5-2011

Irrigation Plus Nitrogen Rate Effects on Hybrid Bermudagrass Hay Yield and Quality, With Preliminary Evaluation of NDVI, Tissue, and Soil Nitrate-N Sampling as Diagnostic Tools

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Recommended Citation
Carter, Timothy Donald, "Irrigation Plus Nitrogen Rate Effects on Hybrid Bermudagrass Hay Yield and Quality, With Preliminary Evaluation of NDVI, Tissue, and Soil Nitrate-N Sampling as Diagnostic Tools. " Master's Thesis, University of Tennessee, 2011.
http://trace.tennessee.edu/utk_gradthes/861

To the Graduate Council:

I am submitting herewith a thesis written by Timothy Donald Carter entitled "Irrigation Plus Nitrogen Rate Effects on Hybrid Bermudagrass Hay Yield and Quality, With Preliminary Evaluation of NDVI, Tissue, and Soil Nitrate-N Sampling as Diagnostic Tools." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering Technology.

Hubert J. Savoy, Major Professor

We have read this thesis and recommend its acceptance:

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Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Irrigation Plus Nitrogen Rate Effects on Hybrid Bermudagrass Hay Yield and Quality, With Preliminary Evaluation of NDVI, Tissue and Soil Nitrate-N Sampling as Diagnostic Tools

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Timothy Donald Carter
May 2011

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my loving and supportive wife, without whom I could not have dedicated the long days and long nights that it took to accomplish this goal. Her long days and long nights supported this effort more than any other. I would also like to thank my major professor Dr. Hugh Savoy, both mentor and advisor, who gave direction and motivation to accomplish this degree. I would also like to thank Dr. Arnold Saxton and Dr. Roland Roberts, whose tireless dedication to the University of Tennessee, helped me, analyze and bring about a higher level of thought to this project. And to Brad Fisher, whose steadfast dedication and determination to produce accurate plot treatments, made the construction of scientific analysis possible. And last to my fellow graduate students, whose eclectic backgrounds and experiences afforded me a true education in life.

ABSTRACT

A nitrogen fertility study with Vaughn's hybrid bermudagrass conducted on a Crider silt loam soil (fine, silty, mixed, active, mesic Typic Paleudalfs) over three (3) years (2008-2011) at the Highland Rim Research and Education Center near Springfield, Tennessee is evaluated in this manuscript. Nitrogen applications are evaluated in both irrigated and non-irrigated plots at five (5) different application rates: 0, 56, 112, 168, and 224 kg N ha^{-1}. These rates are applied beginning in late April, and three (3) additional times upon harvests occurring in June, July, and August. Irrigation plots receive enough water to bring total weekly water up to 2.24 cm/plot whenever rainfall is less than that amount. Normalized difference vegetative index (NDVI) measurements are collected mid harvest and on harvest dates to investigate new nitrogen status indicators between Vaughn's hybrid bermudagrass yields. Plant tissue samples are collected at harvest. Soil samples are collected mid harvest to investigate soil nitrate nitrogen and its relationship with bermudagrass yields.

The results of the study show irrigation has no effect on yields during the period of this study. There is a significant effect resulting from the interaction between month and nitrogen application on yield. Investigation of this interaction reveals two (2) distinct periods of production potential during the growing season. A low to medium yielding period produces an average harvest yield maximum of 3.14 Mg ha^{-1}. A medium to high yield period produces an average harvest yield maximum of 5.4 Mg ha^{-1}. Based on an analysis of variance and mean separation, a nitrogen rate of 56 kg N ha^{-1} rate is recommended for harvests occurring during the low to medium yielding period, and a nitrogen rate of 113 kg N ha^{-1} is recommended for those occurring during the high to medium yielding period. NDVI is highly correlated with yield on date of harvest. The results also show NDVI is correlated with mid-harvest yields also, which suggests a possible development of using NDVI as a mid harvest nitrogen status indicator. The results show soil nitrate is not correlated with yield, but did indicate accumulation in the soil as the growing season progressed.

