodiode detectors and interference filters for red and NIR. For this study, simple numerator/denominator indices were useful in predicting biomass, N uptake and

P uptake. Numerator wavelengths that ranged between 705 and 735 nm and denominator wavelengths between 505 and 545 nm provided reliable prediction of forage biomass, N and P uptake over locations and Feekes growth stages 4 through 6. Using the photodiode sensor, NDVI (NIR-red)/(NIR+red) and NR (NIR/red) were also good indices to predict biomass and N and P uptake. However, no index was found to be good for detecting solely N and P concentration either using the spectrometer or photodiode sensor.

INTRODUCTION

Water contamination and the economic importance of this problem has led to the need for improved nitrogen (N) and phosphorus (P) fertilizer management. Due to the significance that N and P fertilizers have on crop production, application of these two fertilizers often exceed the recommended rate. A quick method to determine the status of N and P in wheat plant tissue could be valuable to improve N and P fertilizer management practices.

Use of spectral radiance as a tool to determine the nutrient status in plants has several advantages compared to other non-destructive methods. Spectral radiance measurements can be obtained without attaching the meter to a specific leaf and many readings can be acquired in a short time thus reducing variability (Blackmer et al., 1994). In addition, sensors combined with other technologies such as GIS and GPS should be able to make local specific fertilizer recommendations (Schepers, 1994). Therefore, undesired environmental effects associated with excess fertilization might be reduced.

Some indices have been proposed to predict biological growth (biomass) and nutrient status. The normalized pigment chlorophyll index (NPCI = Reflectance at 430 nm (R430) - reflectance at 680 nm (R680)/(R680+R430)) was recently used to predict carotenoid/Chl A ratio (Penuelas et al., 1993). Similarly, the normalized difference vegetation index (NDVI = NIR-red/NIR+red) has provided good correlation with dry biomass (Mahey et al., 1991 and Penuelas et al., 1993). Also, moisture in leaves can be predicted at 1300 and 2400 nm (Kleman and Fagerlund, 1987). However, less has been done concerning the use of spectral radiance measurements for detecting plant P deficiencies. Therefore, the objectives of this study were to (1) identify the optimum sensor and reflectance wavelength for detecting dual N and P deficiencies in winter wheat, (2) identify the ideal stage of growth for detecting N and P deficiencies and (3) determine the use of spectral radiance on N*P interactions.

MATERIALS AND METHODS

Two field experiments were conducted at Tipton (Tillman-Hollister clay loam, fine-loamy, mixed, thermic, Pachic Argiustoll) and Perkins (Teller sandy loam, fine-loamy, mixed, thermic Udic Argiustoll), Oklahoma. Soil characteristics at each of these locations are reported in Table 1. A factorial arrangement of treatments for N and P rate was used at each location (0, 56, 112, and 168 kg N ha^{-1} with 0, 14.5, and 29 kg P ha^{-1}). The experimental design was a randomized complete block with three replications with individual plots measuring 3.1 m x 9.1

m. Harvested area for forage sample was 0.5 m^2.

Spectrometer Readings

Spectral readings and forage yield were collected at Feekes growth stages 4, 5, 6 and 9 at Tipton and 5, 6 and 7 at Perkins (Large, 1954). A wide range of spectral radiance measurements (300 to 1100 nm) were obtained from each plot using a PSD1000 portable dual spectrometer manufactured by Ocean Optics Inc., from two overlapping bandwidths, 300-850 nm and 650-1100 nm. The PSD1000 was connected to a portable computer through a PCMCIA slot using a PCM-DAS 16D/12 A/D converter manufactured by Computer Boards Inc.. The fiber optic spectrometer which has 200 μ diameter and no slit has spectral resolution as low as 5 nm. The bifurcated fiber was lifted with an hemispherical lucite™ lens which increased its angle of acceptance to 34°. The lens was held at 1.5 m and the area sensed was 0.8 m^2 per plot.

All spectral readings were partitioned into 10 nm bandwidths (78 spectral bands per reading). In addition to these spectral bands collected from each reading, spectral indices such as NDVI (Normalized Difference Vegetation Index) and other combinations of single indices were generated (Table 2). All spectral radiance readings were standardized using a barium sulfate ($BaSO_4$) background reading. Statistical analysis was performed using SAS (SAS institute, 1988).

Photodiode Sensor Readings

The collection of spectral radiance readings using the spectrometer was different from that obtained using the photodiode sensors. Photodiode spectral radiance readings were collected at growth stages Feekes 4, 5, 6 and 7 at Perkins and 5, 6 and 9 at Tipton from 0.19 m (3 rows) and 0.91 m long area.

Spectral radiance readings using photodiode sensors were obtained using an integrated sensor and signal processing system created by Stone et al (1996). The integrated sensor has photodiode detectors and interference filters for red and NIR spectral bands with a 0.305 m wide by 0.075 m spatial resolution. This sensor allowed for red (671± 6 nm) and two kinds of NIR: long NIR (1050 ± 6 nm) and short NIR (780 ± 6 nm); therefore, NDVI (Normalized Difference Vegetation Index = (NIR-red)/(NIR+red) consisted of two indices (LNDVI and SNDVI). LNDVI refers to using long NIR in the NDVI formula and SNDVI refers to using short NDVI. The same is true for the simple ratio NR (NIR/red) where LNR refers to long NIR/red and SNR referred to short NIR/red.

Individual wavelengths and combination indices were evaluated to determine the proper indices for predicting wet biomass, dry biomass, total N uptake, total P uptake, and total N and P concentration in winter wheat forage. All spectral radiance readings were standardized using a barium sulfate ($BaSO_4$) background reading. Statistical analysis was performed using SAS (SAS institute, 1988).

RESULTS AND DISCUSSION

At both sites, a significant increase in wheat forage yield due to applied N was observed at all stages of growth (Tables 3 and 4). A forage yield response to applied P was not significant at Tipton but was significant at Perkins. No N*P interaction was detected at either location. The lack of a P response at Tipton was due to high inorganic soil test P (Table 1). The main effect of growth stage was significant at both sites, a result of increased biomass with growth stage. Dry biomass decreased from Feekes growth stage 6 to 9 due to frost which caused tissue death and subsequent loss.

Linear Regression:

Using data combined over all growth stages, the best three indices (single and multi-wavelength combinations) to predict N rate, P rate, wet biomass, dry biomass, moisture, P concentration, P uptake, N concentration and N uptake were determined (Table 9). No one index, either single or multi-wavelength combination was consistent over time in being correlated with N rate, P rate, wet and/or dry biomass, P concentration, P uptake and N concentration. However, over growth stages, consistent correlation from 10 nm bands between 625 and 695 nm was found with N uptake. The best three indices (single and multi-wavelength combinations) to predict N rate, P rate, wet biomass, dry biomass, moisture, P concentration, P uptake, N concentration and N uptake were determined by growth stage (Tables 5-8). Single 10 nm band indices provided inconsistent prediction of the agronomic variables measured at both sites

(Tables 5 and 7). Consistent correlation over growth stages was found for numerator (705-735 nm) and denominator (505-545 nm) combinations when predicting N uptake at both locations (Tables 6 and 8). Other dependent variables did not result in consistent correlation with spectral indices over growth stages and locations. The use of denominator wavelengths that were not independently correlated with the dependent variable assisted in removing variability that was present when using the numerator wavelength alone (Tables 5 vs. 6 and Tables 7 vs. 8, Tipton and Perkins, respectively).

Spectrometer: N rate and Prate by growth stage:

The indices that could be used to predict N rate varied (Tables 5-8). The highest correlation at Tipton was found at Feekes 5 with the index w715/545. Correlation tended to increase from Feekes 4 to Feekes 7. At Tipton, no index was significant to predict N rate at Feekes 4, but improved at later stages of growth. This indirectly suggests that percent foliage cover was critical in the establishment of indices for N status in winter wheat since the percent coverage was low when the first readings were taken at Tipton. As was expected, correlation of indices to predict P rate at Tipton was lower than at Perkins.

Spectrometer: wet biomass, dry biomass and moisture by growth stage:

As has been demonstrated by others, NDVI has been commonly used to predict biomass in various studies (Mahey et al, 1991 and Penuelas et al. 1993). However, we did not observe consistent correlation between NDVI and wet biomass (Tables 5-8). Dry biomass correlation with several indices increased with advancing stages of growth at both Tipton and Perkins. The index that was common to both locations in predicting dry biomass was w735/665.

Analysis by growth stage suggested that moisture in plants could not be adequately predicted until Feekes 5. The same observation was noted for biomass, indicating that a critical amount of coverage is needed in order to override background soil interference. However, results at Perkins were not consistent with observations at Tipton. At Perkins, moisture could be detected at earlier growth stages but not at later stages.

Spectrometer: P tissue concentration, P uptake, N tissue concentration, and N uptake by growth stage:

Analysis by growth stage suggested that P concentration could be predicted at earlier growth stages using W705/505 at Perkins and NR at Tipton. However, at later growth stages, none of these indices could predict P concentration (Tables 5-8). It may be that P deficiencies were not detected at later stages of growth due to increased root proliferation in profiles where subsoil P was greater.

At Tipton, P uptake could be predicted using w695/405 at Feekes growth stage 4 but this did not hold true at later growth stages. At Perkins, P uptake could be predicted using W715/505. Similarly, this index was not reliable at later growth stages. The same indices for predicting P uptake at Perkins were not always good at Tipton and visa-versa. Similar to N uptake, correlation between P uptake and several of the spectral indices evaluated tended to increase with advancing stages of growth.

At Tipton, N concentration could not be reliably predicted at Feekes growth stage 4 but could be predicted at later growth stages. The same trend was observed at Perkins. However, indices were not consistently the same at Tipton and Perkins (Tables 5-8). It was interesting to note that w735/545 at Perkins and PFR at Tipton appeared at Feekes growth stages 5 and 6. In addition, w695/405 was also observed at both locations between Feekes growth stages 5 and 6.

At Tipton, N uptake could not be reliably predicted at Feekes growth stage 4 but could be predicted at later growth stages. This same trend was observed at Perkins. Although correlation increased with time, indices were not consistently the same at Tipton and Perkins (Tables 5-8). This indirectly suggest that beginning at Feekes 5, top-dress applications (based on growth) could be applied, given that a yield response was achieved using a highly correlated index with N uptake. In addition, W725/525 was highly correlated with N uptake at growth stages Feekes 4 and 9 at Tipton and at Feekes 5 at Perkins. Because of the similarities in numerator and denominator wavelength the use of broad bands may need to be further evaluated.

Spectrometer: N rate and P rate over growth stages:

Similar to by growth stage results, w725/525 (± 20 nm for both the numerator and denominator) provided good prediction of N rate over growth stages. Using all data over growth stages, no index could be used to reliably predict P rate at Tipton, however, at Perkins, P rate could be predicted using w705/535, w705/545 and w705/525 (Table 9). The inconsistency of this observation by growth stage limits the utility.

Spectrometer: wet biomass, dry biomass, and moisture over growth stages:

There were several indices that reliably predicted wet biomass including w705/505, w715/515 and w715/505 at Tipton and 735/665, NPCIX and w735/655 at Perkins. Dry biomass could be predicted by w705/515 and NPCIX at Tipton and Perkins, respectively (Table 9). Using all data combined over growth stages, the highest correlation coefficient for predicting moisture was with w795/735 at Tipton and w705/505 for Perkins (Table 9).

Spectrometer: P tissue concentration, P uptake, N tissue concentration, and N uptake over growth stages:

Using all data combined over growth stages, the highest correlation for predicting P concentration and P uptake was achieved with w785/505 and w705/545 at Tipton and NR and PFR at Perkins (Table 9).

The highest correlation for predicting N concentration was w705/505 at Tipton and w735/535 at Perkins. N uptake was highly correlated with w795/735 and PFR at Tipton and Perkins, respectively (Table 9).

Photodiode sensors vs. agronomic variables

Analysis of variance and associated means from spectral properties determined at various growth stages are reported in Tables 10 and 11 for Tipton and Perkins, respectively. Simple correlation coefficients between spectral radiance measured with photodiode sensor and wet biomass, dry biomass, moisture, P concentration, P uptake, N concentration and N uptake are reported in Tables 12 and 13 for Tipton and Perkins, respectively. Wet biomass was highly correlated with NDVI (LNDVI and SNDVI) at all growth stages at both locations. Correlation coefficients from linear regression with wet biomass ranged from 0.56 to 0.93 for SNDVI, 0.64 to 0.95 for LNDVI, 0.44 to 0.97 for LNR and 0.58 to 0.97 for SNR. Similarly, these same indices were highly correlated with dry biomass. Moisture tended to be less correlated with these same indices.

Combined over growth stage, tissue P concentration could not be reliably predicted with an index. However, P concentration could be predicted at Perkins at Feekes growth stages 4 and 5 using NDVI and NR. In addition, red was also a reliable predictor at earlier growth stages compared to later. P uptake could be predicted using NDVI and NR at various stages of growth.

At Perkins and Tipton, N concentration was highly correlated with several of the indices evaluated, however, consistency over time was not observed. NDVI and NR were consistently correlated with N uptake over growth stages and locations. This suggests that using N uptake is better than just using tissue N concentration. Similar to results from spectrometer readings, combinations of wavelengths within indices provided superior correlation with dependent agronomic variables compared to single wavelengths.

Grain yield vs. spectral indices

Analysis of variance and associated means for grain yield, grain N, grain N uptake, grain P and grain P uptake at Tipton and Perkins are reported in Table 14. It was found that only grain N and grain N uptake were affected by N rate. Grain N levels increasing with increasing N applied at both sites, even though no yield response was detected. Grain yield levels were low at both sites (late frost at Tipton and Perkins).

Correlation of grain yield, grain N, grain N uptake, grain P and grain P uptake with spectral indices is reported in Table 15. It was interesting to note that grain N uptake was highly correlated with SNDVI, SNR and LNR at Feekes stage 5 at Perkins and 6 at Tipton. However, no index could reliably predict grain P and grain P uptake.

A positive relationship between forage N uptake and a spectral property at early stages of growth does not guarantee that it will be correlated with grain yield. It is suggested that an experiment be conducted where fertilizer rates are determined based on spectral properties at different growth stages to document time of top-dressing when using indirect measures.

CONCLUSIONS

Spectral indices with numerator wavelengths that ranged between 705 and 735 nm and denominator wavelengths between 505 and 545 nm provided reliable prediction wheat forage biomass, N and P uptake over locations and Feekes growth stages 4 to 6. It was found that NDVI and NR were good indices for the prediction of biomass, and N and P uptake; however, no index could reliably predict N and P concentration either using the spectrometer or sensor. Grain N uptake could be predicted using SNDVI and SNR and LNR from spectral readings collected at Feekes stage 5. This finding was encouraging since there are many biological and environmental variables that can impact grain yield between Feekes stage 5 and physiological maturity.

This work demonstrates the difficulty in identifying constant indices that can be used over time for predicting chemical and biological parameters using spectrometer readings. One particular index is sometimes good at a given reading but not for others. Some of the problems encountered with using spectral properties to predict biological properties of plants include, light intensity, weed pressure, clouds and the sensitivity of the sensor in capturing the images of the plant canopy. In addition, part of the problem might be the resolution at which sensed data is collected.

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Table 1. Initial surface (0 - 15cm) soil test characteristics at Tipton and Perkins, OK, 1996

Characteristics	Extractant	Unit	Tipton	Perkins
pH	1:1 soil:H_2O	-	7.8	5.9
Organic Carbon$^{\omega}$	Dry Combustion	g kg^{-1}	7.158	5.336
Total Nitrogen$^{\omega}$	Dry Combustion	g kg^{-1}	0.719	0.504
NH_4-N$^{\Pi}$	2 M KCl	mg kg^{-1}	3.0	3.0
NO_3-N$^{\Pi}$	2 M KCl	mg kg^{-1}	4.0	2.8
P$^{\Psi}$	Mehlich-3	mg kg^{-1}	43.9	8.9
K$^{\Psi}$	Mehlich-3	mg kg^{-1}	464.5	133.0

$^{\Pi}$Lachat instruments (1989), $^{\omega}$Schepers et al. (1989)
$^{\Psi}$ Mehlich (1984)

Table 2. Combinations of multi-wavelength indices tested for winter wheat forage spectral radiance readings collected at Perkins and Tipton OK, 1997

NPCIX1= (W685 - W435)/(W685 + W435)
NPCIX = (NPCI1 + NPCI2)/2
NW2 = W965-W895
PRI1 = (W555-W535)/(W555+W535)
PRI = (PRI1+PRI2)/2
NDVI = (W805-W695)/(W805+W695)
NR= W805/W695
W735/665=W735/W665
W805_415 = W805/W415
W735_655 = W735/W655
W705_515 = W705/W515
W705_535 = W705/W535
W715_505 = W715/W505
W715_525 = W715/W525
W715_545 = W715/W545
W725_515 = W725/W515
W725_535 = W725/W535
W735_505 = W735/W505
W735_525 = W735/W525
W735_545 = W745/W545
W735_715 = W735/W715
W695_405 = W695/W405

NPCIX2 = (W675 - W425)/(W675 + W425)
NW1= W975-W905
WBI=W955/W905
PRI2 =(W545-W525)/(W545+W525)
GR = (W515+W525+W535+W545)/4
NIRGI = W795/(1/W545)
PFR = W725/655
W405_635=W405/W635
W795_735 = W795/W735
W705_505 = W705/W505
W705_525 = W705/W525
W705_545 = W705/W545
W715_515 = W715/W515
W715_535 = W715/W535
W725_505 = W725/W505
W725_525 = W725/W525
W725_545 = W725/W545
W735_515 = W735/W515
W735_535 = W735/W535
W725_715 = W725/W715
W785_505 = W785/W505
W405_635 = W405/W635.

Table 3. Analysis of variance for wet biomass, dry biomass, moisture, P tissue concentration, P uptake, N tissue concentration, and N uptake in wheat forage at Feekes growth stages 4, 5, 6 and 9 at Tipton OK, 1997

Source of variation	df	Wet biomass	Dry Biomass	Moisture	P tissue conc.	P tissue uptake	N tissue conc.	N uptake
		---Mean squares---						
Rep	2	ns	ns	ns	*	ns	ns	ns
N rate	3	***	***	**	ns	***	ns	***
P rate	2	ns	ns	ns	ns	ns	ns	ns
NxP	6	ns	ns	ns	ns	ns	ns	ns
Error (a)	22	9267264	1630115	33	108191	13.0	8.9	666
GS	3	***	***	***	***	***	***	***
GS*N	9	***	***	***	ns	***	ns	***
GS*P	6	ns	ns	ns	ns	ns	ns	ns
GS*N*P	18	ns	ns	ns	ns	ns	ns	ns
Error (b)	71	8733477	1577047	17	96772	15.5	6.4	691
Growth Stage		---Means---						
	N, kgha^{-1}	kg ha^{-1}	kg ha^{-1}	%	mg kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}
Feekes 4	0	4113	2112	49	2268	4.7	22.7	47.3
	56	4894	2425	50	2226	3.9	23.8	55.4
	112	4268	2165	49	2412	11.6	13.6	51.8
	168	5019	2503	49	2222	6.4	10.0	58.0
Feekes 5	0	3631	1745	51	2288	5.3	23.1	41.7
	56	4301	1967	53	2159	4.2	23.8	47.0
	112	4667	2145	53	2274	16.2	13.9	48.7
	168	5169	2478	51	2035	8.0	9.9	60.2
Feekes 6	0	6375	4701	24	2506	5.2	23.9	63.6
	56	10560	6987	31	2314	4.8	22.9	98.4
	112	18040	10517	40	2297	24.2	16.6	179.9
	168	18112	10526	41	2462	12.0	10.5	183.6
Feekes 9	0	9369	3071	67	2094	5.5	23.2	30.5
	56	12899	4050	68	1997	4.9	24.3	40.6
	112	21362	6601	69	1816	26.1	17.4	69.9
	168	23141	7083	69	2108	15.5	10.8	77.2
SED		1393	591	2	146	1.8	1.2	12.4
Growth Stage (over N and P rates)								
Feekes	4	4573	2301	49	2282	5.2	23.2	53.1
Feekes	5	4442	2084	52	2189	4.5	23.7	49.4
Feekes	6	13271	8183	34	2395	19.5	15.4	131.4
Feekes	9	16693	5201	68	2004	10.5	10.3	54.6
SED		696	296	1	73	0.9	0.6	6.2
P, kgha^{-1} (over N rates and growth stages)								
	0	9241	4240	50	2155	9.0	17.8	67.5
	14.5	10216	4582	52	2219	10.1	18.5	75.1
	29	9778	4505	51	2278	10.7	18.2	73.7
SED		603	256	1	63	0.8	0.5	5.3

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

ns = not significant; SED = standard error difference between two equally replicated means

GS = growth stage

Table 4. Analysis of variance for wet biomass, dry biomass, moisture, P tissue concentration, P uptake, N tissue concentration, and N uptake in wheat forage at Feekes growth stages 4, 5, 6 and 7, Perkins OK, 1997

Source of variation	df	Wet biomass	Dry biomass	Moisture	P tissue conc.	P uptake	N conc.	N uptake
		Mean squares						
Rep	2	ns	*	ns	ns	ns	*	ns
N rate	3	***	***	***	ns	***	***	***
P rate	2	***	***	**	*	***	ns	**
NxP	6	ns	ns	ns	ns	ns	ns	ns
Error (a)	22	15503480	855384	23	177711	4.8	18.5	499.9
GS	3	***	***	***	***	***	***	***
GS*N	9	***	***	**	*	*	*	**
GS*P	6	***	***	***	ns	**	ns	ns
GS*N*P	18	ns	ns	ns	ns	ns	ns	ns
Error (b)	71	4615287	495417	24	127449	1.3	16.6	148.0
		Means						
GS	N, kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	%	mg kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}
Feekes 4	0	1615	675	61	1558	0.9	23.4	13.4
	56	2628	810	68	1873	1.6	29.9	24.6
	112	3226	935	70	1869	1.7	31.5	29.1
	168	3910	1186	69	2239	2.6	32.4	38.4
Feekes 5	0	3418	1692	51	1573	2.4	17.7	29.1
	56	5227	2150	57	1573	3.4	19.8	42.3
	112	7078	2695	61	1501	4.0	22.6	59.4
	168	7421	2338	66	1716	4.2	27.0	63.2
Feekes 6	0	4913	1287	73	1825	2.3	23.2	30.0
	56	7802	2006	74	1523	3.1	21.4	40.9
	112	11423	2724	75	1656	4.7	23.3	63.3
	168	13399	3103	77	1579	5.1	25.2	74.4
Feekes 7	0	9673	2705	72	1337	3.5	14.1	39.6
	56	12116	3312	73	1240	4.2	13.4	44.4
	112	18685	5183	72	1218	6.6	14.5	74.2
	168	20050	5680	72	1195	6.9	16.6	94.0
SED		1012	331	2	168	0.5	1.9	5.7
GS	P, kgha^{-1}							
Feekes 4	0	2155	784	63	1661	1.2	27.5	19.8
	14.5	2871	867	69	1902	1.7	29.8	27.1
	29	3508	1052	69	2091	2.2	30.6	32.2
Feekes 5	0	4889	2180	54	1474	2.9	21.8	45.4
	56	5490	2173	59	1479	3.2	21.3	47.0
	112	6980	2303	64	1819	4.3	22.2	53.1
Feekes 6	0	7048	1645	75	1596	2.6	26.3	44.1
	14.5	8640	2184	74	1596	3.4	22.1	48.5
	29	12380	3002	75	1759	5.3	21.1	62.8
Feekes 7	0	12370	3334	73	1125	3.7	15.1	51.7
	14.5	14314	3916	72	1264	4.8	14.9	60.0
	29	18708	5410	71	1353	7.3	14.0	77.5
SED		877	287	2	146	0.4	1.6	4.9

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

ns = not significant; SED = standard error difference between two equally replicated means

GS = growth stage

Table 5. Spectral radiance measurements and simple correlation from the three best models with N rate, P rate, biomass, moisture, P tissue concentration, P uptake, N tissue concentration and N uptake by growth stage at Tipton OK, 1997

	Growth Stage 4			Growth Stage 5			Growth Stage 6			Growth Stage 9		
Dependent variables	1	2	3	1	2	3	1	2	3	1	2	3
N rate	W345 0.18915 (0.2692)	W355 0.17944 (0.295)	W365 0.16742 (0.3291)	W1095 -0.92014 (0.0001)	W1085 -0.9201 (0.0001)	W565 -0.91982 (0.0001)	W685 -0.86759 (0.0001)	W675 -0.86483 (0.0001)	W665 -0.86474 (0.0001)	W625 -0.84157 (0.0001)	W635 -0.84076 (0.0001)	W695 -0.84006 (0.0001)
P rate	W1035 0.16068 (0.3492)	W1045 0.15576 (0.3643)	W1145 -0.13514 (0.432)	W915 -0.21139 (0.2159)	W925 -0.20139 (0.2389)	W795 -0.19027 (0.2663)	W1085 0.08392 (0.6265)	W1095 0.08364 (0.6277)	W1105 0.07908 (0.6466)	W445 0.03114 (0.8569)	W1005 -0.03044 (0.8601)	W985 -0.02837 (0.8695)
Wet Biomass	W735 0.19301 (0.20414)	W745 0.19569 (0.2527)	W725 0.18374 (0.2834)	W345 -0.49744 (0.002)	W745 0.47978 (0.0031)	W755 0.47944 (0.0031)	W635 -0.78207 (0.0001)	W625 -0.78004 (0.0001)	W645 -0.78003 (0.0001)	W695 -0.89895 (0.0001)	W625 -0.89634 (0.0001)	W615 -0.89614 (0.0001)
Dry biomass	W745 0.20414 (0.2324)	W735 0.19966 (0.243)	W725 0.18806 (0.272)	W755 0.49719 (0.002)	W745 0.494 (0.0022)	W345 -0.47776 (0.0032)	W635 -0.78188 (0.0001)	W645 -0.78033 (0.0001)	W625 -0.77992 (0.0001)	W505 -0.89691 (0.0001)	W625 -0.89454 (0.0001)	W615 -0.89421 (0.0001)
Moisture	W1055 0.15817 (0.3569)	W1035 0.12805 (0.4567)	W1025 0.007478 0.6647	W355 -0.13453 (0.4341)	W365 -0.13102 (0.4463)	W435 -0.12861 (0.4547)	W635 -0.82413 (0.0001)	W645 -0.82349 (0.0001)	W655 -0.82206 (0.0001)	W745 0.68637 (0.0001)	W765 0.67376 (0.0001)	W775 0.67443 (0.0001)
P tissue conc.	W715 0.39165 (0.0182)	W725 0.38935 (0.0189)	W905 0.38832 (0.0193	W745 -0.27232 (0.1081)	W735 -0.24161 (0.1557)	W755 -0.22212 (0.1929)	W1065 -0.25617 (0.1315)	W1025 -0.24859 (0.1437)	W1055 -0.24798 (0.1448)	W1055 -0.16023 (0.3506)	W1045 -0.15253 (0.3745)	W1065 -0.14786 (0.3895)
P uptake	W735 0.35151 (0.0355)	W745 0.35125 (0.0357)	W725 0.34599 (0.0387)	W1065 -0.45159 (0.0057)	W345 -0.43636 (0.0078)	W1065 -0.45159 (0.0057)	W695 -0.71587 (0.0001)	W625 -0.71410 (0.0001)	W615 -0.71279 (0.0001)	W745 0.59531 (0.0001)	W755 0.59208 (0.0001)	W765 0.59169 (0.0001)
N tissue conc.	W365 0.17911 (0.2959)	W355 0.17771 (0.2998)	W685 0.17399 (0.3102)	W345 -0.14290 (0.4057)	W355 -0.12521 (0.4669)	W365 -0.12001 (0.4857)	W925 0.73998 (0.0001)	W935 0.72322 (0.0001)	W915 0.72193 (0.0001)	W775 0.60908 (0.0001)	W765 0.60833 (0.0001)	W755 0.60631 (0.0001)
N uptake	W745 0.26731 (0.1150)	W735 0.26598 (0.1169)	W725 0.25852 (0.1279)	W1055 -0.49130 (0.0023)	W345 -0.48872 (0.0025)	W1075 -0.48711 (0.0026)	W635 -0.74717 (0.0001)	W645 -0.74422 (0.0001)	W615 -0.74245 (0.0001)	W695 -0.88258 (0.0001)	W625 -0.88102 (0.0001)	W505 -0.88093 (0.0001)

wXXX or wXXX/XXX = index combination using specified bandwidth
0.18915 = Correlation coeficient
(0.2692) = probability >|R|

Table 6. Spectral radiance combinations and simple correlation from the three best models with N rate, P rate, biomass, moisture, P tissue concentration, P uptake, N tissue concentration and N uptake by growth stage at Tipton OK, 1997

