EFFECT OF FOLIAR APPLICATION OF PHOSPHORUS ON WINTER WHEAT GRAIN YIELD, AND USE OF IN-SEASON REFLECTANCE FOR PREDICTING YIELD POTENTIAL IN BERMUDAGRASS

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CHAPTER I

EFFECT OF FOLIAR APPLICATION OF PHOSPHORUS ON WINTER WHEAT GRAIN YIELD

ABSTRACT

To date, the best phosphorus (P) fertilizer use efficiency is around 16% when knifed or applied with the seed in winter wheat. Intuitively, one would expect foliar applied P to have higher use efficiencies than when applied to the soil, but limited information is available concerning this. Small amounts of P required to correct deficiencies could theoretically be introduced to the plant by a foliar P application. Six trials were conducted in 2002 and 2003 at Lahoma, Lake Carl Blackwell and Perkins, OK to determine whether foliar applications of P can result in increased winter wheat (*Triticum aestivum* L.) grain yields, and to determine the appropriate rates required for maximizing yields on P deficient soils. A completely randomized block design with three replications was used to evaluate varying foliar P rates of 0, 1, 2 & 4 kg ha^{-1} with and without preplant rates of 30 kg ha^{-1}. Foliar application of P at jointing (first hollow stem) was generally more efficient than applications after the boot stage. Results from this study suggest that low rates of foliar applied P might correct mid-season P deficiency in winter wheat, and that might result in much higher P use efficiencies when compared to soil applications. Foliar P appeared to be more beneficial when yield levels were lower, likely due to moisture stress.

INTRODUCTION

In many agricultural production systems, P has been identified as the most deficient essential nutrient after nitrogen (N). Nutrient inputs into production systems have increased as a result of the need for high yielding crops to sustain the growing population around the world. In Oklahoma, phosphate inputs in winter wheat production ranged from 37.91 x 10^6 kg/ 2.18 x 10^6 ha in 1997 to 29.88 x 10^6 kg /1.42 x 10^6 ha in 2002 (NASS,1998 ; NASS,2003). Even though the average is 21 kg ha^{-1}, these inputs may become excessive where there were already high levels of soil phosphorus leading to many environmental concerns, especially pollution issues. The most essential function of P is storage and transfer of energy in the form of ATP (adenosine triphosphate), ADP (adenosine diphosphate) and the important structural component of nucleic acids, coenzymes, phospholipids, and nucleotides.

Phosphorus originates from the weathering of soil minerals and other stable soil geologic materials and exists in both inorganic and organic forms of which the inorganic fraction is dominant. The inorganic forms are dominated by hydrous sesquioxides, amorphous crystalline aluminum and iron phosphates in acidic soils and as calcium phosphates in alkaline soils. The amount of available soluble P depends on pH, extent of contact between the precipitated phosphorus and the soil solution, the rate of dissolution and diffusion of solid phase phosphorus, time of reaction, organic matter content, temperature and type of clay present. When the available P is less than the crop requirement, P is applied to the soil in the form of both inorganic and organic fertilizer.

Although inorganic fertilizers are readily available, they are slowly converted to unavailable forms due to precipitation. During early growth stages, plants may utilize the readily available form, while they compete for the slowly available forms in the later stages of growth.

Phosphorus fertilizer use efficiency (PUE) averaged 8% when P was broadcast and incorporated and 16% when P was either knifed with anhydrous ammonia or applied with the seed in winter wheat (Sander et al., 1990; Sander et al., 1991). Eghball and Sander (1989) reported that 13.8 to 26.4 kg P ha^{-1} was taken up in corn grain at yield levels between 4.24 and 8.83 Mg ha^{-1}, and a concentration of 0.31% P. Similar results by Raun et al. (1987) showed total P taken up in corn grain ranged from 21.4 to 47.4 kg P ha^{-1} at yield levels from 8.10 to 14.47 Mg ha^{-1}, or 0.30% P. The diffusion coefficient of P in soil is very low, hence the root zone phosphorus is depleted and plants cannot get it when it is needed (Clarkson, 1981). Therefore, the utilization of P as a foliar application becomes increasingly important. The mechanistic processes by which foliar applied nutrients are taken up are through leaf stomata (Eichert and Burkhardt, 1999) and hydrophilic pores within the leaf cuticle (Tyree et al., 1990).

In general, P deficient soils require preplant broadcast-incorporated rates of 11 to 22 kg P ha^{-1} to correct the deficiency in either wheat or corn. At a PUE of 16%, this addition results in only 1.7 to 3.5 kg of fertilizer P taken up in the grain. Although the literature does not provide information on relative efficiencies (soil applied versus foliar applied P), intuitively, one would expect the foliar applied P to be much higher. Thus, small amounts required to correct deficiencies can be easily introduced to the plant by a foliar P application. This approach has been overlooked for decades because it was assumed that the amounts of fertilizer P required by the crop were too large to be satisfied by a single foliar application. That assumption was easily accepted when P fertilizers were first used because soil deficiencies tended to be greater than today and solution fertilizers were uncommon.

Leach and Hameleers (2001) reported that there is a significant increase in the starch content and cob index but no effect on dry matter production in maize due to foliar application of P and Zinc (Zn). Sherchand and Paulsen (1985) reported that foliar applications of KH_2PO_4 delayed leaf senescence and increased winter wheat grain yields during hot and dry summers, which was supported with similar research by Batten et al. (1986). Batten (1987) later reported that net CO_2 assimilation, N concentration and chlorophyll content decreased when wheat leaf P concentration falls below a critical level. Increased yields in barley were obtained using dilute solutions of foliar P (Qaseem et al., 1978). Barel and Black (1979) reported findings in corn that 66% of foliar applied P to youngest mature leaf in a pot culture experiment as ammonium tripolyphosphate was absorbed within 10 days and 87% of that absorbed was translocated within that time. However, Harder et al. (1982) presented contradicting results showing that the foliar application of P applied 2 weeks after silking, significantly reduced grain yields.

Foliar fertilization with nitrogen, phosphorus, and potassium (NPK) can be supplemented with soil applied fertilizers but cannot replace soil fertilization in the case of maize (Ling and Silberbush, 2002), because demand for P is 1/10 that of N foliar application might be beneficial. Therefore, correcting the plant's deficiency by foliar application seems plausible. Very little research has been conducted on the use of P as foliar spray at early stages of wheat and corn. However, recent work by Benbella and Paulsen (1998) showed that foliar applications after anthesis of 5 to 10 kg KH_2PO_4 ha^{-1} (1.1 to 2.2 kg P ha^{-1}) increased wheat grain yields by up to 1 Mg ha^{-1}. Wheat grain yields are hindered due to senescence of wheat during grain filling. Therefore, to effectively prolong senescence, P has to be applied during later stages of growth, which is why foliar application seems particularly promising (Benbella and Paulsen, 1998).

Elliott et al. (1997) reported that critical P concentration wheat grain to be between 0.19 to 0.23% (at 90% maximum grain yield) and 0.21% to 0.24% (at maximum grain yield). Earlier it was reported by Bolland and Paynter (1994) that critical P concentration in wheat decreased from 0.91% to 0.23% (in shoot) with the growing season and 0.27% in grain.

Haloi (1980) reported that when initial P deficiency symptoms appeared 25 days after sowing in wheat, higher doses of ammonium phosphate as a foliar spray gave greatest reduction in P deficiency and highest yields. The efficiency of basal and/or foliar application of P was found to be similar (Kalyan Singh et al., 1981).

The objectives of this study were to determine whether foliar applications of P can result in increased wheat grain yields, and to determine the appropriate rates required for maximizing yields on P deficient soils.

MATERIALS AND METHODS

Three experimental sites were established in the fall of 2001 at Lahoma (Grant silt loam-fine-silty, mixed thermic Udic Argiustoll), Lake Carl Blackwell (Port silt loam-fine-silty, mixed, thermic Cumulic Haplustolls), and Perkins (Teller sandy loam-fine-loamy, mixed, thermic Udic Argiustoll), Oklahoma for evaluating the response of foliar application of P in winter wheat. Initial soil test data is reported in Table 1.

A completely randomized block design with three replications was used to evaluate 14 treatments. Plots were 2.43 m by 3.04 m in size. At all locations, a fixed preplant N rate of 80 kg N ha^{-1} was applied using ammonium nitrate (34-0-0 N-P-K respectively). Varying foliar P rates of 0, 1, 2 and 4 kg ha^{-1} were evaluated with and without preplant rates of 30 kg P ha^{-1} at different growth stages at all three sites. Preplant P was broadcasted and incorporated using triple super phosphate (0-46-0 N-P-K respectively). The treatment structure is reported in table 2. Foliar P was applied at Feekes growth stage 7 (second node of stem formed), Feekes 10.1 (heads emerging) and Feekes 10.54 (flowering completed) (Large, 1954) using KH_2PO_4 solution with a pulse modulated handheld sprayer.

Field activities are reported in Table 3 and Table 4. Wheat was harvested with a Massey Ferguson 8XP experimental combine in June, removing an area of 2.0 x 3.04 m from the center of each plot, it was then weighed and sub sampled for total P analysis. Grain samples were dried in a forced-air oven at 66°C, ground to pass a 140 mesh sieve (100 μm), and analyzed for total P content.

The concentration of P in the wheat grain was determined with a wet acid digestion procedure (Jones and Case, 1990), and analyzed using a high-resolution inductively coupled plasma spectrophotometer (Thermo-Jarrell Ash IRIS ICP). Soft winter wheat flour standard reference material (SRM) (National Institute of Standards and Technology) was used to evaluate the wet acid digestion procedure of the grain tissue and resulted in 94% recovery of P in the grain.

Analysis of variance and single degree of freedom contrasts were performed for evaluating the differences in grain yield, grain P concentration and grain P uptake using SAS (2001). Regression equations and coefficients of determination (R^2) values were determined using Microsoft Excel and verified using SAS (SAS, 2001)

RESULTS

Grain Yield

A significant treatment effect for grain yield at Lahoma in 2002 and in 2003, and at Perkins in 2002 (Table 5) was observed. At Lake Carl Blackwell (LCB) and Perkins in 2003, some single degree of freedom comparisons at each site were also significant (Table 5). Neither overall treatment effects nor single degree of freedom contrasts were found to be significant at LCB in 2002.

At the LCB site, no significant treatment differences were observed in either year. Even though this site had high grain yields and the initial soil test results showed a low extractable P level, no actual P deficiencies were noted (mean grain yields across 14 treatments are presented in Table 6). Preplant P fertilizer grain yields significantly exceeded topdress P grain yields both years at the Perkins location (556 and 746 kg ha^{-1} increases in yield in 2002 and 2003). A comparison made between a combination of preplant and foliar P fertilization versus only 30 kg P ha^{-1} pre-plant incorporated showed a significant increase at Lahoma in 2002 (grain yield increased by 630 kg ha^{-1},Table 6).

At Lahoma in 2002 and Perkins 2003, mean grain yields were superior for foliar P applied at 2 kg ha^{-1} at Feekes 7 growth stage compared to foliar P applied at Feekes 10.54 (cf. 2485 and 1841 kg ha^{-1}, and 3088 and 2521 kg ha^{-1}, respectively). Alternatively, at Lahoma in 2003 the opposite was observed whereby foliar P applied at Feekes 7 at 2 kg ha^{-1} resulted in lower yields than same rate applied at Feekes 10.54 (cf. 3443 and 4277 kg ha^{-1}).

At LCB with no preplant P, 2 kg P ha^{-1} applied at Feekes 10.54 significantly increased yields when compared to the check and other 0 preplant P treatments that received P at Feekes 7. This increase was not noted at all sites.

At LCB in both years and Lahoma in 2003, it was apparently advantageous to delay applying foliar P until Feekes 10.54 when compared to Feekes 7(3 vs. 11, Table 6, 0 –P preplant). At Lahoma in 2002, foliar P application at Feekes 10.1 increased mean grain yield by 513 kg ha^{-1} compared with that at Feekes 10.54, while at Lahoma in 2003 and LCB in 2003, mean grain yield was superior by 1172 and 335 kg ha^{-1}, respectively at Feekes 10.54 compared with Feekes 10.1.

At Lahoma in 2002, foliar P applied at Feekes 7 vs. flowering (Feekes 10.1 and 10.54) resulted in increased yields when the foliar rate was 2 kg P ha^{-1} with no pre-plant P. Mean grain yields increased by 131, 644 kg ha^{-1} when applied at Feekes 7 versus that applied at Feekes 10.1 and 10.54.

Trend analysis of mean grain yields for foliar P at Feekes growth stage 7 with no pre-plant P revealed a significant quadratic relationship between foliar P rates and grain yield at Lahoma in 2002 (Figure 1) . On the other hand, at a preplant rate of 30 kg P ha^{-1}, foliar P at Feekes 7 showed a linear trend at Lahoma in 2002 (Figure 2).

Grain P Concentration

Grain P concentration was significant in four of six site-year combinations (Table 7). Like grain yield, grain P was high (>0.31%) at LCB in both years and low (0.18%) at Perkins in 2003, while it ranged between 0.20 and 0.26% for the remaining trials (Table 8).

At Lahoma in 2002, grain P was higher by 0.017% for P applied preplant (Trt-5) compared to topdress (Trt-4). On the other hand, the preplant plus foliar treated plots showed a 0.022 and 0.039% lower grain P at Lahoma in 2002 and 2003, respectively, compared with only preplant treated plots. Alternatively, at LCB in 2003, 0.039% more was observed in preplant plus foliar treated plots.

At LCB in 2002, foliar P applied at Feekes 7 showed lower grain P concentration than rates applied at Feekes 10.1 (0.033%), Feekes 10.54 (0.031%) or a combination of both (0.033%).

Grain P concentration showed a linear relationship at Lahoma in 2002, and a quadratic relationship at LCB and Perkins in 2003 at 0 kg ha^{-1} preplant rate (Figure 3). At 30 kg P ha^{-1} preplant, two linear trends, one at LCB 2002 and another at Perkins 2003 (Figure 4) were obtained while at Lahoma and Perkins (Figure 5) in 2002, a quadratic trend was revealed.

Grain P uptake

Grain P uptake was significant and influenced by treatments in three trials (Table 9). Grain P uptake was highest (>13.50 kg ha^{-1}) for LCB sites and lowest (<4.32 kg ha^{-1}) at Perkins in 2002, while it ranged between 5.29 and 9.80 kg ha^{-1} for other sites (Table 10). For all trials, one or more contrasts were significant. A trend for increased grain P uptake was observed when foliar P was applied with preplant P (treatments 5-8) but this was not consistent over sites. At Lahoma 2002, 1.17 and 1.68 kg ha^{-1} more P was taken up when foliar P was applied at Feekes 7 than either Feekes 10.1 or 10.54 with 0 preplant. On the other hand, at LCB in 2002, grain P uptake was lower by 2.01 and 2.59 kg ha^{-1} at Feekes 7 than Feekes 10.1 and 10.54 respectively. At Lahoma in 2003, grain P uptake increased by 2.84 and 3.06 kg P ha^{-1} at Feekes 10.54 compared to Feekes 7 and 10.1, respectively (treatments 11, 2 & 9 respectively).

Phosphorus Use Efficiency (PUE)

Over all sites and years, PUE was higher when P was foliar applied at 2 kg P ha^{-1}. PUE was as high as 86, 16, & 159% at LCB (2002), Lahoma (2002), and Lahoma (2003) respectively when 2 kg P was foliar applied at Feekes 10.54 (Table 11). On an average, PUE was higher when P was foliar applied at 2 kg P ha-1 at Feekes 7 (39%) and Feekes 10.54 (47%).

DISCUSSION

Conventional P-soil test correlation utilizes knowledge that soil deficiencies may be represented as a percentage of the maximum yield when there is no P deficiency (Mitscherlich-Sufficiency Concept). Consequently, soil test calibrations resulted that identified amounts of fertilizer-P required for correcting the plant deficiency for a season, but which had little immediate effect on long-term available soil-P. This is appropriate for soil-applied P as rates do not need to be adjusted for yield level. However, rates of foliar P need to address uptake deficiencies of the plant, which are influenced both by potential yield (biomass) and available soil-P.

Grain yield and P concentration were not highly correlated. The poor correlation between P concentration and grain yield is not surprising since the role of foliar P on growth of wheat is more on delaying maturity. P concentrations in plants can be affected by limited P uptake due to variations in soil moisture stress (McLachlan, 1984), root temperature (MacKay and Barber, 1984) and various other environmental factors (Bates, 1971).

Regardless of the method of P application, response to P fertilization should have been observed across all trials. This is because initial soil test P levels were all below 100% sufficiency. Despite this, only 50% of the trials showed significant treatment effects. The significant grain yield response to P at Lahoma can be explained by the fact that the soil has a relatively low level of initial soil P compared to the other two locations. At Lahoma, the number of significant single degree of freedom comparisons obtained were more than the other two sites (with the exception of Perkins 2003) owing to the low initial soil P level.

Preplant P application consistently increased grain yield compared with topdress P. Application of P preplant with supplemental foliar P also resulted in a better grain yield than preplant application in most instances where significance was observed. In high yielding environments with sufficient supply of P, supplemental foliar P might not be desirable. However, in the same environments where soil P supply is limited, foliar application of P might correct deficiencies and maintain higher yield (Dixon, 2003). Green and Racz (1999) reported a 300 kg ha^{-1} grain yield increment of wheat due to foliar P applied to a P deficient wheat crop.

In plots treated with only foliar rates at Feekes 7 and flowering, there was an apparent response which indicates that foliar P in wheat is still a potential option to manage P deficiency in wheat. In a different study (Chambers and Devos,2003), it was indicated that depending on soil P status, foliar feeding of small amounts of P after heading increased yields over no P up to 672 kg ha^{-1} and added up to 538 kg ha^{-1} to the preplant P plots. However, the results were from trials conducted on a soil testing low in P and one would not expect to see these large yield increases on higher P fertility soils by foliar fertilization.

Benbella and Paulsen (1998) also showed that foliar applications after anthesis of 5 to 10 kg KH_2PO_4 ha^{-1} (1.1 to 2.2 kg P ha^{-1}) increased wheat grain yields by up to 1 Mg ha^{-1}.

The foliar rates considered in this study also showed apparent grain yield, and phosphorus use efficiency increases. Presumably increasing the foliar rates might show a clear difference in grain yield due to applied foliar P since the locations under consideration were low in P. The results from single degree of freedom comparisons generally lack consistency.