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Chapter I: Introduction and General Information

Because of nitrogen's volatility in soil, monitoring the status of nitrogen is a key component of any hybrid bermudagrass hay production strategy. Its concentration in the soil and plant tissue serves as the basis for producing real time evaluations of past and future nitrogen applications. Past studies show that by using plant and soil nitrogen data, nitrogen use efficiencies can be increased. Nitrogen use efficiency is calculated by subtracting nitrogen uptake in the unfertilized plot from that in the fertilized plot divided by the fertilizer nitrogen rate times 100 (Westerman and Kurtz, 1972). Comparing nitrogen efficiencies result in the development of split application practices which increase the efficiencies of nitrogen applications. Although nitrogen efficiencies are increased, more comprehensive monitoring is needed in order to develop a more complete nitrogen management strategy. For example, a producer may allow several weeks, months, even years between soil and tissue nitrate tests. Since soil nitrate nitrogen is a highly mobile compound, its concentration can vary significantly within days or weeks depending on rainfall. Current research shows the use of optical sensing as a dependable test for evaluating the potential for response to additional nitrogen. Soil and tissue nitrate tests combined with real time optical sensing data can produce highly accurate nitrogen application strategies that could further increase profit and production. Through use of new innovative techniques, producers can best achieve high production levels and minimize environmental problems often associated with excess nitrogen.

Objectives

The objectives of this study are to:

1. Evaluate Vaughn’s hybrid bermudagrass yield response to irrigation and rate of nitrogen application.
2. Evaluate tissue nitrate accumulations in Vaughn’s hybrid bermudagrass.
3. Characterize Vaughn’s hybrid bermudagrass yield response to soil nitrate nitrogen.
4. Analyze most profitable nitrogen application rates and yields in Vaughn’s hybrid bermudagrass
5. Characterize NDVI measurements with hybrid bermudagrass yield.

Chapter II Literature Review

Hybrid Bermudagrass Fertility

Increasing cost of fertilizers, combined with the need to monitor nitrate toxicity in the forage, requires the investigation of hybrid bermudagrass and nitrogen's mobile status over different soil type regions such as the sandy, coastal regions in Georgia and loamy soils across Tennessee. Efficient nitrogen application and optimization of N rates are keys for more sustainable pasture and hay production systems (Silveira, et al., 2007).

Research performed by G. W. Burton and H. DeVane in 1952 shows 18 Mg ha^{-1} annually of bermudagrass hybrid number 104 is produced by applying 450 kg N ha^{-1} in five (5) equal split applications in Tifton, Georgia. These applications are applied, in this study, beginning in March and after the first four (4) harvests. A second study by Fisher and Caldwell (1959) shows that applying 455 kg N ha^{-1} of nitrogen annually can produce 12 Mg ha^{-1} of coastal bermudagrass hay annually in Texas. On the coastal plain in Georgia, an experiment performed by Prine and Burton (1956) produces a recommendation of 410 kg N ha^{-1} applied annually in a split application. The split application includes one half of the nitrogen being applied in the spring before clipping, and the other half being applied after the 12 week clipping date.

More recently, in a study conducted by Silveira et al., (2007) in College Station, Texas, increased nitrogen application rates produce an increase in dry matter yields of bermudagrass. In year one of the study, the maximum bermudagrass yields are obtained at the annual rate of 360 kg N ha^{-1}. This nitrogen rate is applied in equal split applications at the completion of each harvest (4). As opposed to unfertilized control plots, adding nitrogen at the annual rate of 180 kg N ha^{-1} rate results in the doubling of yields in a loamy fine sand soil.

These previously cited studies reveal that increasing nitrogen fertilizer quantities can steadily increase yields, however, it should also be noted that yield by itself is not the sole concern of producing quality forage, as protein content and levels of nitrate in the forage also figure into nitrogen budgets. Nitrogen use efficiency and protein content are essential considerations for evaluating the profitability of a forage program (Silveira et al., 2007).

Any forage containing 5,000 mg kg^{-1} is deemed dangerous for cattle consumption (Ball et al., 1991). With nitrate toxicity posing a threat to cattle production, a study performed by Oklahoma State in Ardmore and Burneyville, Oklahoma by Osborne et al., (1999), shows nitrogen recovery could be maximized (up to 85%) at rates of 112 and 224 kg N ha^{-1} when applied in the early spring and late summer, respectively. According to the results of the study, annual nitrogen rates of 1344 kg N ha^{-1} seldom result in nitrate concentrations in the forage above 2,000 mg kg^{-1}.