	Growth Stage 4			Growth Stage 5			Growth Stage 6			Growth Stage 9		
Dependent variables	1	2	3	1	2	3	1	2	3	1	2	3
N rate	W735/665 0.25546 (0.1326)	W735/545 -0.25489 (0.1336)	W785/505 -0.25161 (0.1388)	W715/545 0.92254 (0.0001)	W725/545 0.9252 (0.0001)	W725/715 0.91961 (0.0001)	W735/545 -0.89003 (0.0001)	W725/715 -0.88367 (0.0001)	W735/715 -0.88153 (0.0001)	NDVI 0.88195 (0.0001)	W735/715 0.8742 (0.0001)	W735/525 0.86949 (0.0001)
P rate	W735/655 -0.21561 (0.2066)	735/665 -0.21385 (0.2104)	W805/415 0.18178 (0.2887)	W795/735 -0.19322 (0.2589)	NW 0.15971 (0.3521)	NIRGI -0.16864 (0.3255)	PRI2 0.24767 (0.1453)	NPCIX1 0.18003 (0.2934)	PRI 0.13254 (0.441)	W705/525 -0.17445 (0.3089)	W705/515 -0.10269 (0.5512)	W705/505 -0.08342 (0.6286)
Wet Biomass	NDVI -0.21585 (0.2061)	W725/505 0.20775 (0.2241)	W725/515 0.20649 (0.2269)	W725/715 0.4862 (0.0026)	W725/545 0.4803 (0.003)	W725/535 0.49598 (0.0033)	W735/525 -0.80198 (0.0001)	W735/545 -0.80426 (0.0001)	W735/515 -0.80058 (0.0001)	W725/525 0.92866 (0.0001)	W725/515 0.92755 (0.0001)	W725/735 0.92667 (0.0001)
Dry biomass	W695/405 0.34843 (0.0373)	NDVI -0.26098 (0.1242)	W725/535 0.20588 (0.2283)	W705/525 -0.48096 (0.003)	W725/545 0.47612 (0.0033)	W735/715 0.47571 (0.0034)	W735/545 -0.79948 (0.0001)	W735/525 -0.79921 (0.0001)	W735/515 -0.79619 (0.0001)	W715/515 0.91748 (0.0001)	W725/525 0.91669 (0.0001)	NDVI 0.91662 (0.0001)
Moisture	735/665 -0.26977 (0.1116)	W735/655 0.26897 (0.1127)	NDVI 0.25511 (0.1332)	NIRGI -0.15383 (0.3704)	W705/515 0.15126 (0.3785)	PRI 0.12521 (0.4669)	W735/515 -0.85808 (0.0001)	W735/505 -0.85587 (0.0001)	W735/545 -0.85373 (0.0001)	W735/655 0.74467 (0.0001)	NR 0.74392 (0.0001)	735/665 0.74365 (0.0001)
P tissue conc.	NR 0.42476 (0.0098)	NW -0.39688 (0.0165)	W715/545 0.36387 (0.0291)	PRI 0.45146 (0.0057)	W705/525 0.22945 (0.1783)	NPCIX 0.18476 (0.2807)	W705/505 0.22155 (0.1941)	PRI1 0.21873 (0.2000)	W715/535 0.21817 (0.2011)	PRI 0.27068 (0.1103)	NIRGI 0.16680 (0.3309)	NW -0.10726 (0.5335)
P uptake	W695/405 0.36901 (0.0268)	W725/545 0.34808 (0.0375)	NW -0.34595 (0.0388)	W725/715 0.39722 (0.0164)	NDVI 0.39301 (0.0177)	W735/715 0.39291 (0.0178)	W735/525 -0.71835 (0.0001)	W735/515 -0.71630 (0.0001)	W725/515 -0.71215 (0.0001)	PRI 0.65702 (0.0001)	W715/515 0.63480 (0.0001)	W715/525 0.63374 (0.0001)
N tissue conc.	NPCIX 0.31860 (0.0582)	NR 0.31718 (0.0594)	W735/655 -0.22597 (0.1851)	PFR 0.20279 (0.2355)	W695/405 0.19355 (0.2580)	W735/655 0.18187 (0.2884)	W735/715 -0.70963 (0.0001)	W725/715 -0.67718 (0.0001)	PFR -0.67525 (0.0001)	NW -0.60679 (0.0001)	W785/505 0.59596 (0.0001)	W795/735 0.59170 (0.0001)
N uptake	W725/545 0.28006 (0.0981)	W725/535 0.27875 (0.0997)	W725/525 0.27609 (0.1031)	W705/525 -0.48259 (0.0029)	W725/715 0.48112 (0.0030)	W735/715 0.47763 (0.0032)	W735/545 -0.78225 (0.0001)	W735/515 -0.78076 (0.0001)	W735/505 -0.77521 (0.0001)	W725/525 0.93466 (0.0001)	W725/515 0.93323 (0.0001)	W725/535 0.93267 (0.0001)

wXXX or wXXX/XXX = index combination using specified bandwidth

0.18915 = Correlation coeficient

(0.2692) = probability >|R|

Combination indices defined in Table 2

Table 7. Spectral radiance measurements and simple correlation from the three best models with N rate, P rate, biomass, moisture, P tissue concentration, P uptake, N tissue concentration and N uptake by growth stage at Perkins OK, 1997

	Growth Stage 5			Growth Stage 6			Growth Stage 7		
Dependent variables	1	2	3	1	2	3	1	2	3
N rate	W385 -0.61817 (0.0001)	W395 -0.61247 (0.0001)	W375 -0.61084 (0.0001)	W1105 -0.791 (0.0001)	W1095 -0.77925 (0.0001)	W705 -0.77671 (0.0001)	W885 0.70485 (0.0001)	W875 0.70194 (0.0001)	W845 0.70137 (0.0001)
P rate	W675 -0.43822 (0.0075)	W665 -0.43774 (0.0079)	W655 -0.42928 (0.0090)	W735 0.34739 (0.0379)	W765 0.34566 (0.0389)	W755 0.34428 (0.0398)	W845 0.34492 (0.0394)	W885 0.33916 (0.0430)	W815 0.33873 (0.0433)
Wet Biomass	W745 0.70762 (0.0001)	W755 0.68863 (0.0001)	W395 -0.6708 (0.0001)	W765 0.85282 (0.0001)	W775 0.85153 (0.0001)	W785 0.85116 (0.0001)	W775 0.88523 (0.0001)	W.785 0.88445 (0.0001)	W765 0.88399 (0.0001)
Dry biomass	W745 0.47733 (0.0032)	W755 0.45844 (0.0049)	W735 0.45411 (0.0054)	W765 0.75125 (0.0001)	W785 0.75058 (0.0001)	W775 0.75056 (0.0001)	W795 0.62196 (0.0001)	W815 0.62178 (0.0001)	W805 0.62109 (0.0001)
Moisture	W675 -0.72574 (0.0001)	W665 -0.71589 (0.0001)	W395 -0.71456 (0.0001)	W1105 -0.34121 (0.0417)	W1085 -0.3362 (0.0450)	W1095 -0.3327 (0.0474)	W705 0.17039 (0.3204)	W695 0.16409 (0.3389)	W615 0.15766 (0.3584)
P tissue conc.	W675 -0.30029 (0.0752)	W665 -0.29812 (0.0774)	W645 -0.29190 (0.0841)	W345 0.24133 (0.1562)	W355 0.20673 (0.2264)	W365 0.15123 (0.3786)	W385 0.37597 (0.0238)	W395 0.36345 (0.0293)	W405 0.35783 (0.0321)
P uptake	W745 60331 (0.0001)	W745 0.59849 (0.0001)	W865 0.57117 (0.0003)	W705 -0.68180 (0.0001)	W595 -0.67376 (0.0001)	W485 -0.67325 (0.0001)	W815 0.55865 (0.0004)	W845 0.55852 (0.0004)	W855 0.55811 (0.0004)
N tissue conc.	W755 0.57090 (0.0003)	W745 0.56442 (0.0003)	W765 0.54862 (0.0005)	W1065 -0.48550 (0.0027)	W1055 -0.48337 (0.0028)	W1075 -0.44717 (0.0063)	W1105 -0.43669 (0.0077)	W1115 -0.42397 (0.0090)	W1125 -0.40889 (0.0133)
N uptake	W745 0.69534 (0.0001)	W755 0.68339 (0.0001)	W765 0.65176 (0.0001)	W1045 0.20035 (0.2414)	W1035 0.19870 (0.2453)	W1025 0.19611 (0.2517)	W795 0.54926 (0.0005)	W805 0.54660 (0.0006)	W775 0.54598 (0.0006)

wXXX or wXXX/XXX = index combination using specified bandwidth
0.18915 = Coefficient correlation
(0.2692) = probability >|R|

Table 8. Spectral radiance combinations and simple correlation from the three best models with N rate, P rate, biomass, moisture, P tissue concentration, P uptake, N tissue concentration, and N uptake by growth stage at Perkins OK, 1997

	Growth Stage 5			Growth Stage 6			Growth Stage 7		
Dependent variables	1	2	3	1	2	3	1	2	3
N rate	W715/525 0.75816 (0.0001)	W735/525 0.73421 (0.0001)	W715/515 0.73356 (0.0001)	GR -0.75836 (0.0001)	W725/715 0.75534 (0.0001)	W735/715 0.74887 (0.0001)	W725/525 0.81423 (0.0001)	W725/535 0.80448 (0.0001)	W725/515 0.80139 (0.0001)
P rate	W705/505 -0.42877 (0.0091)	W715/505 0.41148 (0.0127)	W715/515 0.38759 (0.0195)	W705/545 -0.40782 (0.0135)	W705/535 -0.40744 (0.0136)	W715/505 0.37008 (0.0263)	W705/535 -0.40635 (0.0139)	W705/545 -0.40355 (0.0147)	W705/525 -0.40286 (0.0148)
Wet Biomass	W715/505 -0.87938 (0.0001)	W725/505 0.87607 (0.0001)	W725/515 0.86914 (0.0001)	NPCIX -0.90696 (0.0001)	735/665 0.90245 (0.0001)	NR 0.89835 (0.0001)	NPCIX -0.93237 (0.0001)	W735/655 0.93166 (0.0001)	NDVI 0.93059 (0.0001)
Dry biomass	W715/525 -0.56584 (0.0003)	W715/515 0.56161 (0.0004)	W715/505 0.554968 (0.0004)	W795/735 0.82798 (0.0001)	NR 0.8188 (0.0001)	735/665 0.80999 (0.0001)	W735/655 0.90883 (0.0001)	NPCIX -0.90553 (0.0001)	735/665 0.90457 (0.0001)
Moisture	W715/505 0.86203 (0.0001)	W725/505 0.85645 (0.0001)	W715/505 0.84919 (0.0001)	NPCIX -0.34763 (0.0378)	W705/525 -0.33853 (0.0434)	W705/545 -0.33702 (0.0444)	W705/525 0.23633 (0.1652)	W705/535 0.22965 (0.1832)	NR -0.22453 (0.188)
P tissue conc.	W705/505 0.38926 (0.0189)	W715/505 0.38615 (0.0200)	PFR2 0.38376 (0.0209)	W705/505 0.20885 (0.2216)	PFR 0.19859 (0.2456)	NR 0.15518 (0.3662)	PRI -0.34375 (0.0401)	W695/405 -0.33097 (0.0486)	W715/525 -0.30279 (0.0727)
P uptake	W715/505 0.78018 0.0001	W725/515 0.76325 (0.0001)	W715/515 0.76275 (0.0001)	PFR 0.77748 (0.0001)	W735/655 0.77439 (0.0001)	NR 0.75740 (0.0001)	PFR 0.68011 (0.0001)	W735/655 0.66102 (0.0001)	NR 0.65721 (0.0001)
N tissue conc.	W735/715 0.68386 (0.0001)	W735/545 0.68383 (0.0001)	W735/525 0.68073 (0.0001)	W695/405 -0.66641 (0.0001)	W705/505 -0.47315 (0.0036)	W705/515 -0.41791 (0.0112)	W735/545 0.34326 (0.0404)	W735/535 0.32546 (0.0750)	W735/525 0.30049 (0.0750
N uptake	W725/525 0.84490 (0.0001)	W735/505 0.84233 (0.0001)	W735/515 0.84269 (0.0001)	W735/655 0.74180 (0.0001)	W735/715 0.74073 (0.0001)	NPCIX -0.74056 (0.0001)	PFR 0.72486 (0.0001)	W735/655 0.70050 (0.0001)	NR 0.69722 (0.0001)

wXXX or wXXX/XXX = index combination using specified bandwidth
0.18915 = Coefficient correlation
(0.2692) = probability >|R|
Combination indices defined in Table 2

Table 9. Spectral radiance measurements, combination indices, and simple correlation coefficients from the three best models with N rate, P rate, biomass, moisture, P tissue concentration, P uptake, N tissue concentration and N uptake over growth stages at Tipton and Perkins OK, 1997

Dependent variables		Tipton			Perkins	
	1	2	3	1	2	3
	Single wavelength					
N rate	W795 0.13138 (0.1165)	W805 0.13861 (0.00976)	W755 0.12595 (0.1325)	W745 0.58795 (0.0001)	W635 -0.50142 (0.0001)	W625 -0.49548 (0.0001)
P rate	W805 0.0336 (0.6893)	W825 0.03301 (0.6945)	W795 0.03306 (0.6941)	W665 -0.26892 (0.0049)	W675 -0.26221 (0.0049)	W655 -0.26585 (0.0054)
Wet biomass	W575 -0.45293 (0.0001)	W585 -0.45255 (0.0001)	W535 -0.45181 (0.0001)	W685 -0.81457 (0.0001)	W675 -0.81335 (0.0001)	W665 -0.81013 (0.0001)
Dry biomass	W435 -0.72607 (0.0001)	W425 -0.72492 (0.0001)	W655 -0.72489 (0.0001)	W685 -0.68412 (0.0001)	W695 -0.68352 (0.0001)	W675 -0.68094 (0.0001)
Moisture	W345 0.80618 (0.0001)	W355 0.80535 (0.0001)	W365 0.8029 (0.0001)	W375 -0.7616 (0.0001)	W1145 -0.75754 (0.0001)	W375 -0.75677 (0.0001)
P tissue concentration	W355 -0.34385 (0.0001)	W365 -0.33865 (0.0001)	W375 -0.33426 (0.0001)	W455 -0.12349 (0.2029)	W465 -0.12215 (0.2079)	W485 -0.12206 (0.2083)
P uptake	W665 -0.71706 (0.0001)	W675 -0.71562 (0.0001)	W655 -0.71354 (0.0001)	W745 0.50670 (0.0001)	W635 -0.49027 (0.0001)	W645 -0.48797 (0.0001)
N tissue concentration	W1055 -0.47274 (0.0001)	W1045 -0.47258 (0.0001	W1035 -0.47145 (0.0001)	W635 -0.30364 (0.0014)	W625 -0.30293 (0.0014)	W645 -0.30257 (0.0015)
N uptake	W675 -0.69256 (0.0001)	W685 -0.69469 (0.0001)	W695 -0.68925 (0.0001)	W635 -0.48418 (0.0001)	W625 -0.48184 (0.0001)	W645 -0.47934 (0.0001)
	1	2	3	1	2	3
	Combination					
N rate	W805/415 0.34598 (0.0001)	W735/515 0.354 (0.0001)	W725/505 0.32625 (0.0001)	W725/525 0.68502 (0.0001)	W725/535 0.67856 (0.0001)	W735/525 0.6755 (0.0001)
P rate	W735/655 -0.10762 (0.1992)	W735/665 -0.10673 (0.2029)	W695/405 -0.08693 (0.3002)	W705/535 -0.34858 (0.0002)	W705/545 -0.34744 (0.0002)	W705/525 -0.33181 (0.0005)
Wet Biomass	W705/505 0.60158 (0.0001)	W715/505 0.58621 (0.0001)	W715/515 0.50834 (0.0001)	735/665 0.91322 (0.0001)	NPCIX -0.90999 (0.0001)	W735/655 0.90104 (0.0001)
Dry biomass	W705/515 0.68415 (0.0001)	PRI1 0.67914 (0.0001)	W705/545 0.66926 (0.0001)	NPCIX -0.84064 (0.0001)	735/665 0.82017 (0.0001)	W735/655 0.80008 (0.0001)
Moisture	W795/735 0.76862 (0.0001)	W785/505 0.70083 (0.0001)	W705/535 -0.66325 (0.0001)	W705/505 0.63476 (0.0001)	W715/505 0.63399 (0.0001)	W715/515 0.59326 (0.0001)
P tissue concentration	W785/505 -0.31502 (0.0001)	W795/735 -0.31232 (0.0001)	W725/715 -0.26799 (0.0012)	NR 0.15075 (0.1194)	PFR2 0.14934 (0.1229)	PFR 0.14666 (0.1299)
P uptake	W705/545 0.67112 (0.0001)	W705/535 0.66387 (0.0001)	W705/525 0.66109 (0.0001)	PFR 0.68156 (0.0001)	W735/655 0.67936 (0.0001)	NPCI2 -0.65864 (0.0001)
N tissue concentration	W705/505 -0.60678 (0.0001)	W715/505 -0.50821 (0.0001)	W705/515 -0.49321 (0.0001)	W735/535 0.42392 (0.0001)	W725/545 0.41954 (0.0001)	W735/715 0.41768 (0.0001)
N uptake	W795/735 -0.6403 (0.0001)	W705/545 0.60489 (0.0001)	PRI 0.58325 (0.0001)	PFR 0.68849 (0.0001)	W735/655 0.68496 (0.0001)	W735/715 0.67037 (0.0001)

WXXX or WXXX/XXX = index combination using specified bandwidth, Combination indices defined in Table 2
0.18915 = Correlation coeficient, (0.2369) = probability >|R|

Table 10. Analysis of variance for Red, LNIR, SNIR, LNDVI, SNDVI, LNR, and SNR in wheat forage at Feekes growth stages 5, 6 and 9, Tipton OK, 1997

Source of variation	df	Red	LNIR	SNIR	LNDVI	SNDVI	LNR	SNR
		------------Mean squares------------						
Rep	2	ns	ns	ns	ns	ns	ns	ns
N rate	3	***	ns	ns	***	****	***	***
P rate	2	ns	ns	ns	ns	ns	ns	ns
NxP	6	ns	ns	ns	ns	ns	ns	ns
Error (a)	22	22732	17778	286612	0.03	0.01	0.45	49.55
GS	2	***	ns	ns	***	***	***	***
GS*N	6	***	ns	ns	***	***	***	**
GS*P	4	ns	ns	ns	ns	ns	ns	ns
GS*N*P	12	ns	ns	ns	ns	ns	ns	ns
Error (b)	48	19003	13168	216721	0.02	0.00	0.36	61.75
GS	N rate, kg ha^{-1}	------------Means------------						
Feekes 5	0	601	386	1609	-0.24	0.45	0.65	2.74
	56	637	446	1919	-0.19	0.49	0.72	3.11
	112	543	378	1647	-0.21	0.49	0.71	3.09
	168	547	387	1737	-0.18	0.52	0.74	3.35
Feekes 6	0	449	382	1956	-0.15	0.62	0.84	4.42
	56	270	331	1896	0.07	0.76	1.46	9.01
	112	116	291	1868	0.29	0.88	2.78	25.47
	168	121	377	2154	0.48	0.90	3.96	25.02
Feekes 9	0	971	509	2746	-0.31	0.48	0.55	3.01
	56	747	512	2827	-0.18	0.58	0.72	4.07
	112	427	565	3202	0.14	0.76	1.40	8.10
	168	381	589	3434	0.20	0.80	1.65	9.64
	SED	65	54	219	0.06	0.03	0.28	3.70
GS	Feekes							
	5	582	399	1728	-0.21	0.49	0.71	3.07
	6	239	345	1968	0.17	0.79	2.26	15.98
	9	631	544	3052	-0.04	0.66	1.08	6.21
	SED	32	27	109	0.03	0.01	0.14	1.85
P rate	P, kg ha^{-1}							
	0	503	434	2281	-0.04	0.63	1.31	7.73
	14.5	444	421	2220	0.00	0.67	1.38	9.92
	29	504	433	2248	-0.04	0.64	1.36	7.61
	SED	35	31	126	0.04	0.02	0.16	1.66

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
ns = not significant; SED = standard error difference between two equally replicated means
GS = growth stage

Table 11. Analysis of variance for Red, LNIR, SNIR, LNDVI, SNDVI, LNR, and SNR in wheat forage at Feekes growth stages 4, 5, 6 and 7, Perkins OK, 1997

Source of variation	df	Red	LNIR	SNIR	LNDVI	SNDVI	LNR	SNR
		---------------------------------------Mean squares--						
Rep	2	*	ns	ns	ns	ns	ns	ns
N rate	3	***	***	***	***	****	***	***
P rate	2	**	ns	ns	**	**	**	**
NxP	6	ns	ns	*	ns	ns	ns	ns
Error (a)	22	28682	12915	448126	0.07	0.02	0.45	14.14
GS	3	***	***	***	***	***	***	***
GS*N	9	**	**	**	*	ns	***	***
GS*P	6	ns	ns	ns	ns	ns	*	*
GS*N*P	18	ns	ns	ns	**	ns	ns	ns
Error (b)	71	8563	3417	66813	0.01	0.00	0.09	2.85
GS	N, kg ha^{-1}	---Means---						
Feekes 4	0	652	403	1938	-0.24	0.50	0.63	3.04
	56	492	437	2249	-0.05	0.64	0.99	5.11
	112	448	485	2481	0.05	0.69	1.18	6.07
	168	437	500	2570	0.08	0.71	1.26	6.49
Feekes 5	0	502	193	1532	-0.47	0.51	0.39	3.14
	56	436	266	1880	-0.28	0.61	0.62	4.48
	112	345	316	2202	-0.08	0.72	0.95	6.61
	168	348	381	2515	0.02	0.74	1.18	7.87
Feekes 6	0	817	576	2795	-0.17	0.55	0.73	3.56
	56	588	648	3146	0.05	0.68	1.20	5.90
	112	437	690	3604	0.23	0.78	1.88	9.95
	168	409	724	3839	0.30	0.80	2.15	11.53
Feekes 7	0	552	446	2479	-0.09	0.63	1.00	5.56
	56	431	474	2774	0.03	0.73	1.16	6.87
	112	291	594	3388	0.33	0.84	2.17	12.47
	168	311	693	3859	0.38	0.84	2.52	14.06
	SED	44	27	122	0.04	0.02	0.15	0.80
	P, kg ha^{-1}							
Feekes 4	0	602	435	2195	-0.15	0.57	0.79	4.03
	14.5	491	468	2318	-0.01	0.65	1.07	5.35
	29	428	466	2417	0.05	0.69	1.18	6.15
Feekes 5	0	458	279	1922	-0.28	0.59	0.66	4.53
	56	415	276	2004	-0.24	0.64	0.72	5.21
	112	349	311	2171	-0.10	0.70	0.98	6.84
Feekes 6	0	629	648	3199	0.03	0.66	1.29	6.48
	14.5	594	651	3252	0.08	0.69	1.35	6.96
	29	470	675	3566	0.20	0.76	1.80	9.60
Feekes 7	0	439	522	2855	0.08	0.72	1.38	7.63
	14.5	420	523	3042	0.13	0.75	1.60	9.25
	29	330	610	3480	0.29	0.81	2.16	12.34
	SED	38	23	105	0.04	0.02	0.13	0.69

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
ns = not significant; SED = standard error difference between two equally replicated means
GS = growth stage

Table 12. Spectral radiance measurements, combination indices, and simple correlation wet biomass, dry biomass, moisture, P tissue concentration, P uptake, N tissue concentration and N uptake by growth stage at Tipton OK, 1997

Dependent variables	GS	Red	LNIR	SNIR	LNDVI	SNDVI	LNR	SNR
Wet biomass	All	-0.48***	0.26***	0.58***	0.80***	0.74***	0.44***	0.58***
	Feekes 5	-0.38*	0.18^{ns}	0.36*	0.75***	0.56***	0.77***	0.60***
	Feekes 6	-0.74***	-0.14^{ns}	-0.00^{ns}	0.64***	0.77***	0.45***	0.71***
	Feekes 9	-0.88***	0.52***	0.84***	0.92***	0.93***	0.91***	0.90***
Dry biomass	All	-0.72***	-0.09***	0.20*	0.90***	0.85***	0.63***	0.79***
	Feekes 5	-0.26^{ns}	0.18^{ns}	0.35^{ns}	0.64***	0.48**	0.64***	0.49**
	Feekes 6	-0.73***	-0.11^{ns}	0.01^{ns}	0.86***	0.77***	0.43**	0.69***
	Feekes 9	-0.88***	0.49**	0.81***	0.92***	0.92***	0.90***	0.89***
Moist	All	0.42***	0.51***	0.56***	-0.15^{ns}	-0.12^{ns}	-0.21*	-0.20*
	Feekes 5	-0.40*	0.02^{ns}	0.05^{ns}	0.40*	0.32^{ns}	0.44**	0.40*
	Feekes 6	-0.76***	-0.13^{ns}	0.05^{ns}	0.92***	0.78***	0.51***	0.70***
	Feekes 9	-0.61***	0.58***	0.72***	0.67***	0.72***	0.70***	0.72***
P tissue conc.	All	-0.21*	-0.25*	-0.24*	0.08^{ns}	0.11^{ns}	0.11^{ns}	0.20^{ns}
	Feekes 5	-0.23^{ns}	-0.20^{ns}	-0.20^{ns}	-0.01^{ns}	-0.05^{ns}	0.00^{ns}	-0.00^{ns}
	Feekes 6	0.02^{ns}	0.13^{ns}	0.10^{ns}	-0.09^{ns}	0.09^{ns}	-0.08^{ns}	0.13^{ns}
	Feekes 9	0.12^{ns}	-0.09^{ns}	-0.00^{ns}	-0.10^{ns}	-0.12^{ns}	-0.08^{ns}	-0.12^{ns}
P uptake	All	-0.68***	-0.13^{ns}	0.12^{ns}	0.82***	0.80***	0.59***	0.78***
	Feekes 5	-0.38*	0.08^{ns}	0.25^{ns}	0.65***	0.47***	0.66***	0.51**
	Feekes 6	-0.66***	-0.02^{ns}	0.08^{ns}	0.80***	0.80***	0.39^{ns}	0.73***
	Feekes 9	-0.55***	0.28^{ns}	0.55***	0.59***	0.57***	0.57***	0.54***
N tissue conc.	All	-0.09^{ns}	-0.37***	-0.63***	-0.33***	-0.17^{ns}	-0.08^{ns}	-0.05^{ns}
	Feekes 5	-0.37*	-0.19^{ns}	-0.15^{ns}	0.25^{ns}	0.16^{ns}	0.27^{ns}	0.21^{ns}
	Feekes 6	-0.62***	-0.18^{ns}	-0.05^{ns}	0.63***	0.59***	0.38*	0.63***
	Feekes 9	-0.39*	0.47**	0.67***	0.47**	0.52***	0.57***	0.57***
N uptake	All	-0.75***	-0.29**	-0.08^{ns}	0.78***	0.79***	0.63***	0.82***
	Feekes 5	-0.39*	0.06^{ns}	0.24^{ns}	0.68***	0.49**	0.70***	0.52***
	Feekes 6	-0.72***	-0.14^{ns}	-0.01^{ns}	0.83***	0.75***	0.43***	0.71***
	Feekes 9	-0.86***	0.54***	0.87***	0.91***	0.92***	0.92***	0.91***

0.18915 = Coefficient correlation

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

ns = not significant

GS = growth stage (s)

Table 13. Spectral radiance measurements, combination indices, and simple correlation wet biomass, dry biomass, moisture, P tissue concentration, P uptake, N tissue concentration, and N uptake by growth stage at Perkins OK, 1997