Foliar application of P at Feekes 7 was generally better than applied P pre or post flowering stages of wheat growth. In a preliminary foliar rate study made in Virginia, yield obtained from foliar rates applied at vegetative wheat stages surpassed that of the foliar rate applied at reproductive stages (personal communication with Steve Phillips, Virginia Tech). In another study (Haloi,1980), it was suggested that the delayed P applications resulted in a “stay green” effect whereby photosynthesis continued to take place during grain fill and that without the foliar P, more rapid senescence would be present. In order to realize any “stay green” benefit, environmental conditions must have been ideal (no moisture stress) from post flowering to maturity. Whenever plants are under moisture stress P uptake is reduced (MCLachlan 1984; Bollard 1992).

When looking at Table 6 and 10, data suggests that increases in grain yield from foliar P generally took place when yield levels were lower, likely due to increased moisture stress. This would make sense since P uptake due to contact exchange would be less under moisture stress, thus enhancing the benefits of foliar P in these years.

CONCLUSIONS

Although some of the results presented here confirm the beneficial use of foliar P fertilization in wheat, the conditions in which this method would be used should be sought carefully. For major nutrients like P, the amount that can be applied at any one time is small and thus it requires several applications to meet the needs of a crop for this nutrient as well as realizing that the rates applied here might have been too low and higher rates should be tested. Even the method of application can be changed by addition of surfactant which might enhance P uptake. Also research has to be directed to see if foliar P applications during early stages of plant produce significant results. However, increased P use efficiency from low rates of foliar application was encouraging and will be pursued further.

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Table 1. Initial surface (0-15cm) soil test characteristics at Lahoma, Lake Carl Blackwell, and Perkins, OK.

Location	pH	NH_4-N	NO_3-N	P	K
		----------mg kg^{-1}----------			
Lahoma	6.2	8.0	1	5.9	155
LCB	5.5	8.2	0	10.3	107
Perkins	5.8	12.7	0	9.2	279

NH_4-N and NO_3-N- 2 M KCl extraction
P and K – Mehlich -III extraction
pH – 1:1 Soil: Water

Table 2. Treatment structure for foliar P study experimental sites at Lahoma, Lake Carl Blackwell, and Perkins, OK.

Treatment	Chemical	Preplant P rate kg ha^{-1}	Foliar P in kg ha^{-1} at different growth stages		
			Feekes 7	Pre-flowering	Post-flowering
1. 0-PP, 0-foliar,	KH_2PO_4	0	-	0	0
2. 0-PP, 1-foliar, at F7	KH_2PO_4	0	1	0	0
3. 0-PP, 2- foliar, at F7	KH_2PO_4	0	2	0	0
4. 0-PP, 4 foliar, at F7	KH_2PO_4	0	4	0	0
5. 30-PP, 0 foliar, at F7	KH_2PO_4	30	-	0	0
6. 30-PP, 1 foliar, at F7	KH_2PO_4	30	1	0	0
7. 30-PP, 2 foliar, at F7	KH_2PO_4	30	2	0	0
8. 30-PP, 4 foliar, at F7	KH_2PO_4	30	4	0	0
9. 0-PP, 2 foliar, F10.1	KH_2PO_4	0	0	2	0
10. 30-PP, 2 foliar, F10.1	KH_2PO_4	30	0	2	0
11. 0-PP, 2 foliar, F10.54	KH_2PO_4	0	0	0	2
12. 30-PP, 2 foliar, F10.54	KH_2PO_4	30	0	0	2
13. 0-PP, 0P, 2.5K Fol F7	$KHCO_3$	0	0	0	0
14. 0-PP, 0.9N Fol,F7	$NH_4H_2PO_4$	0	2	0	0

Foliar P is applied using a pulse modulated handheld sprayer developed at OSU

Table 3. Field plot activities and climatological observations for the foliar P experiment at three locations for the crop year 2001-2002.

Plot Activity	Lahoma	LCB	Perkins
Preplant N application Date	09/21/01	09/25/01	09/14/01
Planting date	10/03/01	10/17/01	10/16/01
Variety	Jagger	Custer	Custer
Seeding rate (kg ha^{-1})	89.6	87.6	87.6
1st foliar application date	04/15/02	04/04/02	04/04/02
2nd foliar application date	05/01/02	05/01/02	05/01/02
3rd foliar application date	05/07/02	05/07/02	05/07/02
Harvest	06/25/02	06/29/02	06/11/02

Table 4. Field plot activities and climatological observations for the foliar P experiment at three locations for the crop year 2002-2003.

Plot Activity	Lahoma	LCB	Perkins
Preplant N application date	09/06/02	09/05/02	09/12/02
Planting date	10/08/02	10/01/02	10/14/02
Variety	Jagger	2174	Jagger
Seeding rate (kg ha^{-1})	89.6	100.8	89.6
1st foliar application date	03/25/03	03/25/03	03/25/03
2nd foliar application date	04/29/03	04/22/03	04/22/03
3rd foliar application date	05/06/06	05/06/03	05/06/03
Harvest	06/15/03	06/20/03	05/31/03

Table 5. Analysis of variance and single degree of freedom contrasts for grain yields at all locations during 2001-2002, 2002-2003 crop years.

Source	Lahoma		LCB		Perkins	
	2002	2003	2002	2003	2002	2003
Treatment	**	**	NS	NS	***	NS
Contrasts						
Preplant vs. Foliar	NS	NS	NS	NS	***	***
PP+Foliar vs. PP (30 kg ha^{-1})	**	NS	NS	NS	NS	**
F7 @ 0 PP linear	NS	NS	NS	NS	NS	NS
F7 @ 0 PP quadratic	*	NS	NS	*	NS	NS
F7 @ 30 PP linear	**	NS	NS	NS	NS	*
F7 @ 30 PP quadratic	NS	NS	NS	NS	NS	NS
F7vs F10.1 @ 0 PP,2 kg foliar	NS	NS	NS	NS	NS	NS
F7vs F10.54 @ 0 PP,2 kg foliar	***	*	NS	NS	NS	*
F10.1vs F10.54 @0 pp,2 kg foliar	**	**	NS	*	NS	NS
F7 vs. flowering @ 0 pp,2 kg foliar	*	NS	NS	NS	NS	NS
Potassium Vs Others	***	NS	NS	NS	**	NS
Nitrogen Vs Others	***	***	NS	NS	NS	*

*, **, *** and NS - significant at 0.1, 0.05, 0.01 significance level and non-significant; PP is preplant of either 0 or 30 kg ha^{-1}; top-dress denote all foliar rates with no pre-plant rate; F7, F10.1 and F10.54 denote Feekes growth stages 7, 10.1, and 10.54, respectively.

Table 6. Mean wheat grain yields for treatments at Lahoma, Lake Carl Blackwell, and Perkins, OK during 2001-2002, 2002-2003 crop years.

Treatment	Lahoma 2002	Lahoma 2003	LCB 2002	LCB 2003	Perkins 2002	Perkins 2003
	----------	----------	---------- kg ha^{-1}	----------	----------	----------
1. 0-PP, 0-foliar,	1998	3440	4191	4375	1700	2891
2. 0-PP, 1-foliar, at F7	2126	3535	4211	4291	1906	2672
3. 0-PP, 2- foliar, at F7	2485	3442	4246	4103	1872	3088
4. 0-PP, 4 foliar, at F7	2119	3607	4598	4458	1841	2995
5. 30-PP, 0 foliar, at F7	1740	4067	4095	4479	2412	2915
6. 30-PP, 1 foliar, at F7	2416	4484	4238	4579	2337	2754
7. 30-PP, 2 foliar, at F7	2158	3856	4005	4345	2407	2872
8. 30-PP, 4 foliar, at F7	2529	4591	4138	4412	2429	2771
9. 0-PP, 2 foliar, F10.1	2354	3105	4236	3928	1766	2848
10. 30-PP, 2 foliar, F10.1	2421	4109	4065	4501	2271	2766
11. 0-PP, 2 foliar, F10.54	1841	4277	4603	4263	1816	2520
12. 30-PP, 2 foliar, F10.54	2317	4724	4214	4157	2048	3173
13. 0-PP, 0P, 2.5K Fol F7	1816	3498	4402	4404	1824	3069
14. 0-PP, 0.9N Fol,F7	1809	3078	4573	4036	1935	2406
SED	362.9	971.9	281.5	291.1	352.0	383.3

F7, F10.1 and F10.54 are growth stages as defined in materials and methods

Table 7. Analysis of variance and single degree of freedom contrasts for grain P concentration at all locations during 2001-2002, 2002-2003 crop years.

Source	Lahoma		LCB		Perkins	
	2002	2003	2002	2003	2002	2003
Treatment	**	NS	***	*	NS	**
Contrasts						
Preplant vs. Foliar	**	NS	NS	NS	NS	NS
PP+Foliar vs. PP (30 kg ha^{-1})	**	**	NS	***	NS	NS
F7 @ 0 PP linear	NS	NS	**	NS	NS	NS
F7 @ 0 PP quadratic	NS	NS	NS	*	NS	**
F7 @ 30 PP linear	NS	NS	**	NS	NS	***
F7 @ 30 PP quadratic	**	NS	NS	NS	**	NS
F7vs F10.1 @ 0 PP,2 kg foliar	NS	NS	**	NS	NS	NS
F7vs F10.54 @ 0 PP,2 kg foliar	NS	NS	**	NS	NS	NS
F10.1vs F10.54 @0 pp,2 kg foliar	NS	NS	NS	NS	NS	NS
F7 vs. flowering @ 0 pp,2 kg foliar	NS	NS	**	NS	NS	NS
Potassium Vs Others	NS	NS	NS	**	NS	NS
Nitrogen Vs Others	NS	NS	NS	NS	NS	NS

*, **, *** and NS - significant at 0.1, 0.05, 0.01 significance level and non-significant; PP is preplant of either 0 or 30 kg ha^{-1}; top-dress denote all foliar rates with no pre-plant rate; F7, F10.1 and F10.54 denote Feekes growth stages 7, 10.1, and 10.54, respectively.

Table 8. Mean wheat P concentration (%) at Lahoma, Lake Carl Blackwell, and Perkins, OK during 2001-2002, 2002-2003 crop years.

Source	Lahoma		LCB		Perkins	
	2002	2003	2002	2003	2002	2003
	------------------------		% P		------------------------	
1. 0-PP, 0-foliar,	0.241	0.251	0.324	0.353	0.200	0.165
2. 0-PP, 1-foliar, at F7	0.234	0.254	0.291	0.324	0.180	0.181
3. 0-PP, 2- foliar, at F7	0.254	0.261	0.293	0.335	0.202	0.183
4. 0-PP, 4 foliar, at F7	0.256	0.253	0.286	0.358	0.210	0.167
5. 30-PP, 0 foliar, at F7	0.273	0.282	0.321	0.315	0.197	0.188
6. 30-PP, 1 foliar, at F7	0.232	0.240	0.343	0.337	0.205	0.170
7. 30-PP, 2 foliar, at F7	0.256	0.256	0.315	0.349	0.258	0.202
8. 30-PP, 4 foliar, at F7	0.270	0.236	0.295	0.347	0.216	0.211
9. 0-PP, 2 foliar, F10.1	0.240	0.282	0.327	0.347	0.223	0.173
10. 30-PP, 2 foliar, F10.1	0.262	0.253	0.334	0.382	0.211	0.187
11. 0-PP, 2 foliar, F10.54	0.254	0.273	0.324	0.333	0.201	0.184
12. 30-PP, 2 foliar, F10.54	0.239	0.223	0.330	0.357	0.221	0.187
13. 0-PP, 0P, 2.5K Fol F7	0.238	0.255	0.318	0.315	0.216	0.183
14. 0-PP, 0.9N Fol,F7	0.262	0.283	0.314	0.332	0.204	0.183
SED	0.013	0.023	0.015	0.018	0.016	0.011

F7, F10.1 and F10.54 are growth stages as defined in materials and methods

Table 9. Analysis of variance and single degree of freedom contrasts for grain P uptake at all locations during 2001-2002, 2002-2003 crop years.

Source	Lahoma		Lake Carl Blackwell		Perkins	
	2002	2003	2002	2003	2002	2003
Treatment	*	NS	NS	*	***	NS
Contrasts						
Preplant vs Foliar	NS	**	NS	NS	***	**
PP+Foliar vs PP (30 kg ha^{-1})	NS	NS	NS	*	NS	*
F7 @ 0 PP linear	NS	NS	NS	NS	NS	NS
F7 @ 0 PP quadratic	NS	NS	*	**	NS	NS
F7 @ 30 PP linear	**	NS	NS	NS	NS	NS
F7 @ 30 PP quadratic	NS	NS	NS	NS	**	NS
F7vs F10.1 @ 0 PP,2 kg foliar	NS	NS	NS	NS	NS	NS
F7vs F10.54 @ 0 PP,2 kg foliar	**	**	**	NS	NS	NS
F10.1vs F10.54 @0 pp,2 kg foliar	NS	**	NS	NS	NS	NS
F7 vs flowering @ 0 pp,2 kg foliar	*	NS	**	NS	NS	NS
Potassium Vs Others	**	NS	NS	NS	NS	NS
Nitrogen Vs Others	*	NS	NS	NS	NS	NS

*, **, *** and NS - significant at 0.1, 0.05, 0.01 confidence level and non-significant; PP is preplant of either 0 or 30 kg ha^{-1}; top-dress denote all foliar rates with no pre-plant rate;
F7, F10.1 and F10.54 denotes Feekes growth stages 7, 10.1, and 10.54, resp.

Table 10. Mean grain P uptake (kg ha^{-1}) for treatments at Lahoma, Lake Carl Blackwell, and Perkins, OK during 2001-2002, 2002-2003 crop years.

Treatments	Lahoma 2002	2003	Lake Carl Blackwell 2002	2003	Perkins 2002	2003
	----------	----------	---------- kg ha^{-1}	----------	----------	----------
1. 0-PP, 0-foliar,	4.8	8.7	13.6	15.5	3.6	4.8
2. 0-PP, 1-foliar, at F7	4.9	9.0	12.3	13.9	3.4	4.6
3. 0-PP, 2- foliar, at F7	6.3	9.0	12.4	13.8	3.8	5.7
4. 0-PP, 4 foliar, at F7	5.4	9.0	13.1	15.9	3.9	5.0
5. 30-PP, 0 foliar, at F7	4.8	11.4	13.1	14.1	4.8	6.5
6. 30-PP, 1 foliar, at F7	5.6	10.8	14.5	15.5	4.8	4.7
7. 30-PP, 2 foliar, at F7	5.5	9.6	12.6	15.2	6.5	5.8
8. 30-PP, 4 foliar, at F7	6.9	10.8	12.3	15.2	5.2	5.9
9. 0-PP, 2 foliar, F10.1	5.7	8.8	13.9	13.7	3.9	4.9
10. 30-PP, 2 foliar, F10.1	6.3	10.1	13.6	17.2	4.8	5.2
11. 0-PP, 2 foliar, F10.54	4.7	11.8	15.0	14.2	3.7	4.7
12. 30-PP, 2 foliar, F10.54	5.6	10.5	13.8	14.8	4.2	5.9
13. 0-PP, 0P, 2.5K Fol F7	4.3	8.8	14.0	13.9	3.9	5.6
14. 0-PP, 0.9N Fol,F7	4.8	8.7	14.4	15.2	3.9	4.4
SED	0.72	1.28	0.98	1.01	0.49	0.74

F7, 10.1 and 10.54 denotes - Feekes 7, 10.1 and 10.54, respectively.

Table 11. Phosphorus Use Efficiency (PUE) for treatments at Lahoma, Lake Carl Blackwell, and Perkins, OK during 2001-2002, 2002-2003 crop years

Source	Lahoma		LCB		Perkins		
	2002	2003	2002	2003	2002	2003	Average
	--------------------	-----	%	-----	-----	-----	-----
1. 0-PP, 0-foliar,							
2. 0-PP, 1-foliar, at F7	22	37	0	22	10	11	17
3. 0-PP, 2- foliar, at F7	77	67	0	23	14	55	39
4. 0-PP, 4 foliar, at F7	15	28	4	31	8	13	16
5. 30-PP, 0 foliar, at F7	0	11	0	1	4	6	4
6. 30-PP, 1 foliar, at F7	4	8	2	4	4	0	4
7. 30-PP, 2 foliar, at F7	4	4	0	0	6	3	3
8. 30-PP, 4 foliar, at F7	6	6	0	1	5	3	4
9. 0-PP, 2 foliar, F10.1	64	23	22	0	18	19	24
10. 30-PP, 2 foliar, F10.1	5	5	0	6	4	2	4
11. 0-PP, 2 foliar, F10.54	16	159	86	0	9	10	47
12. 30-PP, 2 foliar, F10.54	4	6	0	1	3	4	3
13. 0-PP, 0P, 2.5K Fol F7							
14. 0-PP, 0.9N Fol,F7							
SED	19	33	20	16	8	19	

F7, F10.1 and F10.54 are growth stages as defined in materials and methods

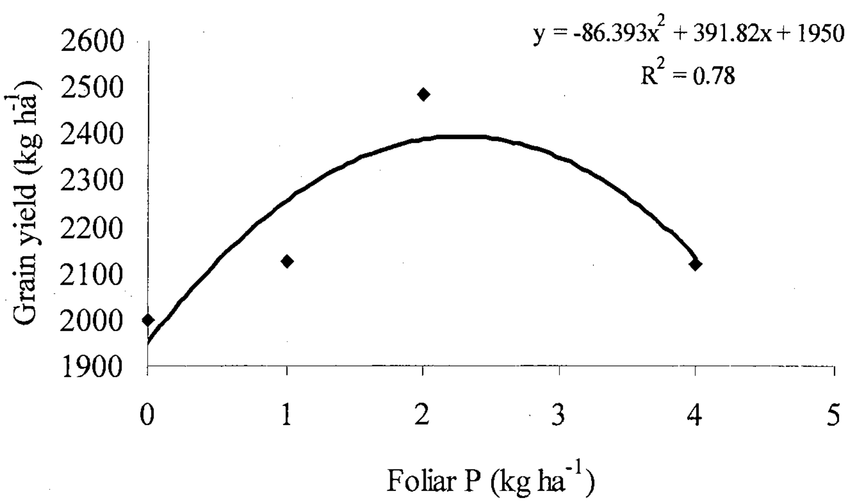

Figure 1. Relationship between grain yield and foliar P rates applied at Feekes 7 without pre-plant P at Lahoma, 2002.