Unlike previous studies where bermudagrass yields are the only concern, later studies look at nitrogen efficiencies and time of application in determining the most cost effective approach in developing a fertility program. Altom et al. (1976) performed an experiment using bermudagrass with Rye being sod seeded for winter and spring forage production. Like previous studies, higher rates of nitrogen produce the highest yields, however. The lower annual rates of nitrogen (171 kg N ha^{-1} and 246 kg N ha^{-1}) are the most efficient nitrogen application rates. The results of the experiment also show the cheapest cost per pound was 171 kg N ha^{-1}. The study also reveals that increasing the annual nitrogen rate above 112 kg N ha^{-1}, the amount of protein is increased only slightly, where a maximum amount of protein was produced using a 1,493 kg N ha^{-1} annually. This study shows that approximately 10 to 40 percent more nitrogen is needed to increase protein contents as does the total yield of forage. Work done by Fisher and Caldwell

(1959) reveals a range of protein contents ranging from 8% protein produced by the check plot and 14% protein produced by applying 2,000 kg ha^{-1} annually.

In summary, recommended annual application rates for bermudagrass hay production range from a low rate of 171 kg N ha^{-1} to a higher rate of 450 kg N ha^{-1}. In each study, however, timely rainfall proves to be an important factor in plant production as proved by the study performed by Prine and Burton (1956). This study contains an evaluation of a wet year and a drought year, and found that the lack of rainfall decreased yields by 50%. University of Tennessee annual recommendations for fertilizing hybrid bermudagrass hay are 448 kg N ha^{-1}.

NDVI (Normalized Difference Vegetation Index)

NDVI is a vegetative index that is used to estimate biomass. Photosynthetically active radiation (400-700 nm), is strongly absorbed by plant pigments. Red radiation (650 nm) is absorbed by healthy plants, and near-infrared (NIR) radiation (700-1300 nm) is highly reflected due to low absorption (Knipling, 1970; Asrar et al., 1984). It is comprised of a ratio of the difference between near infrared radiation and far red radiation. Its formula is given by $(\lambda NIR-\lambda R)/(\lambda NIR+\lambda R)$, where λ refers to light wavelength.

Research using NDVI technology to improve bermudagrass yields has been evaluated since the 1990's with research conducted at Oklahoma State University. A study performed by Taylor et al., (1998) evaluates the use of NDVI in an effort to correct nitrogen deficiencies and estimating soil test variability in a bermudagrass pasture. The study correlates NDVI indices with bermudagrass forage nitrogen removal and yield. According to the results, correlation coefficients range from 0.51 to 0.74. All NDVI harvest values are significant at the 0.01 and 0.05 probability levels, respectively. The study also reveals significant correlations between NDVI and total N. NDVI correlation coefficients are not significant in pre-fertilization scenarios. The experiment indicates that as yield increase, so does the correlation of NDVI with yields and tissue nitrogen. During the experiment, NDVI values are obtained at the start of the experiment and prior to each harvest. Variable nitrogen rates are applied based on a linear NDVI-nitrogen rate scale in which readings with the highest NDVI value receiving the lowest fertilizer rate and vice versa. A 60% reduction in nitrogen application is achieved by utilizing NDVI in variable rate applications.