Dependent variables	GS	Red	LNIR	SNIR	LNDVI	SNDVI	LNR	SNR
Wet biomass	All	-0.58***	0.60***	0.79***	0.77***	0.77***	0.85***	0.88**
	Feekes 4	-0.84***	-0.76***	0.85***	0.92***	0.91***	0.93***	0.92***
	Feekes 5	-0.56***	0.70***	0.76***	0.82***	0.81***	0.81***	0.81***
	Feekes 6	-0.89***	0.81***	0.95***	0.95***	0.91***	0.97***	0.97***
	Feekes 7	-0.82***	0.87***	0.93***	0.93***	0.90***	0.92***	0.94***
Dry biomass	All	-0.60***	0.43***	0.65***	0.65***	0.69***	0.75***	0.81***
	Feekes 4	-0.60***	0.61***	0.66***	0.69***	0.68***	0.71***	0.70***
	Feekes 5	-0.37*	0.40*	0.42**	0.49**	0.50**	0.47**	0.46**
	Feekes 6	-0.88***	0.78***	0.91***	0.94***	0.90***	0.93***	0.93***
	Feekes 7	-0.79***	0.86***	0.92***	0.89***	0.86***	0.89***	0.92***
Moist	All	-0.08^{ns}	0.74***	0.69***	0.64***	0.53***	0.51***	0.43***
	Feekes 4	-0.63***	0.45***	0.48***	0.63***	0.63***	0.60***	0.59***
	Feekes 5	-0.56***	0.73***	0.80***	0.84***	0.85***	0.81***	0.83***
	Feekes 6	-0.49**	0.50**	0.63***	0.53***	0.52**	0.58***	0.59***
	Feekes 7	0.15^{ns}	-0.18^{ns}	-0.22^{ns}	-0.17^{ns}	-0.14^{ns}	0.21^{ns}	-0.23^{ns}
P tissue conc.	All	-0.02^{ns}	0.05^{ns}	0.01^{ns}	0.10^{ns}	0.06^{ns}	0.03^{ns}	0.00^{ns}
	Feekes 4	-0.63***	0.46**	0.51**	0.64***	0.63***	0.64***	0.63***
	Feekes 5	0.02^{ns}	0.39*	0.39*	0.34*	0.25^{ns}	0.35*	0.33*
	Feekes 6	-0.07^{ns}	0.08^{ns}	0.10^{ns}	0.14^{ns}	0.04^{ns}	0.23^{ns}	0.17^{ns}
	Feekes 7	0.02^{ns}	-0.01^{ns}	0.13^{ns}	-0.01^{ns}	-0.01^{ns}	0.03^{ns}	0.08^{ns}
P uptake	All	-0.62***	0.47***	0.70***	0.70***	0.74***	0.78***	0.84***
	Feekes 4	-0.79***	0.71***	0.78***	0.87***	0.85***	0.88***	0.87***
	Feekes 5	-0.39*	0.62***	0.64***	0.68***	0.64***	0.69***	0.68***
	Feekes 6	-0.82***	0.74***	0.87***	0.89***	0.84***	0.91***	0.91***
	Feekes 7	-0.68***	0.75***	0.86***	0.77***	0.75***	0.77***	0.82***
N tissue conc.	All	0.00^{ns}	0.04^{ns}	-0.06^{ns}	0.06^{ns}	0.02^{ns}	-0.04^{ns}	-0.09^{ns}
	Feekes 4	-0.63***	0.37*	0.44**	0.58***	0.61***	0.56***	0.56***
	Feekes 5	-0.49**	0.55***	0.62***	0.65***	0.66***	0.66***	0.69***
	Feekes 6	0.09^{ns}	0.12^{ns}	0.07^{ns}	-0.04^{ns}	-0.06^{ns}	0.02^{ns}	0.01^{ns}
	Feekes 7	-0.23^{ns}	0.48^{ns}	0.38*	0.37*	0.32^{ns}	0.39*	0.34*
N uptake	All	-0.68***	0.52***	0.73***	0.76***	0.81***	0.84***	0.89***
	Feekes 4	-0.86***	0.73***	0.82***	0.92***	0.91***	0.93***	0.92***
	Feekes 5	-0.58***	0.66***	0.72***	0.78***	0.79***	0.79***	0.79***
	Feekes 6	-0.86***	0.84***	0.96***	0.94***	0.89***	0.96***	0.97***
	Feekes 7	-0.75***	0.89***	0.92***	0.88***	0.84***	0.91***	0.91***

0.18915 = Coefficient correlation

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

ns = not significant

GS = growth stage (s)

Table 14. Analysis of variance for grain, grain N, grain N uptake, grain P, grain P uptake at Tipton and Perkins OK, 1997

Source of variation	df	Grain yield	Grain N	Grain N uptake	Grain P	Grain P uptake
Tipton		----------Mean squares----------				
Rep	2	ns	ns	ns	ns	ns
N rate	3	ns	***	ns	ns	ns
P rate	2	ns	ns	ns	ns	ns
NxP	6	ns	ns	ns	ns	ns
N lin	1	ns	***	*	ns	ns
N quad	1	ns	*	ns	ns	ns
P lin	1	ns	ns	ns	ns	ns
P quad	1	ns	ns	ns	ns	ns
Error	22	9339	1.6	8.4	872862	0.3
CV, %		18	4	19	20	23
		----------Means----------				
N rate, kg ha^{-1}		kg ha^{-1}	g kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}
0		482	27.9	13.4	4453	2.1
56		519	27.8	14.4	4803	2.5
112		530	28.8	15.3	4895	2.6
168		548	30.5	16.8	4087	2.2
SED		45	0.6	1.37	440	0.3
P rate, kg ha^{-1}						
0		495	28.9	14.4	4682	2.3
14.5		530	28.9	15.3	4441	2.3
29		534	28.4	15.2	4556	2.3
SED		39	0.5	1.2	381	0.2
Perkins		----------Mean squares----------				
Rep	2	ns	ns	ns	ns	ns
N rate	3	ns	***	ns	ns	ns
P rate	2	ns	ns	ns	ns	ns
NxP	6	ns	ns	ns	ns	ns
N lin	1	ns	***	ns	ns	ns
N quad	1	ns	ns	ns	ns	ns
P lin	1	ns	ns	ns	ns	ns
P quad	1	ns	ns	ns	*	ns
Error	22	24378	4.5	26.4	241857	0.9
CV, %		20	7	23	12	30
		----------Means----------				
N rate, kg ha^{-1}		kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}
0		828	26.6	22.1	4136	3.4
56		721	27.5	19.7	4069	3.0
112		789	29.3	23.2	3901	3.1
168		786	31.2	24.4	4094	3.3
SED		74	1.0	2.4	232	0.4
P rate, kg ha^{-1}						
0		772	29.5	22.6	3808	3.0
14.5		795	28.5	22.7	4311	3.4
29		777	27.9	21.7	4032	3.1
SED		64	0.9	2.1	201	0.4

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
ns = not significant; SED = standard error difference between two equally replicated means

Table 15. Spectral radiance measurements, combination indices, and simple correlation with grain, grain N, grain N uptake, grain P, grain P uptake over growth stages at Tipton and Perkins OK, 1997

Dependent variables	GS	Red	LNIR	SNIR	LNDVI	SNDVI	LNR	SNR
Tipton								
Grain	Feekes 5	-0.26^{ns}	-0.09^{ns}	0.02^{ns}	0.12^{ns}	0.27^{ns}	0.13^{ns}	0.27^{ns}
	Feekes 6	-0.38*	-0.44*	-0.39*	0.19^{ns}	0.30^{ns}	0.34*	0.36*
	Feekes 9	-0.23^{ns}	0.08^{ns}	0.19^{ns}	0.19^{ns}	0.23^{ns}	0.18^{ns}	0.17^{ns}
Grain N	Feekes 5	-0.16^{ns}	-0.16^{ns}	-0.07^{ns}	-0.07^{ns}	0.12^{ns}	0.05^{ns}	0.14^{ns}
	Feekes 6	-0.53^{ns}	-0.19^{ns}	-0.11^{ns}	0.41*	0.51**	0.54***	0.39*
	Feekes 9	-0.56***	0.37*	0.53***	0.62***	0.59***	0.62***	0.61***
Grain N uptake	Feekes 5	-0.26^{ns}	-0.09^{ns}	0.02^{ns}	0.12^{ns}	0.27^{ns}	0.14^{ns}	0.29^{ns}
	Feekes 6	-0.50**	-0.46**	-0.39*	0.29^{ns}	0.42*	0.47**	0.46**
	Feekes 9	-0.37*	0.18^{ns}	0.32*	0.35*	0.38*	0.34*	0.33*
Grain P	Feekes 5	-0.06^{ns}	0.03^{ns}	-0.02^{ns}	0.09^{ns}	0.03^{ns}	0.13^{ns}	0.07^{ns}
	Feekes 6	0.02^{ns}	-0.02^{ns}	-0.07^{ns}	-0.02^{ns}	-0.01^{ns}	-0.04^{ns}	-0.02^{ns}
	Feekes 9	0.08^{ns}	0.28^{ns}	0.19^{ns}	0.04^{ns}	-0.03^{ns}	0.07^{ns}	0.07^{ns}
Grain P uptake	Feekes 5	-0.25^{ns}	0.00^{ns}	0.02^{ns}	0.22^{ns}	0.25^{ns}	0.26^{ns}	0.28^{ns}
	Feekes 6	-0.23^{ns}	-0.29^{ns}	-0.33 *	0.11^{ns}	0.19^{ns}	0.18^{ns}	0.23^{ns}
	Feekes 9	-0.08^{ns}	0.38^{ns}	0.36^{ns}	0.20^{ns}	0.15^{ns}	0.23^{ns}	0.20^{ns}
Perkins								
Grain	Feekes 4	-0.23^{ns}	0.28^{ns}	0.32^{ns}	0.26^{ns}	0.27^{ns}	0.24^{ns}	0.25^{ns}
	Feekes 5	0.12^{ns}	0.50*	0.48*	0.35^{ns}	0.26^{ns}	0.31^{ns}	0.23^{ns}
	Feekes 6	-0.26^{ns}	0.16^{ns}	0.15^{ns}	0.24^{ns}	0.21^{ns}	0.28^{ns}	0.26^{ns}
	Feekes 7	-0.31^{ns}	0.04^{ns}	0.13^{ns}	0.20^{ns}	0.24^{ns}	0.22^{ns}	0.25^{ns}
Grain N	Feekes 4	-0.08^{ns}	0.06^{ns}	0.12^{ns}	0.09^{ns}	0.12^{ns}	0.09^{ns}	0.10^{ns}
	Feekes 5	-0.38*	0.13^{ns}	0.20^{ns}	0.23^{ns}	0.31^{ns}	0.27^{ns}	0.32^{ns}
	Feekes 6	-0.19^{ns}	0.36*	0.39*	0.25^{ns}	0.26^{ns}	0.25^{ns}	0.25^{ns}
	Feekes 7	-0.29^{ns}	-0.50^{ns}	0.42^{ns}	0.42*	0.33*	0.42*	0.40*
Grain N uptake	Feekes 4	-0.28^{ns}	0.31^{ns}	0.37^{ns}	0.30^{ns}	0.33^{ns}	0.30^{ns}	0.30^{ns}
	Feekes 5	-0.09ns	0.55***	0.56***	0.45**	0.42*	0.44**	0.39*
	Feekes 6	-0.36*	0.35*	0.35*	0.37*	0.34*	0.41*	0.39*
	Feekes 7	-0.44**	0.28ns	0.34*	0.40*	0.41*	0.42*	0.44**
Grain P	Feekes 4	-0.23^{ns}	0.41*	0.41*	0.32^{ns}	0.31^{ns}	0.32^{ns}	0.32^{ns}
	Feekes 5	0.23^{ns}	0.38*	0.37*	0.21^{ns}	0.12^{ns}	0.18^{ns}	0.11^{ns}
	Feekes 6	-0.23^{ns}	0.08^{ns}	0.12^{ns}	0.22^{ns}	0.19^{ns}	0.20^{ns}	0.20^{ns}
	Feekes 7	-0.10^{ns}	-0.11^{ns}	0.01^{ns}	0.02^{ns}	0.05^{ns}	0.05^{ns}	0.09^{ns}
Grain P uptake	Feekes 4	-0.23^{ns}	0.36^{ns}	0.38^{ns}	0.29^{ns}	0.29^{ns}	0.28^{ns}	0.28^{ns}
	Feekes 5	0.21^{ns}	0.51^{ns}	0.49^{ns}	0.31^{ns}	0.22^{ns}	0.28^{ns}	0.19^{ns}
	Feekes 6	-0.26^{ns}	0.13^{ns}	0.15^{ns}	0.24^{ns}	0.21^{ns}	0.27^{ns}	0.26^{ns}
	Feekes 7	-0.25^{ns}	-0.03^{ns}	0.08^{ns}	0.13^{ns}	0.18^{ns}	0.16^{ns}	0.19^{ns}

0.18915 = Correlation coefficient

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

ns = not significant

GS = growth stage (s)

CHAPTER II

DETECTION OF NITROGEN AND PHOSPHORUS NUTRIENT STATUS IN BERMUDAGRASS (*CYNODON DACTYLON* L.) USING SPECTRAL RADIANCE

ABSTRACT

Nitrogen (N) and phosphorus (P) are two of the most limiting nutrients for crop production. Because of this, continued interest focuses on improving N and P use efficiency. Spectral radiance measurements were evaluated to identify optimum wavelengths for dual detection of N and P status in bermudagrass (*Cynodon dactylon* L.). A factorial arrangement of treatments (0, 112, 224 and 336 kg N ha^{-1} and 0, 29 and 58 kg P ha^{-1}) was applied to an established bermudagrass pasture for further study using a randomized complete block design. A wide range of spectral radiance measurements (276 - 831 nm) was obtained from each plot using an ocean PSD1000 fiber optic spectrometer. The resulting spectra were partitioned into 10 nm bands. Added indices were generated to test for correlation of N and P content with spectral radiance. Additional spectral radiance readings were collected using an integrated sensor which has photodiode detectors and interference filters for red and near infrared (NIR). The 435 nm band (430-440 nm) was found to be independent of N and P treatment, and as a covariate, significantly decreased residual error. Using 435 nm as a covariate, it was found that biomass, N uptake, P uptake, and N concentration could be predicted using 695/405. No index reliably predicted bermudagrass forage P concentration. Spectral radiance has the potential to be used for predicting N and P nutrient status, but further work is needed to document response in different environments.

INTRODUCTION

Recent work has documented micro-variability in soil test N and P, thus enhancing the potential use of sensor-based-variable-rate-technology (s-VRT) for fertilizer application. Optimizing fertilizer application using s-VRT may reduce N and P fertilizer input costs as well as surface and ground water contamination from over fertilization.

Light reflectance can be used to detect the nutrient status of plants because plants have strong absorption of light by chlorophyll and NIR (Thomas and Oerther, 1972). In addition, organic compounds have unique absorption properties due to vibration of molecular bonds (Morra et al, 1991). However, several factors affect the reflectance such as nonuniformity of incident solar radiation, plant structure, leaf area, background reflectivity (tillage), diseases, physiological stress (Knipling, 1970) and leaf thickness (Wooley, 1971). Nutrient status affects crop performance and visual symptoms; therefore, the effect of fertilizer on plant growth may be detected using spectral radiance.

There are several existing indices that have been used to predict nutrient status. In corn, nitrogen status was estimated using spectral radiance at 550 nm (Blackmer et al, 1994) and NIR/red (Walburg et al, 1982). In winter wheat, NDVI (normalized difference vegetation index = NIR-red/NIR+red) was used to predict N uptake and biomass (Stone et al, 1996). Milton et al. (1991) found that P deficiencies resulted in higher reflectance in the green and yellow portions of the electromagnetic spectrum. Little research has been done concerning the use of spectral radiance on detecting P deficiencies. The objective of this research was to identify indices for the dual detection of N and P deficiencies in bermudagrass.

MATERIALS AND METHODS

One study was conducted on an established bermudagrass (*Cynodon dactylon* L.) pasture near Burneyville, OK on a Minco fine sandy loam (coarse-silty, mixed thermic Udic Haplustoll). Initial soil test characteristics are reported in Table 1. An N rate x P rate factorial arrangement of treatments (0, 112, 224, and 336 kg N ha^{-1} with 0, 29, and 58 kg P ha^{-1}) was evaluated in a randomized complete block experimental design with three replications. The nitrogen and phosphorus fertilizers were applied on April 18, 1996 and August 9, 1996. The plots were 3.1 x 9.1 m with 6.1 m alleys. Spectral readings and forage yields were collected on May 29, 1996 (the first harvest after the first fertilization), June 27, 1996 (the second harvest after the first fertilization), August 9, 1996 (the third harvest after the first fertilization) and September 13, 1996 (the first harvest after the second fertilization).

Spectral data were collected within each plot using a PSD1000 portable dual spectrometer manufactured by Ocean Optics Inc., from two overlapping bandwidths 276-831 nm and 650-1100 nm. The fiber optic spectrometer which has 200 μ diameter and no slit has spectral resolution as low as 5 nm. The bifurcated fiber was lifted with an hemispherical lucite^{TM} lens which increased its angle of acceptance to 34°. The lens was held at 1.5 m and the area sensed was 0.8 m^2 per plot.

All spectral readings were partitioned into 10 nm bandwidths. In addition to these spectral bands collected from each reading, the spectral indices NDVI (Normalized Difference Vegetation Index) and other combinations of single indices were generated. Total N in forage was determined using a Carlo-Erba (Milan, Italy) NA 1500 dry combustion analyzer (Schepers et al, 1989). Total P was determined using a nitric-perchloric acid digest and concentration determined as per a modified method developed by Murphy and Riley (1962). N and P uptakes were calculated by multiplying N or P concentration by biomass. Individual wavelengths and combinations of wavelengths (or ratios) were used to predict agronomic responses such as N and P concentration, N and P uptake, and biomass.

Statistical analyses included regression, analysis of variance and covariance. All were performed using procedures defined in SAS (SAS institute, 1988). Since the wavelengths and indices were not consistent over time, analysis of covariance was performed for spectrometer readings. The selection criteria for covariates included no significant effect of treatment, no correlation with dependent variables and variances with normal distributions. Bandwidths which adhered to these criteria were 375, 395, 435, 445, 455, 465, 475, 485, 495, 785, 795 and 805 nm. The indices used to predict agronomic responses were chosen based on similarity in AOV.

RESULTS AND DISCUSSION

Agronomic responses

Analysis of variance models with factorial effects of N, P and N*P are reported in Tables 2 and 3 for biomass, N, N uptake, P and P uptake for the three dates where comprehensive data were collected. Similar to the first fertilization, no significant interaction of N and P was detected for the second fertilization (Tables 2 and 3) thus allowing direct interpretation of main effects of N and P independently. Forty-one days following the first fertilization, a significant quadratic response to N fertilization was found for dry biomass, N concentration, N uptake, P concentration and P uptake. This result suggests that N was limiting response since increases with N rate were shown for biomass, N concentration and N uptake, P concentration and P uptake. It was interesting to find that N rate influenced P concentration in bermudagrass tissue. As N rate increased P concentration increased (Tables 2 and 3). Following 71 and 113 days from the first fertilization, a linear response to N rate was observed for N concentration, N uptake and P uptake. Tissue P concentration responded linearly to N applied 41 days following the first fertilization. A linear trend for increased N to increase biomass, N concentration, N uptake, P concentration and P uptake by the second fertilization was also observed (Table 3).

Spectrometer readings

If significant differences in measured biological variables were found, we expected reflectance changes to be significant as well. However, no one index was consistently related to measured plant response over time. It was thought that the consistency of one index over multiple sampling dates could be increased using covariance. The 435 nm band (430-440 nm) was found to be independent of N and P treatment, and as a covariate, significantly decreased residual error (Tables 4 and 5). This was consistent over several cuttings but results did vary with time in terms of the percentage error accounted for by the 435 nm covariate.

The indices which behaved similarly to observed differences in N concentration (means and significance of AOV) were 695/405 and NDVI. Their response was consistent with time. The effect of N rate was highly significant for N concentration as well as 695/405 and NDVI. The relationship between 695/405 and forage N concentration for the May 29, 1996 and September 13, 1996 dates is reported in Figures 1 and 2, respectively. Although both indices were not highly correlated with forage N, they were significant (Probability of greater F value from the model, Pr>F).

Similar to results for N concentration, 695/405 was highly correlated with N uptake (Figures 3 and 4). It was important to find a consistent, positive relationship with N uptake even when values changed significantly with time

(100 kg ha^{-1} vs. 200 kg ha^{-1} from May 29 to Sept 13, 1996).

No consistent index or 10 nm band was correlated with P concentration at any sampling date. However, similar to N uptake, the index that best predicted P uptake was 695/405. This index was obviously providing good prediction of biomass since similar response in N and P uptake were observed. Correlation between 695/405 and P uptake was good for both May 29 and September 13 harvest dates. It is important to note that several indices were positively correlated with biomass (NDVI and 695/405). NDVI has been commonly used to predict biomass, which was consistent with what is reported here. Correlation between biomass and 695/405 is presented in Figures 5 and 6 for May 29, 1996 and Sep 13, 1996; and biomass with NDVI in Figures 7 and 8, respectively. Using a linear model, correlation with dry biomass was consistently better using 695/405 when compared to NDVI.

CONCLUSIONS

The 435 nm band (430-440 nm) was found to be independent of N and P treatment, and as a covariate, significantly decreased residual error. Using 435 nm as a covariate, it was found that N uptake, P uptake, and N concentration could be predicted using 695/405; whereas, biomass was best predicted using NDVI. However, no index reliably predicted bermudagrass forage P concentration. Spectral radiance has the potential to be used for predicting N and P nutrient status, but further work is needed to document response in different environments.

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Table 1. Initial surface (0 - 15cm) soil test characteristics, Burneyville, OK 1996

Characteristics	Extractant	Unit	Value
pH	1:1 soil:H_2O		5.68
Organic Carbon[ω]	Dry Combustion	g kg^{-1}	9.564
Total Nitrogen[ω]	Dry Combustion	g kg^{-1}	0.872
NH_4-N[Π]	2 M KCl	mg kg^{-1}	13.1
NO_3-N[Π]	2 M KCl	mg kg^{-1}	6.4
P[Ψ]	Mehlich 3.	mg kg^{-1}	23.8
K[Ψ]	Mehlich 3.	mg kg^{-1}	163.5

[Π] Lachat instruments (1989), [ω]Schepers et al. (1989)
[Ψ] Mehlich (1984)

Table 2. Analysis of variance for total forage N, N uptake, total P concentration, P uptake, May 29 and June 27, Burneyville OK., 1996

	Last fertilization: April 18, 1996 Harvest: May 29, 1996					Last fertilization: April 18, 1996 Harvest: June 27, 1996				
Source of variation	Biomass	N Conc.	N uptake	P Conc.	P Uptake	Biomass	N Conc.	N uptake	P Conc.	P uptake
	----Mean squares----									
Rep	ns	ns	ns	ns	ns	ns	**	ns	***	ns
N rate	***	***	***	***	***	ns	***	**	***	*
P rate	ns	ns	ns	**	ns	ns	ns	ns	ns	ns
NxP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Residual	207216.9	1.5	80.92	15433.9	0.755	1256671.0	3.4	711.1	65790.3	9.8
CV, %	17.8	5.7	16.0	6.4	17.1	40.7	7.1	37.7	8.9	39.6
Contrasts:										
N linear	***	***	***	***	***	ns	***	***	***	**
N quadratic	***	**	***	**	***	ns	ns	ns	**	ns
P linear	ns	ns	ns	***	ns	ns	*	ns	ns	ns
P quadratic	ns	ns	ns	Ns	ns	ns	ns	ns	ns	ns
	----Means----									
N rate, kg ha^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}
0	1667.4	14.4	24.6	1597.1	2.7	2150.8	18.3	38.8	2265.4	4.9
112	2737.6	20.3	55.4	1902.3	5.2	2896.6	22.5	65.4	2713.4	7.8
224	3042.9	23.8	71.4	2137.1	6.4	3131.9	29.1	86.6	3314.2	9.8
336	2780.8	26.6	72.8	2131.4	5.9	2820.9	32.9	91.8	3224.4	9.2
SED	214.6	0.6	4.2	58.6	0.4	528.4	0.9	12.6	120.9	1.5
P rate, kg ha^{-1}										
0	2480.8	21.2	53.9	1823.4	4.6	2652.1	26.4	69.3	2828.6	7.5
29	2632.8	21.3	59.0	1967.1	5.3	2728.0	26.0	72.2	2972.3	8.2
58	2558.0	21.2	55.2	2035.4	5.3	2869.9	24.7	70.5	2837.2	8.1
SED	185.8	0.5	3.7	50.7	0.4	457.6	0.7	10.9	104.7	1.3

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
ns = not significant; SED = standard error difference between two equally replicated means

Table 3. Analysis of variance for total forage N, N uptake, total P concentration, P uptake, August 9 and Sept 13, Burneyville OK, 1996

	Last fertilization: April 18, 1996 Harvest: August 9, 1996					Last fertilization: August 9, 1996 Harvest: September 13, 1996				
Source of variation	Biomass	N Conc.	N uptake	P Conc.	P uptake	Biomass	N Conc.	N uptake	P Conc.	P uptake
	--------Mean squares--------									
Rep	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
N rate	ns	***	***	***	**	***	***	***	***	***
P rate	ns	ns	ns	ns	ns	ns	**	ns	ns	ns
NxP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Residual	898846.3	1.9	402.3	119479.1	15.5	1913863.5	1.2	946.4	105319.2	17.0
CV, %	18.1	7.4	20.5	9.0	19.5	23.8	5.1	24.2	9.0	19.6
Contrasts:										
N linear	ns	***	***	***	**	**	***	***	***	***
N quadratic	ns	ns	ns	ns	ns	**	*	**	***	**
P linear	ns	ns	ns	ns	ns	ns	*	ns	ns	ns
P quadratic	ns	ns	ns	ns	ns	ns	*	ns	ns	ns
	--------Means--------									
N rate, kg ha^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}
0	4765.2	14.1	67.7	3285.5	16.0	3702.6	16.9	62.5	3095.2	11.5
112	5583.4	17.8	97.9	3662.1	20.4	6931.6	20.7	143.1	3251.9	22.4
224	4885.2	20.5	98.0	4092.7	19.9	6267.6	23.2	142.9	4026.0	24.9
336	5762.3	22.4	126.7	4237.6	24.6	6386.5	25.2	159.8	4059.5	25.3
SED	446.9	0.7	9.5	162.9	1.9	652.1	0.5	14.5	153.0	1.9
P rate, kg ha^{-1}										
0	4986.9	19.1	93.9	3837.4	19.4	5504.2	22.3	124.6	3574.5	19.6
29	5273.0	18.4	95.9	3762.8	20.2	5912.4	20.8	126.6	3588.5	21.7
58	5487.3	18.6	103.1	3858.2	21.1	6049.5	21.3	129.9	3661.5	21.9
SED	387.1	0.6	8.2	141.1	1.6	564.8	0.4	12.6	132.5	1.7

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
ns = not significant; SED = standard error difference between two equally replicated means

Table 4. Analysis of variance for selected indices from various readings using 435 nm as a covariate for readings on May 29 and June 27, Burneyville OK, 1996

Source of variation	725/535	695/405	NDVI	PNSI	805/695
May 29, 1996	Mean squares				
Rep	***	ns	ns	ns	ns
Nrate	**	***	***	***	***
Prate	*	ns	ns	ns	ns
NxP	ns	ns	ns	ns	ns
w435	***	ns	ns	ns	ns
Contrasts:					
N linear	***	***	***	***	***
N quadratic	ns	***	**	**	*
P linear	*	ns	ns	ns	ns
P quadratic	ns	ns	ns	ns	ns
Error	0.00	0.00	0.00	0.00	0.02
CV, %	2.0	2.5	2.7	2.7	4.1
N rate, kg ha^{-1}	Means				
0	2.76	2.43	0.51	1.95	3.12
112	2.87	2.25	0.55	1.82	3.44
224	2.86	2.24	0.55	1.82	3.44
336	2.90	2.23	0.55	1.80	3.50
SED	0.03	0.03	0.01	0.02	0.07
P rate, kg ha^{-1}					
0	2.81	2.30	0.53	1.87	3.30
29	2.86	2.29	0.54	1.84	3.41
58	2.87	2.27	0.55	1.84	3.41
SED	0.02	0.02	0.01	0.02	0.06
June 27, 1996	Mean squares				
Rep	ns	ns	ns	ns	ns
Nrate	ns	*	ns	ns	ns
Prate	ns	ns	ns	ns	ns
NxP	ns	ns	ns	ns	ns
w435	***	ns	ns	ns	*
Contrasts:					
N linear	ns	*	*	ns	*
N quadratic	ns	*	ns	ns	ns
P linear	*	ns	ns	ns	ns
P quadratic	ns	ns	ns	ns	ns
Error	0.01	0.01	0.00	0.03	0.11
CV, %	3.2	4.9	8.1	9.1	10.6
N rate, kg ha^{-1}	Means				
0	2.89	2.58	0.49	2.08	2.94
112	3.03	2.39	0.52	1.92	3.21
224	3.08	2.44	0.53	1.91	3.26
336	3.06	2.42	0.53	1.91	3.29
SED	0.03	0.06	0.02	0.08	0.16
P rate, kg ha^{-1}					
0	2.30	2.46	0.50	2.03	3.06
29	2.33	2.46	0.52	1.94	3.19
58	2.38	2.45	0.53	1.89	3.27
SED	0.03	0.05	0.02	0.72	0.14

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
ns = not significant; SED = standard error difference between two equally replicated means

Table 5. Analysis of variance for selected indices from various readings using 435 nm as a covariate for readings on August 9, and Sept 13, Burneyville OK, 1996

Source of variation	725/535	695/405	NDVI	PNSI	805/695
August 9, 1996			---Mean squares---		
Rep	ns	ns	ns	ns	ns
Nrate	ns	*	ns	ns	ns
Prate	ns	ns	ns	ns	ns
NxP	ns	ns	ns	ns	ns
w435	*	***	**	**	**
Contrasts:					
N linear	ns	**	ns	ns	ns
N quadratic	ns	ns	ns	ns	ns
P linear	ns	ns	ns	ns	ns
P quadratic	ns	ns	ns	ns	ns
Error	0.01	0.00	0.00	0.34	0.00
CV, %	6.5	1.1	6.7	6.8	1.6
N rate, kg ha^{-1}			---Means---		
0	1.63	4.57	0.12	8.55	1.27
112	1.63	4.57	0.12	8.35	1.27
224	1.58	4.54	0.12	8.70	1.26
336	1.58	4.49	0.11	8.80	1.26
SED	0.05	0.02	0.00	0.27	0.01
P rate, kg ha^{-1}					
0	1.59	4.55	0.12	8.68	1.26
29	1.58	4.53	0.12	8.60	1.26
58	1.64	4.55	0.12	8.52	1.27
SED	0.04	0.02	0.00	0.24	0.01
September 13, 1996			---Mean squares---		
Rep	ns	ns	ns	ns	ns
Nrate	***	***	***	***	***
Prate	ns	ns	ns	ns	ns
NxP	ns	ns	ns	ns	ns
w435	***	***	***	***	***
Contrasts:					
N linear	**	***	***	***	***
N quadratic	***	***	***	***	***
P linear	ns	ns	ns	ns	ns
P quadratic	ns	ns	ns	ns	ns
Error	0.00	0.01	0.00	0.00	0.09
CV, %	1.0	4.1	2.8	3.2	6.2
N rate, kg ha^{-1}			---Means---		
0	2.58	2.60	0.58	1.72	3.90
112	2.63	2.13	0.67	1.50	5.16
224	2.63	2.14	0.67	1.49	5.11
336	2.61	2.19	0.66	1.51	4.93
SED	0.13	0.01	0.00	0.02	0.14
P rate, kg ha^{-1}					
0	2.63	2.28	0.64	1.57	4.71
29	2.60	2.28	0.65	1.56	4.73
58	2.61	2.24	0.65	1.54	4.89
SED	0.01	0.01	0.00	0.02	0.12

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

ns = not significant; SED = standard error difference between two equally replicated means.