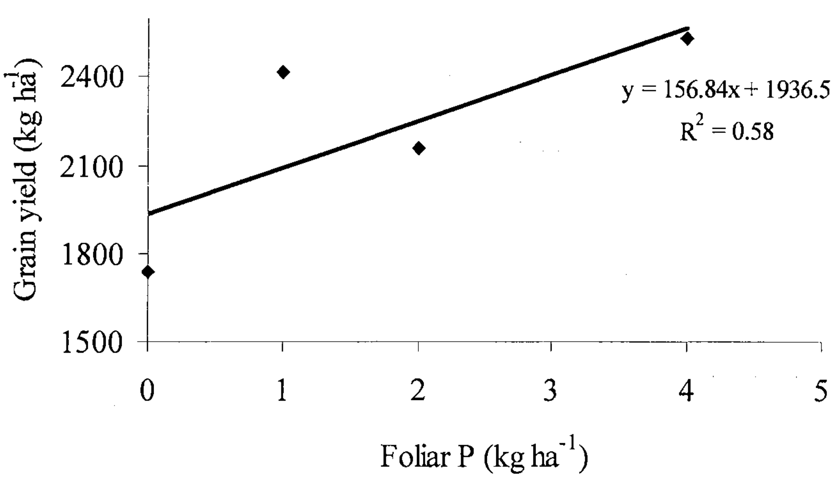

Figure 2. Relationship between grain yield and foliar P rates applied at Feekes 7 with pre-plant rate of 30 kg ha^{-1} at Perkins, 2002.

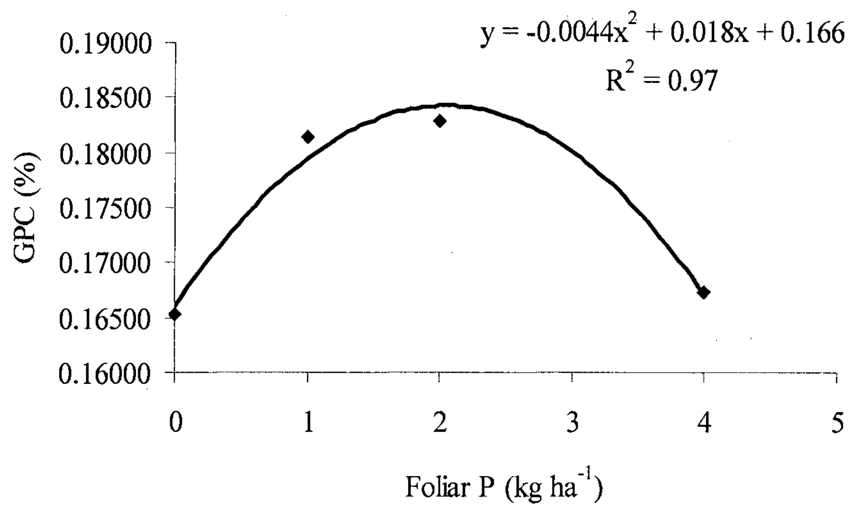

Figure 3. Relationship between grain P concentration and foliar P rates applied at Feekes 7 without pre-plant rate at Perkins, 2003.

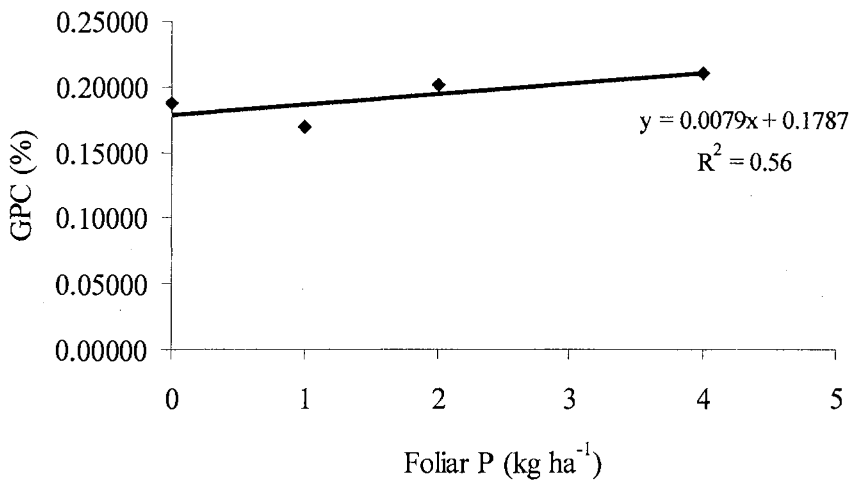

Figure 4. Relationship between grain P concentration and foliar P rates applied at Feekes 7 with pre-plant P rate of 30 kg ha^{-1} at Perkins, 2003.

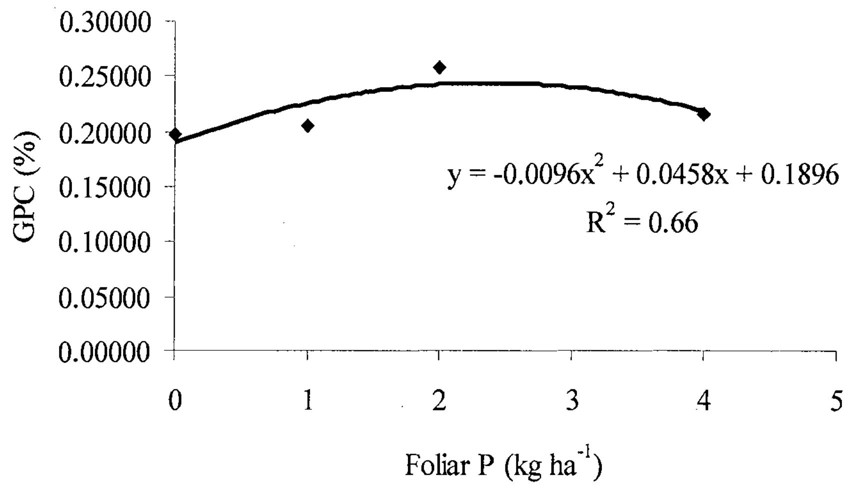

Figure 5. Relationship between grain P concentration and foliar P rates applied at Feekes 7 with pre-plant P rate of 30 kg ha^{-1} at Perkins, 2002.

APPENDIX-1

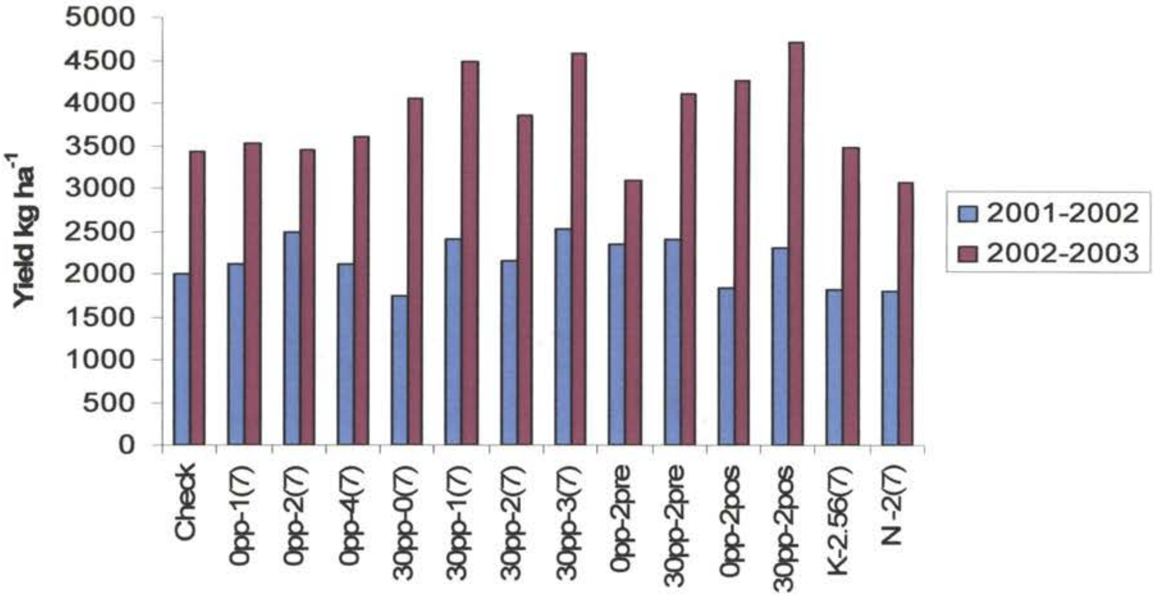

Figure 1. Effect of phosphorus (kg ha^{-1}) on wheat grain yield at Lahoma during 2001-2002 and 2002-2003 crop years.

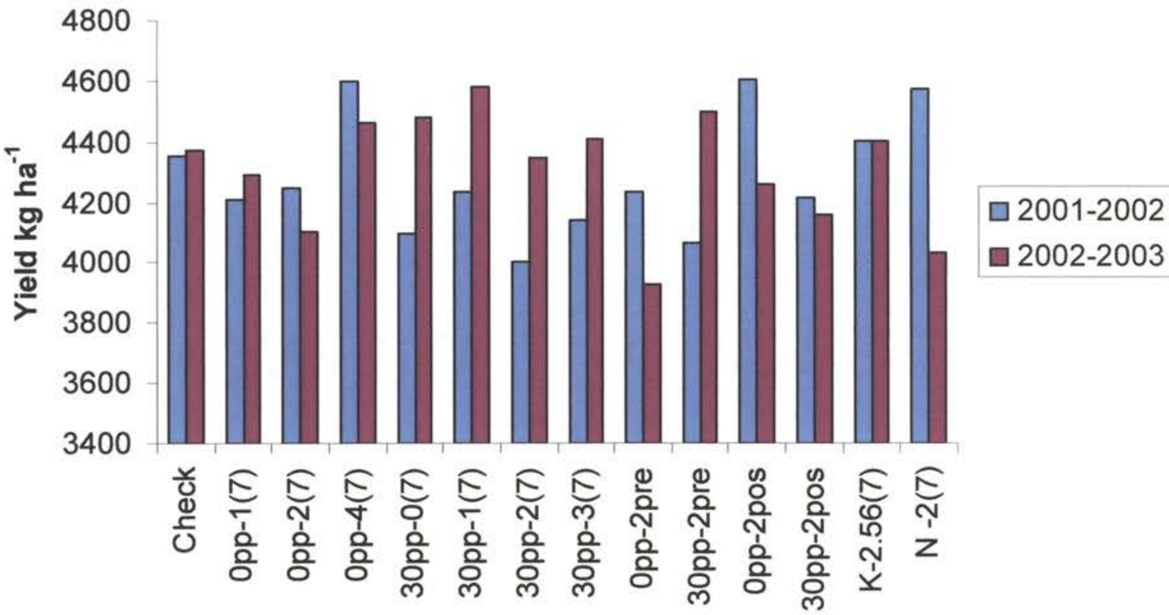

Figure 2. Effect of phosphorus (kg ha^{-1}) on wheat grain yield at Lake Carl Blackwell during 2001-2002 and 2002-2003 crop years.

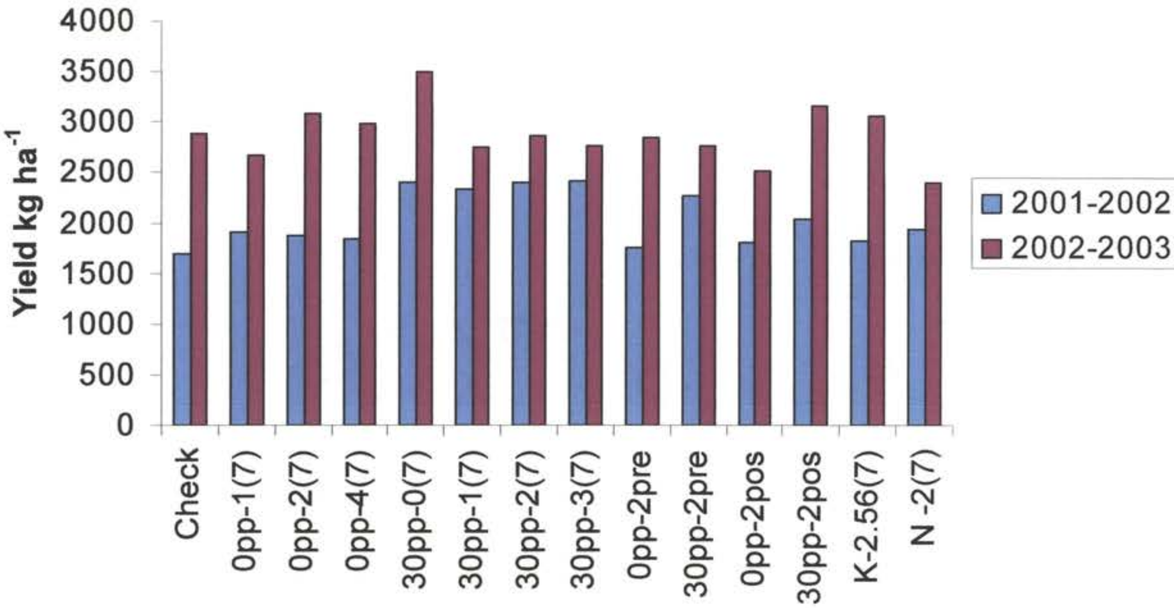

Figure 3. Effect of phosphorus (kg ha^{-1}) on wheat grain yield at Lake Carl Blackwell during 2001-2002 and 2002-2003 crop years.

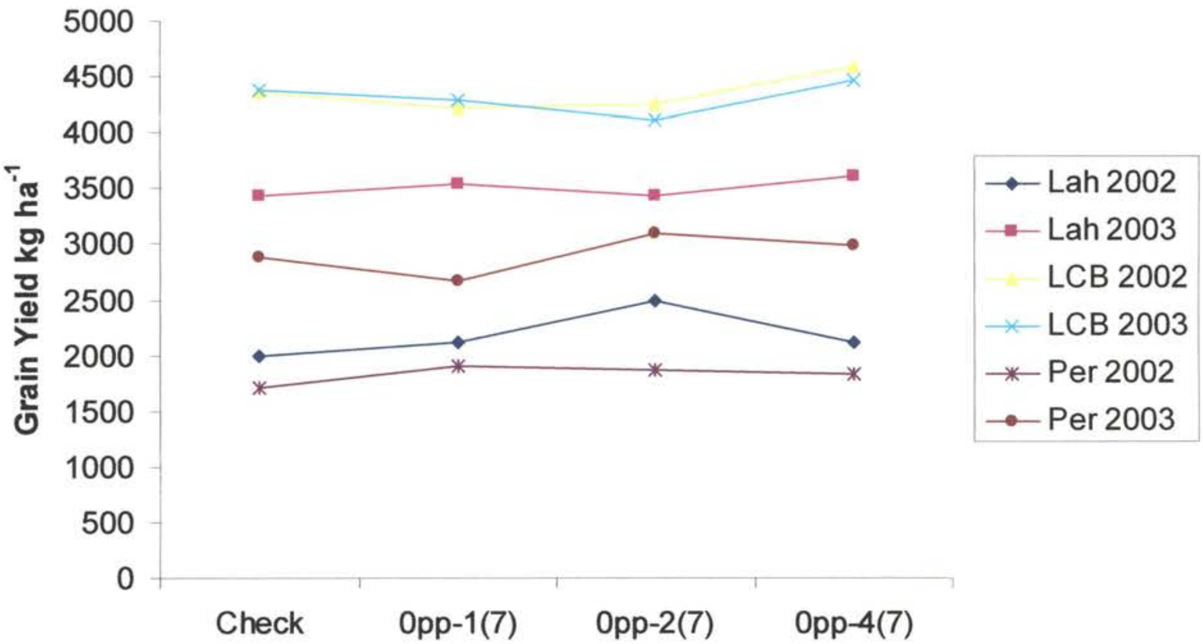

Figure 4. Grain yield response to foliar applied phosphorus with 0 kg ha^{-1} preplant at all locations during 2001-2002, 2002-2003 crop years.

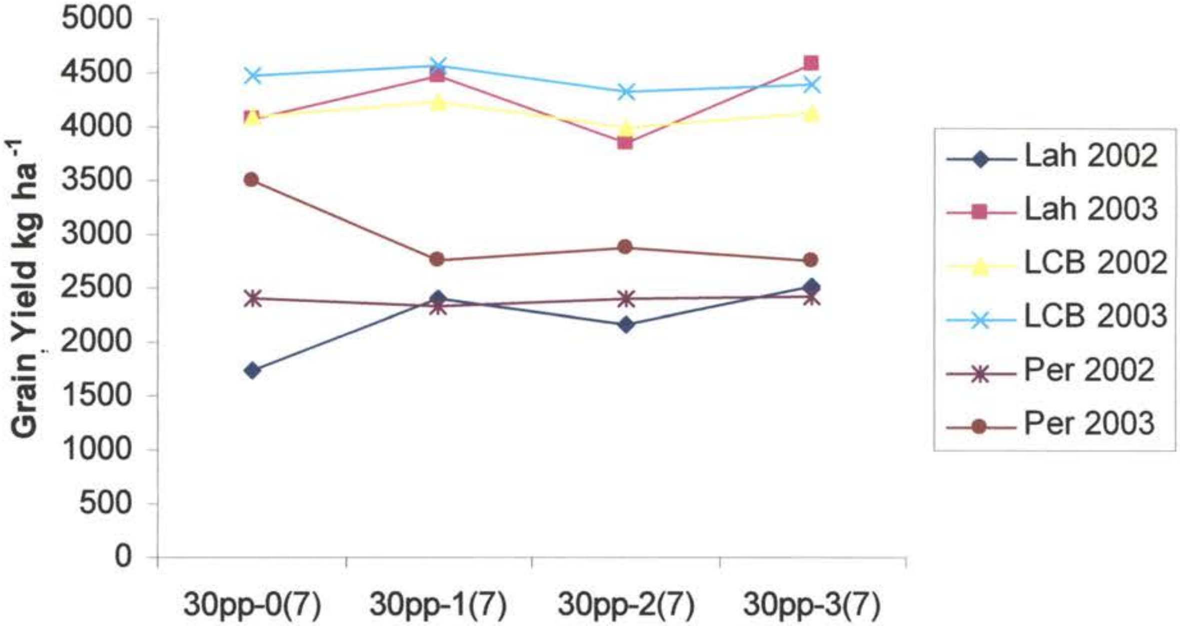

Figure 5. Grain yield response to foliar applied phosphorus with 30 kg ha^{-1} preplant at all locations during 2001-2002, 2002-2003 crop years.