According to work done by Taylor et al., (1998), NDVI is found to be highly correlated with yield also with correlation coefficients ranging from 0.51 to 0.74. For year 2010, NDVI is strongly correlated with yield, producing a Pearson correlation value of 0.88. NDVI is weakly correlated with tissue nitrate; however, the regression model is significant at the .05 significance level. Work done by Raun et al., (1998) also shows high correlations between NDVI and bermudagrass yields. Mean NDVI values display seasonal trends, with decreasing means as days of the year increased. A second study conducted at Oklahoma State University by Xiong et al., (2007), bermudagrass responses to nitrogen fertilization and irrigation are observed using optical sensing. During the experiment, NDVI, along with GNDVI, R/NIR, and G/NIR are collected. Compared against other vegetative indices, NDVI is significantly correlated at the probability level of 0.001 with visual turf quality collected in 2004. The study also reveals that NDVI can indicate a significant nitrogen application response with respect to bermudagrass. NDVI proves to the best indicator of season, as well as nitrogen and irrigation needs. The study produces results using the GreenSeeker handheld sensor and reveals that NDVI can serve as a nitrogen fertilizer indicator, and a nitrogen fertilizer program can be developed and adjusted according to seasonal changes in bermudagrass response to nitrogen fertilization.

Current research involving optical sensing and vegetative indices deals with the development of an algorithm from which a variable rate calculation can be sent to fertilizer equipment. The implementation of a ramp calibration strip (RCS) is added to the composition of the algorithm. Edmonds et al. (2008) describes the process of using the ramp strip. By observing in the strip where NDVI values no longer change and no visible changes in plant growth are observed, an agriculture producer can produce an estimated sidedress application rate. As a result, applied maps and yield mapping can be created for agricultural producers. In a study done at Oklahoma State, Raun et al. (2005), Optical Sensor-Based Algorithm for Crop Nitrogen Fertilization, the researchers develop a formula for integrating NDVI values into a variable rate algorithm. This work shows that yield potential prediction equations for winter wheat can be reliably established with only 2 years of field data.

In other studies, the creation of the algorithm shows calculating a series of values involving an in season estimate of the potential or predicted yield, determining the yield response to additional nitrogen, and calculating the nitrogen required to obtain that additional yield (Raun et al., 2002) In a study by Xiong et al. (2007), where cereal grain seasonal responses were monitored using optical sensing, the group found that NDVI response to N fertilization is not strongly affected by irrigation treatment and can be used as an indicator of N status and need regardless of irrigation treatment.

Using Soil nitrate to predict the need for additional nitrogen

Past research on producing an accurate soil nitrate test for predicting the need for additional nitrogen during the growing season has focused on three (3) nitrogen analyses: biological methods (including inorganic nitrogen mineralized during various types of incubations), direct measurement of various nitrogen fractions (such as nitrate nitrogen and organic nitrogen), and inorganic nitrogen releases from organic matter by chemical treatment of the soil (Magdoff et al., 1984). Assessing soil nitrate nitrogen at a particular growth stage has been the most successful approach. Most of the work initially is associated with corn production systems due to their high acreage and nitrogen requirement. The original work on a pre-sidedress soil nitrate test (PSNT) is done by Dr. Magdoff of Vermont in a study researching nitrogen availability for corn. Soil samples are obtained at the upper 30 cm range, when corn plants were 15 to 30 cm tall and analyze for soil nitrate nitrogen. The study finds that an estimated one third of the total estimated available nitrogen needed to increase yields by 1 Mg per hectare is accounted for by the nitrogen in the soil test. The results of the study reveal that lower nitrogen rate applications and better site fertility responses could be obtained through using a soil nitrate test.

In a study conducted by Fox et al., (1989), tissue and soil nitrate values are evaluated to see if accurate predictions of sidedress nitrate applications could be made with respect to corn. The study reveals that nitrate concentrations in the upper 30 cm of soil, 4 to 5 weeks after emergence are a good indicator of whether a response to sidedress nitrogen fertilizer can be attained. However, the study concludes that soil nitrate tests are better at predicting a non response to fertilizer, rather than predicting nitrogen fertilizer rates. The study also shows that there is a very poor correlation between pre-sidedress soil nitrate concentrations and relative yield. Work done by Durieux et al. (1995) compares the PSNT with the yield-goal-based cropping and manure history (CMH) method and finds that the PSNT provides recommendations that more closely match corn nitrogen requirements than the CMH method. It is also noted that the PSNT may also result in improved economic savings because of reductions in over applied nitrogen. A study conducted by Ma et al. (2005) compare crop-based indicators with soil nitrate testing for corn nitrogen management. The study reveals each crop indicator was efficient at differentiating plant nitrogen at around corn growth stage V6. Further research done by Raun et al. (1998) looks at micro variability in soil test, plant nutrient, and yield parameters in bermudagrass. Soil nitrate tests are performed throughout the growing season and are not correlated with yields due to low nitrate testing soils. The study shows that only when N, P, or K are non limiting, can a significant relationship between a specific soil test procedures and yield can be established. Using a soil test to investigate current responses to added fertilizer is consistently proven beneficial to the producer.