Figure 1. Correlation between N concentration and 695/405 on May 29, 1996

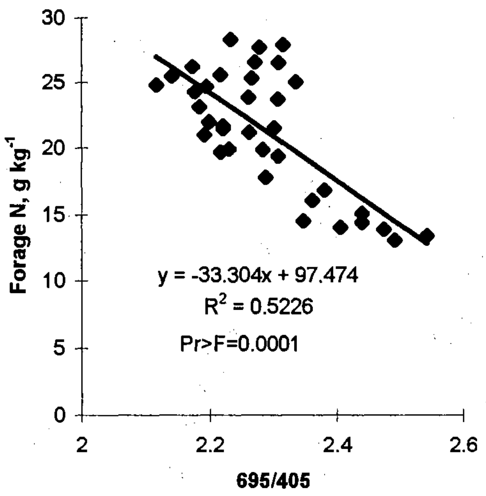


Figure 2. Correlation between N concentration and 695/405 on Sept 13, 1996

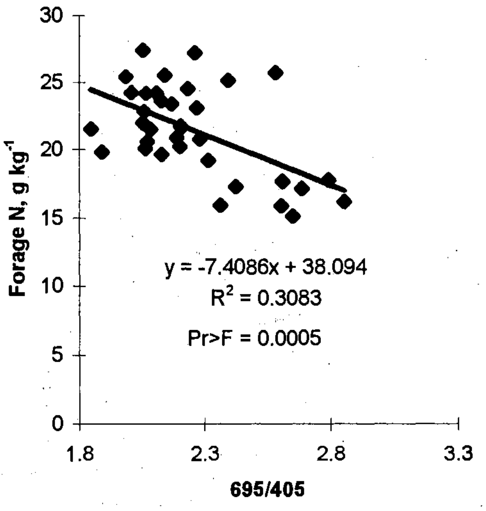


Figure 3. Correlation between 695/405 and N uptake on May 29, 1996

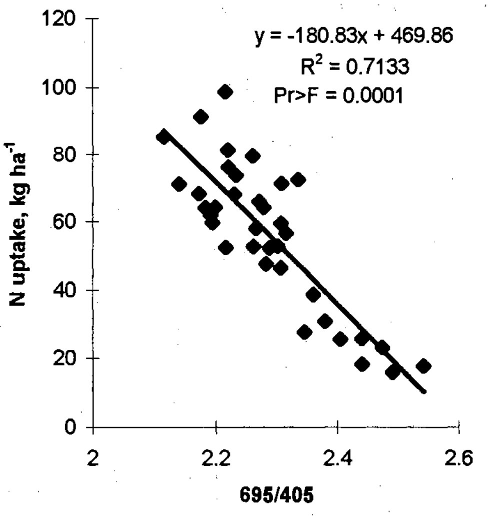


Figure 4. Correlation between N uptake and 695/405 on Sept 13, 1996

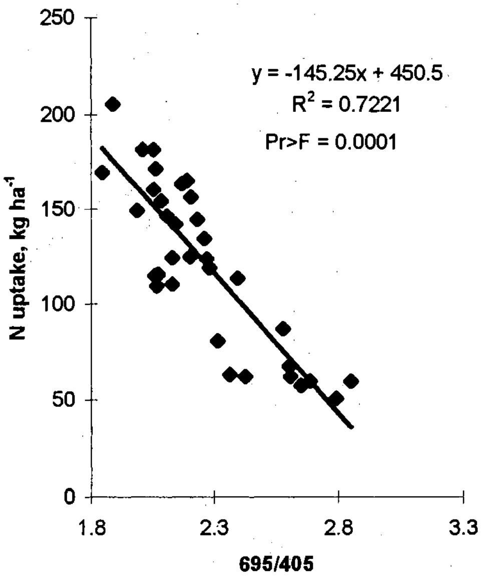


Figure 5. Correlation between biomass and 695/405 on May 29, 1996

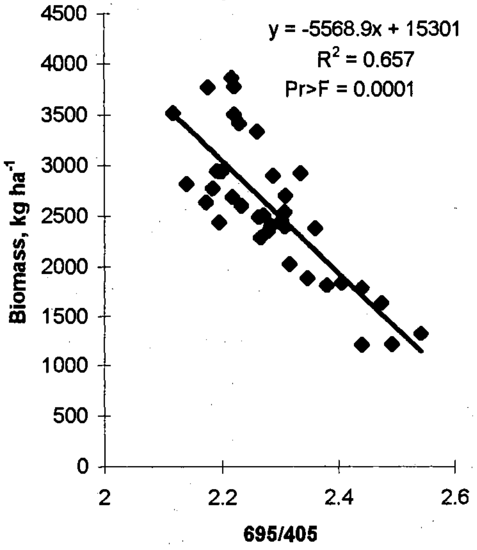


Figure 6. Correlation between biomas and 695/405 on Sept 13, 1996

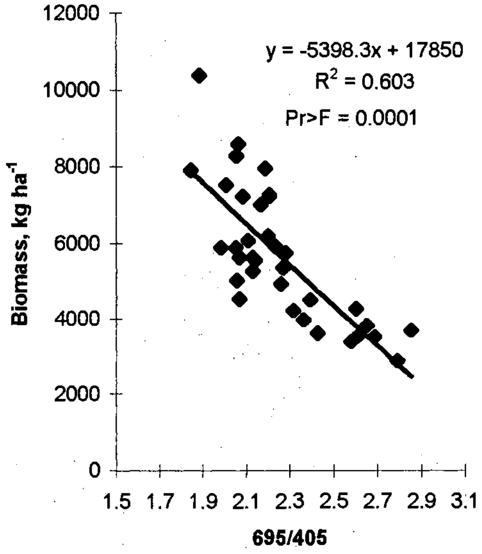


Figure 7. Correlation between biomass and NDVI on May 29, 1996

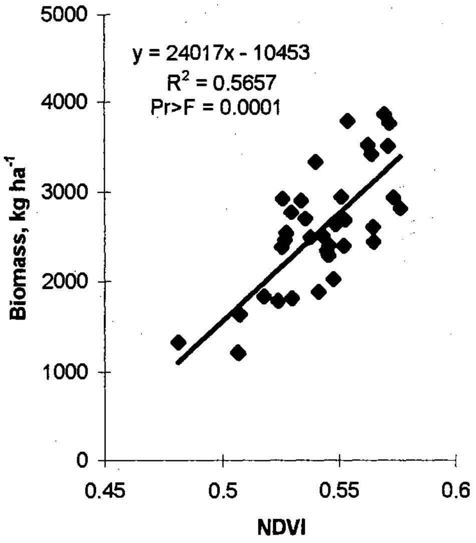
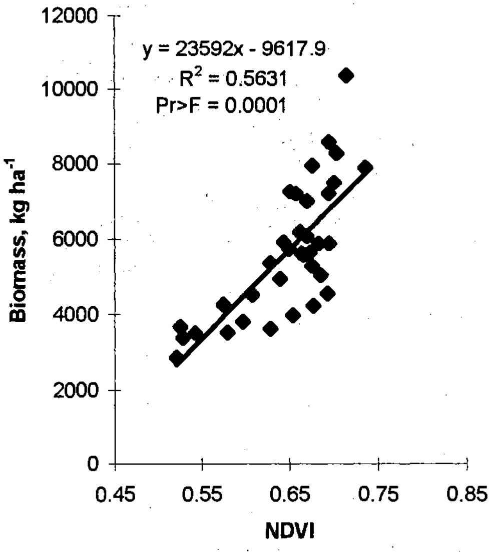


Figure 8. Correlation between biomass and NDVI on Sept 13, 1996



CHAPTER III

NITROGEN ACCUMULATION EFFICIENCY: RELATIONSHIP BETWEEN EXCESS FERTILIZER AND SOIL-PLANT BIOLOGICAL ACTIVITY IN WINTER WHEAT

ABSTRACT

The point at which N applied approaches 100 percent recovery in the soil has not been determined in winter wheat (*Triticum aestivum* L.) production systems. In dryland winter wheat, subsoil accumulation has not been found to occur until nitrogen rates exceed that required for maximum yield. Many conventional N rate experiments have not properly evaluated subsoil N accumulation due to the lack of equally spaced N rates at the high end of the spectrum, over which accumulation is expected to occur. Therefore, the objectives of this study were to (1) determine when soil profile accumulation efficiencies reach 100% in continuous winter wheat production and (2) evaluate the potential for NO_3-N leaching in continuous winter wheat when extremely high rates of fertilizer N are used. Two field experiments (T505 and T222) were conducted for two years using ten N rates (preplant-incorporated) ranging from 0 to 5376 kg ha^{-1}. No additional preplant fertilizer was applied in the second year. Following the first and second year wheat harvest, soil cores were taken to 2.4

m and bulk density, NH_4-N and NO_3-N were determined. Crop nitrogen use efficiency (NUE) (N uptake treated - N uptake check/rate applied) and soil profile inorganic N accumulation efficiencies (NAE) (net inorganic N accumulation in the soil profile/(fertilizer applied - net N removed in the crop) changed with fertilizer rate and were inversely related. Priming may have occurred since increased NUE was observed at low N rates. The highest nitrogen accumulation efficiencies were at N rates 168 and 448 kg ha^{-1} in experiments T505 and T222, respectively. At both T222 and T505 no subsoil accumulation of NH_4-N or NO_3-N beyond 100 cm was observed for any of the N treatments when compared to the 0-N check, even when N rates exceeded 448 kg ha^{-1}.

INTRODUCTION

Previous studies have indicated poor efficiency for subsoil accumulation of mineral N from excess fertilizer applications. Evaluation of long-term N rate studies have reported that subsoil accumulation did not occur until rates exceeded winter wheat maximum yield requirements by about 20 kg ha^{-1}. Delayed accumulation is a result of natural processes which are responsible for poor nitrogen use efficiency (NUE). Combined, they help explain the concept of soil-plant buffering of inorganic soil N, proposed by Raun and Johnson (1995) and Johnson and Raun (1995). Conventional N rate experiments do not allow evaluation of subsoil N accumulation because the high rates are at the low end of the range over which accumulation is expected to occur.

The soil-plant buffering concept proposed by Raun and Johnson (1995), documents that increased plant protein, gaseous loss of N from plants, denitrification, immobilization, and ammonia volatilization from soils, all take place when N rates exceed that required from maximum yield. Increased plant protein and plant N volatilization probably account for more of the total buffer size of the soil-plant system than the other sinks. Therefore, these mechanisms provide an effective buffer against increased soil profile accumulation of inorganic N (and potential NO_3 leaching) when N is applied at rates in excess of that required for maximum yields. The size and/or magnitude of each mechanism depends on the climate, soil type, fertilizer source and method of fertilizer application (Johnson and Raun, 1995).

Four long-term winter wheat experiments in Oklahoma with various nitrogen rates have been evaluated to examine the dynamics of nitrogen in the soil profile. Raun and Johnson (1995) concluded that the threat of fertilizer N use on groundwater contamination was minimal when N fertilizer rates were less than those required for maximum yield. Even at fertilizer N rates beyond those necessary to achieve maximum yield, soil profile inorganic N did not immediately increase. However, at high fertilizer N rates, the soil-plant system can no longer buffer against inorganic N accumulation. Buffering is used here to reflect an entire mechanism that would result in N loss when N rates exceed that required for maximum yield, but prior to observing significant increases in soil profile inorganic N. At present, no work has documented the N rate (for a particular soil) at which an additional one kg of N applied results in an increase in one kg of soil profile inorganic N. As per the work of Raun and Johnson (1995), this should take place once all buffering mechanisms are saturated (N uptake, immobilization, denitrification and plant N loss). However, each of these buffering mechanisms are expected to be saturated at different N rates. Therefore, the objectives of this study were (1) to determine when soil profile accumulation efficiencies reach 100% in continuous winter wheat production and (2) to evaluate the potential for NO_3-N leaching in continuous winter wheat when extremely high rates of fertilizer N are used.

MATERIALS AND METHODS

Two experiments within two years periods (1995/96 and 1996/97) were conducted near long-term winter wheat experiments in Stillwater (#222) and Lahoma (#505). At each of these sites, soil-plant inorganic N buffering was evaluated in 1988 and 1993. These new experiments are referred to as T222 and T505. Experiment T222 is on a Kirkland silt loam (fine-mixed, thermic, Udertic Paleustoll) and T505 is on a Grant silt loam soil (fine-silty, mixed, thermic Udic Argiustoll). Results from initial soil samples taken prior to the start of each experiment are reported in Table 1. The experimental design was a randomized complete block with two replications. Nitrogen as ammonium nitrate was applied at rates of 0, 56, 112, 168, 224, 448, 896, 1792, 3584 and 5376 kg ha^{-1} on October 2, 1995 to T222 and October 6, 1995 to T505. No fertilizer was applied for the year 1996/97. Fertilizer was immediately incorporated using a

John Deere GT262 rotary tiller. Individual plots were 3.1 m x 3.1 m with 1.5 m alleys between each plot. Following the incorporation of fertilizers, winter wheat was planted in 19.1 cm rows using a John Deere 450 grain drill. The variety 'Tonkawa' was planted at a rate of 67.2 kg ha^{-1}. Grain yield was determined in each plot by harvesting the entire area on June 10, 1996 and June 20, 1997 for T222 and June 13, 1996 and June 28, 1997 for T505. Rainfall distribution during the growing cycle at T222 and T505 is presented in Figures 1, 2 and 3.

Following harvest each year, three soil cores (4.5 cm diameter) from each plot were taken to a depth of 2.4 m and partitioned into increments of 0 to 15, 15 to 30, 30 to 45, 45 to 60, 60 to 90, 90 to 120, 120 to 150, 150 to 180, 180 to 210 and 210 to 240 cm. Once cores were removed, topsoil that had previously been dried and ground was added. Samples were air-dried at ambient temperature and ground to pass a 2 mm screen. They were then extracted using 2 M KCl and analyzed for NH_4-N and NO_3-N using an automated flow injection analysis system (Lachat, 1989 and 1990).

Nitrogen accumulation efficiency (NAE) was calculated as $NAE=[(N_s - N_{s\phi})/[N_A - (N_c - N_{c\phi})]]$; where, N_s was the total NH_4-N and NO_3-N accumulated in soil profile (0-210 cm) of fertilized plots; $N_{s\phi}$ was the total NH_4-N and NO_3-N accumulated in soil profile (0-210 cm) in the check, O-N; N_A was the total N applied; N_c was the total N removed in the crop from fertilized plots; $N_{c\phi}$ was the total N removed in the check/unfertilized plot. Nitrogen use efficiency (NUE) was calculated as $NUE=(N_c - N_{c\phi})/N_A$, fertilizer recovery was calculated using the formula; $((N_c - N_{c\phi}) + (N_s - N_{s\phi}))/N_A$ using the same nomenclature above and assuming that the amount of mineralization in the check and fertilized plots was the same. Statistical analysis was performed using SAS (SAS institute, 1988).

RESULTS AND DISCUSSION

Yield and N uptake

Analysis of variance and associated treatment means (by year) for grain yield, grain N and grain N uptake are reported in Table 2 for both locations. The poor yields at T222 in 1995/96 were a function of having a poor stand at planting and moisture stress throughout the growing season. Total seasonal rainfall was 18.7 cm at T222 compared to 29.7 cm at T505 in 1995/96. In 1995/96, limited wheat growth was observed when N rates exceeded 896 kg ha^{-1} at T222; whereas, at T505 wheat continued to grow when N was applied at 3584 kg N ha^{-1}. In 1996/97, wheat growth was improved compared to 1995/96 even without adding additional fertilizer at both locations. It was interesting to note that grain N uptake peaked at or near the 896 kg ha^{-1} rate, at both sites, in both years. This far exceeds N rates that have reportedly maximized winter wheat grain N uptake (Raun and Johnson, 1995).

Fertilizer Recovery

Analysis of variance for fertilizer recovery at T222 and T505 is reported in Table 3. Fertilizer recovery was markedly different at the two sites. At the end of the experiment, the highest fertilizer recovery was 78% at an N rate 448 kg ha^{-1} at T222 and 80% at an N rate of 168 kg ha^{-1} at T505 (Figure 4). At comparable rates, Raun et al. (1996) found that fertilizer N recovery at experiment 502 (close to T505) was higher compared to experiment 222 (close to T222). Grain yields were maximized at higher N rates at 502 and the soil-plant buffer was narrowed at this site compared to 222 (Raun and Johnson, 1995).

The increased fertilizer recoveries noted for T505 compared to T222 at the low N rates is worthy of further discussion. Two of the factors believed to be responsible are priming and soil-plant buffering. Westerman and Kurtz (1973) described priming as the result of stimulation of microbial activity by N fertilizer (at low N rates) which increases mineralization of soil N, thus making more soil N available for plants. Raun et al. (1996) suggested that soil-plant buffering will be greater in soils where priming is observed, a result of increased N from easily mineralizable pools. They also noted that these soil-plant environments will be capable of immobilizing excess mineral N. Combined these results help explain why fertilizer N recovery was greater in experiment T505 (no priming, less easily mineralizable N and less soil-plant buffering).

Nitrogen use efficiency (NUE)

The highest NUE at T222 was 29.9% at an N rate of 56 kg N ha^{-1}, whereas at T505 it was 30% at an N rate 56 kg N ha^{-1}. The lowest NUE occurred at the highest N rate at both locations either in 1995/96 or 1996/97 (Figures 5 and 6). In 1996/97, it was found that the highest NUE was 35% at an N rate 224 at T505 and 29% at an N rate 56 kg ha^{-1} at T222. Increasing N rate leads to increased denitrification, volatilization, immobilization and N plant loss and lower NUE.

Nitrogen accumulation efficiency (NAE)

The highest NAE at T222 was at an N rate of 448 kg N ha^{-1}, whereas at T505 it was at an N rate of 168 kg N ha^{-1} in 1996/97 (Figure 7). NAE was expected to reach 100% between 0 and 448 kg N ha^{-1} at both sites. At high fertilizer N rates the soil-plant system can no longer buffer against inorganic N accumulation. Therefore, an additional one kg of N applied should theoretically result in an increase in one kg of soil profile inorganic N. Buffering is used here to reflect the combined mechanisms which would prevent soil profile accumulation, via N loss when N rates exceed that required for maximum yield. Increased soil profile inorganic N accumulation should take place once all buffering mechanisms are saturated (N uptake, immobilization, denitrification and plant N loss).

NAE was expected to reach 100% at both sites when applied N saturated all of the buffering mechanisms discussed. However, an NAE of 100% was not observed at either site, even when N rates reached 5376 kg ha^{-1}. This suggests that possible analytical bias errors for NH_4-N and NO_3-N were encountered in the laboratory. Also because mass-balance recovery was based on estimated bulk density, bias errors for this parameter may have contributed to the low recoveries found. It is also possible that denitrifying organisms flourished at the

N saturated rates and subsequently accounted for the low NAE's via denitrification.

Because maximum NAE was observed at lower applied N rates at T505 compared to T222, this indicates that the soil-plant buffer was larger at T222 compared to T505. Similar results were reported by Raun and Johnson (1995).

The distribution of organic C and total N in soil profiles as influenced by N rate at both sites is reported in Figures 8-13. This analysis was only performed on the upper four surface horizons. As expected, organic C did not change over time, therefore only data for the 1996/97 cycle are reported. Organic C levels were higher in the surface horizons at both sites with levels somewhat higher at T505 when compared to T222 (Figures 8 and 9). Total N levels were high in the surface horizons and declined to check levels by the 15 cm depth.

It was interesting to note that some movement of inorganic N remained detectable the following year since total N levels were higher in the high N rates at 45 cm. The precision of this procedure is low (± 0.01) which roughly translates into ± 200 kg N ha^{-1}. However, rates were high enough to detect these differences despite the limited precision. The same observation was confirmed in the analysis of variance where a significant year*Nrate*depth interaction was detected (Table 4).

Distribution of NH_4-N and NO_3-N and total Inorganic N in soil profiles

Applied N influenced total NH_4-N and NO_3-N and total inorganic N recovered in the soil profile following the first and second year of winter wheat production (Tables 5 and 6). The distribution of NO_3-N, NH_4-N, and NH_4-N+NO_3-N in the soil profile for T222 and T505 are reported in Figures 14-19 and 20-25, respectively. At both locations, no subsoil accumulation of NH_4-N +NO_3-N beyond 45 cm was observed for any of the N rates when compared to the 0-N check in 1995/96. This was expected since limited precipitation was received following fertilization and prior to sampling. No differences between any of the N rate treatments could be detected at depths >45 cm in 1995/96.

One year later, inorganic N accumulation was considerably different in soil profiles at both sites. At T222 at rates >168 kg N ha^{-1} significant accumulation was detected at depths >30 cm (Figures 17-19). This is easily observed by noting the first lines (bulge) that depart from baseline levels in the 0-N checks. At T505, significant accumulation was detected when N rates exceeded 224 kg N ha^{-1} (Figures 23-25). These results are very similar to that reported by Raun and Johnson 1995, where no soil profile inorganic N accumulation was detected until annual N rates exceeded 102 and 114 kg N ha^{-1} (T222 and T505, respectively). These results differ in that accumulation was not detected until N rates were greater than that reported above. It should be noted, however, that these results are from a two-year study with limited differences in the environment and Raun and Johnson reported results following more than 23 years of annual N applied in wheat production.

CONCLUSIONS

The highest NAE at T222 was at an N rate of 448 kg N ha^{-1}, whereas at T505 it was at an N rate of 168 kg N ha^{-1} in 1996/97. At both T222 and T505 no subsoil accumulation of NH_4-N or NO_3-N beyond 100 cm was observed following two years for any of the N treatments when compared to the 0-N check, even when N rates exceeded 448 kg ha^{-1}. NAE's were expected to reach 100% at both sites, especially at the high N rates. Because this was not detected, analytical errors and possible denitrification losses may have contributed to this finding.

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Table 1. Initial surface (0 - 15cm) soil test characteristics experiments T222 and T505

Characteristic	Extractant	Unit	T222	T505
pH	1:1 soil:H_2O	-	6.3	5.0
Organic Carbon$^{\omega}$	Dry Combustion	g kg^{-1}	7.9	7.1
Total Nitrogen$^{\omega}$	Dry Combustion	g kg^{-1}	0.95	0.62
C:N		-	8.3	11.5
NH_4-N$^{\Pi}$	2 M KCl	mg kg^{-1}	12	5
NO_3-N$^{\Pi}$	2 M KCl	mg kg^{-1}	8	5
P$^{\Psi}$	Mehlich 3.	mg kg^{-1}	5	45
K$^{\Psi}$	Mehlich 3.	mg kg^{-1}	190	320

$^{\Pi}$Lachat instruments (1989), $^{\omega}$Schepers et al. (1989), $^{\Psi}$ Mehlich (1984)

Table 2. Analysis of variance and treatment means for grain yield, N uptake and grain N at T222 and T505.

Source of variation	df	Grain yield	Grain N uptake	Grain N	Grain yield	Grain N uptake	Grain N
		------------------T222		----------------	------------------T505		------------------
		------------------------------	Mean squares	------------------	------------------	------------------	------------------
Rep	1	ns	ns	ns	**	ns	ns
N rate	9	*	*	**	***	*	*
Error (a)	9	151507	138.4	3.8	279937628	552.6	24.1
Year	8	***	**	**	***	*	ns
Year*Nrate	72	*	*	ns	*	**	ns
Error (b)	80	54437	58.4	3.1	165550	265.5	24.0
Contrasts:							
N rate linear	1	ns	ns	***	***	ns	***
N rate quad.	1	*	*	*	***	***	ns
		------------------	------------------	------------------Means	------------------	------------------	------------------
Year	kg N ha^{-1}	kg ha^{-1}	kg N ha^{-1}	g N ha^{-1}	kg N ha^{-1}	kg N ha^{-1}	g kg^{-1}
1996	0	312	7.4	23.5	2558	59.8	23.3
	56	944	24.1	26.6	3321	79.5	24.0
	112	584	17.9	30.6	3302	86.3	26.1
	168	524	16.7	32.1	2833	82.4	28.9
	224	260	8.1	32.2	3484	103.3	29.6
	448	691	23.2	33.0	2964	92.9	31.2
	896	877	30.1	34.2	3090	99.2	32.1
	1792	706	24.9	35.2	2041	67.7	33.1
	3584	346	11.5	33.3	1584	51.4	32.7
	5376	115	3.6	32.9	952	32.4	34.5
1997	0	529	13.5	25.0	2793	67.4	24.2
	56	514	13.2	25.9	2496	63.7	25.6
	112	873	23.0	26.5	3294	75.7	22.9
	168	646	19.6	29.7	3664	101.1	27.6
	224	586	15.9	26.8	3679	102.5	27.9
	448	979	29.1	29.7	3640	98.7	27.1
	896	1814	58.0	31.8	3887	105.6	27.2
	1792	2018	57.4	28.3	3909	181.2	46.3
	3584	552	18.2	32.9	2447	85.6	35.0
	5376	624	20.8	33.6	724	28.6	39.5
	SED	233	7.6	1.8	407	16.3	4.9

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
SED = standard error of the difference between two equally replicated means,
df = degrees of freedom

Table 3. Analysis of variance and treatment means for fertilizer recovery and nitrogen accumulation efficiency (NAE) and nitrogen use efficiency (NUE) for T222 and T505, 1996/97

Source of variation	df	T222	T505	T222	T505	T222	T505
		Fertilizer recovery		--------NAE--------		-------NUE-------------	
		---------------------------------Mean squares---					
Rep	1	ns	ns	ns	ns	ns	ns
N rate	8	ns	ns	ns	ns	ns	ns
Error	8	213.4	676.6	611.2	1353.9	244.9	158.8
Contrasts:							
N linear	1	ns	ns	ns	ns	ns	**
N quadratic	1	*	ns	*	ns	ns	ns
		----------------------Means included in --					
		-----Figure 4------		----- Figure 7-----		------Figure 6-----------	
SED		14.6	26.0	24.7	36.8	15.6	12.6

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
SED = standard error of the difference between two equally replicated means,
df = degrees of freedom

Table 4. Analysis of variance for organic C and total N in the soil profile (0-60 cm), experiments T222 and T505, 1995-97

Source of Variation	df	Organic C	Total N	Organic C	Total N
		-------------T222----------		-----------T505------------	
		----------------------Mean squares	----------------------------------		
Rep	1	ns	ns	ns	ns
N rate	9	*	**	ns	*
Error (a)	9	0.284	0.057	0.437	0.129
Depth	3	***	***	***	**
Nrate*depth	27	ns	***	ns	ns
Error (b)	30	0.408	0.008	0.856	0.128
Year	1	ns	***	***	***
Year*Nrate	9	ns	*	ns	ns
Year*depth	3	ns	***	ns	ns
Year*Nrate*depth	27	ns	***	ns	ns
Error (c)	40	0.681	0.013	0.267	0.124
		----------------------Means, g kg^{-1}	--------------------------------		
N rate, kg N ha^{-1}	0	5.023	0.554	7.535	0.863
	56	5.308	0.584	7.479	0.845
	112	5.617	0.598	7.343	0.831
	168	5.434	0.561	7.484	0.855
	224	5.243	0.574	7.637	0.883
	448	5.412	0.611	7.392	0.878
	896	5.917	0.720	7.410	1.169
	1792	5.446	0.719	7.454	0.944
	3584	5.7575	0.958	7.436	1.207
	5376	4.986	1.062	7.475	1.252
SED		0.292	0.041	0.183	0.124
Depth, cm	0-15	7.114	0.989	7.986	1.106
	15-30	5.730	0.724	7.973	1.079
	30-45	4.555	0.553	7.436	0.883
	45-60	4.221	0.507	6.462	0.824
	SED	0.185	0.026	0.116	0.079
Year	19955/96	5.471	0.741	7.699	1.107
	1996/97	5.363	0.647	7.229	0.839
	SED	0.131	0.018	0.082	0.056

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
SED = standard error of the difference between two equally replicated means,
df = degrees of freedom

Table 5. Analysis of variance NO_3-N, NH_4-N and total inorganic N in the soil profile (0-210 cm), experiments T222 and T505, 1995/96

Source of variation	df	NH_4-N	NO_3-N	NH_4-N+NO_3-N	NH_4-N	NO_3-N	NH_4-N+NO_3-N
		T222			T505		
		Mean squares					
Rep	1	ns	ns	ns	ns	ns	ns
N rate	9	***	***	***	***	**	***
Error (a)	9	9697.1	5848.0	26905.4	402.7	4185.6	6945.6
Depth	8	***	***	***	***	***	***
Nrate*depth	72	***	***	***	***	***	***
Error (b)	80	7189.4	4662.2	18557.7	194.4	3590.0	4839.9
SED		84.8	68.3	136.2	13.9	59.9	69.57
		Means included in Figures 14-16					

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
SED = standard error of the difference between two equally replicated means
df = degrees of freedom.