CHAPTER-II

USEOF IN-SEASON REFLECTANCE FOR PREDICTING YIELD POTENTIAL IN BERMUDAGRASS

ABSTRACT

Spatial variability of soil nutrients is known to exist at distances less than 1 meter. This variability in nutrient content must be addressed if fertilizer use efficiency has to be maximized in a given field. Plant recovery of applied nitrogen (N) fertilizer generally decreases with increasing rates in current production systems. This is probably due to the previously mentioned variability as well as differences in potential plant use. Recently, an on-the-go system for application of N fertilizer based on spectral measurements known as in-season estimated yield (INSEY) was developed, which takes into account both temporal and spatial variability, and that improved N use efficiency by as much as 17% in winter wheat. Six trials were conducted in 2001,2002 and 2003 at Ardmore and Burneyville, OK with an objective to develop an index similar to INSEY for use in predicting yield potential in bermudagrass and that can be used for adjusting fertilizer N rates. Initial results indicate that 55% of variation in predicted bermudagrass forage yield was explained by a B-INSEY index and where 54% of the variation in forage N uptake was explained using normalized difference vegetative index (NDVI). The remaining challenge is to develop appropriate N fertilizer rates based on this information and apply these rates using on-the-go technology.

INTRODUCTION

Nitrogen (N), Phosphorus (P) and Potassium (K) are the major nutrients that play a pivotal role in the growth of all crops. During the past few decades, the largest increase in the use of agricultural inputs has been fertilizer N (Johnston, 2000). Because many plant nutrients are non-renewable and depleting rapidly, efficient use of applied fertilizers is important in these times of high production costs and environmental concern. Currently, nitrogen use efficiency (NUE) for worldwide cereal production is estimated to be 33% (Raun and Johnson, 1999) and for forage production, around 45%. Bermudagrass is classified as warm season forage, which is extensively grown in the central plains of North America. The uniqueness of this crop is that it has the potential of several harvests (1 to 4) in one year depending on the soil conditions and the rainfall in a particular region. The general production practice is to apply most of the N based on a yield goal early in the spring. Johnson (1991) suggested that in order to take advantage of the above average growing conditions in dryland agriculture, it is better to set the yield goal above that of average yields. Yield goal is the "yield per acre you hope to grow" clearly indicating the risk the farmer is taking when he calculates the amount of fertilizer for the crop before production (Dahnke et al., 1988). Usually, fertilizer rates are defined by a specified yield goal, taking into account available soil N (Raun et al., 2001).

Osborne et al. (1999) reported that though yield increased with increasing rates of N fertilizer, N fertilizer recovery levels in bermudagrass were greatest (85%) at N rates less than 224 kg N ha^{-1}, and recovery was less than 20% when

1344 kg N ha^{-1} was applied. Mathias et al. (1978) reported that bermudagrass yields and N concentration increased while percent recovery decreased with rising N applications up to 448 kg N ha^{-1}.

The presence of spatial variability in agricultural landscapes is an issue demanding careful consideration for efficient use of fertilizers. One approach to increase fertilizer use efficiency is variable rate technology (VRT). Different methods of VRT include the use of satellite imaging, grid sampling, and high resolution sensing by ground-based sensors. Spatial variability of crop nutrient status can be assessed using aerial or satellite remote sensing and can be used to detect N stress for further fertilizer application at variable rates (Ferguson, 1997; Mangold, 1998).

Carr et al. (1991) investigated economic efficiency of uniform fertilizer rates for the whole field versus variable rates for dryland wheat in accordance with soil units that had different crop yield potential. They showed positive returns of \$21.68- \$23.51 ac^{-1} when optimum treatments for a specific soil were applied rather than uniform rates for the whole field. Although soil units and satellite images distinguish field elements by nutrient availability, their separation is rather poor (coarse scale), which results in low efficiency of variable versus uniform application.

NUE is also complicated by cropland spatial variability that is known to exist at resolutions smaller than 1 m^2 (Solie et al., 1996, Raun et al., 1998). Raun et al. (1998) and Solie et al. (1999) reported that variability exists even in 0.3m by 0.3m bermudagrass plots with regard to the availability of nutrients. The variability in P and K was not as large when compared to N variability where major differences were observed. The same work reported that variable fertilizer treatment of crops, where each field element is treated separately, can be an effective alternative to the existing uniform fertilizer application practices. Nitrogen fertilizer requirements depend on the potential N uptake by the crop and are related to the overall yield potential. Potential yield is the yield that can be produced on specific soil under specific weather conditions which changes with time (Raun et al., 2001).

It was reported by Makowski and Wallach (2001) that profitable N fertilizer recommendations can be made using models that include end of winter soil mineral N. Cabrera and Kissel (1988) made fertilizer N recommendations based on N mineralized from organic matter. According to Rodriguez and Miller (2000) there was a positive linear relationship between total Kjeldahl nitrogen (TKN) and near infrared reflectance spectroscopy (NIRS). Spectral radiance measurements were evaluated by Sembiring et al. (1998) to identify optimum wavelengths for dual detection of N and P status in bermudagrass (*Cynodon dactylon* L.) when 0, 112, 224, and 336 kg N ha^{-1} and 0, 29 or 58 kg P ha^{-1} were applied in a factorial arrangement of treatments. It was found that biomass, N uptake, P uptake, and N concentration could be predicted using 695/405 nm, with 435 nm as a covariate. Taylor et al. (1998) reported that correlation of forage yield and N removal with red, near infrared (NIR), and normalized difference vegetative index (NDVI) were best with maximum forage production, however, when forage production levels were low, correlation decreased dramatically for the red wavelength compared with NIR and NDVI.

Overman and Wilkinson (1992) noted the importance of long-term experiments and suggested that 3 years of data in yield response trials to applied N gives a reasonable first approximation to a steady state in perennial grasses. Wiedenfield (1988) reported that N removal increased with an increase in yields up to 224 kg N ha^{-1} in bermudagrass. With a spilt application of N, the N fertilizer recovery increased up to 448 kg N ha^{-1} on perennial grasses compared to early spring application (Hanson et al., 1978). Crawford et al. (1961) reported that the stage of growth, level of N fertilization, plant part, and light intensity all influenced NO_3-N concentration, while cultivar, source, time and method of placement had no effect in forages. Overman and Scholtz (2003) reported that in bermudagrass short intervals (2 weeks) in cutting produced low yield but resulted in higher protein content, where as yields were higher with low protein content with longer intervals of more than 12 weeks. Kincheloe (1994) reported that the field practices should be site specific and the areas within the field to be categorized as best management practices (BMP). He defined BMP's as those practices that have been tested in research and proven on the farmers' fields as most effective in terms of input efficiency, production potential and environmental protection.

In-season knowledge of potential yield might be the key to successful variable rate fertilizer applications. Raun et al. (2001) demonstrated that the estimated yield (EY) index was a good predictor of grain yield over a wide range of environmental conditions in winter wheat. They further noted that EY could be used to refine in-season fertilizer N based on predicted potential yield. Raun et al. (2001) reported that sensor readings using NDVI (NDVI = (NIR-red)/ (NIR+red)) mid-season (Feekes 4 to 6) could predict yield potential in winter wheat. This initial work used the sum of two post dormancy NDVI readings divided by cumulative growing degree days ($\Sigma GDD = (T_{min}+T_{max})/2 - 4.4^{o}C$). Raun et al.(2002) later refined this index where only one NDVI reading is taken post dormancy divided by only those days where GDD>0 (including this environmental factor eliminates the days where growth is not possible) from planting to the date of sensing. The same work showed that yield potential based on mid-season estimates increased NUE by 15% when compared to the uniform rates and this was attributed to collecting readings from each $1m^2$ and fertilizing each $1m^2$, recognizing that the spatial variability exists at $1m^2$ resolutions and the potential yield of each $1m^2$ is different.

The Response Index (RI) has been used to determine the extent the crop will respond to fertilizer application under particular growing conditions, both location and year dependent (Mullen et al., 2003). This work showed that RI can be calculated by taking the average NDVI from N-rich strips (where N is non-limiting) divided by NDVI or other means of measurement collected from the farmer's practice or check plot. RI varies from year to year and is independent of whether the yields were low or high during the past year (Johnson and Raun, 2003). This same work reported that the response to applied N is variable from year to year over a period of 30 years in a replicated long term study where the same plots received the same amount of N year after year. Differing responses to applied N was attributed to highly variable weather conditions which change N mineralization, and atmospheric depositions. Raun et al. (2004b) showed that yield potential prediction equations for winter wheat can be reliably established with only 2 years of field data. As reported before, the N supplying capacity of the soil varies both spatially and temporally. This creates a scope where there are cases in which the farmer might not need any external input of nitrogen.

The objective of this study is to develop an index similar to INSEY for wheat for use in predicting forage yield potential in bermudagrass which can later be used for adjusting fertilizer N.

MATERIALS AND METHODS

Two field experiments with minimum fertilization located at Burneyville, (Minco silt loam, coarse-silty, mixed, superactive, thermic Udic Haplustolls) and Ardmore, (Wilson silt loam, fine, smectitic, thermic oxyaquic vertic Haplustalfs) Oklahoma were initiated in April, 2001. These were previously established pastures with “midland” bermudagrass. The experiments were laid out in a randomized complete block design with eight treatments and three replications. The plots received Urea-N rates of 0, 56, 112, 168 and 224 kg N ha^{-1} broadcast applied early in the spring at the time of breaking dormancy (last week of March to first week of April) for the first five treatments and treatments 6, 7 & 8 were included for added nitrogen use efficiency evaluation using the Nitrogen Fertilization Optimization Algorithm (NFOA) (Appendix).

Plot sizes were 3.04m x 6.08m with 3.04m alleys. Phosphorus and potassium were broadcast applied at both the sites at the initiation of the experiment. During early March of each year, a mix of LoVol 6, Pendimax was used to control weeds. Initial soil test data is reported in Table 1. Treatment structure is reported in Table 2 and dates of activities are reported in Tables 3, 4 & 5.

Sensor readings were collected for three years at both locations at the time of harvest for each cutting and during in-season growth for most cuttings. In-season readings were collected following at least 10-14 days of active growth (around 3 inches of height). Spectral reflectance measurements during 2001 from the bermudagrass canopy was measured using a handheld sensor that was developed at Oklahoma State University, which included two upward and two downward looking photodiode sensors that collected readings in two bands, red (671$\pm$ 6nm) and near infrared (780$\pm$6nm) bandwidths during 2001(Stone et al., 1996b). The reflectance sensor employed photodiode detectors with inference filters. One pair of filters (up-looking) received incoming light from the sun, and the other pair (down-looking) received light reflected by vegetation and/or soil surface. The instrument used a built-in 16-bit A/D converter that converted the signals from all four photodiode sensors simultaneously. The ratio of readings from down looking to up-looking photodiodes allowed the elimination of fluctuation among readings due to differences in atmospheric conditions, and/or shadows. During 2002 and 2003, sensor readings were taken using a GreenSeeker® Hand Held Optical Sensor (NTech Industries, Inc.) to measure crop reflectance and calculate the NDVI. This sensor is an active sensor (which means it has it's own self-contained illumination in the both red (650+ 10 nm full width half magnitude) and NIR (770+ 15 nm)) when held approximately at a distance of 60cm to 100cm above the crop, it senses an area of 60cm x 10 cm.

This device measures reflectance which is the fraction of emitted light in the sensed area that is returned to the sensor (Raun et al., 2004a). NDVI is calculated based on the following formula

$$NDVI = \frac{\frac{NIRref}{NIRinc} - \frac{REDref}{REDinc}}{\frac{NIRref}{NIRinc} + \frac{REDref}{REDinc}}$$

When the bermudagrass was at or near morphological stage of 41 to 49 (anthesis) as defined by West (1990), the forage was harvested. Caution was taken to collect harvest data prior to anthesis since the grass turns a pale color after this stage and there are increased opportunities to underestimate N uptake thus altering the N content in the grass. Forage was harvested in the center of each plot using a John Deere (GT 262) lawn mower with a cutting width of 96.52cm which has a forage collection device attached. Forage samples were weighed for fresh weight and sub-sampled for moisture content at the time of harvest. The samples were then dried for 48 hours in a forced air oven at 70^0C and ground to pass a 0.125mm (120-mesh) sieve.

The total nitrogen content was analyzed using a Carlo-Erba (Milan, Italy) NA-1500 dry combustion analyzer (Schepers et al., 1989). Early-season plant N uptake was determined by multiplying dry matter yield by the total N concentration determined from dry combustion. The difference method (N removed in the check plot subtracted from the N removed in the fertilized plot divided by the amount of fertilizer N applied) was used to determine nitrogen use efficiency.

Similar to the steps reported by Lukina et al (2001) who developed a nitrogen fertilization optimization algorithm for wheat (NFOA), an NFOA was developed for bermudagrass and used for N fertilization rates in treatments 6, 7, and 8. Response index (RI) was calculated in-season using NDVI as proposed by Johnson et al. (2000) and Mullen et al. (2003). Data was analyzed using Microsoft Excel and SAS (SAS, 2001). Growing degree days (GDD) was calculated by subtracting the base temperature from the daily average minimum and maximum temperatures. The minimum temperature at which a plant can grow is called the base temperature (Eastin and Sullivan, 1984).

$$GDD = \frac{TEMPmax + TEMPmin}{2} - 10^{o}C$$

$$B - INSEY = \frac{NDVI}{\sum GDD}$$

$$RI = \frac{NDVI\ of\ N - Rich\ plot}{NDVI\ of\ Check\ plot\ /\ Farmers\ practice}.$$

At each trial, an N rich strip (N applied at a rate when N would not be limiting through out the growth cycle) was established and 336 kg N ha^{-1} was applied at the time of breaking of dormancy, followed by 224 kg N ha^{-1} applied after every harvest until September.

RESULTS AND DISCUSSION

Crop year 2001

NDVI measurements collected at the time of harvest were highly correlated with forage N uptake (Figure 1). This takes into consideration three harvests at Burneyville and two at Ardmore. It shows us that the amount of N present in forage can be predicted using NDVI at the time of sensing, which is consistent with early work by Stone et al. (1996a) who showed that NDVI was highly correlated with wheat forage N uptake.

Sensor readings were taken 15-20 days after breaking dormancy and after the 1st cutting when the grass was around 7-9cm high and correlated with forage yield. Each crop requires a specific amount of heat and moisture to reach maturity, therefore, cumulative GDD was incorporated as an environmental factor to strengthen the B-INSEY index. The B-INSEY index was positively correlated with forage yield (Figure 2). However, it should be noted that this 2001 database was not robust.

Crop year 2002

The relationship between NDVI and forage N uptake in 2002 is reported in Figure 3. The relationship between NDVI and forage N uptake at Ardmore behaved in a different manner due to high weed infestation. When this site was removed, the correlation significantly improved (Figure 4). It should again be noted that these NDVI readings were collected on the same day that harvest data was collected.

The first cutting came up very early, so it was not possible to correlate B-INSEY with forage yield using the 1st cutting. B-INSEY was correlated with the second harvest, noting that 38% of the variation in bermudagrass forage yield was explained (Figure 5).

Crop year 2003

Similar to Ardmore in 2002, the first cutting data set behaved a little different than the others, having a lower correlation (R^2=0.37, Figure 6). When this site was eliminated, there was improved correlation with 65% of the variation explained by the model (Figure 7).

Using only data from the first cutting, B-INSEY was highly correlated with forage yield (Figure 8).

Combined site years

Over sites and years, these trials demonstrate that spectral reflectance measurements taken mid-season (B-INSEY with forage yield across 7 site years between harvests) coupled with cumulative GDD (Figure 9) can be used for predicting the forage yield in bermudagrass (R^2=0.55). This tells us that we can predict the forage yield for each harvest when we sense in-season. N uptake with

NDVI also showed a positive correlation (R^2=0.43) across 12 site years (Figure 10). Even when problematic weedy site years (Ardmore) were included, 43% of variation in N uptake was explained (Figure 11). Cumulative growing degree days from dormancy to mid-season and mid-season sensing followed by subsequent harvests provided a reliable estimate for predicting forage yield in bermudagrass after eliminating the problematic 2 site years at Ardmore. ΣGDD worked in bermudagrass contrary to wheat (Raun et al., 2001) because it is a warm season crop and most of the days are warmer than the temperature growth requirement once it breaks dormancy, and no days are cool enough whereby no growth takes place. Either way, it was difficult to use either ΣGDD or days where GDD>0 (data reported in Appendix) because if moisture became a limiting factor and there is no growth for a long period of time, ΣGDD or days where GDD>0 accumulated without concurrent growth in the crop. So, if more in-season sensor readings are available along with rainfall and soil moisture data, the prediction confidence increases using these components of moisture and temperature. Even without the moisture component and enough readings throughout the growing season, it was exciting to see that most of the variation in forage yield was explained by the model.

CONCLUSIONS

NDVI was highly correlated with forage N uptake in bermudagrass for most of the harvest dates, excluding the 1st cutting at Ardmore. B-INSEY (calculated using cumulative GDD's) was also highly correlated with final dry matter forage yield when evaluated over locations and years. The problem with this research is determining the correct time to apply fertilizer. The grass should have sufficient growth (at least 2-3 inches of growth) to make accurate recommendations. This research shows potential in managing the temporal variability that occurs from year to year and harvest to harvest as well as the spatial variability within a bermudagrass field. It was exciting to find out that prediction of bermudagrass forage yield could be accomplished using a single sensor measurement. This research was done under controlled conditions for hay production only. Rainfall combined with profile moisture needs to be incorporated into the model. Also, added work is needed to document the minimum amount of regrowth needed in order to guarantee reliable prediction of yield.

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Table 1. Initial surface (0-15 cm) soil chemical characteristics and classification at Ardmore & Burneyville, OK.

Location	pH	NH_4-N	NO_3-N	P	K
		----------------------mg kg^{-1}	----------------------		
Ardmore	5.2	9.4	1.5	56	225
Burneyville	5.7	10.5	2.6	30	187

NH_4-N and NO_3-N- 2 M KCl extraction
P and K – Mehlich -III extraction
pH – 1:1 Soil: Water

Table 2. Treatment structure for the bermudagrass NFOA experimental sites.

Treatment No.	Pre-Plant N kg ha^{-1}	Topdress N
1	0	0
2	56	0
3	112	0
4	168	0
5	224	0
6 NFOA-1	0	NFOA @ 0.5
7 NFOA-2	0	NFOA @ 1.0
8 NFOA-3	0	NFOA @ 1.0

Preplant N - N applied as urea just before breaking of dormancy during late March and early April
Topdress N – N applied as UAN using Pulse modulated handheld sprayer
Algorithm utilizing total N uptake for topdress
Algorithm using current N uptake for topdress

Table 3. Field activities carried at Ardmore & Burneyville, OK during 2001.

Field Activity	Ardmore	Burneyville
Dormancy fertilization	03/23/01	03/23/01
1st sensor reading	05/22/01	05/22/01
1st harvest	06/20/01	06/20/01
2nd sensing	06/20/01	06/20/01
3rd sensing	07/10/01	07/10/01
2nd harvest	08/10/01	08/10/01
4th sensing	08/10/01	08/10/01
5th sensing	10/02/01	10/02/01
Final harvest	10/02/01	10/02/01

MM/DD/YY – month/day/year

Table 4. Field activities carried at Ardmore & Burneyville, OK during 2002.