Chapter III: Materials and Methods

General Description

One study, over a period of three years from 2008 to 2010, is conducted at the UT Highland Rim Research and Education Center to evaluate yield responses in hybrid bermudagrass (*Cynodon dactylon)*. The study is structured in a split plot, Latin Square design containing five (5) replications of five (5) annual nitrogen applications in the form of 0, 224 kg N ha^{-1}, 448 kg N ha^{-1}, 672 kg N ha^{-1}, and 896 kg N ha^{-1}. An automated drip irrigation system is installed in 2007 and a minimum of 2.54 cm water/plot is applied by the system or by rainfall each week. Each nitrogen application has an irrigated and non-irrigated plot within each replication.

Experimental Site Description at Highland Rim (HR)

The site location for the research study was the UT Highland Rim Research and Education Center located in Robertson County near Springfield, Tennessee. It is located in the northern portion of Tennessee in a physiographic region known as the Western Highland Rim. This area is characterized by sharp valleys, streams, and rolling terrain (USDA-SCS, 1968). This area has mild winters and hot summers with dry times periodically. The average annual precipitation is approximately 127 cm and the annual average temperature is approximately 15.6 °C. Precipitation is distributed fairly evenly throughout the year, with 10 monthly averages being slightly lower in the fall and slightly higher in the winter and early spring (USDA-SCS, 1968).

Highland Rim (HR) Soil Description

Field 6W, located at the UT Highland Rim Research and Education Center, is positioned on Crider silt loam soils which are fine-silty, mixed, active, mesic Typic Paleudalfs (USDA-NRCS 2007). The Crider series consists of well drained, dark brown soils with 2 to 5 percent slopes. About ten (10) percent of the soils in Robertson County contain this association.

Experimental Procedure

Field 6W was planted in 2004 with Vaughn's #1 hybrid bermudagrass variety obtained from Terrell Vaughn of Walling, Tennessee. The experimental layout of the research experiment is a Latin Square, split-plot design containing five (5) replications. The main plots are irrigated or non-irrigated plots, and the subplots are the five (5) different nitrogen application rates applied as ammonium nitrate. The five (5) nitrogen application rates are 0, 56, 112, 168, and 224 kg N ha^{-1} as ammonium nitrate. Each rate is applied in late April, and after the June, July, and August harvests. Each plot is harvested once in June, July, August, and September. Each plot measures 3m wide by 6m long. The ten (10) total treatments are presented in Table 1.1.

Table 1.1 Nitrogen Application Rates

Treatment	Nitrogen kg N ha^{-1}
1	0
2	56
3	112
4	168
5	224
6	0 (irrigated)
7	56 (irrigated)
8	112 (irrigated)
9	168 (irrigated)
10	224 (irrigated)

The center of each individual plot is harvested and weighed using a Carter automated harvester at approximately 30-day intervals. At harvest, the automated harvester harvests a 91cm wide path the length of each plot, leaving the grass at a height of 10.2 cm. Grab samples are taken of each of the harvested plots and immediately weighed and then dried at 50˚C to determine moisture content. An elemental analysis and nitrate analysis of the collected samples is performed by the Soil, Plant, and Pest Center in Nashville, Tennessee. Yield is converted to dry weight using moisture weights determined from grab samples. Harvest Dates are summarized in Table 1.2.

Table 1.2 Harvest Dates

Year	Dates
2008	6-01 7-16 8-20 9-25
2009	6-09 7-08 8-11 9-22
2010	* 7-07 8-11 9-27

* First Harvest was missed due to cold spring and herbicide applications.