Table 6. Analysis of variance NO_3-N, NH_4-N and total inorganic N in the soil profile (0-210 cm), experiments T222 and T505, 1996/97

Source of variation	df	NH_4-N	NO_3-N	NH_4-N+NO_3-N	NH_4-N	NO_3-N	NH_4-N+NO_3-N
		T222			T505		
		Mean squares					
Rep	1	ns	ns	ns	ns	ns	ns
N rate	9	***	***	***	**	***	***
Error (a)	9	81.3	4030.3	5057.9	674.7	1169.1	2573.4
Depth	8	***	***	***	***	***	***
Nrate*depth	72	***	***	***	***	***	***
Error (b)	80	58.6	808.1	1088.9	94.5	1160.1	1253.5
SED		7.6	28.4	33.0	9.7	34.1	35.4
		Means included in Figures 20-22					

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
SED = standard error of the difference between two equally replicated means
df = degrees of freedom.

Figure 1. Rainfall distribution at Stillwater, T222, 1995 to 1996

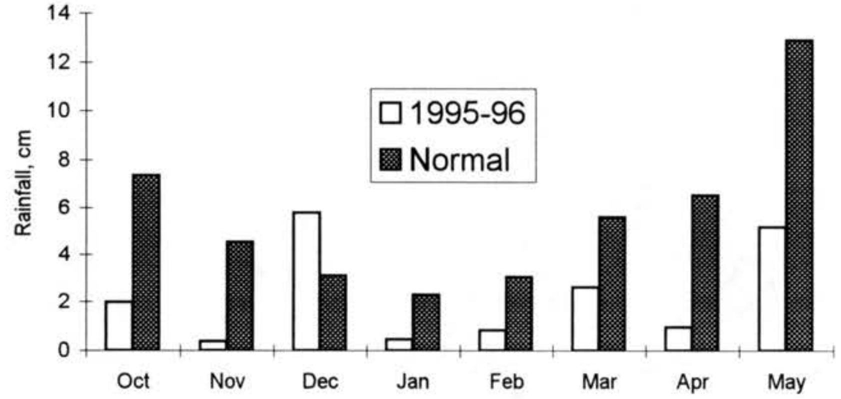


Figure 2. Rainfall distribution at Lahoma, T505, 1995 to 1996

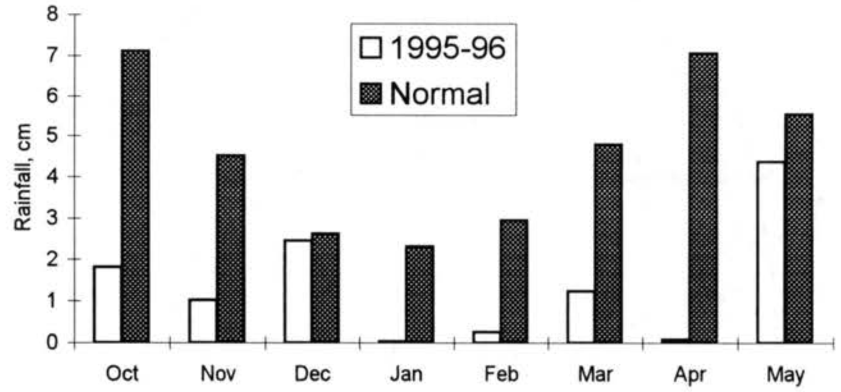


Figure 3. Rainfall distribution at Stillwater (T222) and Lahoma (T505), 1996 to 1997

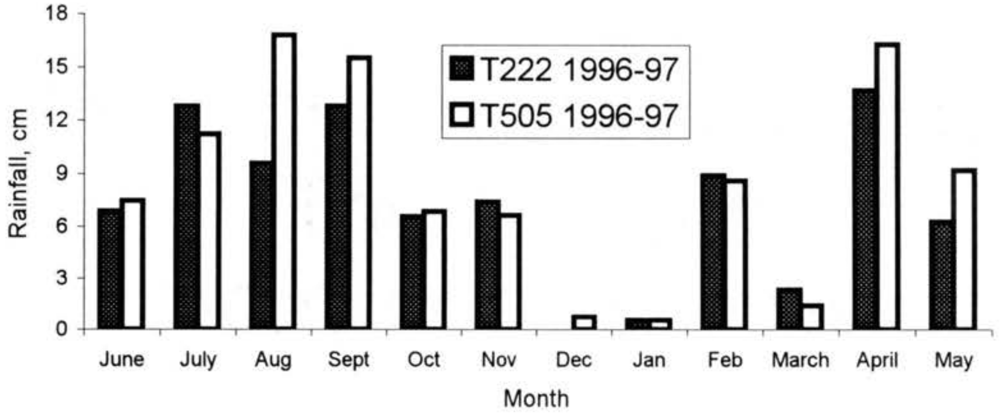


Figure 4. Effect of N rate on N fertilizer recovery at T222 and T505, 1996/97

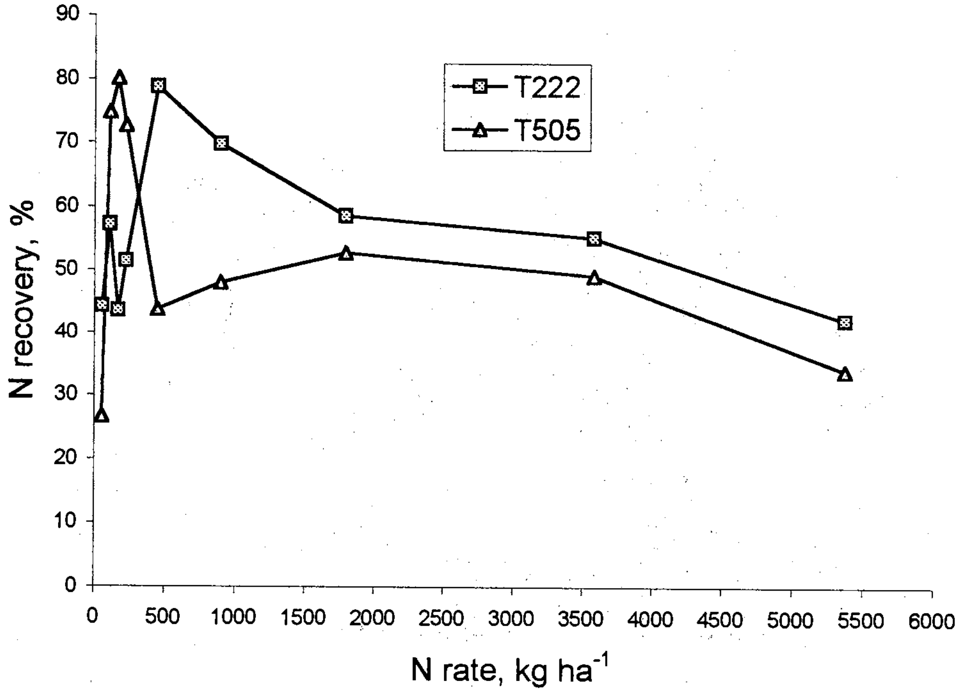


Figure 5. Effect of N rate on N use efficiency (NUE) at T222 and T505, 1995/96

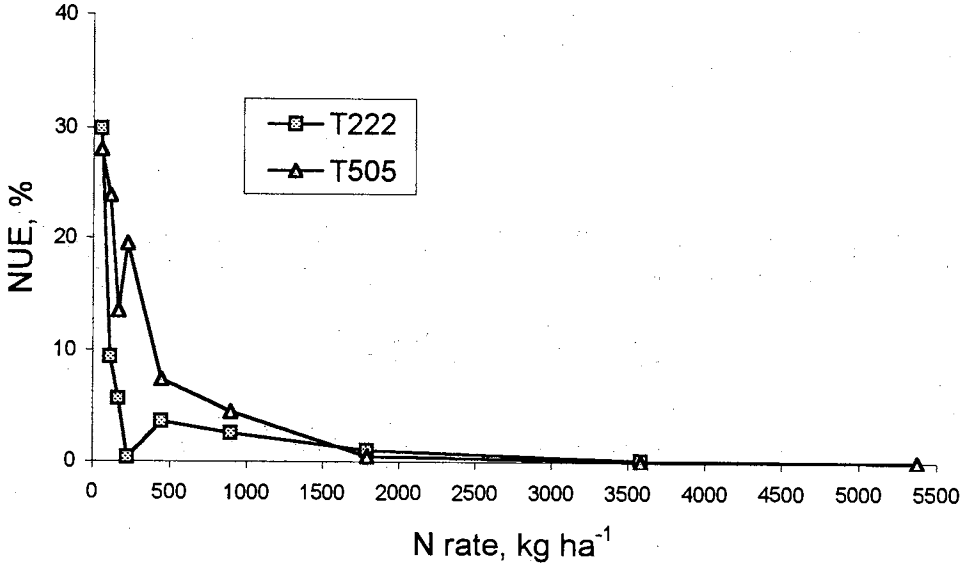


Figure 6. Effect of N rate on N use efficiency (NUE) at T222 and T505, 1996/97

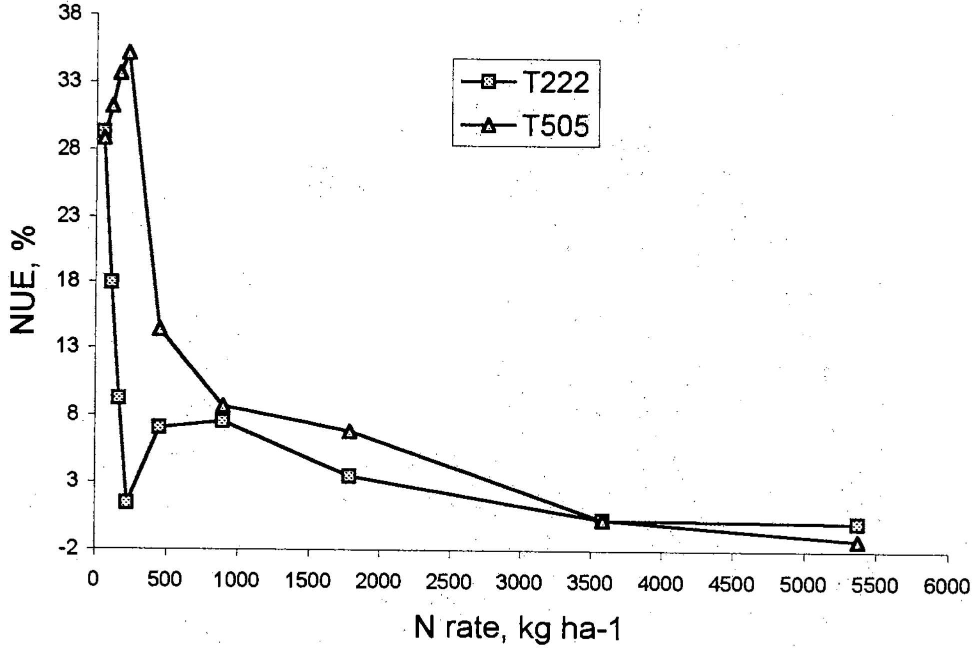


Figure 7. Effect of N rate on N accumulation efficiency (NAE) at T222 and T505, 1996/97

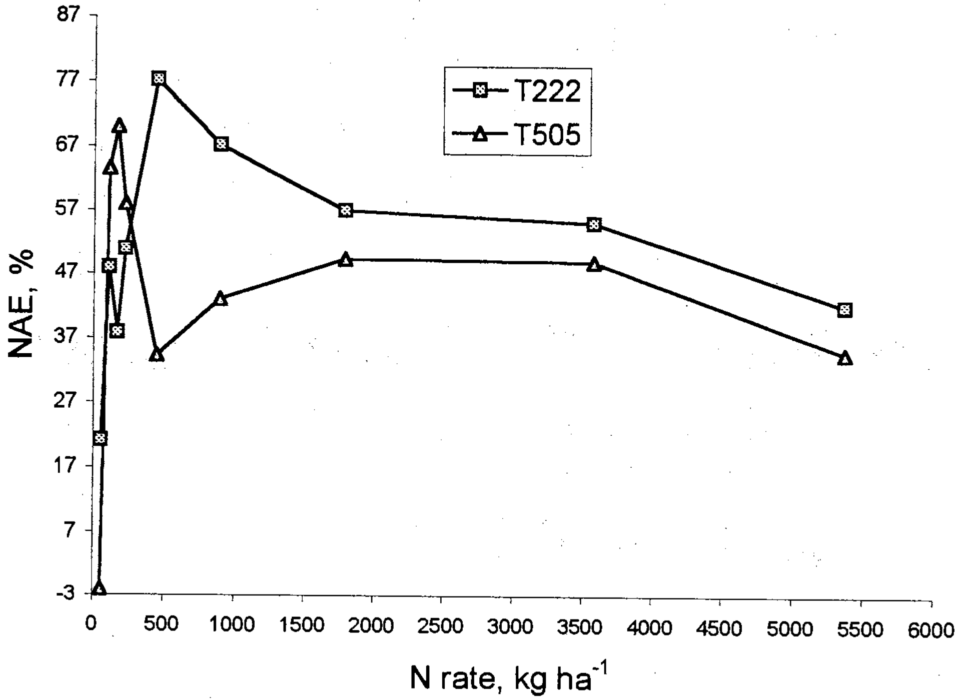


Figure 8. Distribution of organic carbon in the soil profile as influenced by N rate, T222, 1996/97

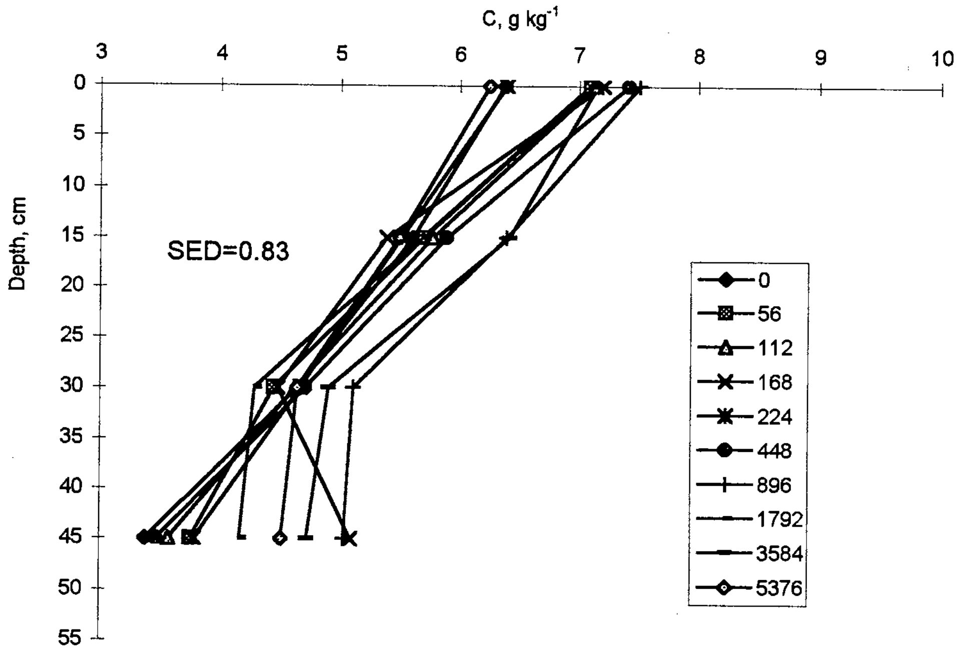


Figure 9. Distribution organic carbon in the soil profile as influenced by N rate, T505, 1996/97

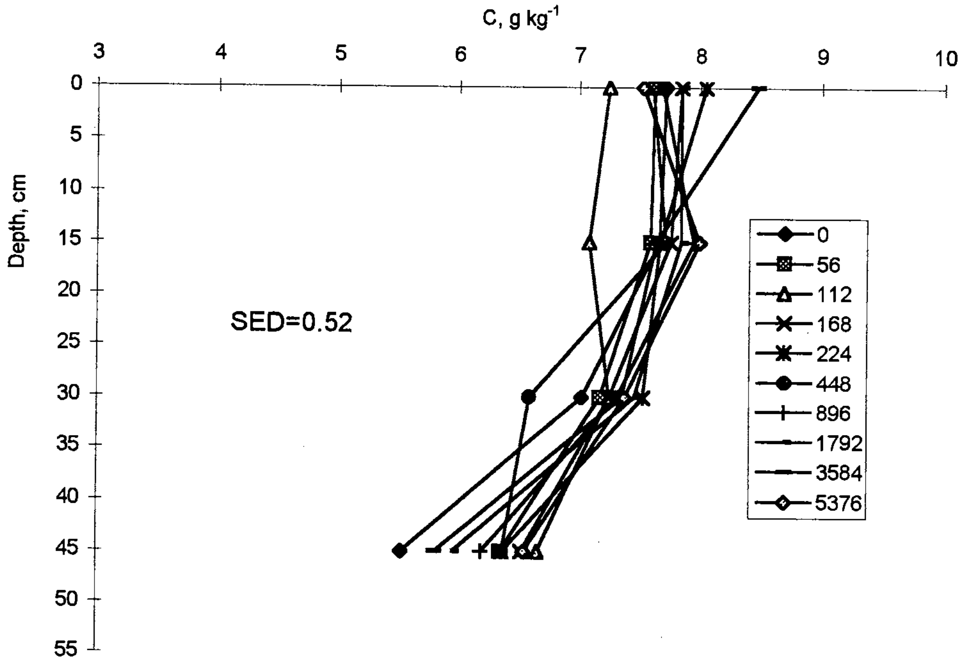


Figure 10. Distribution of total nitrogen in the soil profile as influenced by N rate, T222, 1995/96

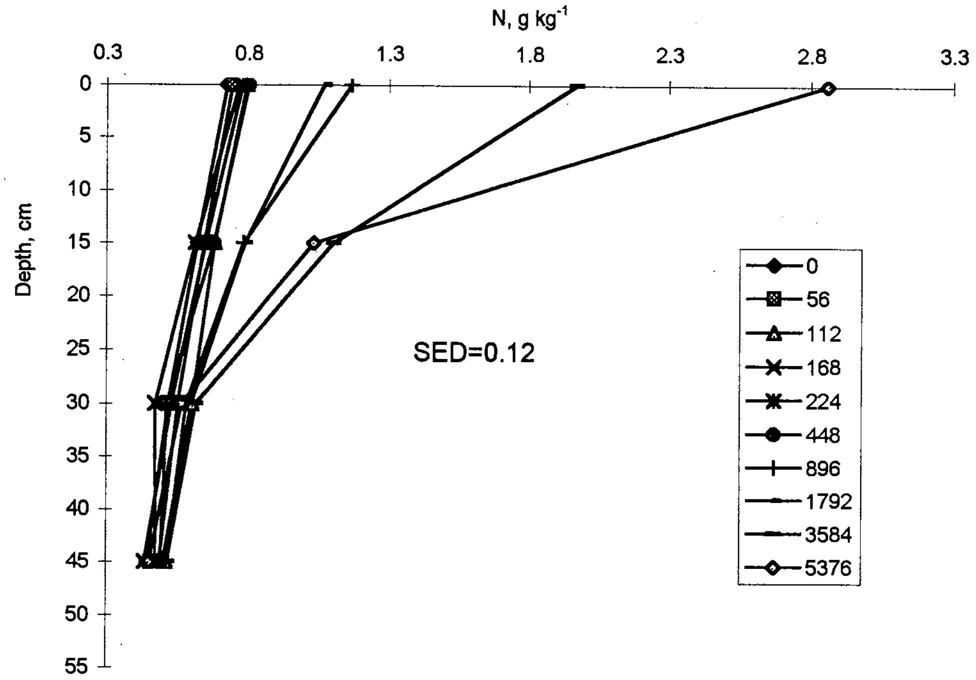


Figure 11. Distribution of total nitrogen in the soil profile as influenced by N rate, T222, 1996/97

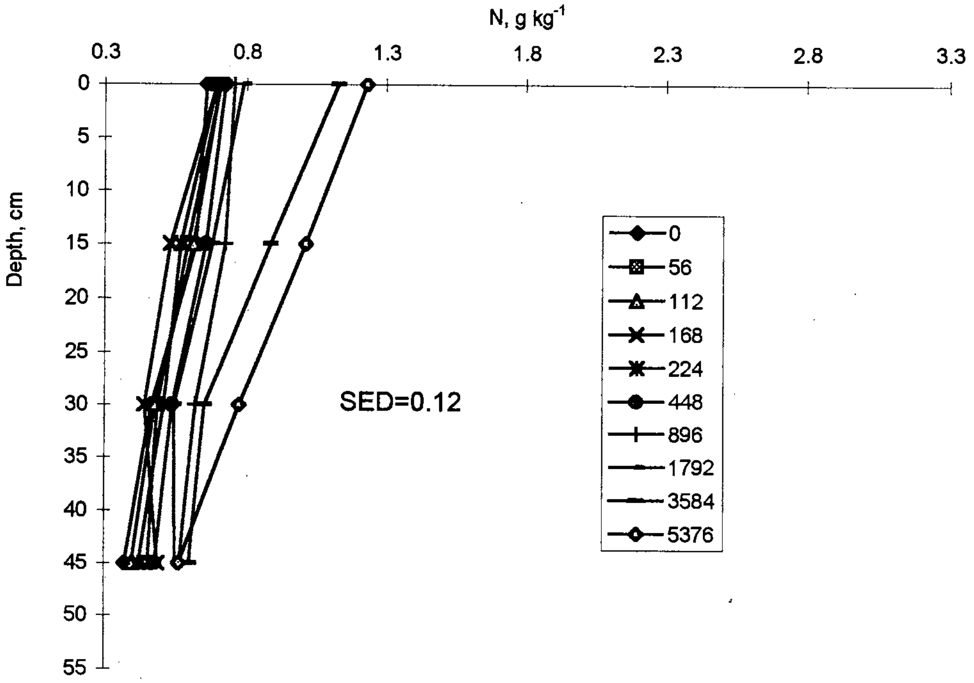


Figure 12. Distribution of total nitrogen in the soil profile as influenced by N rate, T505, 1995/96

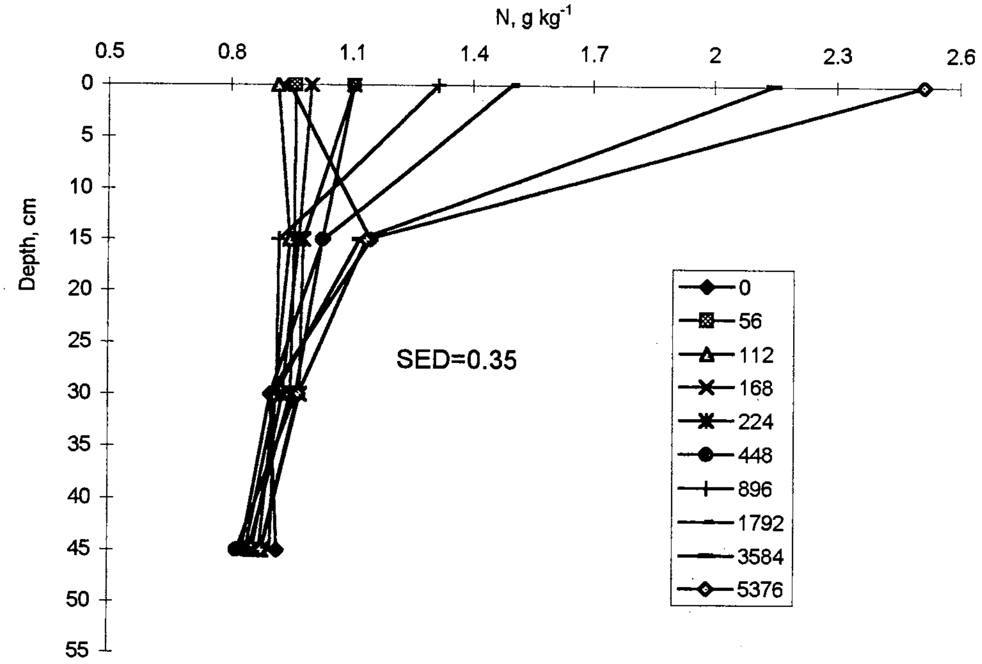


Figure 13. Distribution of total nitrogen in the soil profile as influenced by N rate, T505, 1996/97