Field Activity	Ardmore	Burneyville
Dormancy fertilization	04/10/02	04/10/02
1st harvest	05/15/02	05/15/02
1st sensing	05/15/02	05/15/02
2nd sensing	06/04/02	06/04/02
2nd harvest	10/02/02	07/12/02
3rd sensing	07/12/02	07/12/02
4th sensing	08/09/02	08/09/02
1st NFOA	06/04/02	06/04/02
Final harvest	-	10/02/02

MM/DD/YY – month/day/year

Table 5. Field activities at Ardmore & Burneyville, OK during 2003.

Field Activity	Ardmore	Burneyville
Dormancy fertilization	04/03/03	04/03/03
1st sensing	05/08/03	05/08/03
1st NFOA	05/08/03	05/08/03
1st harvest	06/19/03	06/19/03
2nd sensing	06/19/03	06/19/03
3rd sensing	08/01/03	08/01/03
2nd NFOA	08/01/03	08/01/03
2nd harvest	10/27/03	09/03/03
4th sensing	09/03/03	09/03/03
5th sensing	10/27/03	10/27/03
Final Harvest	-	10/27/03

MM/DD/YY – month/day/year

Table 6. Cropping period, GDD, GDD>0 data used at Ardmore

Year	Cutting	Cropping period(days)	GDD>0	ΣGDD
2001	1	66	38	686
2002	2	57	19	374
2003	1	65	23	437

GDD - Cumulative GDD from previous harvest/ breaking dormancy until sensing date
GDD>0-The number of days where GDD>0 until the date of sensing from previous harvest/ breaking dormancy until sensing date
Cropping period- The time between the 2 harvests

Table 7. Cropping period, GDD, GDD>0 data used at Burneyville

Year	Cutting	Cropping period(days)	GDD>0	ΣGDD
2001	1	66	38	903
2001	2	51	20	591
2002	2	57	19	394
2003	1	65	23	432
2003	2	75	43	1377

GDD - Cumulative GDD from previous harvest/ breaking dormancy until sensing date
GDD>0-The number of days where GDD>0 until the date of sensing from previous harvest/ breaking dormancy until sensing date
Cropping period- The time between the 2 harvests

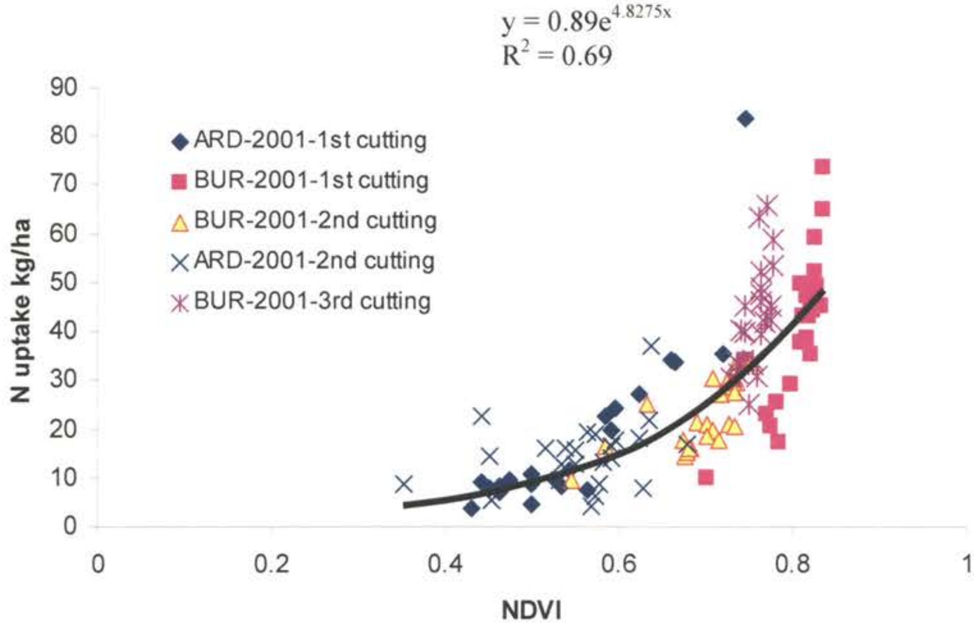

Figure 1. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in 2001 at Burneyville and Ardmore, OK.

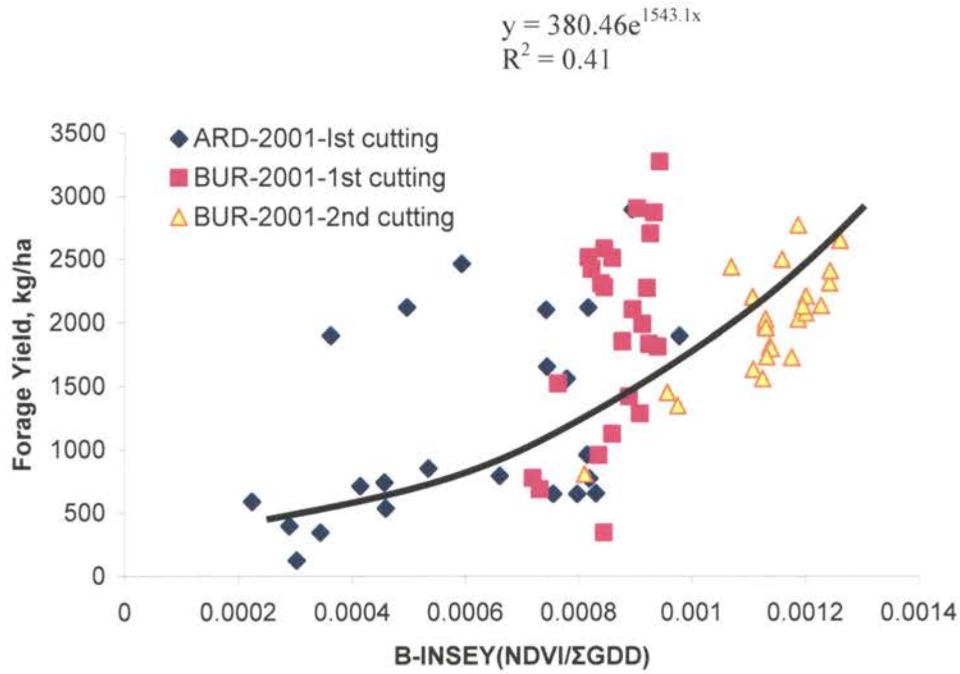

Figure 2: Relationship between forage yield and B-INSEY in 2001 at Burneyville and Ardmore, OK.

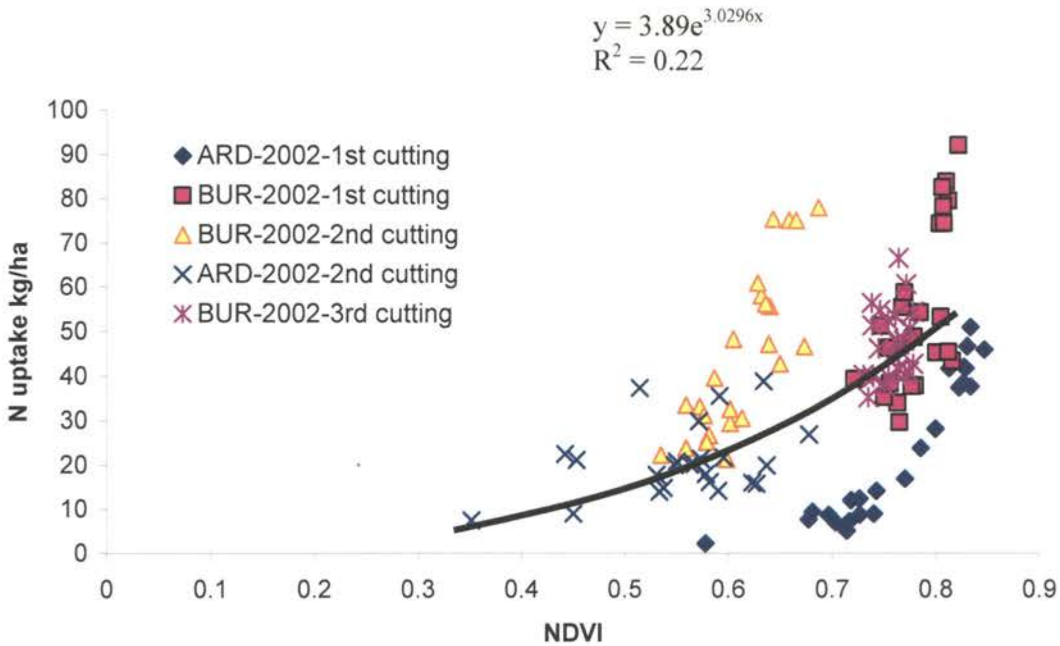

Figure 3. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in 2002 at Burneyville and Ardmore, OK.

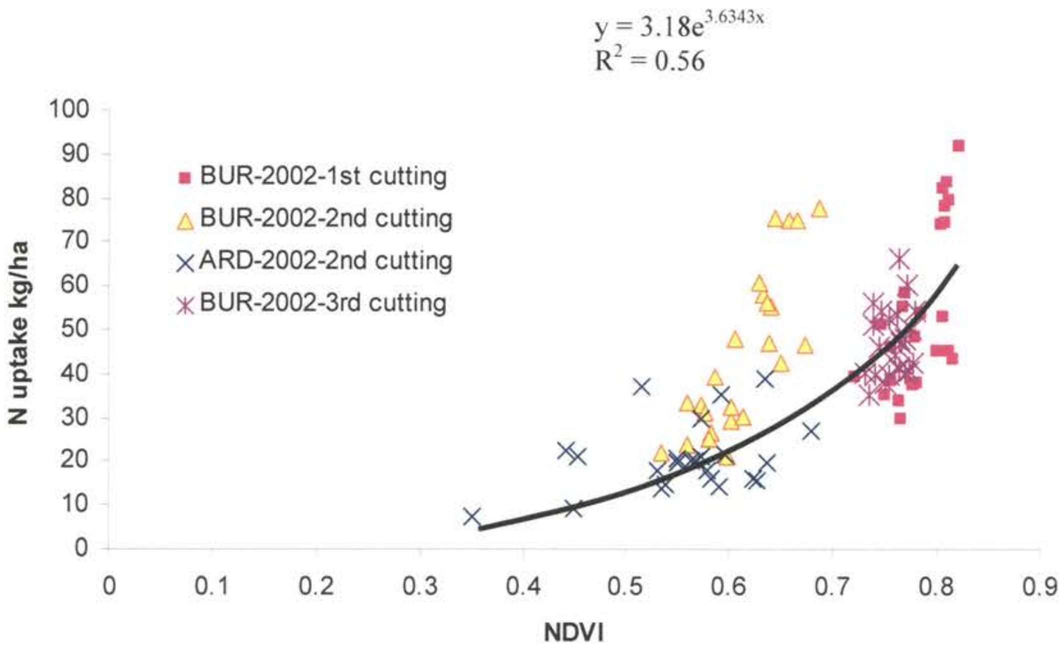

Figure 4. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest without first cutting at Ardmore in 2002 at Burneyville and Ardmore, OK.

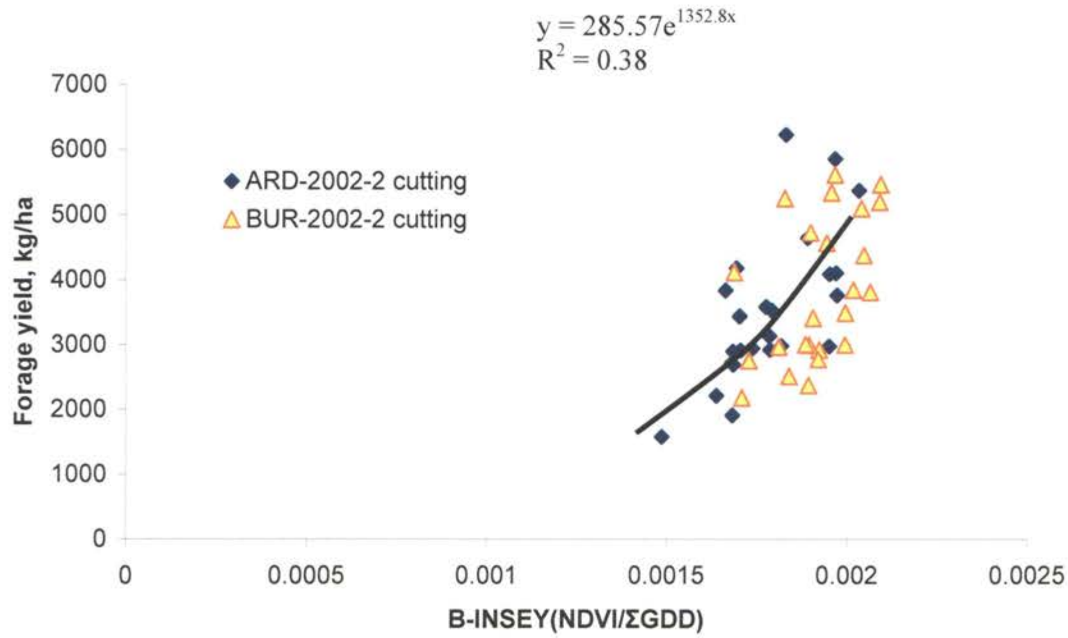

Figure 5. Relationship between forage yield and B-INSEY in bermudagrass forage collected at the time of harvest in 2002 at Burneyville and Ardmore, OK.

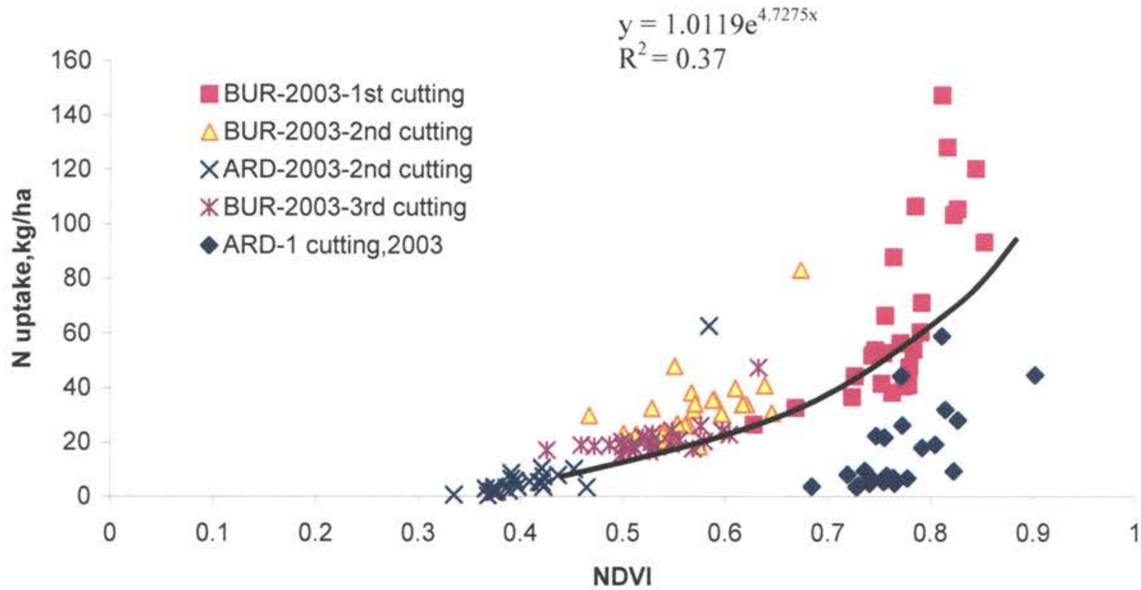

Figure 6. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in 2003 at Burneyville and Ardmore, OK

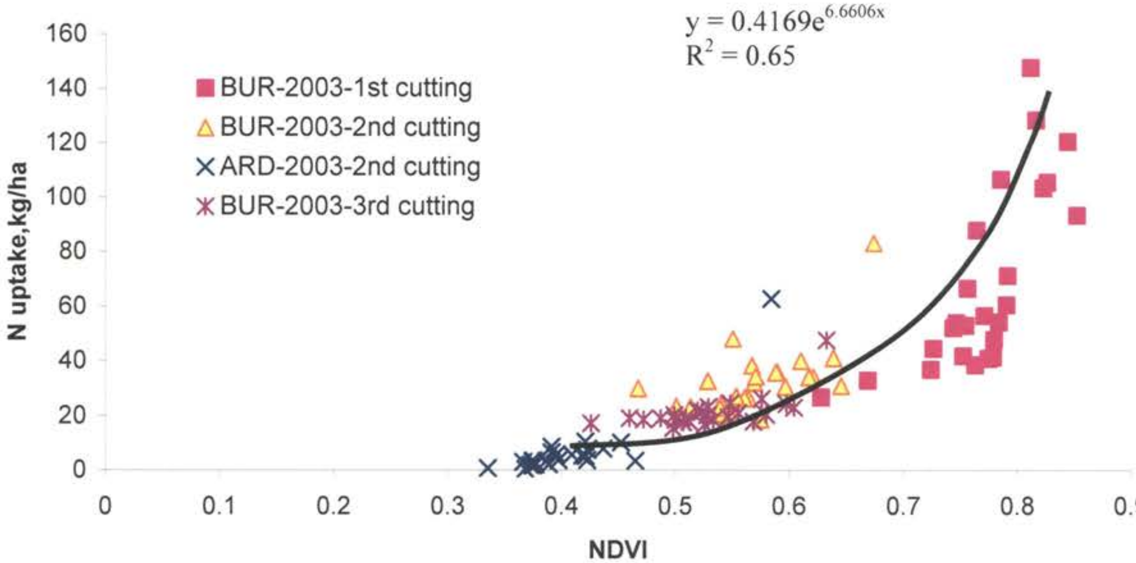

Figure 7. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest without Ardmore 1st cutting in 2003 at Burneyville and Ardmore, OK

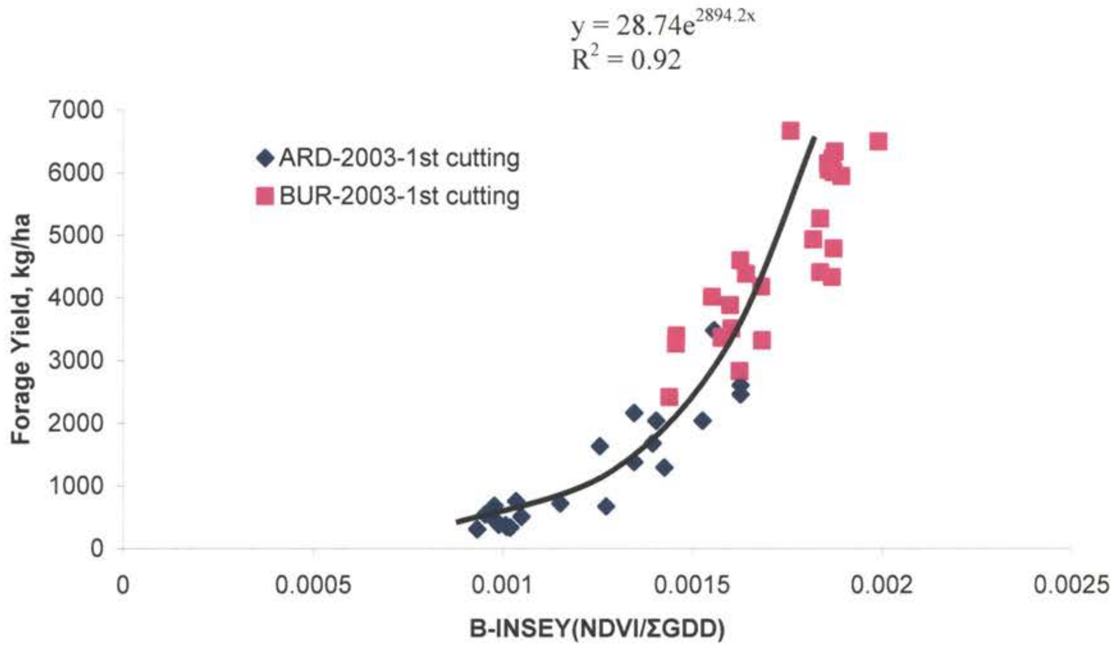

Figure 8. Relationship between B-INSEY and NDVI in bermudagrass forage collected at the time of harvest for first cutting in 2003 at Burneyville and Ardmore, OK.