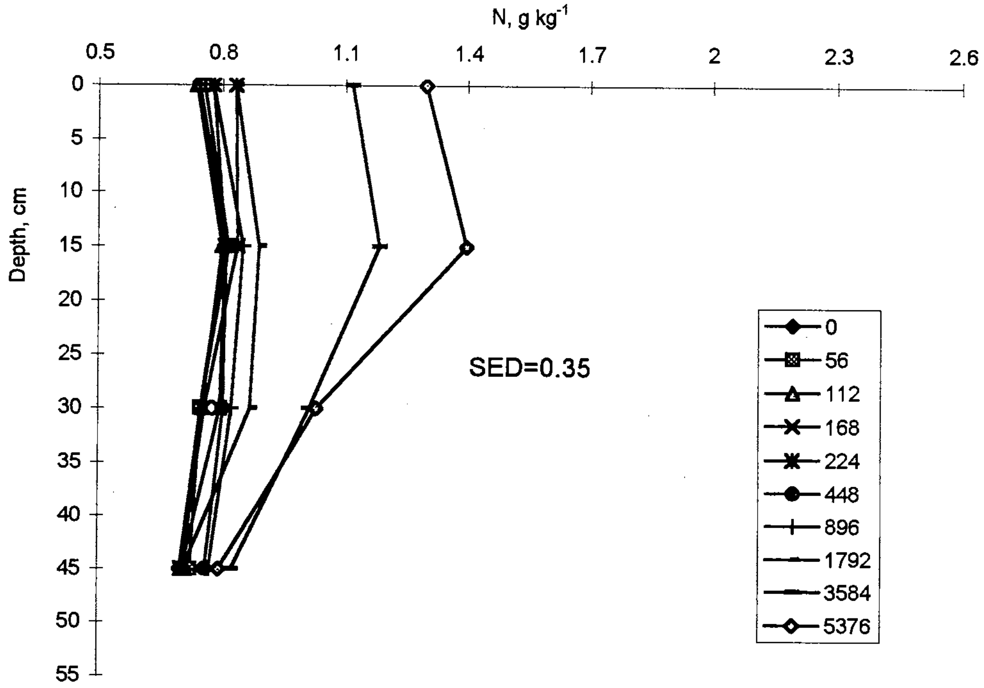


Figure 14. NO_3-N distribution in soil profile at T222, 1995/96

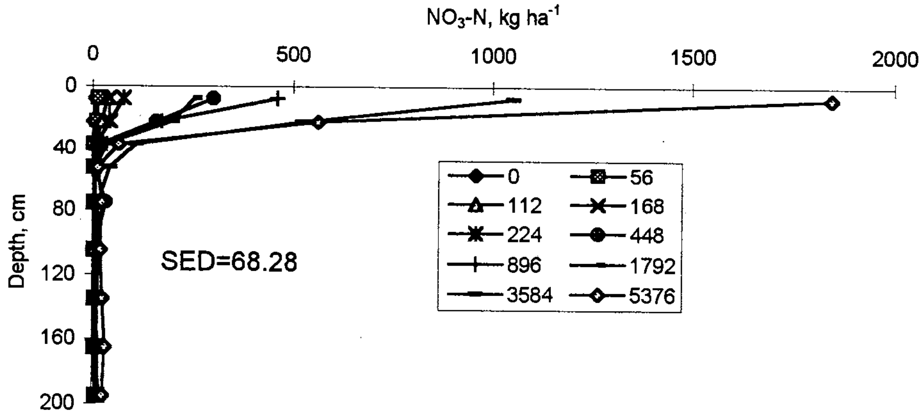


Figure 15. NH_4-N distribution in soil profile at T222, 1995/96

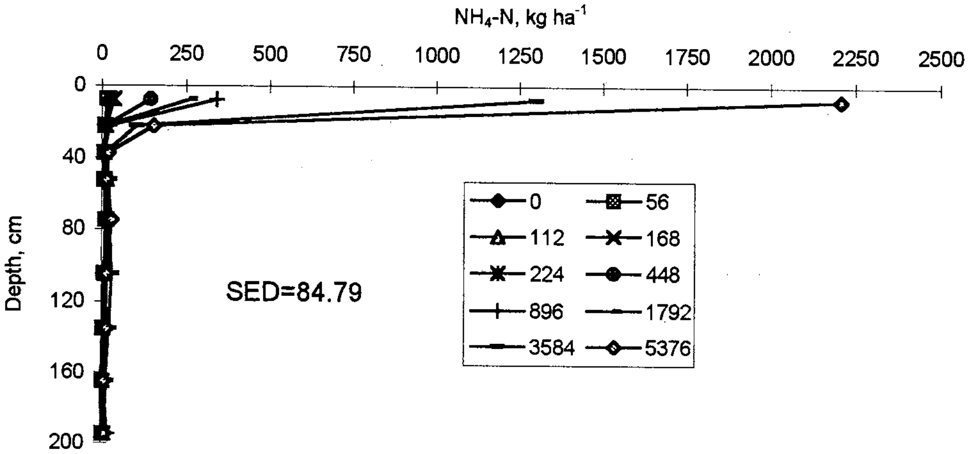


Figure 16. Total inorganic N distribution in soil profile at T222, 1995/96

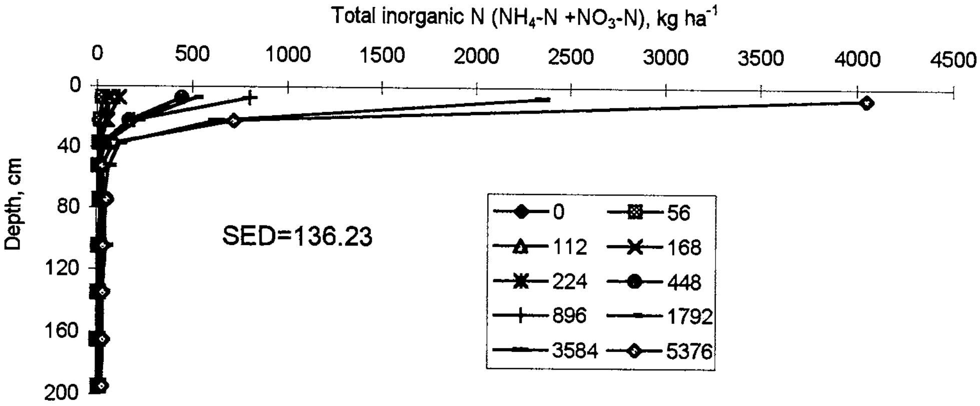


Figure 17. NO_3-N distribution in soil profile at T222, 1996/97

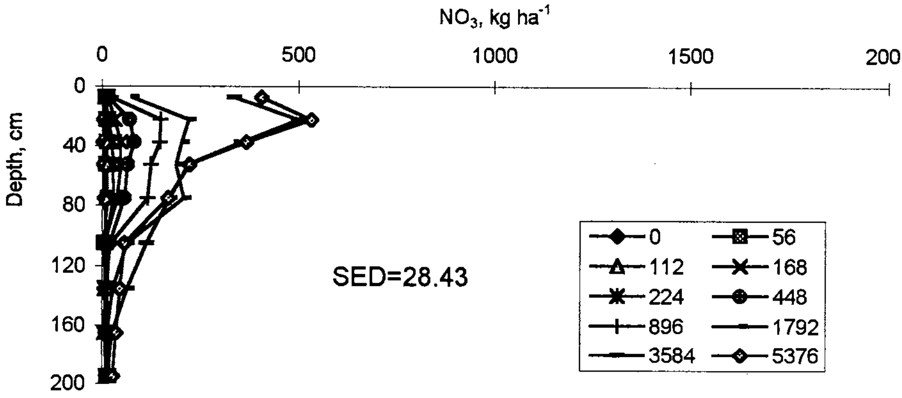


Figure 18. NH_4-N distribution in soil profile at T222, 1996-97

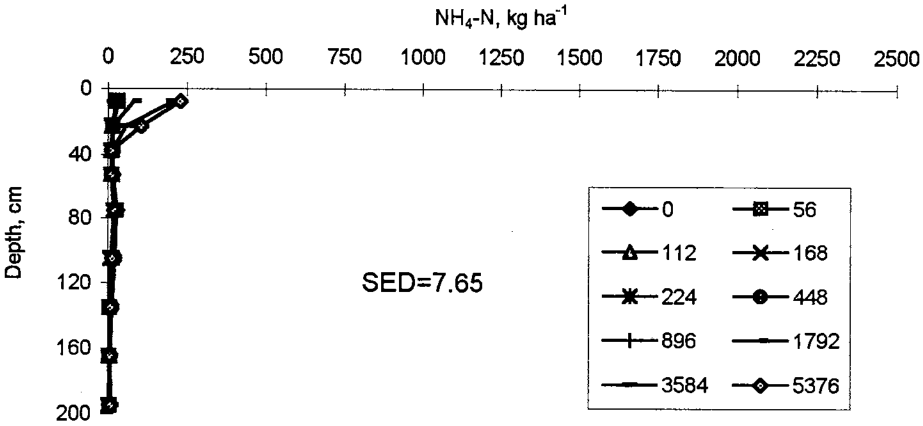


Figure 19. Total inorganic N distribution in soil profile at T222, 1996/97

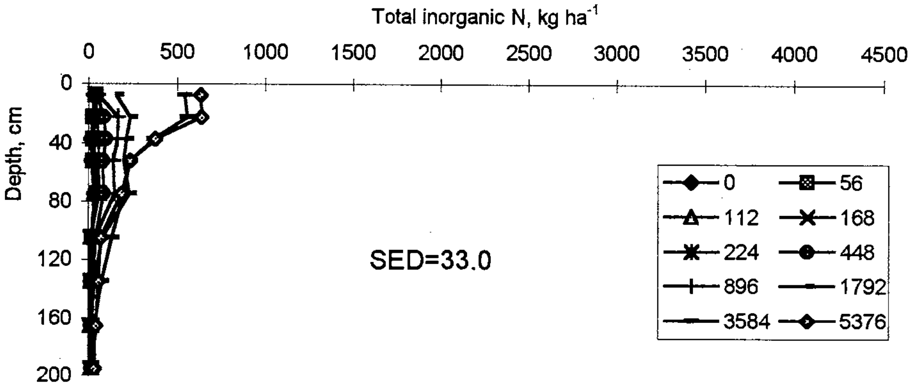


Figure 20. NO_3-N distribution in soil profile at T505, 1995/96

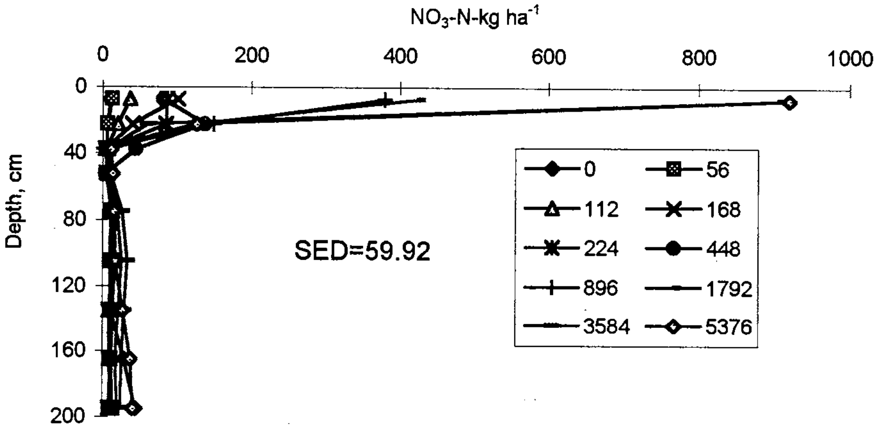


Figure 21. NH_4-N distribution in soil profile at T505, 1995/96

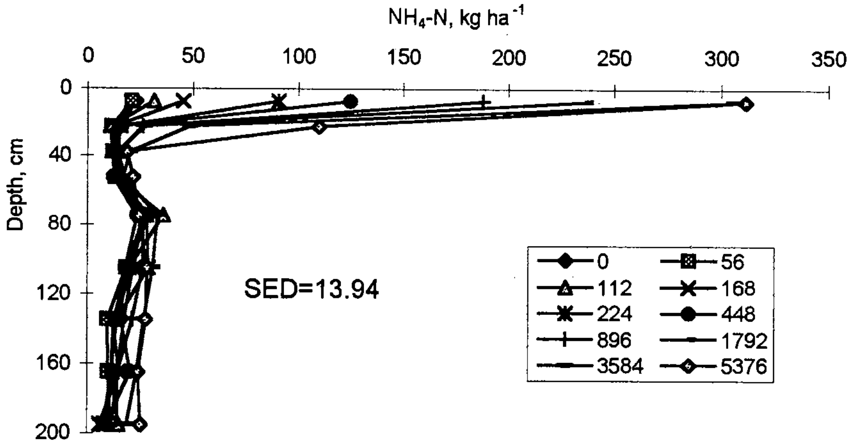


Figure 22. Total inorganic N in soil profile at T505, 1995/96

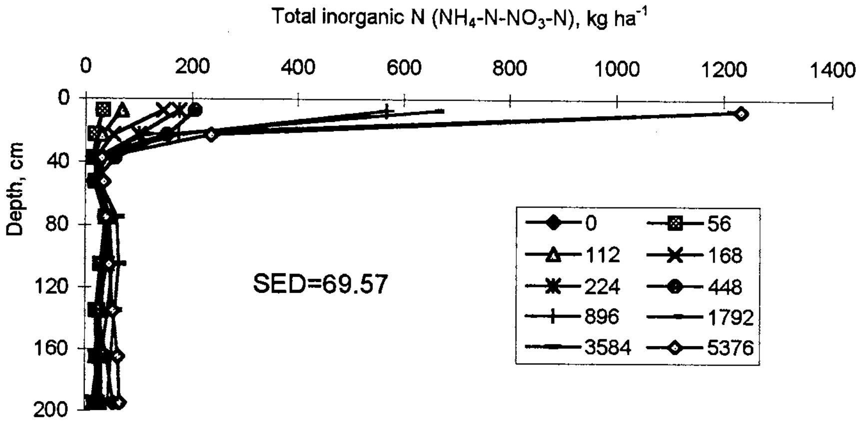


Figure 23. NO_3-N distribution in soil profile at T505, 1996/97

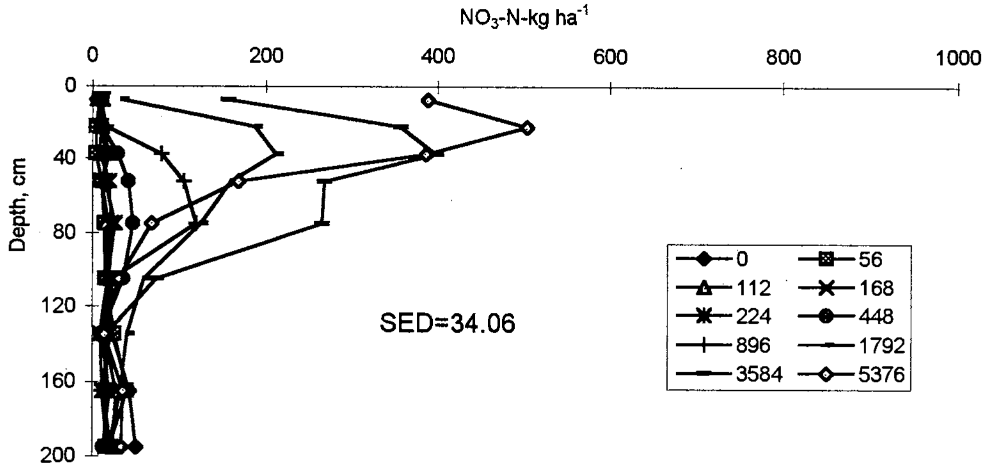


Figure 24. NH_4-N distribution in soil profile at T505, 1996/97

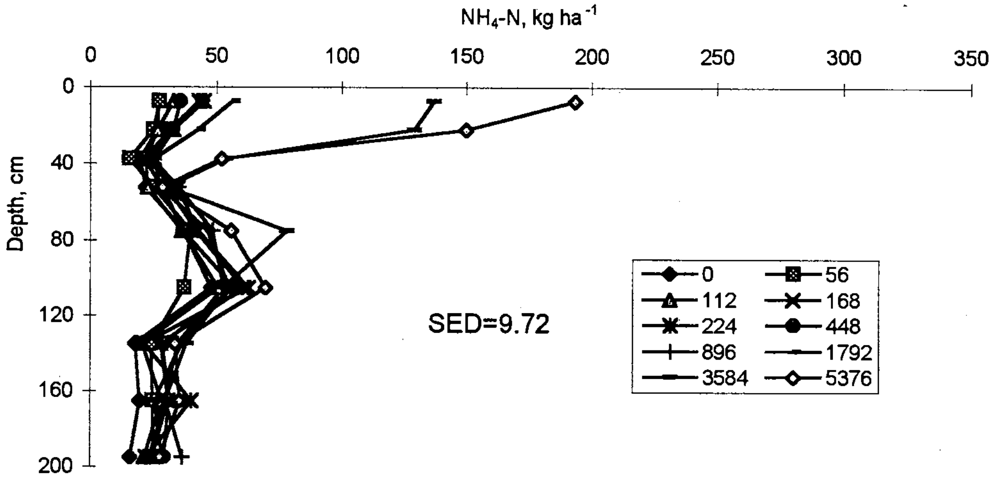
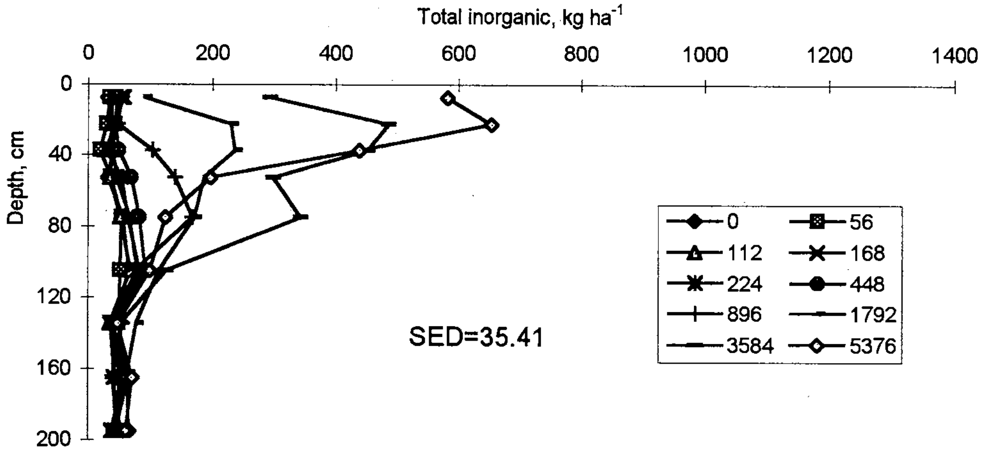


Figure 25. Total inorganic N in soil profile at T505, 1996/97



CHAPTER IV

EXTRACTABLE N USING HOT KCL AS A MINERALIZATION POTENTIAL INDEX

ABSTRACT

Inorganic nitrogen (N) in soils is a primary component of soil-plant N buffering. This study was conducted to determine if non-exchangeable NH_4-N could serve as an index of potentially mineralizable organic N which is an important sink in N buffering. Four long-term winter wheat (*Triticum aestivum* L.) experiments that receive annual fertilizer N at 0 to 272 kg N ha^{-1} were used. Soils from these experiments were extracted by four 10 ml portions of 2 M KCl at room temperature followed by extraction with 20 ml of 2 M hot KCl. Extraction at 100°C for 4 hours using 3 g soil and 20 ml 2 M KCl was found to be the most effective. Hot KCl extractable NH_4-N minus room temperature KCl extractable NH_4-N was considered non-exchangeable NH_4-N. Non-exchangeable NH_4-N was correlated with the long-term N rates, and believed to be a reliable index of potentially mineralizable organic N. The relationship was linear for NH_4-N; where the lowest N rate had the lowest extractable N. The mean non-exchangeable NH_4-N concentration ranged from 8.42 to 16.34 mg kg^{-1}; whereas, NO_3-N ranged from 0.07 to 1.87 mg kg^{-1}. Total inorganic N extracted was similar to that mineralized in a 42 day aerobic, water saturated, incubation. In addition, using a linear-plateau model, extractable NH_4-N was highly correlated with long-term average yield (R^2 =0.92). This method shows promise as a rapid measure of potentially mineralizable N.

INTRODUCTION

Mineralization of organic N is important in terms of providing crop requirements for N when fertilizer inputs are inadequate. Organic N is also a primary sink in soil-plant buffering against inorganic N accumulation. In general, there are two methods that can be used to detect mineralization potential. These are chemical indices and incubation methods (Stanford, 1982). Incubation methods have proved to be reliable but they are time consuming (Campbell et al., 1991, Franzluebbers et al., 1995). However, chemical methods can be done in a short time and may provide a quick test for assessing N-supplying capacity of the soil (Jalil et al., 1996).

A non-exchangeable N method was proposed by Silva and Bremner in 1966 (Keeney and Nelson, 1982), however, this procedure is still time consuming because samples need to settle in beakers overnight. Another method using hot 2 M KCl to extract non-exchangeable NH_4-N was proposed by Jalil et al. (1996). In a preliminary study using Oklahoma soils from long-term N fertilization trials, this method was highly correlated with historical fertilizer N rate; whereas, extraction using 2 M KCl at room temperature gave inconsistent results, unrelated to fertilization history. Pre-extraction of exchangeable NH_4-N and NO_3-N from soils using 2 M KCl increases the correlation coefficient of these parameters with fertilizer use history. This indicates that this method could be a predictor for mineralizable N. The objectives of this study were to evaluate the influence of temperature, time and soil:extractant ratios on extraction of non-exchangeable N and to determine if non-exchangeable NH_4-N could serve as an index of potentially mineralizable N.

MATERIALS AND METHODS

Method refinement

In a preliminary study, soil was used from a 27 year continuous winter wheat study Experiment 222, on a Kirkland silt loam (fine, mixed thermic, Udertic, Paleustoll) sampled on June 15, 1996. The amount of N-P-K annually applied for each N-treatment plot is 0-29-38, 45-29-38, 90-29-38 and 135-29-38. Fifteen cores of 0-15 cm soil depth were sampled from each plot and mixed to obtain a composite sample. This moist soil from each treatment was air dried and sieved through a 20 mesh screen prior to analyses of selected properties (Table 1) and stored in an air dry condition prior to KCl extractions.

Soils were initially extracted by three 10 ml portions of 2 M KCl at room temperature. Soils were weighed into 50 ml test tubes, 10 ml of 2M KCl added and the tubes closed by a lid to protect against evaporation and/or leaking. Samples were shaken for 20 minutes and then centrifuged for 3-4 minutes at 2500 RPM. The supernatant was filtered through a 8-12 μm size filter paper.

This procedure was repeated twice with the additional step of suspending the soil using a vortex mixer for a minute prior shaking the samples. The soils (3, 6, 9 and 12 g) were then extracted with 20 ml of 2 M KCl for 1, 2, 3 or 4 hours at either 100 or 110°C. The solutions collected prior to hot 2 M KCl extraction were analyzed for NH_4-N and NO_3-N. The objective of pretreatment is to make sure that NH_4-N and NO_3-N obtained from 2 M hot KCl are not from typical exchange reaction. The solution from 2 M hot KCl is then also analyzed for NH_4-N and NO_3-N.

Besides, 100 and 110°C, an attempt was also made to extract the samples at 120°C. However, this temperature was so hot that some samples boiled thus reducing the volume of the liquid; therefore, this temperature was not evaluated further. The design used in this experiment was a factorial arrangement of treatments in a randomized complete block design with 3 replications.

Method evaluation

The refined method which resulted in the best correlation between non-exchangeable NH_4-N and long-term N fertilizer rates was further evaluated using several other soils of known historical N fertilizer input. These soils were sampled on June 27, 1997 from long-term winter wheat experiments 222 (fine, mixed thermic, Udertic, Paleustoll), August 10, 1997, from 406 (Tillman-fine, mixed, thermic Typic Paleustolls; Hollister-fine, mixed, thermic Pachic Paleustolls), and June 30, 1997, from 502 and 505 (fine-silty, mixed, thermic

Udic Argiustolls). Composite soil samples were obtained from each N fertilizer treatment, sieved and stored as described for the method refinement study. Samples were extracted four times with 2 M KCl according to the procedure at the preliminary study at room temperature. The fourth sequential extraction at room temperature was included to examine whether soils were free from NH_4-N and NO_3-N. Non exchangeable N was then extracted for four hours at 100°C using 3 g soil and 20 ml 2 M KCl. Additional soil characteristics of this long-term experiment are reported in Table 2.

An automated flow injection analysis system was used for analysis of NH_4-N and NO_3-N (Lachat, 1990); whereas total inorganic N was determined by adding NH_4-N and NO_3-N. The design used in this experiment was a randomized complete block with 3 replications. Statistical analysis was performed using SAS (SAS Institute, 1988).

RESULTS AND DISCUSSION

Method Refinement

Analysis of variance for room temperature extraction of NH_4-N, NO_3-N, and total inorganic N (NH_4-N + NO_3-N) as affected by amount of soil, extraction time, temperature and fertilizer rate is reported in Table 3. Main effects of soil weight and nitrogen rate were both significant, however, the presence of an interaction between soil weight and nitrogen rate on extractable NH_4-N, NO_3-N, and total inorganic N restricted evaluation of main effects. Mean values for the interaction between soil weight and nitrogen rate with total inorganic N, NH_4-N, and NO_3-N are presented in Figures 1, 2 and 3. The higher the ratio of soil to solution in the extraction, the lower amount of exchangeable N was extracted. This indicates that increasing the soil:solution ratio decreases the effectiveness of KCl to extract NH_4-N and NO_3-N. The highest amount of NH_4-N, and NO_3-N was extracted using a ratio of 3 g soil to 20 ml KCl (6.7:1 solution:soil ratio).

From the method that was finally used, a fourth sequential extraction was performed and it was found that no NH_4-N was present (Figures 4, 5, 6, and 7). This indicated that exchangeable NH_4-N was completely extracted from exchange sites by this extraction. Therefore all NH_4-N obtained from the hot KCl extractant was from non-exchangeable sources. Nitrate-N was always present but in very small amounts.

The AOV for hot KCl extractable NH_4-N, NO_3-N and total inorganic N is reported in Table 4. In addition, the graphs of the interactions between N rate and soil on NH_4-N, NO_3-N and total inorganic N are presented in Figures 8, 9 and 10, respectively; between N rate and time on NH_4-N and NO_3-N in Figures 10 and 11. Nitrogen rate was used as the independent variable to determine the relationship of extractable NH_4-N, NO_3-N, and total inorganic N with fertilizer use history. Fertilizer has been applied for 27 years to this soil; therefore, the hot KCl extractable inorganic N should be related to the rate of fertilizer applied if it is related to mineralizable N potential.

From Figures 8 and 11, it was found that 3 g soil provided the best relationship of extractable NH_4-N with historical N rate. In general, increasing the soil:solution ratio increased the amount of ammonium that could be extracted.

However, since the best relationship (R^2) of N rates to hot KCl extractable NH_4-N, NO_3-N, and total inorganic N was at a soil weight of 3 g, this weight was selected for future extraction (Table 5).

From analysis of variance in Table 4, it was found that there was no interaction between N rate and temperature for extractable NH_4-N or total inorganic N. However, this was significant for NO_3-N. Although there were small differences between the 100 and 110°C temperature, at 110°C there was consistently more NH_4-N and NO_3-N. Figures 14, 15 and 16 illustrate the influence of N rate and hot KCl extraction time on NH_4-N, NO_3-N and total inorganic N. The amount of extractable NH_4-N, NO_3-N and total inorganic N was related to N rate using the 3 and 4 hour time periods. This suggested that a 3 hour extraction time was the minimum time to be used.

Effectiveness of the method (variable soil weight, temperature and time) was examined by comparison of R^2 for the appropriate relationships (Table 5). It was found that the 3 g, 110°C, 3 hour combination could be used (Figures 13, 14, and 15). In addition, 100°C was easier to handle because it is below the boiling point of water. On the basis of these studies and for practical reasons, extraction of 3 g soil at 100°C for 4 hours is suggested to determine extractable NH_4-N as an index of potentially mineralizable N (Table 5 and Figures 16, 17, and 17).

To verify the method, initial data were selected for analyses. The AOV of NH_4-N and NO_3-N and total inorganic N using the selected method (100°C, 3 g soil and 4 hour) is presented in Table 6. It was found that N rate had a positive linear effect on hot KCl extractable N (NH_4-N, NO_3-N, and total inorganic N). The NH_4-N concentration ranged from 4.64 to 6.13 mg kg^{-1}; whereas, NO_3-N ranged from 0.58 to 0.78 mg kg^{-1}. Total inorganic N extracted was similar to that mineralized in a 42 day aerobic, water saturated, incubation (Sembiring, et al., 1995).

Extractable N using the selected method on soils from long-term N rate experiments

Analysis of variance for NH_4-N and NO_3-N and total inorganic N using the selected method (100°C, 3 g soil and 4 hour) on long-term winter wheat experiments 222, 406, 502 and 505 are reported in Tables 7-8. Treatment means are illustrated for NH_4-N, NO_3-N, and total inorganic N in Figures 19, 20, 21 and 22, respectively. It was interesting to find that the results were still consistent with the previous results except for Experiment 406. The different response for Experiment 406 may have been due to different time of sampling, as samples were taken after the land was already cultivated. In other experiments (experiments 222, 502 and 505), soil samples were taken immediately after grain harvest. This condition may have resulted in some change in the nitrogen normally available for mineralization.

The effect of N rate on extractable NH_4-N was significant and the trend was linear; however, significant differences in NO_3-N were detected for Experiment 222. In addition, the magnitude of response was not as large as previously reported. It is suspected that these differences may be related to difference in time of sampling the soils (June 15, 1996 compared to June 27, 1997). This indicates that time of sampling may be critical in determining non-exchangeable extractable N. Research dealing with time of sampling in relation to extractable N and yield might be important for further study.

It was of interest to find that extractable N (NH_4-N, NO_3-N and total inorganic N) was not correlated with total N and the C/N ratio (Figures 23-28). This suggested that total nitrogen which includes many N compounds might not release readily available N for crop growth (e.g., lignin). In addition, correlation of N rate with extractable NH_4-N and NO_3-N over all experiments was performed (Figure 29). No relationship was found between N rate and extractable N (NH_4-N and NO_3-N). This finding suggested that the relationship of non-exchangeable N and N rate is location sensitive.

Extractable nitrogen and grain yield

Hot KCl extractable nitrogen and long-term average grain yield obtained from Westerman et al., (1993) was evaluated using linear-plateau models (Figures 30-32). Extractable NH_4-N was highly correlated with yield ($R^2 = 0.92$, Figure 30). However, using NO_3-N and total inorganic N the R^2 was much lower (0.57 and 0.65 for NO_3-N and total inorganic N, respectively). This indicates that long-term yields are related to long-term N fertilizer rates, and the method has potential for predicting residual N related to long-term fertilizer rates.

CONCLUSIONS

Extraction at 100°C for 4 hours using 3 g soil and 20 ml 2 M KCl was the most effective extraction of the combinations tested. Non-exchangeable NH_4-N was highly correlated with the long-term fertilizer N rates, believed to be associated with mineralizable organic N. The relationship was positive and linear for total inorganic N, NH_4-N and NO_3-N; where the lowest N rate had the lowest extractable N. Total inorganic N extracted was similar to that mineralized in a 42 day aerobic, water saturated, incubation. In addition, grain yield was highly correlated with extractable NH_4-N. This method shows promise as a rapid measure of potentially mineralizable N. Future research examining time of sampling may be useful to improve the indexing of potentially mineralizable N.

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Table 1. Initial surface (0 - 15cm) soil test characteristics Experiment 222, Stillwater OK at different N application rates

			Treatment			
Characteristics	Extractant	Unit	0-29-38	45-29-38	90-29-38	135-29-38
pH	1:1 soil:H_2O		5.76	5.49	5.47	5.38
Organic Carbon[ω]	Dry Combustion	g kg^{-1}	6.15	6.16	6.14	6.48
Total Nitrogen[ω]	Dry Combustion	g kg^{-1}	0.79	0.75	0.75	0.84
NH_4-N[Π]	2 M KCl	mg kg^{-1}	3.62	4.56	9.93	8.16
NO_3-N[Π]	2 M KCl	mg kg^{-1}	0.42	0.44	0.85	1.09
P[Ψ]	Mehlich 3.	mg kg^{-1}	81.01	62.02	66.00	56.01
K[Ψ]	Mehlich 3.	mg kg^{-1}	43.01	45.01	32.00	32.02

[Π] Lachat instruments (1989), [ω]Schepers et al. (1989), [Ψ] Mehlich (1984)

Table 2. Soil characteristics and yield from experiments 222, 406, 502 and 505

Experiment	222	406	502	505
Location	Stillwater	Altus	Lahoma	Lahoma
Year established*	1969	1965	1970	1970
Soil sampled	June 27, 1997	August 10, 1997	June 30, 1997	June 30, 1997
Annual rainfall, mm*	817	611	821	821
Soil type*	Kirkland silt loam	Tillman-Hollister clay loam	Grant silt loam	Grant silt loam
Grain mean, Mg ha^{-1} *	1.81	1.91	2.48	2.40
N rate, kg ha^{-1}	pH	Organic C, g kg^{-1}	Total N, g kg^{-1}	C:N ratio
Experiment 222	Means			
0-29-38	6.01	8.051	0.922	8.84
45-29-38	5.68	10.273	1.231	8.32
90-29-38	5.46	8.392	0.912	9.19
135-29-38	5.32	9.591	1.151	8.34
SED	0.27	1.642	0.182	0.19
Experiment 406				
0-0-0	7.23	7.022	0.752	9.40
45-20-0	7.37	7.781	0.771	10.17
90-20-38	7.19	7.104	0.751	9.50
135-20-38	6.90	7.702	0.922	8.33
180-20-38	7.31	7.291	0.831	8.79
SED	0.33	0.362	0.051	0.48
Experiment 502				
0-20-0	5.75	8.822	0.982	9.08
22-0-0	5.73	8.113	0.941	8.83
44-20-0	5.62	10.182	1.082	9.46
66-20-0	5.49	8.011	0.895	8.94
88-20-0	5.42	8.162	0.882	9.27
110-20-0	5.34	7.525	0.822	9.22
SED	0.17	1.934	0.232	0.30
Experiment 505				
0-29-56	6.07	7.852	0.842	9.34
34-29-56	5.41	7.515	0.825	9.30
68-29-56	5.46	7.344	0.902	8.55
136-29-56	5.18	7.653	0.822	9.37
272-29-56	4.49	5.002	0.603	8.14
SED	0.27	1.541	0.212	1.19

*Westerman et al. (1993)

SED = standard error of the difference between two equally replicated means

Table 3. Analysis of variance for NH_4-N, NO_3-N and total inorganic-N (NH_4-N +NO_3-N) from extractable 2M KCl at room temperature

Source of variation	df	NH_4-N	NO_3-N	NH_4-N +NO_3-N
		---------------Mean squares-----------		
Rep	2	1.093	0.00	1.10
N rate	3	403.52***	6.63***	458.50***
Soil	3	426.35	5.77***	520.23***
N rate*Soil	9	21.02***	0.21***	22.89***
Error	414	0.98	0.11	1.02
CV, %		19.1	25.3	17.9
Nrate*soil		----------Means, mg kg-1 -------------		
N0*3g soil		4.14	0.61	4.75
N0*6g soil		3.85	0.31	4.16
N0*9g soil		2.91	0.22	3.13
N0*12g soil		1.79	0.18	1.97
N45*3g soil		5.09	0.60	5.70
N45*6g soil		4.98	0.32	5.30
N45*9g soil		3.48	0.22	3.70
N45*12g soil		1.94	0.16	2.11
N90*3g soil		10.03	0.62	10.65
N90*6g soil		8.98	0.33	9.31
N90*9g soil		5.96	0.23	6.19
N90*12g soil		3.54	0.17	3.71
N135*3g soil		8.62	1.24	9.86
N135*6g soil		8.21	0.93	9.15
N135*9g soil		5.76	0.71	6.47
N135*12g soil		3.30	0.42	3.72
SED		0.27	0.03	0.27

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively, df = degrees of freedom,
SED = standard error of the difference between two equally replicated means,
N0, N45, N90 and N135 = annual N application rates of 0, 45, 90 and 135 kg N ha^{-1}

Table 4. Analysis of variance for NH_4-N, NO_3-N and total inorganic-N (NH_4-N +NO_3-N) from hot extractable 2M KCl

Source of variation	df	NH_4-N	NO_3-N	NH_4-N +NO_3-N
		---------------------------Mean squares------------------------		
Rep	2	5.77*	0.01	6.20*
Temperature	1	634.50***	0.73*	678.42***
N rate	3	134.47***	1.67***	157.05***
Soil	3	206.30***	2.04***	173.18***
Nrate*soil	9	5.69***	0.14***	6.46***
Nrate*temp	3	2.85	0.05***	3.43
Soil*temp	3	8.20**	0.01	8.66*
Nrate*soil*temperature	9	0.99	0.00	0.97
Time	3	327.48***	0.08***	323.01***
Nrate*time	9	3.52**	0.04***	4.18**
Time*soil	9	13.23***	0.04***	12.81***
Time*temperature	3	7.48***	0.23***	5.54**
Nrate*time*soil	27	2.14*	0.01***	2.35
Nrate*time*temperature	9	2.09	0.01	2.24
Time*soil*temp	9	2.06	0.03***	2.26
Nrate*time*soil*temperature	27	2.37**	0.01**	2.51**

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively. df = degrees of freedom

Table 5. Coefficients of determination (R^2) for hot KCl extractable NH_4-N, NO_3-N, and total inorganic N with historical fertilizer N rates using different weights of soil, temperature and time

Variables	3 g soil	9 g soil
110°C and 3 hours	R^2	R^2
NH_4-N vs. N rate	0.83	0.38
NO_3-N vs. N rate	0.90	0.70
NH_4-N + NO_3-N vs. N rate	0.86	0.41
110°C and 4 hours		
NH_4-N vs. N rate	0.77	0.78
NO_3-N vs. N rate	0.85	0.67
NH_4-N +NO_3-N vs. N rate	0.78	0.82
100°C and 3 hours		
NH_4-N vs. N rate	0.13	0.46
NO_3-N vs. N rate	0.02	0.85
NH_4-N + NO_3-N vs. N rate	0.13	0.53
100°C and 4 hours		
NH_4-N vs. N rate	0.85	0.49
NO_3-N vs. N rate	0.82	0.68
NH_4-N + NO_3-N vs. N rate	0.87	0.52

Table 6. Analysis of variance for NH_4-N, NO_3-N and total inorganic-N (NH_4-N +NO_3-N) from extractable 2M KCl using 3 g, 100°C and 4 hour in method refinement

Source of variation	df	NH_4-N	NO_3-N	NH_4-N +NO_3-N
		-----------Mean squares-----------------		
Rep	2	0.04	0.02	0.05
N rate	3	1.34	0.02***	1.70**
Error	6	0.09	0.00	0.10
CV, %		5.6	4.8	5.3
Contrasts:				
N rate linear	1	3.98**	0.06***	5.06***
N rate quadratic	1	0.00	0.01	0.00
N rate, kg ha^{-1}		--------------Means, mg kg^{-1} -----------		
0		4.64	0.58	5.22
45		5.09	0.60	5.69
90		5.76	0.66	6.42
135		6.13	0.78	6.91
SED		0.25	0.03	0.26

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
SED = standard error of the difference between two equally replicated means
df = degrees of freedom

Table 7. Analysis of variance for NH_4-N, NO_3-N and total inorganic-N (NH_4-N +NO_3-N) from extractable 2M KCl of experiments 222 and 406 using the 3 g, 100°C, 4 hour method

Source of variation	df	NH_4-N	NO_3-N	NH_4-N +NO_3-N
Experiment 222		-----------------------	---Mean squares---	-----------------------
Rep	2	1.16	0.01	1.03
N rate	3	2.89*	0.02	3.28
Error	6	0.82	0.01	0.98
CV, %		9.5	73.4	10.2
R^2		0.69	0.56	0.67
R^2 from means		0.98	0.61	0.99
Contrasts:				
N rate linear	1	8.51*	0.04	9.72*
N rate quadratic	1	0.06	0.03	0.01
	N rate, kg ha^{-1}	-----------------------	---Means, mg kg^{-1}---	-----------------------
	0	8.42	0.10	8.52
	45	9.15	0.05	9.20
	90	10.14	0.12	10.27
	135	10.60	0.25	10.85
	SED	0.74	0.08	1.40
Experiment 406		-----------------------	---Mean squares---	-----------------------
Rep	2	9.24	6.45	28.10
N rate	4	21.46	1.96	33.81
Error	8	12.23	1.78	21.48
CV, %		29.6	132.9	36.2
R^2		0.52	0.59	0.53
R^2 from means		0.13	0.21	0.16
Contrasts:				
N rate linear	1	10.88	1.67	21.08
N rate quadratic	1	17.25	3.95	37.71
	N rate, kg ha^{-1}	-----------------------	---Means, mg kg^{-1}---	-----------------------
	0	10.44	0.21	10.65
	45	9.90	0.41	10.31
	90	12.04	1.87	13.91
	135	16.34	1.87	18.22
	180	10.23	0.66	10.89
	SED	2.85	1.09	3.78

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively,
SED = standard error of the difference between two equally replicated means,
df = degrees of freedom

Table 8. Analysis of variance for NH_4-N, NO_3-N and total inorganic-N (NH_4-N +NO_3-N) from extractable 2M KCl of experiments 502 and 505 using the 3 g, 100°C, 4 hour method

Source of variation	df	NH_4-N	NO_3-N	NH_4-N +NO_3-N
Experiment 502		----------Mean squares----------		
Rep	2	19.72**	0.11	22.66**
N rate	3	4.69*	0.09	5.95*
Error	6	1.47	0.04	1.83
CV, %		11.1	65.9	12.0
R^2		0.81	0.61	0.80
R^2 from means		0.71	0.86	0.74
Contrasts:				
N rate linear	1	16.58**	0.38*	22.01**
N rate quadratic	1	0.07	0.00	0.08
	N rate, kg ha^{-1}	----------Means, mg kg^{-1} ----------		
	0	9.40	0.08	9.48
	22	10.25	0.18	10.44
	44	10.66	0.36	11.01
	66	11.74	0.32	12.06
	88	10.52	0.35	10.87
	110	12.96	0.58	13.54
	SED	0.99	0.17	1.10
Experiment 505		----------Mean squares----------		
Rep	2	1.48	0.14	2.43
N rate	4	1.33	0.79**	4.00
Error	8	3.44	0.08	3.92
CV, %		13.83	40.9	14.01
R^2		0.23	0.84	0.40
R^2 from means		0.94	0.94	0.98
Contrasts:				
N rate linear	1	5.01	2.96***	15.68*
N rate quadratic	1	0.18	0.02	0.09
	N rate, kg ha^{-1}	----------Means, mg kg^{-1} ----------		
	0	12.96	0.57	13.02
	34	12.90	0.57	13.47
	68	13.29	0.59	13.89
	136	13.39	0.81	14.20
	272	14.55	1.48	16.03
	SED	1.51	0.23	1.62

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
SED = standard error of the difference between two equally replicated means,
df = degrees of freedom

Figure 1. Effect of N rate and soil weight on total inorganic N extracted at room temperature, Experiment 222

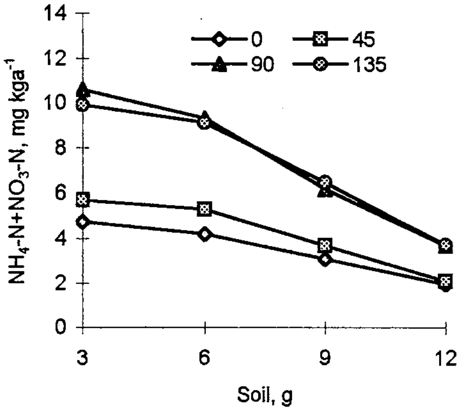


Figure 2. Effect of N rate and soil weight on NH_4-N extracted at room temperature, Experiment 222

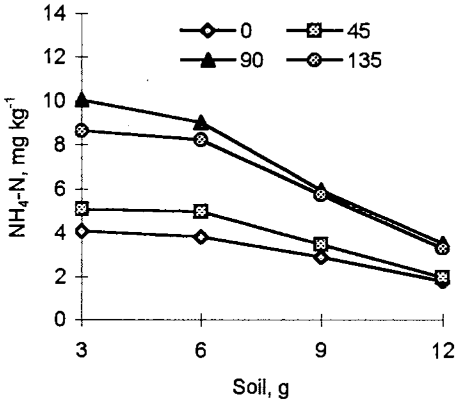


Figure 3. Effect of N rate and soil weight on NO_3-N extracted at room temperature, Experiment 222

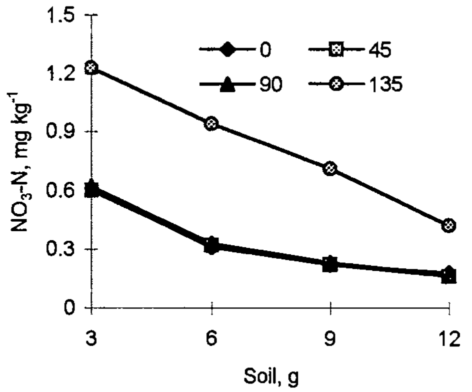


Figure 4. Extractable N from the fourth sequential extraction, Experiment 222

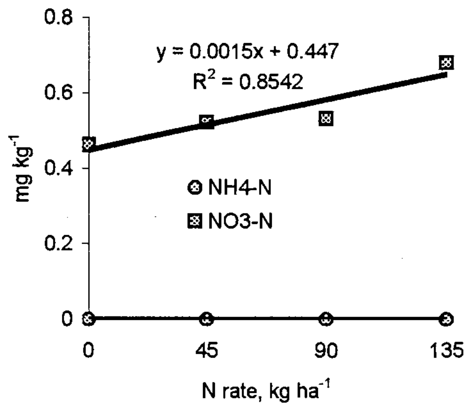


Figure 5. Extractable N from the fourth sequential extraction, Experiment 406

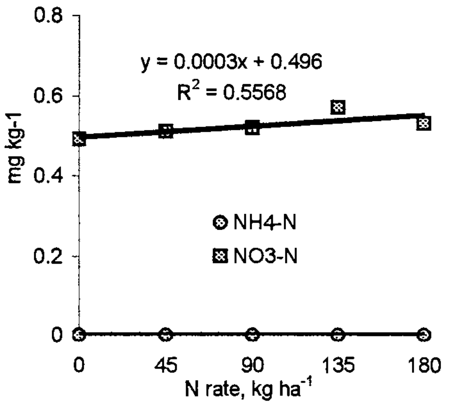


Figure 6. Extractable N from the fourth sequential extraction, Experiment 502

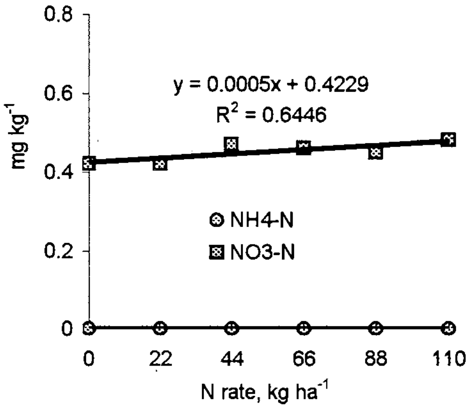


Figure 7. Extractable N from the fourth sequential extraction, Experiment 505

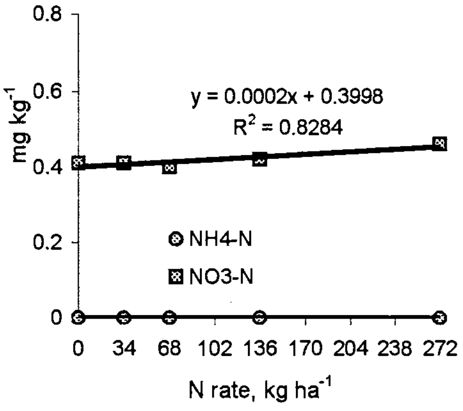


Figure 8. Effect of N rate and soil weight on hot KCl extractable NH_4-N, Experiment 222

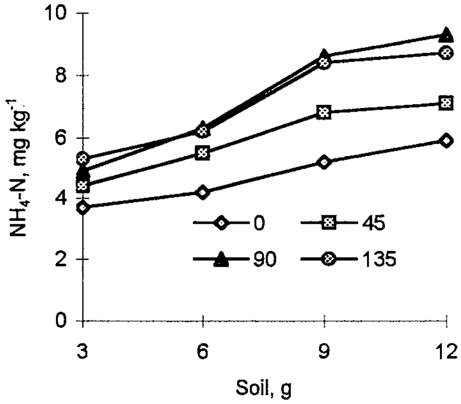


Figure 9. Effect of N rate and soil weight on hot KCl extractable NO_3-N, Experiment 222

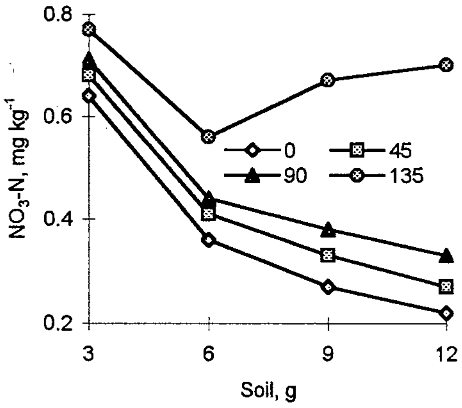


Figure 10. Effect of N rate and soil weight on hot KCl extractable total inorganic N, Experiment 222

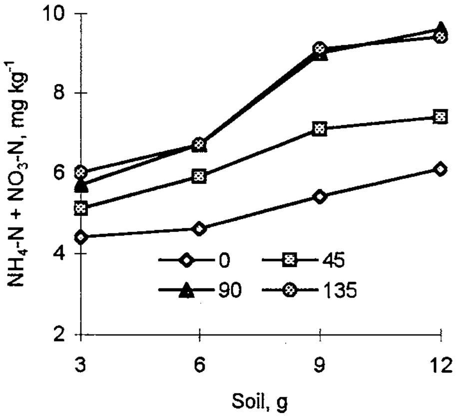


Figure 11. Effect of time and N rate on hot KCl extractable NH_4-N, Experiment 222

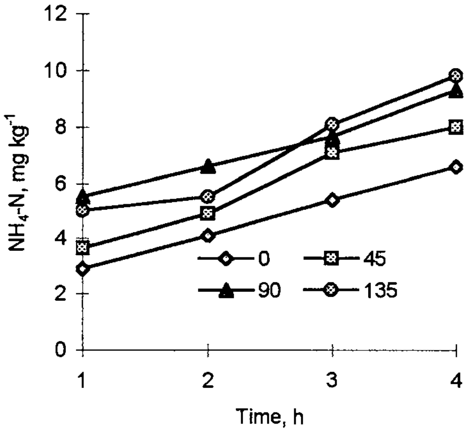


Figure 12. Effect of time and N rate on hot KCl extractable NO_3-N, Experiment 222

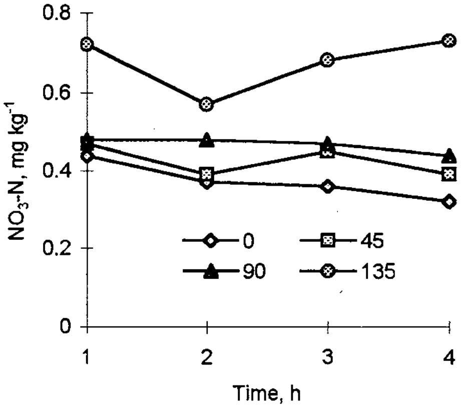


Figure 13. Response of hot KCl extractable NH_4-N to 27 year N rate at 3g, 110°C and 3 hour, Experiment 222

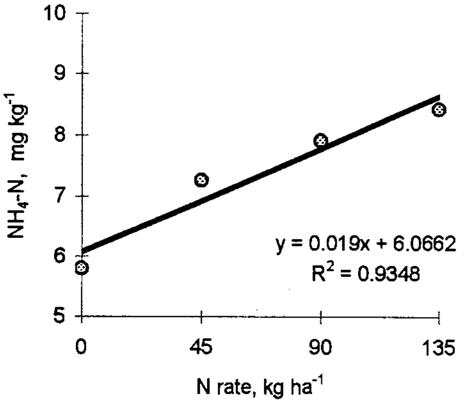


Figure 14. Response of hot KCl extractable NO_3-N to 27 year N rate at 3g, 110°C and 3 hour, Experiment 222

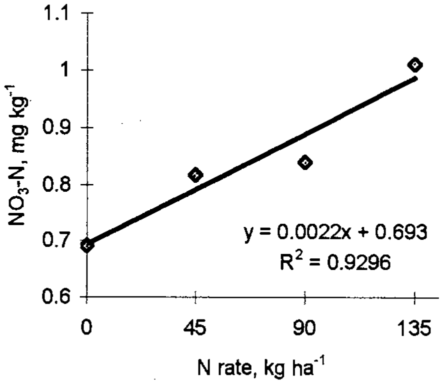


Figure 15. Response of hot KCl extractable total inorganic N to 27 year N rate at 3 g, 110°C and 3 hour, Experiment 222

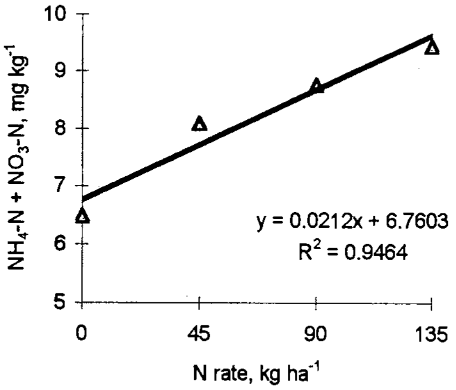


Figure 16. Response of hot KCl extractable NH_4-N to 27 year N rates using 3g, 100°C and 4 hour, Experiment 222

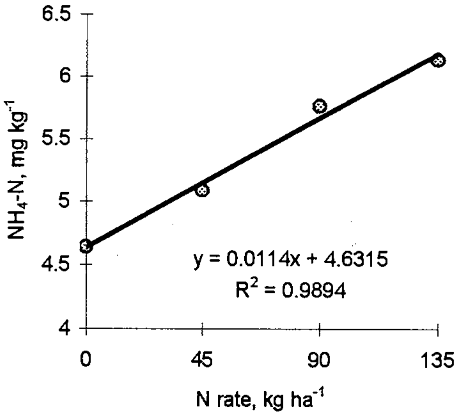


Figure 17. Response of hot KCl extractable NO3-N to 27 year N rates using 3g, 100°C and 4 hour, Experiment 222

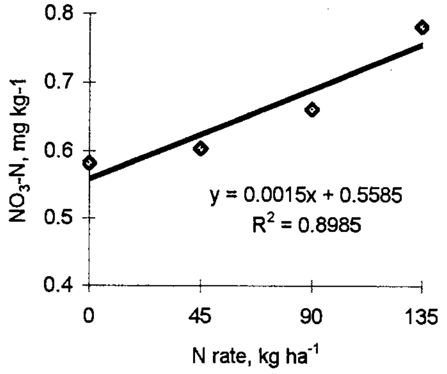


Figure 18. Response of hot KCl extractable total inorganic N to 27 year N rates using 3g, 100°C and 4 hour, Experiment 222

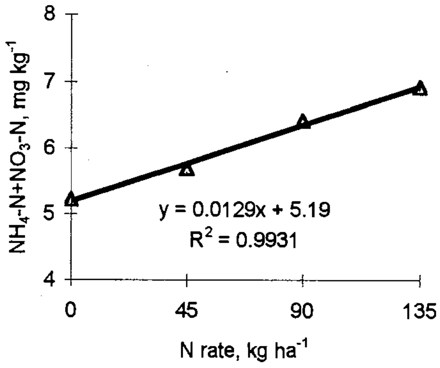


Figure 19. Extractable N using hot 2 M KCl, Experiment 222

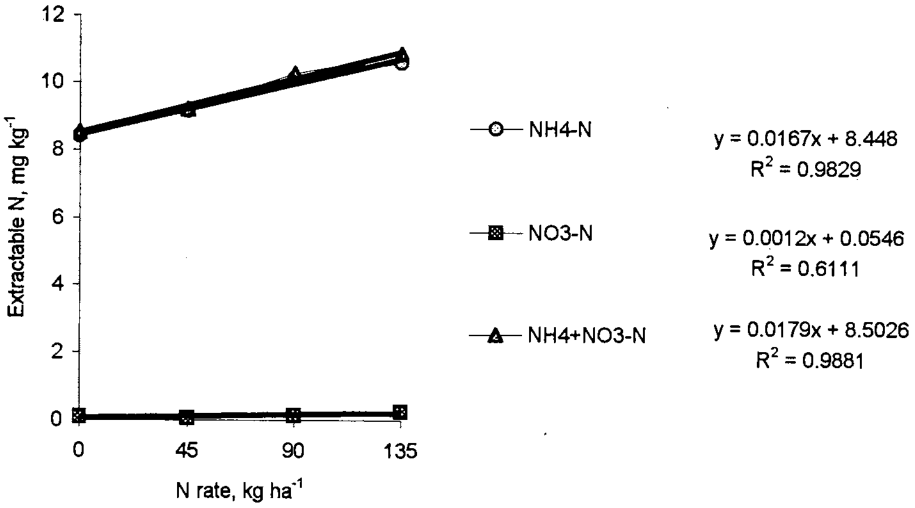


Figure 20. Extractable N using hot 2 M KCl, Experiment 406

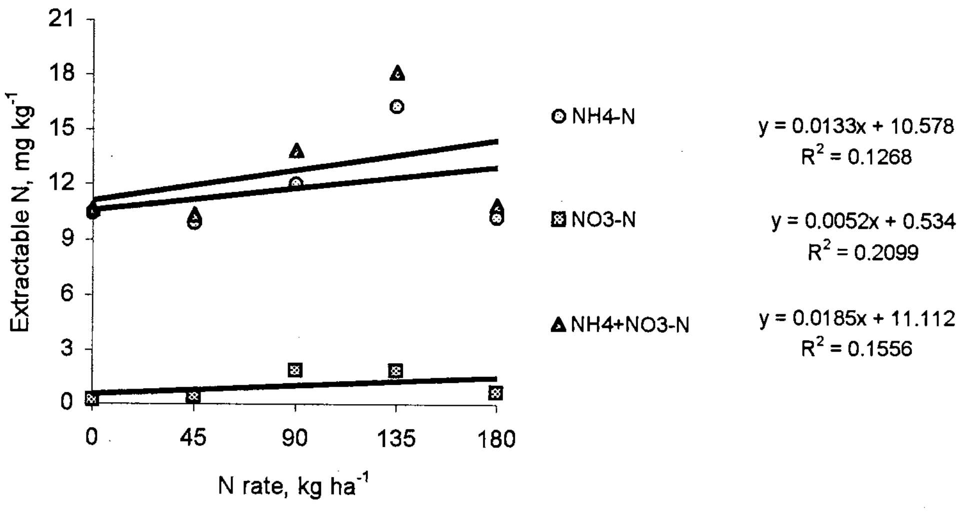


Figure 21. Extractable N using hot 2 M KCl, Experiment 502

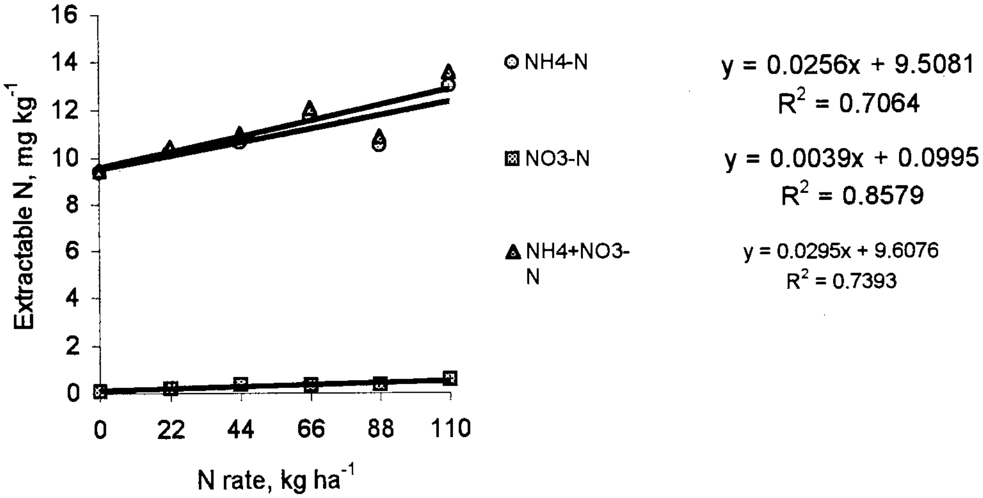


Figure 22. Extractable N using hot 2 M KCl, Experiment 505

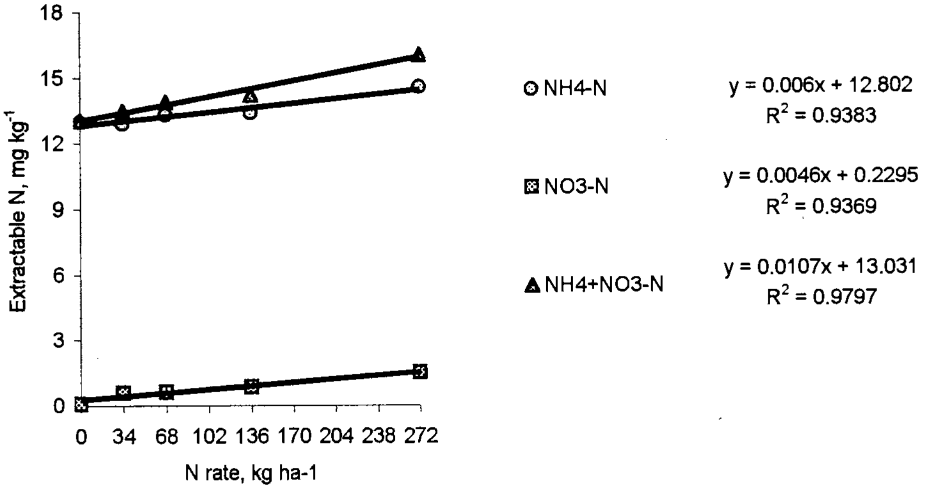


Figure 23. The relationship of total N and hot KCl extractable N, Experiment 222, 406, 502, and 505