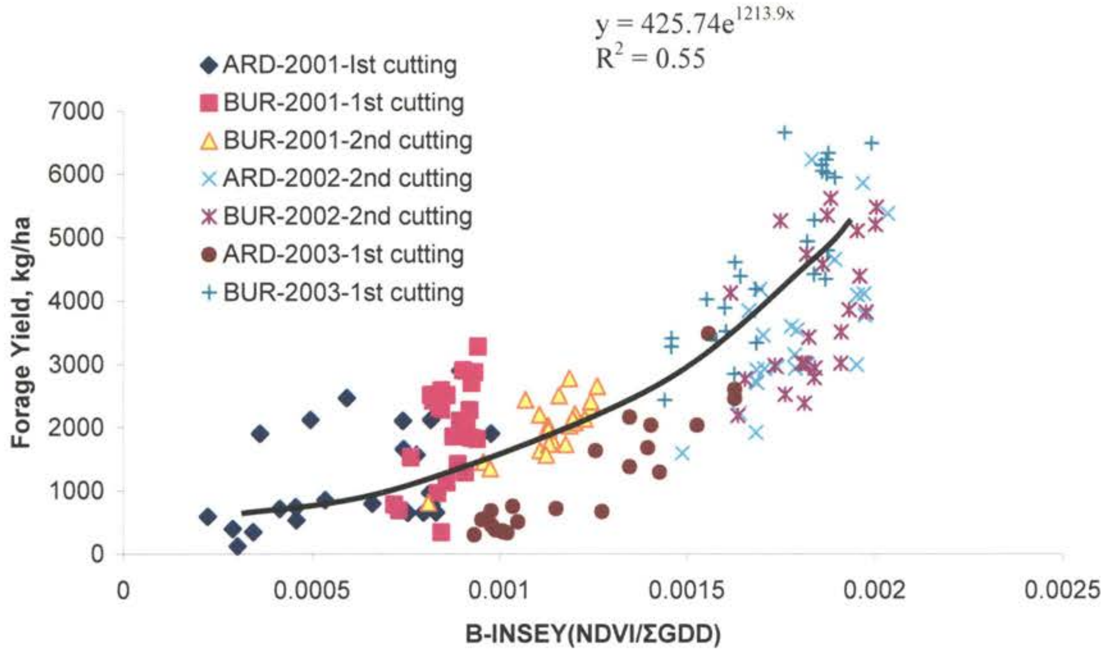

Figure 9. Relationship between B-INSEY and forage yield in bermudagrass forage collected at the time of harvest in all site years at Burneyville and Ardmore. OK.

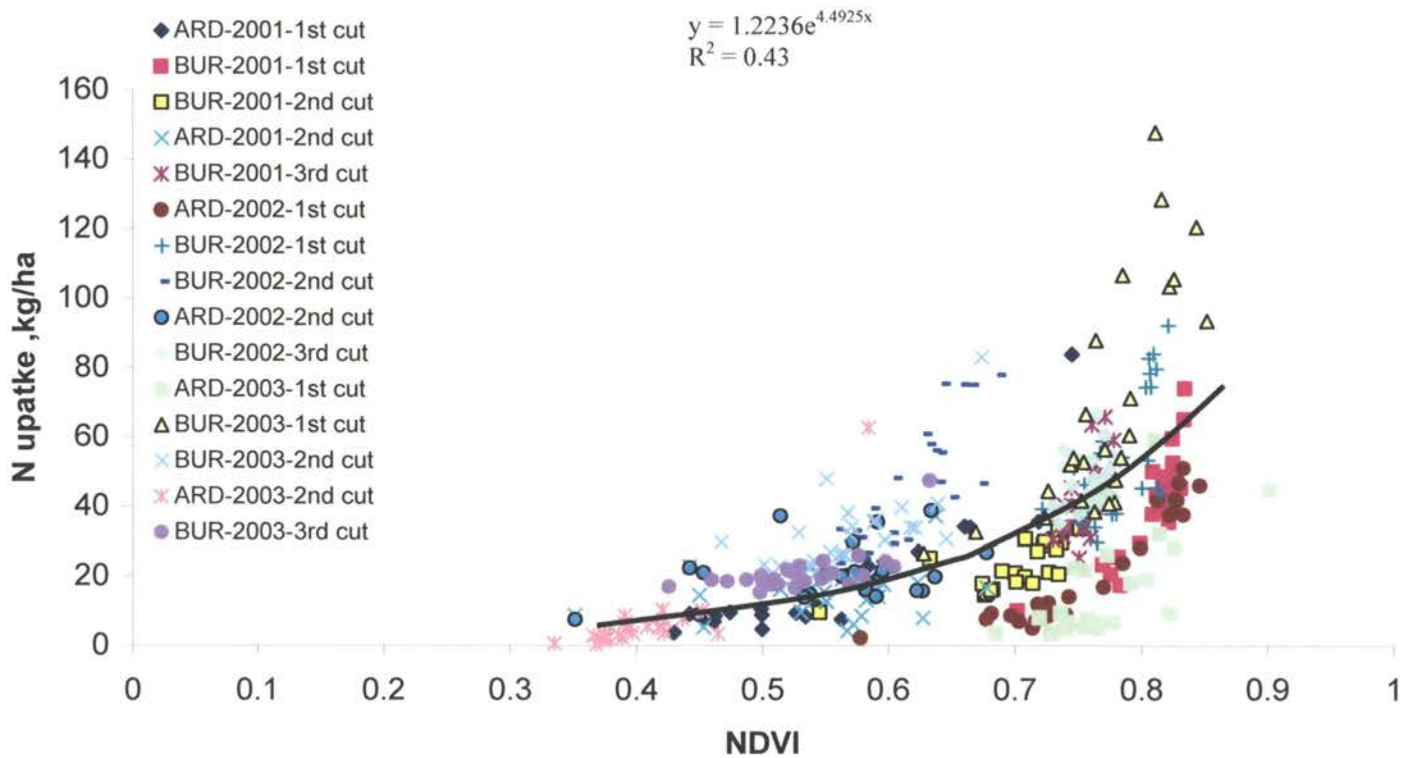

Figure 10. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in all site years at Burneyville and Ardmore. OK.

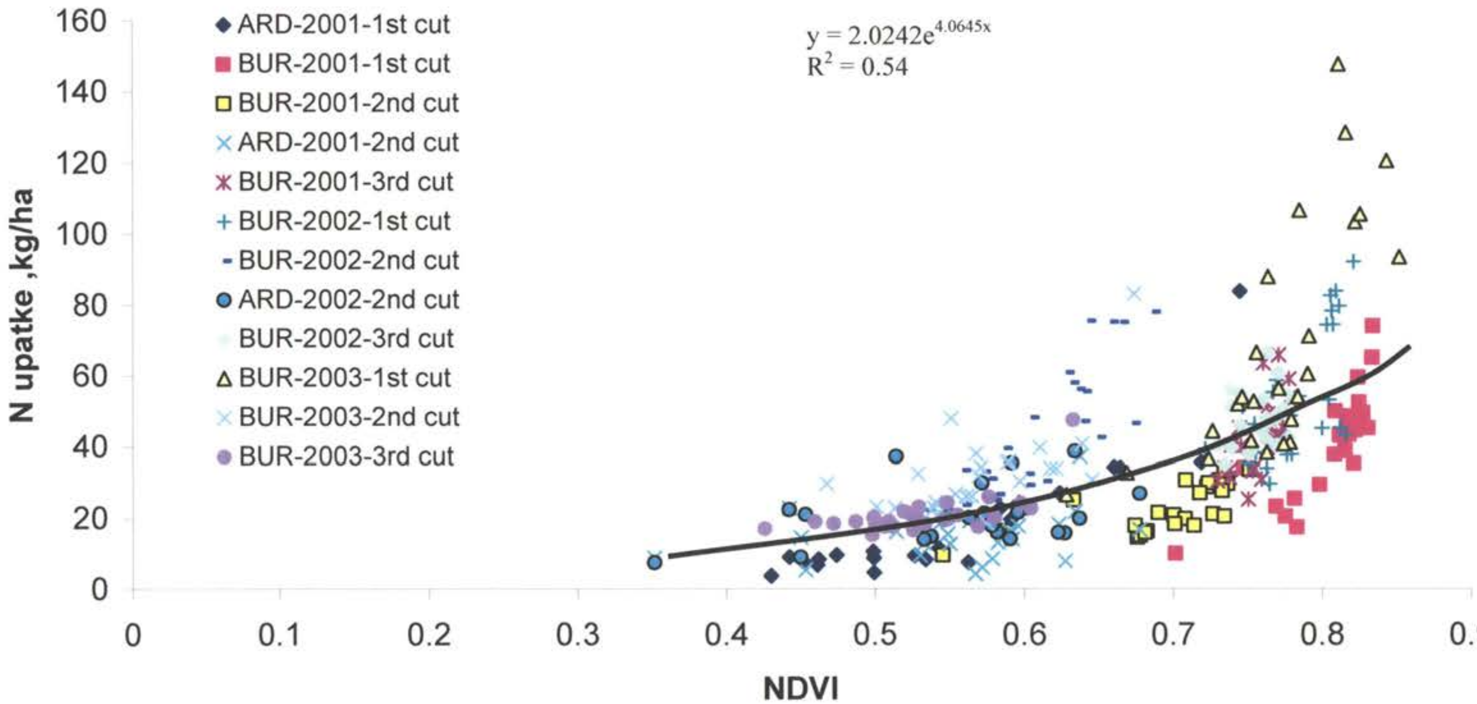

Figure 11. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in all site years (removing the bad sites) at Burneyville and Ardmore. OK.

APPENDIX

Nitrogen Fertilization Optimization Algorithm

Three experimental sites were initiated in 2001 at Burneyville (BUR), Ardmore (ARD) and Efaw, Oklahoma. Out these three, Efaw was removed due to a heavy weed problem and very low yields as compared to the present varieties. In the year 2002, long-term Bermuda NPK study (LT) at Burneyville was also included. In the year 2003, one more site at Ardmore (AH- Ardmore hillside) was established with an additional 2 treatments, which received 112 kg N ha^{-1} at dormancy. Treatments 6, 7, 8, & 9 were evaluated for determining the predictability of bermudagrass forage yield using B-INSEY index. Using the B-INSEY index that was developed and strengthened each year, the Nitrogen Fertilization Optimization Algorithm (NFOA) was developed and topdress N rates were determined for each $1m^2$. Three approaches of NFOA's were employed.

First Approach (NFOA-1):

This NFOA accounts for the amount of N that is already taken up in the forage at the time of sensing. Once the yield is predicted, total N required is back calculated and the current N in forage is subtracted from it. This algorithm is evaluated in treatment 7.

Second Approach (NFOA-2):

This is same as NFOA-1, but the amount of N is applied half the amount of that recommended by NFOA-1. This was evaluated in treatment 6.

Third Approach (NFOA-3):

This approach does not take into account the amount of N that is already present in the forage at the time of sensing and applies the entire N that is required for the predicted forage yield. This is evaluated in treatment 8.

At Ardmore hillside in treatment 9, NFOA-1 was evaluated where as in treatment 10, NFOA-3 was evaluated.

For predicting the bermudagrass forage yield, spectral readings are collected in-season when the forage is around 2-3 inches long and correlated with the forage yield of subsequent harvest. Activities with dates along with GDD's are reported in Table 1. For predicting the amount N present in forage at the time of sensing, spectral readings collected at the time of harvest were used (activities are reported in Table 3, 4, &5 of chapter-2).

The various steps and equations that were employed in NFOA in 2002 and 2003 along with the algorithm that is going to be employed in 2004 are discussed below.

Crop year 2002:

The predicted forage yield (PFY_0) at the time of sensing without added fertilizer N was given by:

$PFY_0 = 380.46e^{1543.1 * B\text{-}INSEY}$ (Figure 2 of chapter 2)

$$B - INSEY = \frac{NDVI}{\sum GDD}$$

$$B1 - INSEY = \frac{NDVI}{GDD > 0}$$

The predicted forage yield when fertilizer N was applied given by:

$PFY_N = PFY_0 * RI$

Where RI is Response Index

$$RI = \frac{NDVI\ of\ \ N - Rich\ \ plot}{NDVI\ of\ \ Check\ \ plot\ /\ Farmers\ \ practice}.$$

The predicted current forage N uptake (PCNU) was given by:

$PCNU = 0.89e^{4.8275 * NDVI}$ (Figure 1 of chapter 2)

$PNU = PFY_N * 0.0134$ (Average N content was 1.34% during 2001)

Topdress N applied (efficiency factor of 0.7)

$$TopdressN = \frac{PNU - PCNU}{0.70}$$

<u>Crop year 2003</u>

The predicted forage yield (PFY_0) at the time of sensing without added fertilizer N was given by:

$PFY_0 = 485.6e^{1115.7 * B\text{-}INSEY}$ (Figure 1)

The predicted forage yield when fertilizer N applied was given by:

$PFY_N = PFY_0 * RI$

The predicted current forage N uptake (PCNU) was given by:

$PCNU = 0.7674e^{5.4313 * NDVI}$ (Figure 2)

$PNU = PFY_N * 0.0145$ (Average N content 1.45%)

Topdress N applied (efficiency factor of 0.7)

$$TopdressN = \frac{PNU - PCNU}{0.70}$$

Crop year 2004

The predicted forage yield (PFY_0 which includes predicted yield+1stdev) at the time of sensing without added fertilizer N was given by:

$PFY_0 = 772.9e^{918.02 * B\text{-}INSEY}$ (Figure 3)

The predicted forage yield when fertilizer is added was given by:

$PFY_N = PFY_0 * RI$

The predicted current forage N uptake (PCNU) was given by:

$PCNU = 1.0993e^{5.1714 * NDVI}$ (Figure 4)

$PNU = PFY_N * 0.0145$

Topdress N applied (efficiency factor of 0.7)

$$TopdressN = \frac{PNU - PCNU}{0.70}$$

ΣGDD and GDD>0 both are tested as a factor which accounts for the environment's role in the model. B-INSEY (Bermuda-INSEY) which used ΣGDD as denominator was able to better predict bermudagrass forage yield than B_1-INSEY (Bermuda one-INSEY) which used GDD>0 as denominator. As discussed in chapter 2, ΣGDD worked in bermudagrass unlike in wheat (Raun et al., 2001) because it is a warm season crop and most of the days are warmer once it breaks dormancy, and no days are cool enough whereby no growth takes place. Table 2 & 3 provides information about how much of nitrogen was applied using the corresponding algorithm NUE's was not evaluated as topdress didn't take place using algorithm for all the harvests.