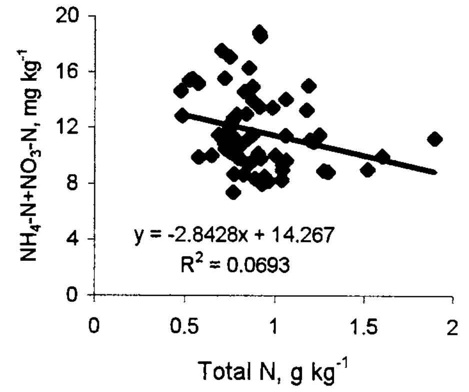


Figure 24. The relationship of C/N ratio and hot KCl extractable N, Experiment 222, 406, 502, and 505

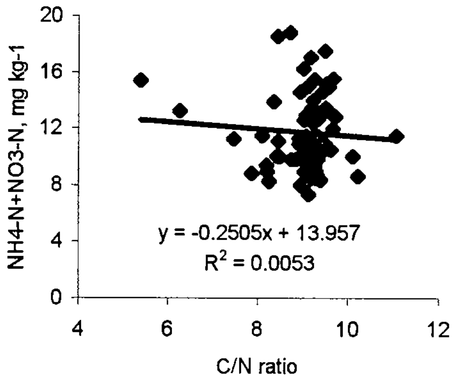


Figure 25. The relationship of Total N and hoot KCl extractable N, Experiment 222, 406, 502, and 505

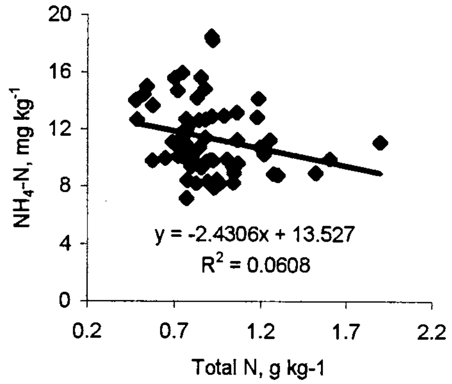


Figure 26. The relationship of to C/N ratio and hot KCl extractable N, Experiment 222, 406, 502, and 505

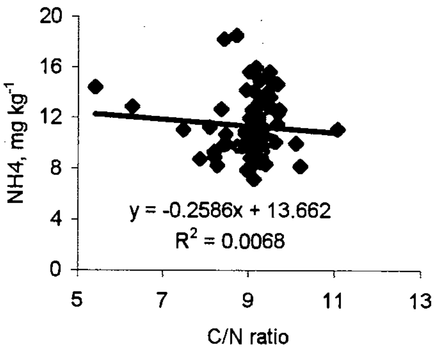


Figure 27. The relationship of total N and Hot KCl extractable N, Experiment 222, 406, 502, and 505

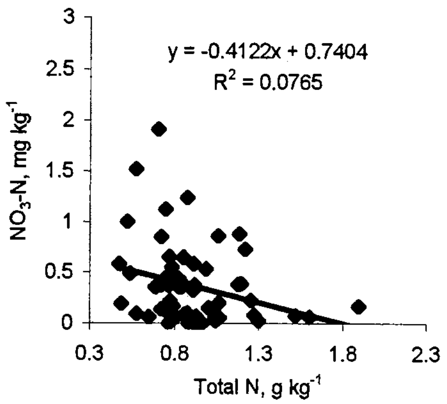


Figure 28. The relationship of C/N ratio and hot KCl extractable N, Experiment 222, 406, 502, and 505

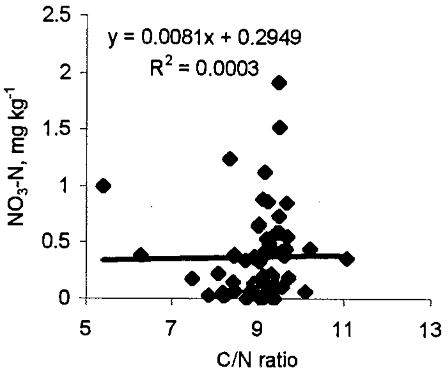


Figure 29. Relationship of N rate and hot 2 M KCl extractable N for all observations and locations, Experiments 222, 406, 502, and 505

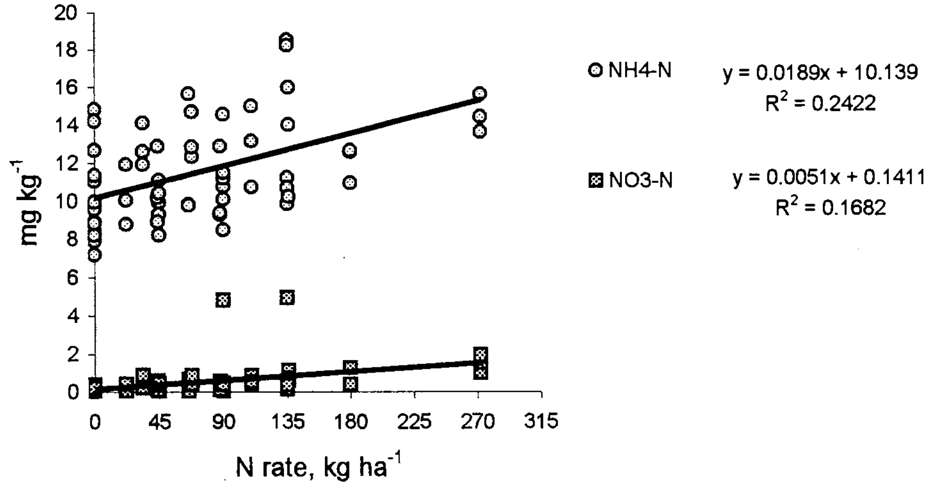


Figure 30. Relationship of non-exchangeable NH_4-N with long-term average yields from all experiments, 222, 406, 502 and 505

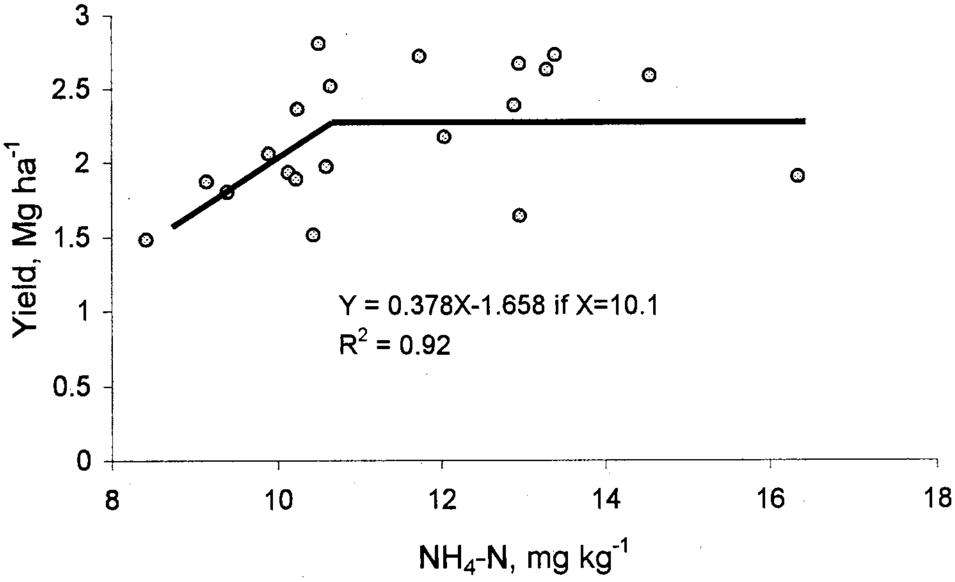


Figure 31. Relationship of non-exchangeable NO_3-N with long term average yields of all experiments, 222, 406, 502, and 505

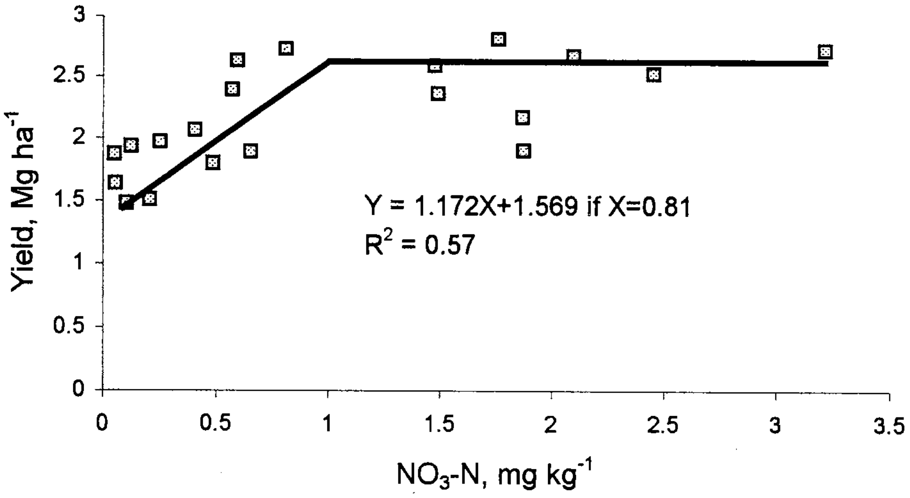
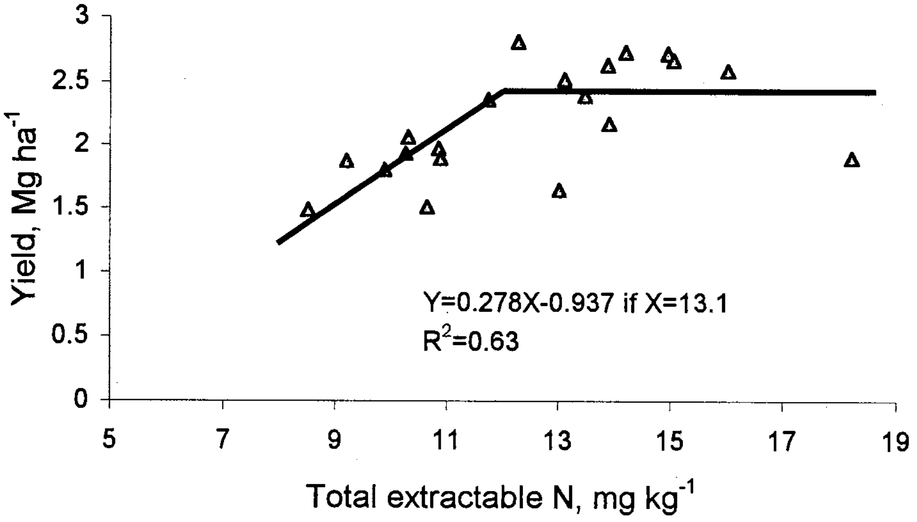


Figure 32. Relationship of total non-exchangeable N with long term average yields from all experiments, 222, 406, 502 and 505



APPENDIX A

MATERIAL RELATED TO CHAPTER II

Table 1. Analysis of variance for selected indices from various readings using a photodiode sensor on May 29 and June 27, Burneyville OK, 1996

Source of variation	Red	Green	NIR	NR	NDVI
May 29, 1996	----------Mean squares----------				
Rep	ns	ns	ns	***	***
N rate	ns	ns	**	***	***
P rate	ns	ns	ns	ns	ns
NxP	ns	ns	ns	ns	ns
Contrasts:					
N linear	ns	ns	*	***	***
N quadratic	ns	ns	**	***	***
P linear	ns	ns	ns	*	ns
P quadratic	***	ns	ns	ns	ns
Error	964	17706	122102	8.6	0.00
CV, %	16	14	15	8	1
N rate, kg ha^{-1}	----------Means----------				
0	204	877	1983	9.8	0.81
112	200	993	2547	12.9	0.85
224	193	979	2558	13.3	0.86
336	178	912	2404	13.6	0.86
SED	22	63	165	1.4	0.02
P rate, kg ha^{-1}					
0	202	964	2370	11.9	0.84
29	195	941	2374	12.4	0.84
58	184	915	2349	12.9	0.85
SED	25	54	143	1.2	0.02
June 27, 1996	----------Mean squares----------				
Rep	ns	ns	ns	*	*
N rate	ns	ns	ns	ns	ns
P rate	ns	ns	ns	ns	ns
NxP	ns	ns	ns	ns	ns
Contrasts:					
N linear	ns	ns	ns	ns	ns
N quadratic	ns	ns	ns	ns	ns
P linear	ns	ns	ns	ns	ns
P quadratic	ns	ns	ns	ns	ns
Error	82781	771828	543258	0.31	0.01
CV, %	39	34	35	19	15
N rate, kg ha^{-1}	----------Means----------				
0	835	2707	2163	2.6	0.4
112	679	2491	2110	3.2	0.52
224	772	2767	2257	3.0	0.48
336	672	2405	1938	3.1	0.49
SED	136	414	347	0.3	0.03
P rate, kg ha^{-1}					
0	735	2472	1969	2.9	0.47
29	706	2557	2107	3.1	0.50
58	777	2749	2274	3.0	0.49
SED	117	359	301	0.2	0.03

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
ns = not significant;
SED = standard error difference between two equally replicated means

Table 2. Analysis of variance for selected indices from various readings using a photodiode sensor on August 9, and Sept 13, Burneyville OK, 1996

Source of variation	Red	Green	NIR	NR	NDVI
August 9, 1996	----------Mean squares----------				
Rep	ns	ns	ns	ns	***
Nrate	ns	ns	ns	*	*
Prate	ns	ns	*	ns	ns
NxP	ns	ns	ns	ns	*
Contrasts:					
N linear	ns		ns	*	*
N quadratic	ns	ns	ns	ns	ns
P linear	ns	ns	ns	ns	ns
P quadratic	ns	*	**	ns	ns
Error	3112	31080	188963	1.7	0.00
CV, %	20	18	20	16	4
N rate, kg ha^{-1}	----------Means----------				
0	303	918	2034	6.8	0.73
112	285	1054	2445	8.7	0.78
224	258	969	2217	8.5	0.78
336	249	938	2078	8.5	0.77
SED	26	83	205	0.6	0.02
P rate, kg ha^{-1}					
0	262	917	2062	7.9	0.76
29	298	1101	2515	8.5	0.78
58	262	891	2003	7.9	0.76
SED	23	72	177	0.5	0.01
September 13, 1996	----------Mean squares----------				
Rep	ns	ns	ns	***	***
Nrate	ns	*	***	***	***
Prate	ns	ns	ns	**	**
NxP	ns	ns	ns	ns	ns
Contrasts:					
N linear	ns	**	**	**	**
N quadratic	ns	*	***	***	***
P linear	ns	ns	ns	***	**
P quadratic	ns	ns	ns	ns	ns
Error	349	9502	59118	0.8	0.00
CV, %	11	10	3	6	1
N rate, kg ha^{-1}	----------Means----------				
0	160	823	1885	12	0.84
112	160	961	2465	15.5	0.88
224	166	967	2426	14.6	0.87
336	171	962	2313	13.5	0.86
SED	9	46	115	0.4	0.01
P rate, kg ha^{-1}					
0	166	907	2175	13.1	0.85
29	161	922	2266	14.0	0.86
58	166	955	2375	14.5	0.87
SED	8	40	99	0.4	0.01

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
ns = not significant;
SED = standard error difference between two equally replicated means

Table 3. Correlation coefficients (r) of various readings using a photodiode sensor, Burneyville OK, 1996

Source of variation	Red	Green	NIR	NR	NDVI
May 29, 1996					
Biomass	-0.09 ns	0.35 ***	0.63 ***	0.71 ***	0.79 ***
N concentration	-0.32 ***	0.02 ***	0.28 ***	0.61 ***	0.62 ***
N uptake	-0.18 ***	0.27 ***	0.58 ***	0.76 ***	0.76 ***
P concentration	-0.33 ***	-0.01 ns	0.24 ***	0.59 ***	0.59 ***
P uptake	-0.18 ***	0.26 ***	0.57 ***	0.75 ***	0.74 ***
June 27, 1996					
Biomass	-0.35 *	-0.11 ns	-0.05 ns	0.45 **	0.39 *
N concentration	-0.11 ns	0.02 ns	0.04 ns	0.31 ns	0.28 ns
N uptake	-0.35 *	-0.13 ns	-0.02 ns	0.59 ***	0.53 ***
P concentration	-0.11 ns	0.09 ns	0.16 ns	0.46 **	0.47 **
P uptake	-0.35 *	-0.10 ns	0.02 ns	0.65 ***	0.60 ***
August 9, 1996					
Biomass	-0.10 ns	0.54 **	0.61 ***	0.86 ***	0.84 ***
N concentration	-0.37 *	-0.25 ns	-0.26 ns	0.03 ns	0.02 ns
N uptake	-0.31 ns	0.28 ns	0.34 *	0.74 ***	0.71 ns
P concentration	-0.25 ns	0.21 ns	0.23 ns	0.48 **	0.52 **
P uptake	-0.17 ns	0.52 **	0.58 ***	0.88 ***	0.87 ***
Sept 13, 1996					
Biomass	0.02 ns	0.39 *	0.55 ***	0.63 ***	0.63 ***
N concentration	0.27 ns	0.43 **	0.42 *	0.25 *	0.28 ns
N uptake	0.11 ns	0.45 **	0.57 ***	0.58 ***	0.59 ***
P concentration	0.26 ns	0.42 *	0.37 *	0.20 ns	0.25 ns
P uptake	0.13 ns	0.51 **	0.63 ***	0.63 ***	0.65 ***

0.18915 = Correlation coefficient

*, **, *** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Figure 1. Correlation between P uptake and 695/405 on May 29, 1996

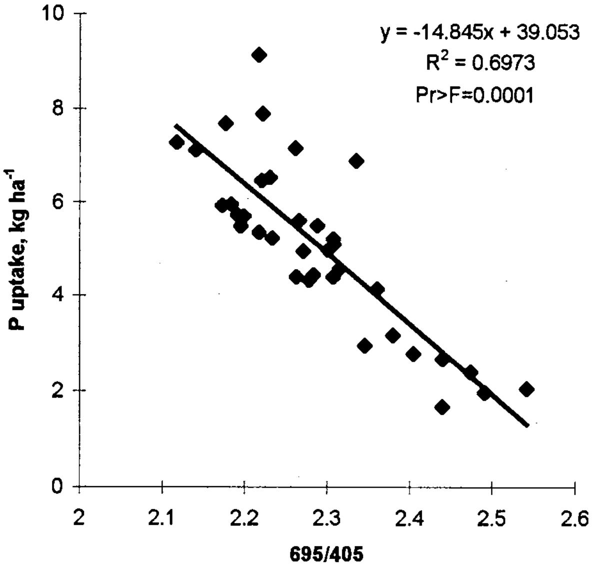
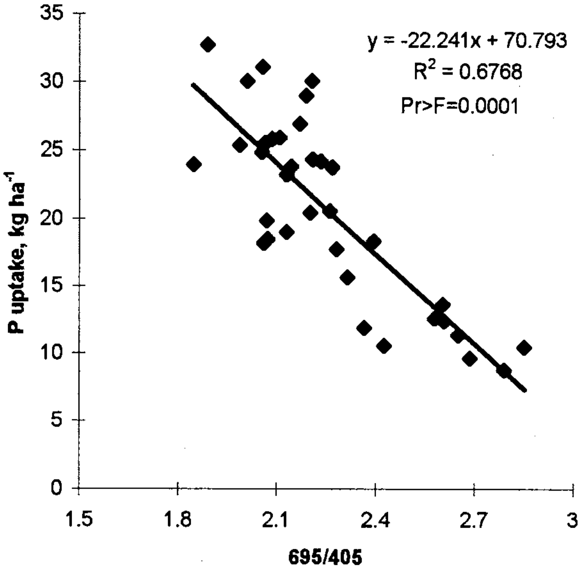


Figure 2. Correlation between P uptake and 695/405 on Sept 13, 1996



APPENDIX B

MATERIAL RELATED TO CHAPTER III

Figure 1. Effect of N rate on grain yield at T222 and T505, 1995/1996 and 1996/97

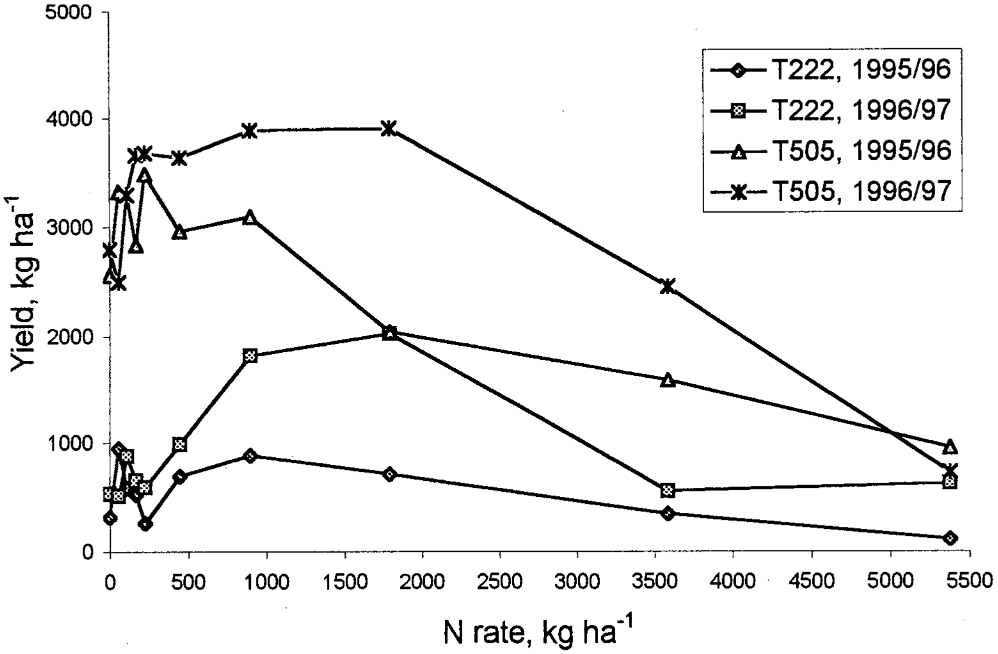


Figure 2. Effect of N rate on grain yield at T222 and T505, 1995/96 and 1996/1997

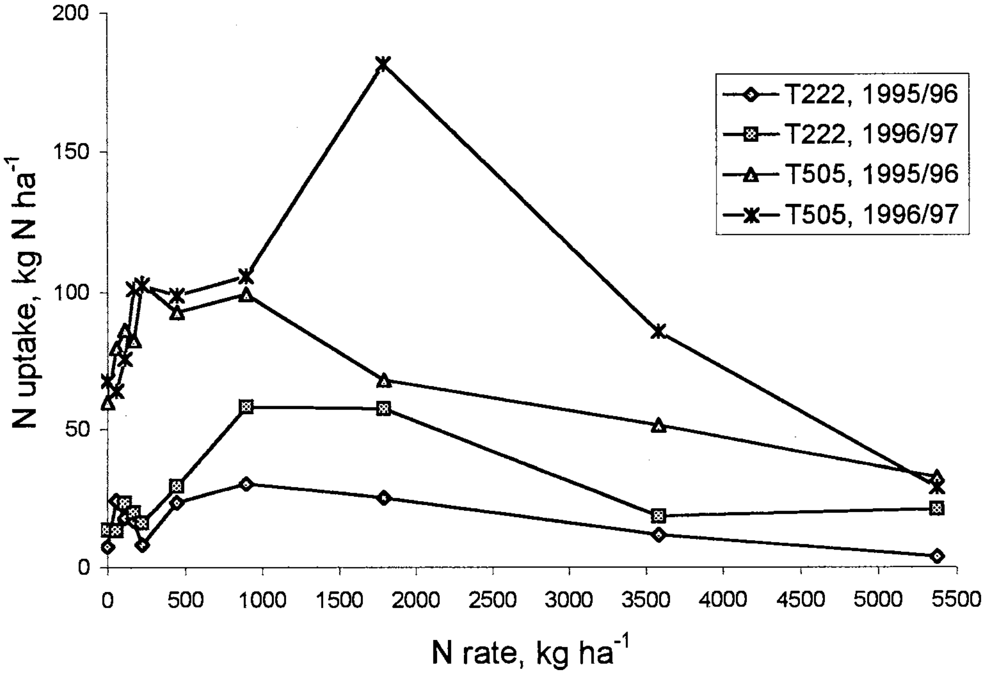


Figure 3. Effect of N rate on fertilizer recovery at T222 and T505, 1995/96

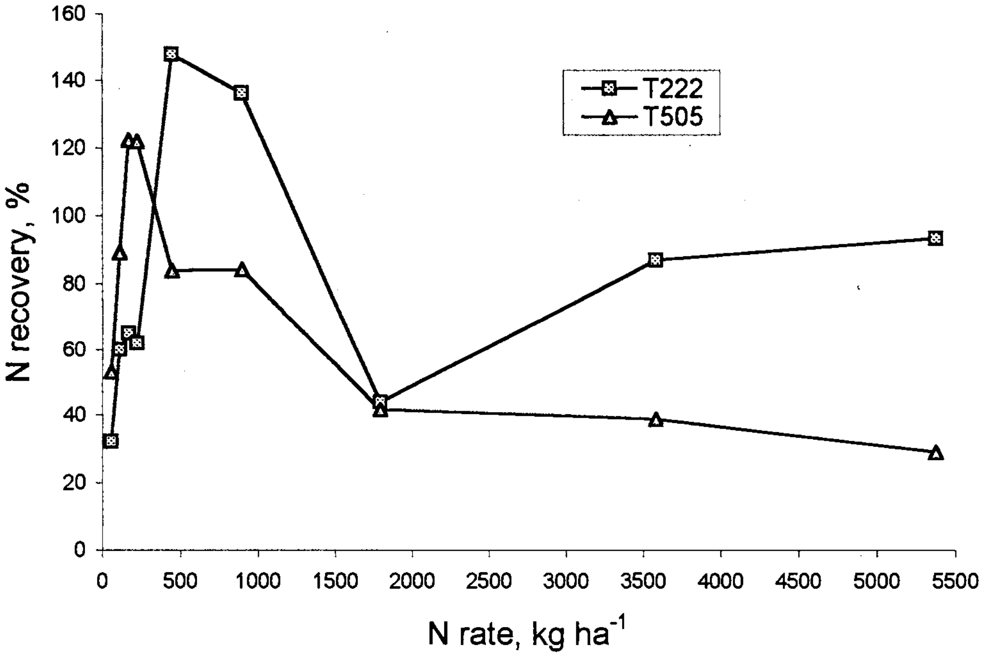
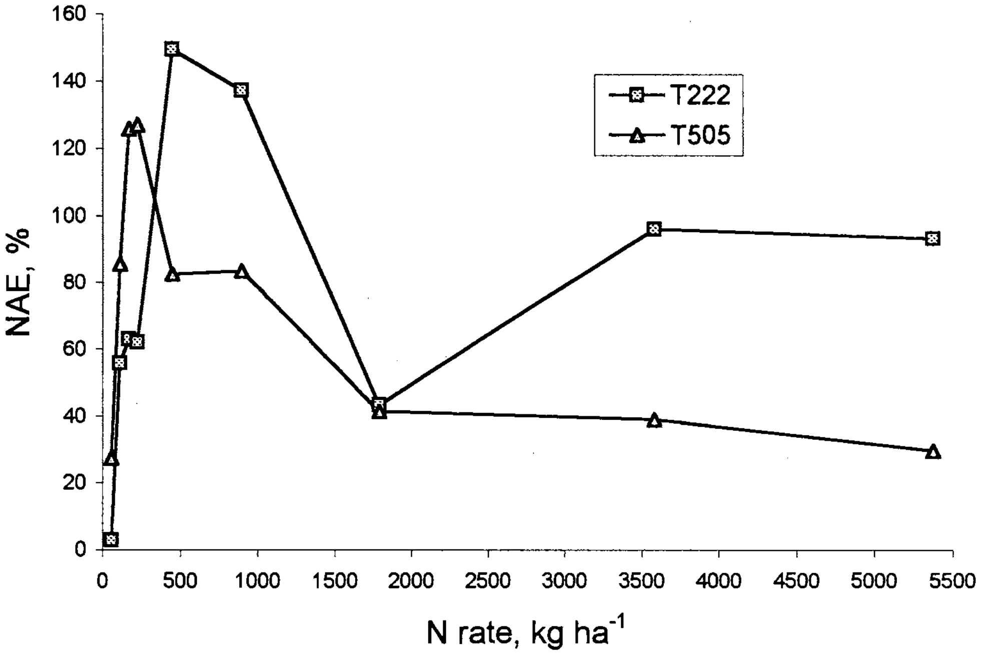


Figure 4. Effect of N rate on N accumulation efficiency (NAE) at T222 and T505, 1995/96



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