Table 1. In-season sensing dates and harvest dates for predicting bermudagrass forage yield

Year	Cutting	Location	In-season sensing date	Harvest date	# Days-sense to harvest	ΣGDD	GDD>0
2001	1st	Ardmore	05/22/01	06/20/01	29	686	38
		Burneyville	05/22/01	06/20/01	29	903	38
	2nd	Ardmore	07/10/01	10/02/01	84	597	20
		Burneyville	07/10/01	08/10/01	31	591	20
2002	2nd	Ardmore	06/04/02	10/02/02	120	374	19
		Burneyville	06/04/02	07/12/02	38	394	19
		Longterm	06/04/02	07/12/02	38	394	19
2003	1st	Ardmore	05/08/03	06/19/03	45	437	23
		Burneyville	05/08/03	06/19/03	45	432	23
		Longterm	05/08/03	06/19/03	45	432	23
		AH	05/08/03	06/19/03	45	437	23
	2nd	Burneyville	08/01/03	09/03/03	34	1377	43
		Longterm	08/01/03	09/03/03	34	1377	43
		AH	08/01/03	09/03/03	34	1364	43

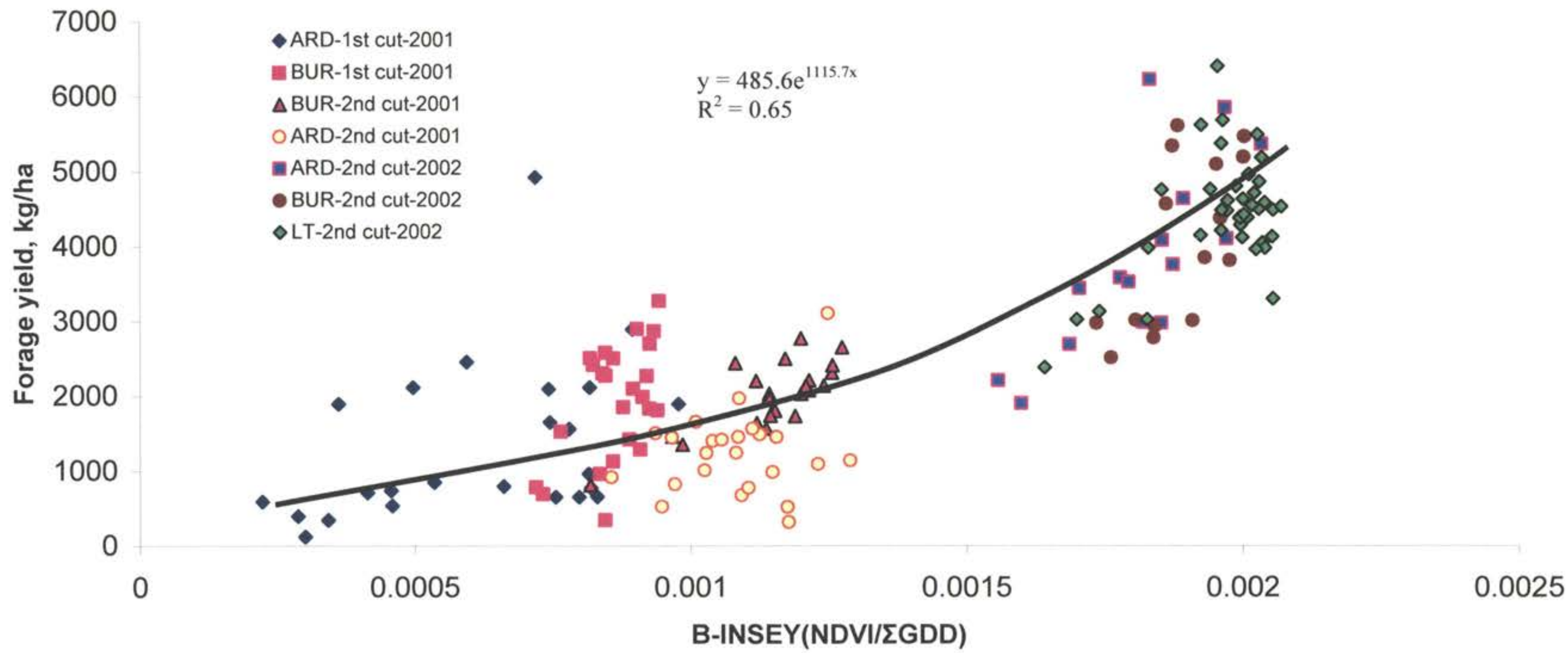

Figure 1. Relationship between bermudagrass forage yield and B-INSEY in 2001 and 2002 at Burneyville (2 sites) and Ardmore, OK

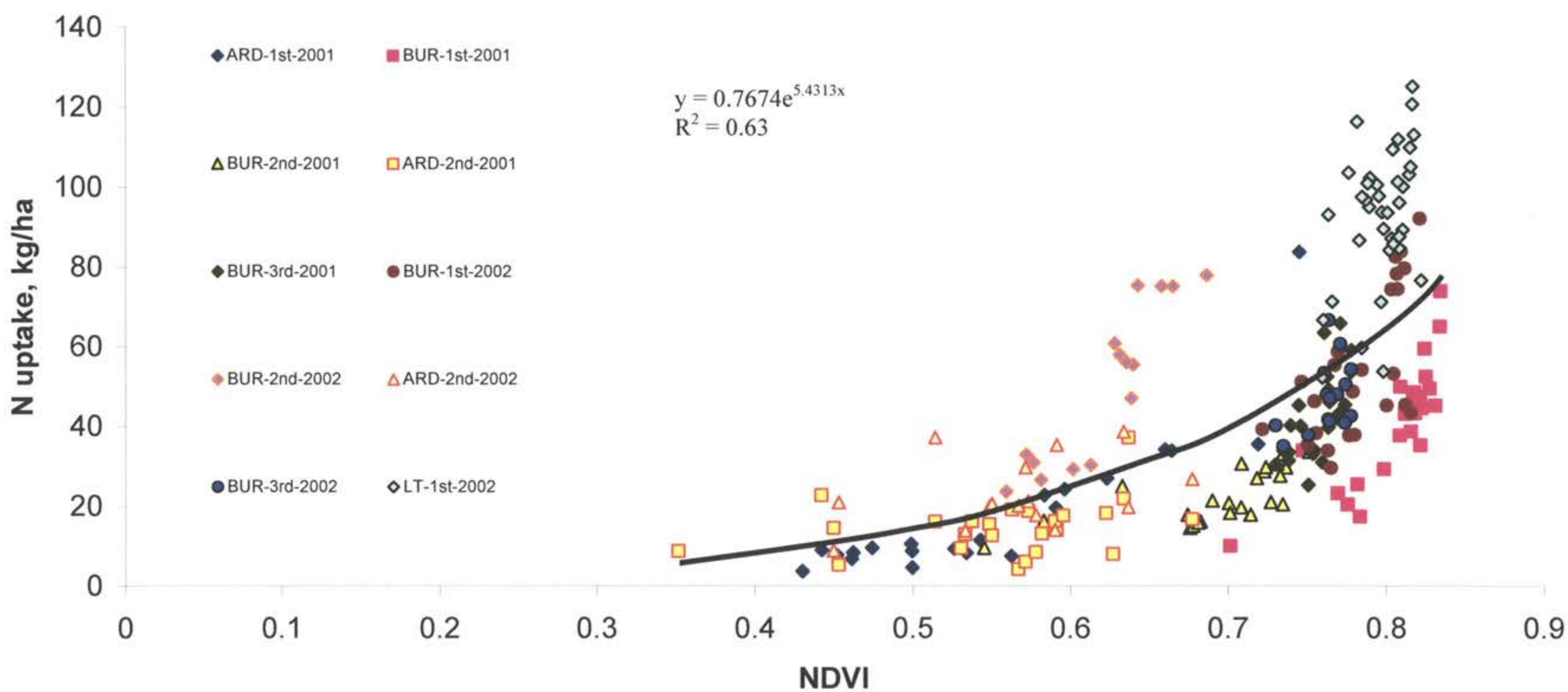

Figure 2. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in 2001and 2002 at Burneyville (2 sites) and Ardmore, OK except LT-2nd cutting

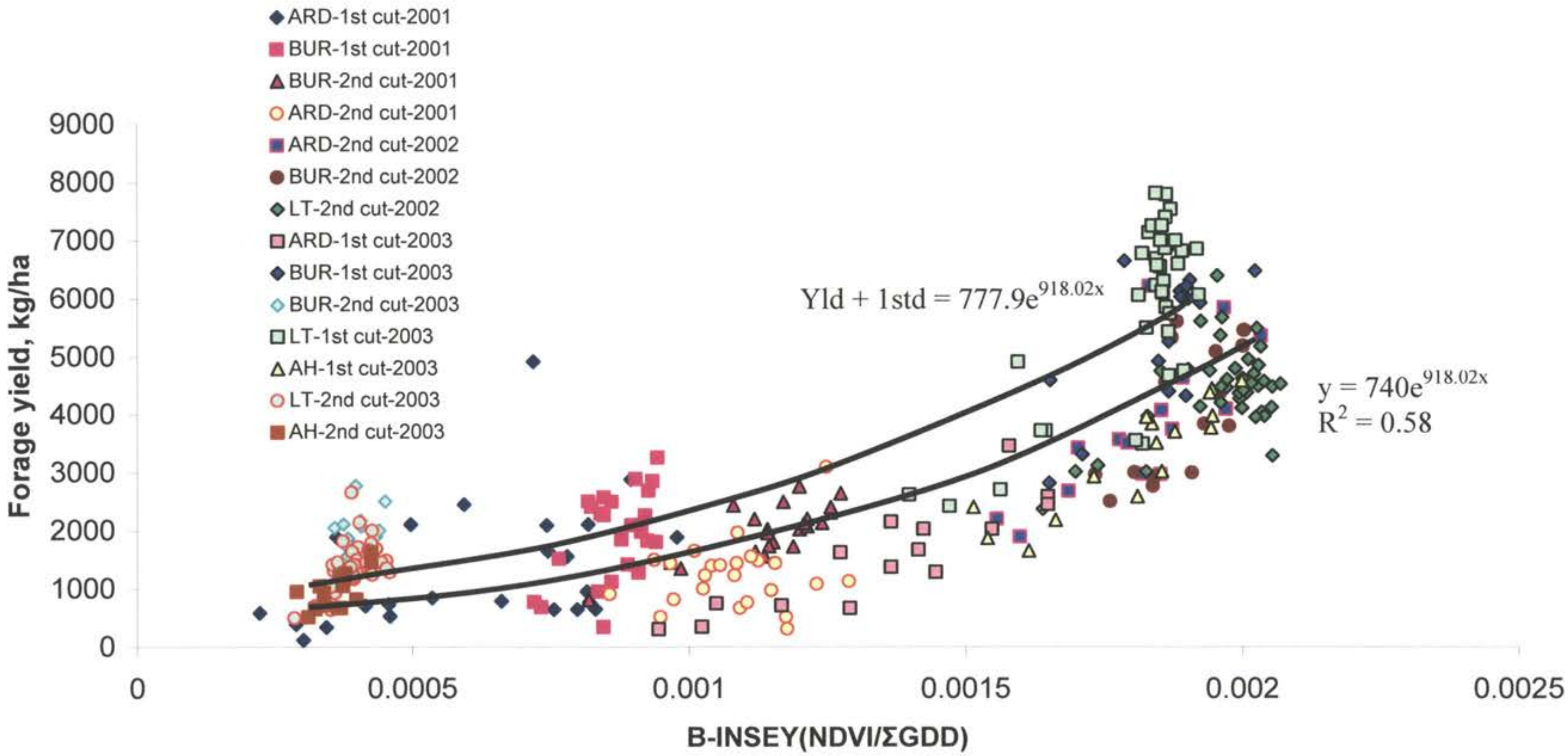

Figure 3. Relationship between bermudagrass forage yield and B-INSEY in 2001, 2002 and 2003 at Burneyville (2 sites) and Ardmore (2 sites), OK.

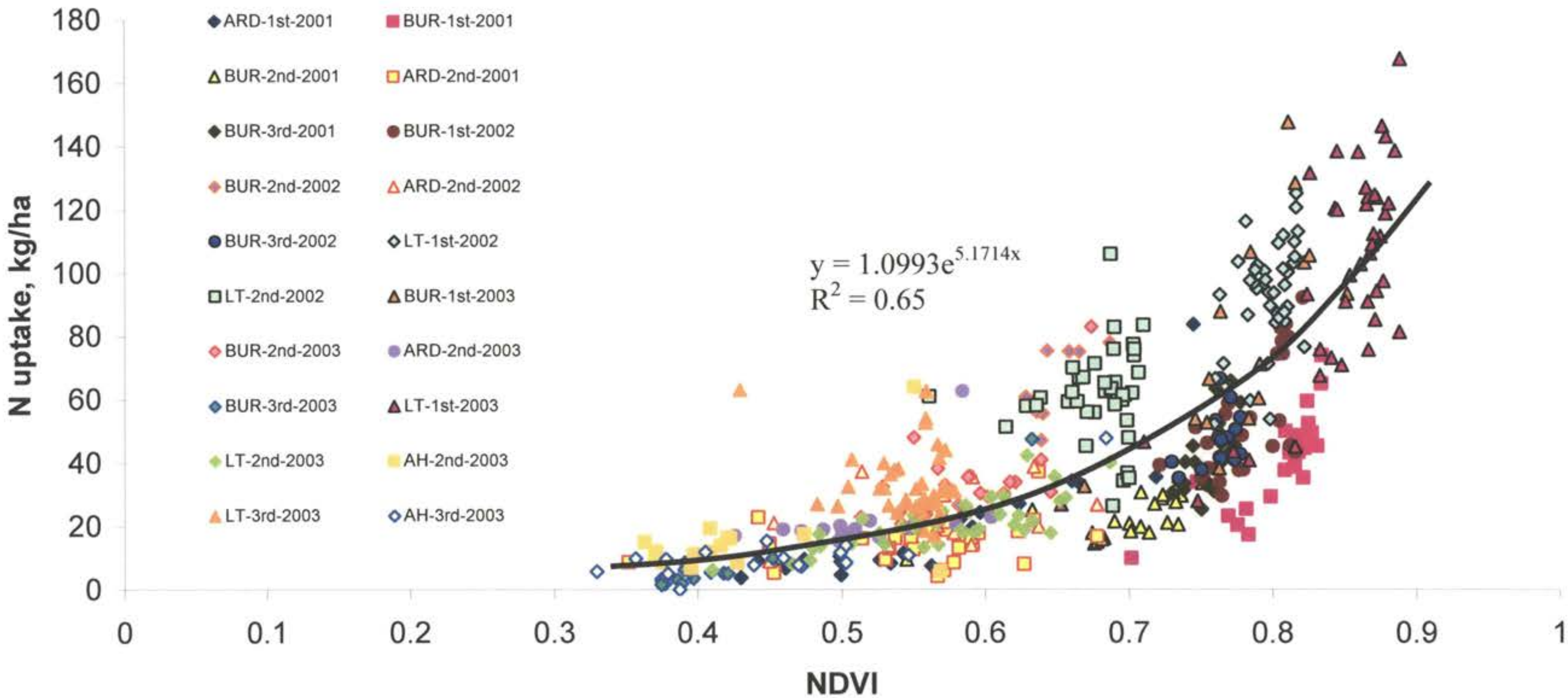

Figure 4. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in 2001, 2002 and 2003 at Burneyville (2 sites) and Ardmore (2 sites), OK excluding Ardmore (both sites) 1st cutting 2003

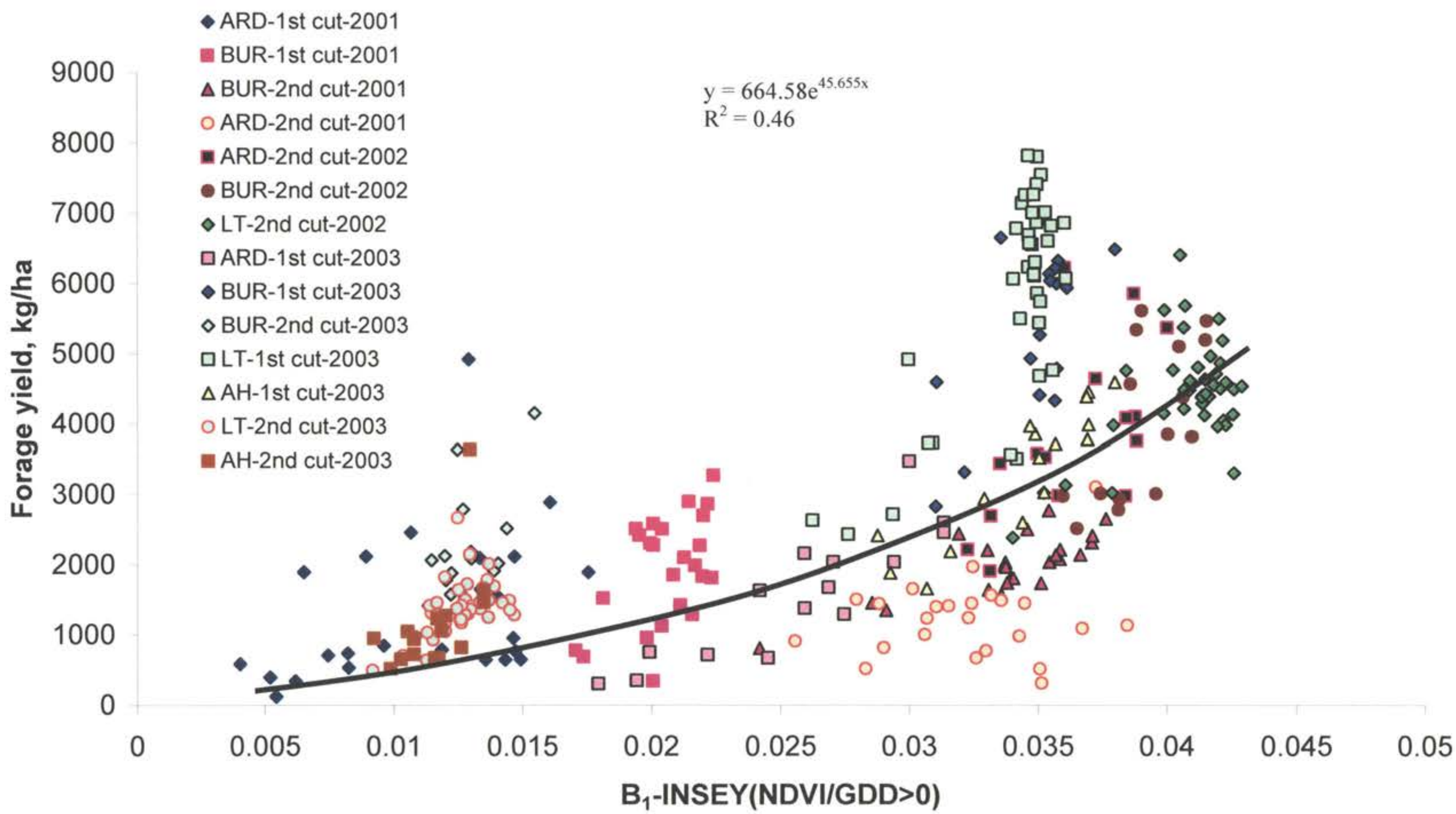

Figure 5. Relationship between bermudagrass forage yield and B_1-INSEY in 2001, 2002 and 2003 at Burneyville (2 sites) and Ardmore (2 sites), OK

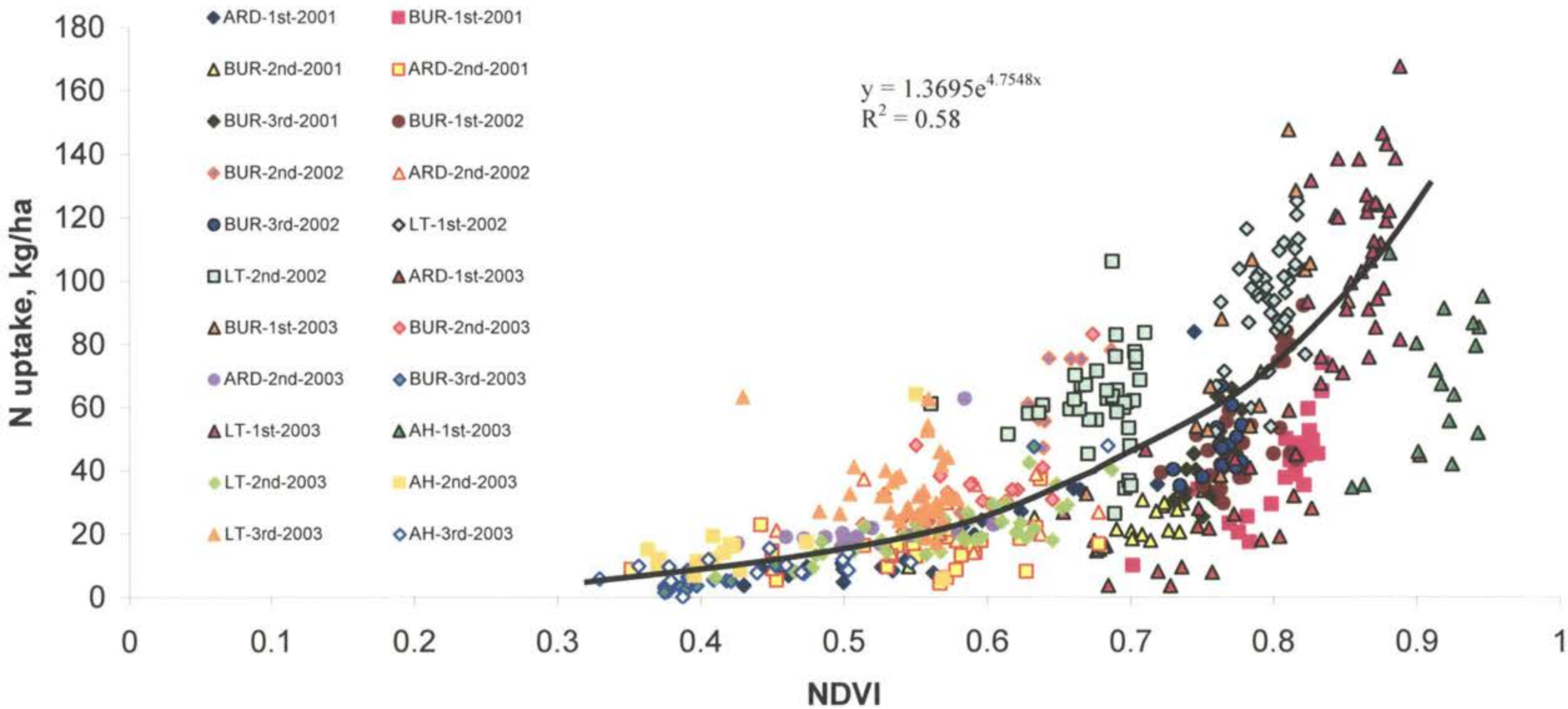

Figure 6. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in 2001, 2002 and 2003 at Burneyville (2 sites) and Ardmore (2 sites)

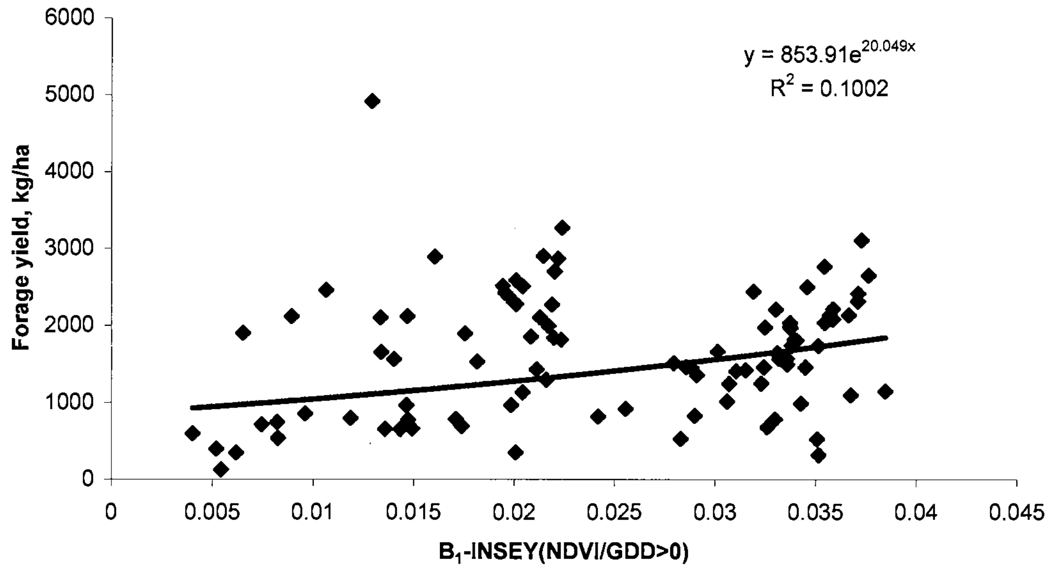

Figure 7. Relationship between bermudagrass forage yield and B_1-INSEY in 2001 at Burneyville and Ardmore, OK

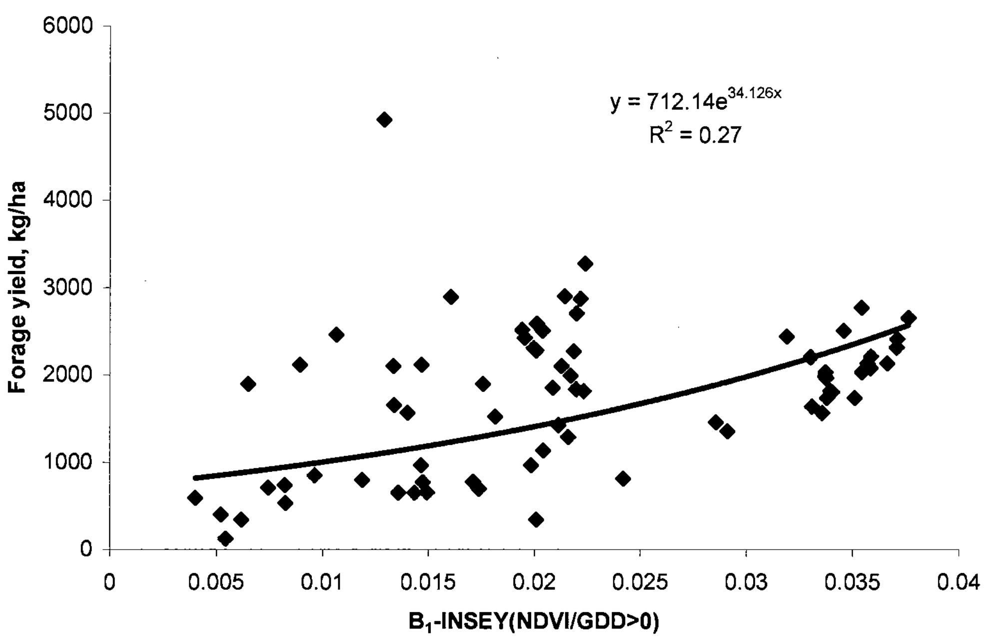

Figure 8. Relationship between bermudagrass forage yield and B_1-INSEY in 2001 at Burneyville and Ardmore, OK, excluding Ardmore 2nd cutting

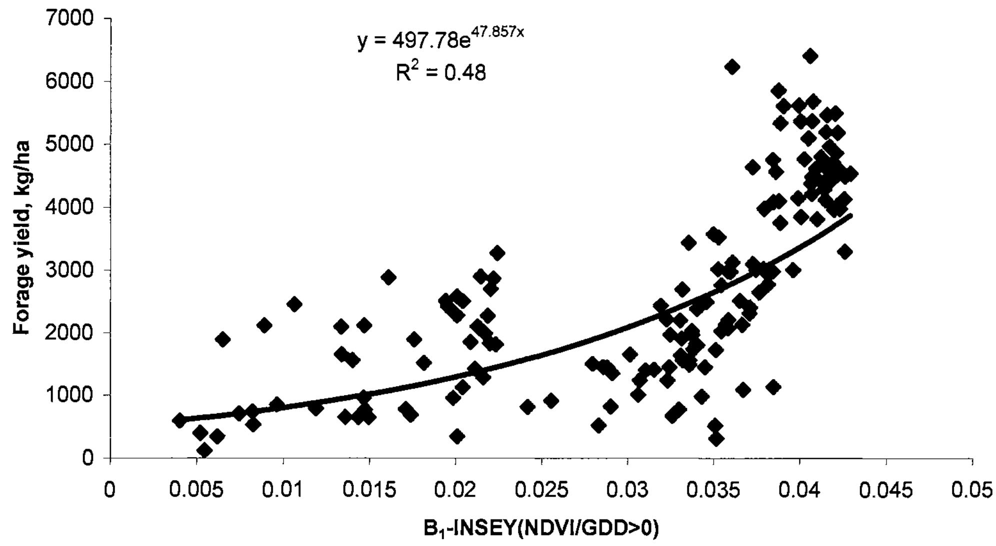

Figure 9. Relationship between bermudagrass forage yield and B_1-INSEY in 2001and 2002 at Burneyville (2 sites) and Ardmore, OK except 2nd cutting Ardmore, 2001

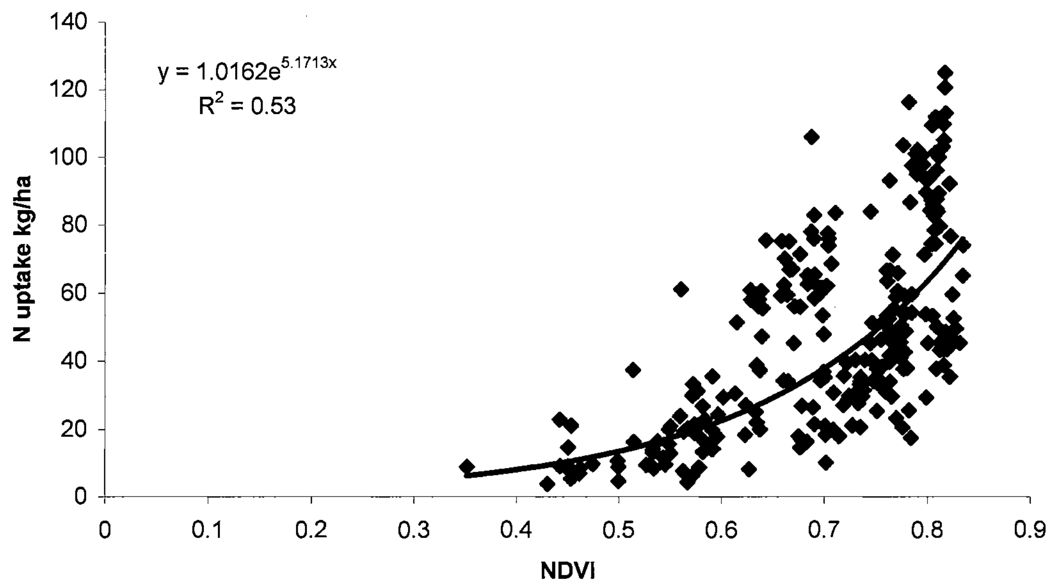

Figure 10. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in 2001and 2002 at Burneyville (2 sites) and Ardmore

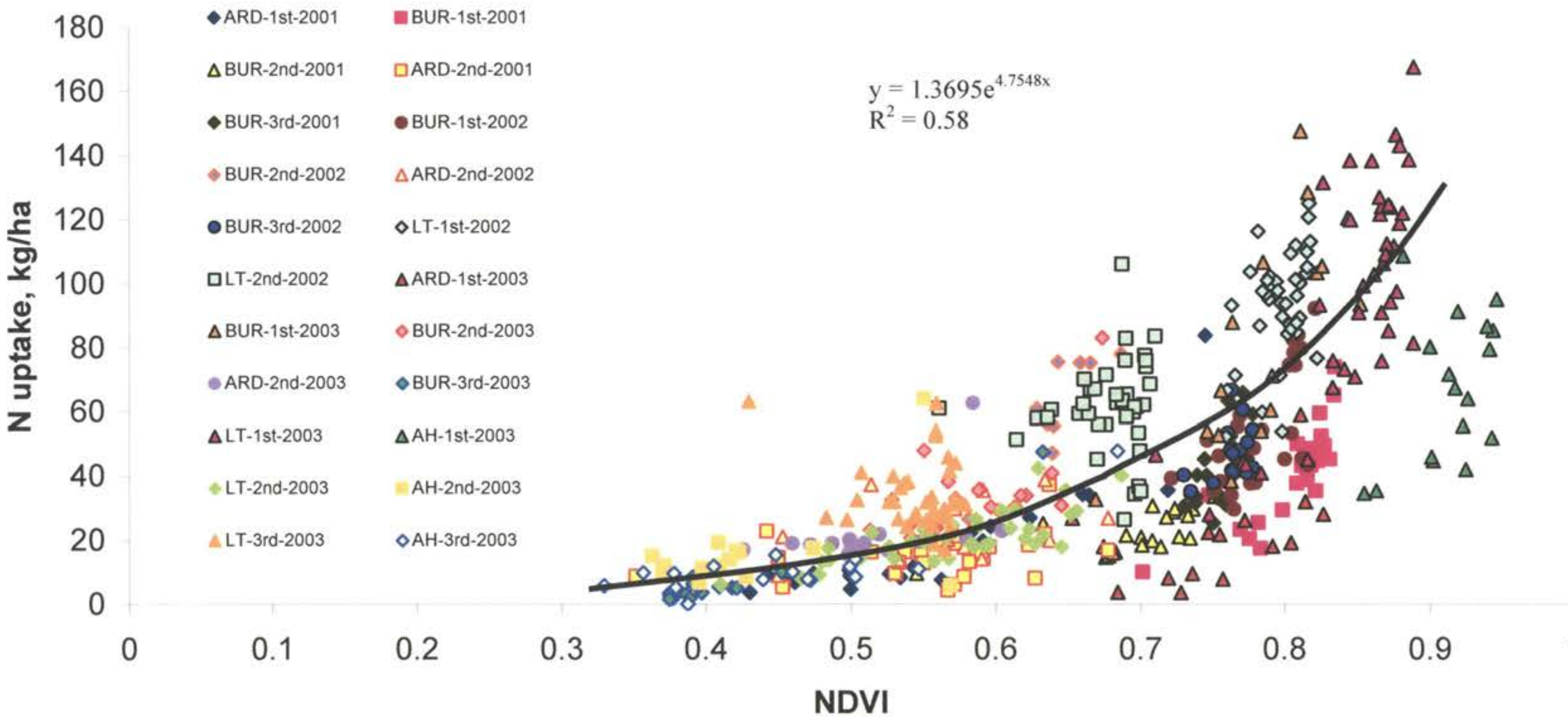

Figure 6. Relationship between N uptake and NDVI in bermudagrass forage collected at the time of harvest in 2001, 2002 and 2003 at Burneyville (2 sites) and Ardmore (2 sites)

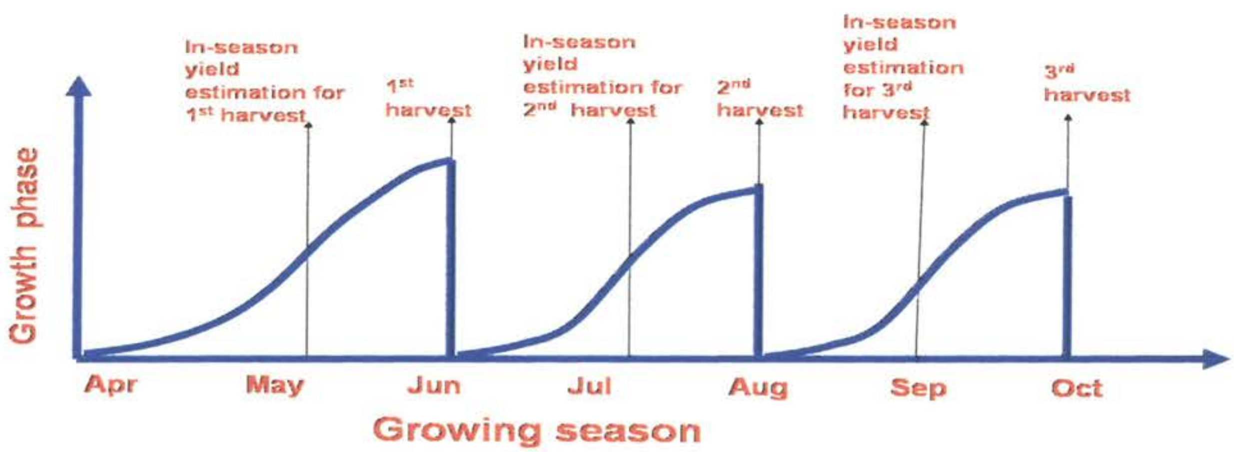

Figure 11. Schematic representation of time of prediction

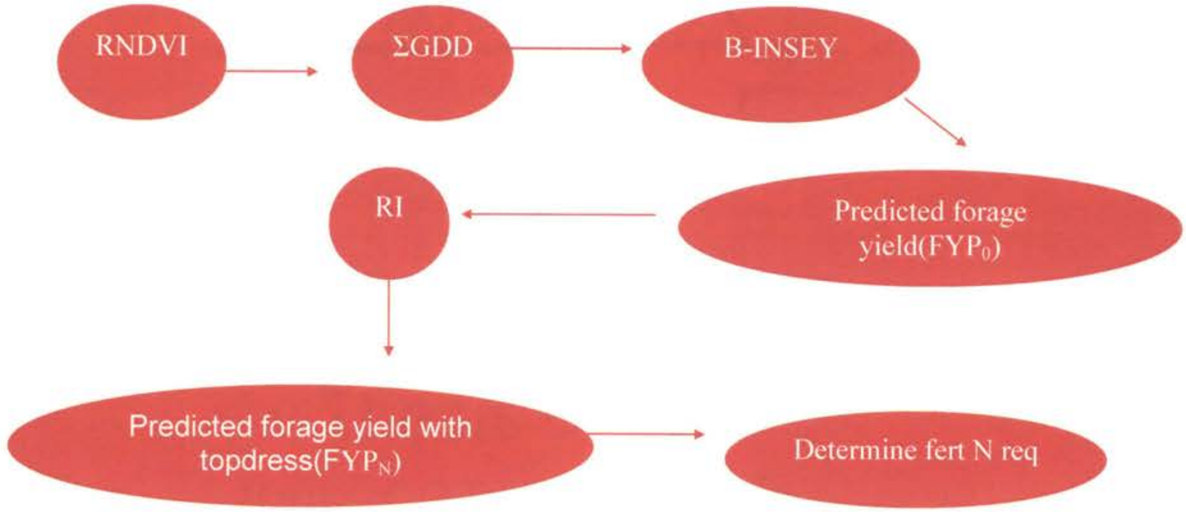

Figure 12. Development of Nitrogen Fertilization Optimization Algorithm (NFOA) for predicting N uptake in-season

VITA (2)

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Candidate for the Degree of

Doctor of Philosophy

Thesis: EFFICACY OF FOLIAR APPLICATION OF PHOSPHORUS ON WINTER WHEAT GRAIN YIELD, AND USE OF IN-SEASON REFLACTANCE FOR PREDICTING YIELD POTENTAIL IN BERMUDAGRASS

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