Soil Sampling and Analysis

Soil nitrate analysis is added to the experiment during the second year of the study. Each non irrigated plot is randomly sampled (four (4) cores per plot) to a depth of 0.3m. Soil samples are obtained between ten (10) and fourteen (14) days after each fertilizer application. Soil samples are then delivered to the Soil, Plant, and Pest Center in Nashville, Tennessee and immediately oven dried for 24 hrs at 50˚C. Soil samples are then ground and analyzed for nitrate nitrogen using a protocol described by Joines (2007). Soil sampling dates are presented in Table 1.3.

Table 1.3 Soil Sampling Dates

Year	Dates
2009	7-23 9-01
2010	5-07 6-22 7-28 8-26

NDVI Collection

NDVI measurements are collected during the last year of the study using the GreenSeeker handheld sensor (NTech Industries, Ukiah, CA). Measurements are collected every two weeks during the growing season. Each data collection event is performed at the same time of day to diminish light reflectance variability. Care is taken to maintain sensor height between 81 and 122 cm above the grass surface to stay within the sensor's vertical focus range (Xiong et al., 2007). The sensor produces a pulse every 110ms, resulting in 50 or more reflectance measurements in a 6m-long plot at a normal walking speed. The resulting measurement is the average NDVI for the individual plots. NDVI measurements are divided into two (2) categories – pre harvest and harvest date measurements respectively. NDVI collection dates are presented in Table 1.4.

Table 1.4 NDVI Collection Dates

Year	Pre Harvest	Harvest Date
2010	6-22 7-20 9-23	7-07 8-11 9-27

Statistical Analysis

There are a total of 550 observations over three (3) years. Analysis of variance using the mixed procedure (SAS 9.2v, 2009) is used to analyze how nitrogen, irrigation, and month treatments affected yields. Least squares means are compared with protected LSD at the five (5) percent significance. The mixed procedure includes fixed effects for each treatment, including irrigation, nitrogen treatment, and row by column effects. The random effects include interactions between year, rows and columns, irrigation, and nitrogen application rates. Each individual year and harvest month is analyzed separately to detect statistical differences in yield, percent protein, and tissue nitrogen. Trends in yield are then summarized using yield response functions in order to group harvest months by maximum yields and by profitability. Nitrate toxicity is investigated by using variable selection techniques which rank each variable in terms of R-square and Cp value. Cp, or Mallow's Statistic is also used to decide on the best model. Cp is a measure of bias and total variation of the model. The difficulty it addresses is that R-square always increases as a variable is added to the model, but the variable may increase prediction errors even more. Cp is more like a measure of total performance of the model. To decide what an acceptable value of Cp is, the criterion is the Cp value should not be much more than p+1, with p being the number of x variables in the model. Within that constraint, then models with small Cp, small number of variables and high R-square are preferred (Saxton, 2010). NDVI and soil nitrate data are analyzed using multiple regression and Pearson's Correlation methods to investigate potential relationships between them and yield, tissue nitrate, and tissue nitrogen.

Chapter IV: Results and Discussion

Yield As Affected By Irrigation, Harvest Month, and Nitrogen Rates

Over the three (3) year period, irrigation (Table 1.5) gave no significant effect on yield. Year variation is accounted for in the model but not as a fixed effect. A statistical difference (p<0.0001) is observed among the nitrogen treatments and the fixed effect caused by month. Nitrogen application effects vary by month of harvest as indicated by the significant interaction between N application and Month (p=0.0008).

Table 1.5 Analysis of Variance of Average Yield Over Three Years

Effect	Num DF	F Value	Pr>F
Irrigation	1	0.11	0.7425
N Application	**4**	**31.37**	**<0.0001**
Irrigation*N Application	4	0.12	0.9766
Month	**3**	**88.55**	**<0.0001**
Irrigation*Month	3	1.95	0.1216
N Application*Month	**12**	**2.87**	**0.0008**
Irrigation*N Application*Month	12	0.24	0.9961

Significance at P<0.05

Because of the significance of the interaction between month and nitrogen application rate, the characterization of each effect require the analysis of how bermudagrass yields change with both nitrogen application rate and month together. To better illustrate this significant interaction between month and nitrogen application rate, Figure 1 shows average yields for each harvest month for each of the nitrogen application rates over the three (3) years.

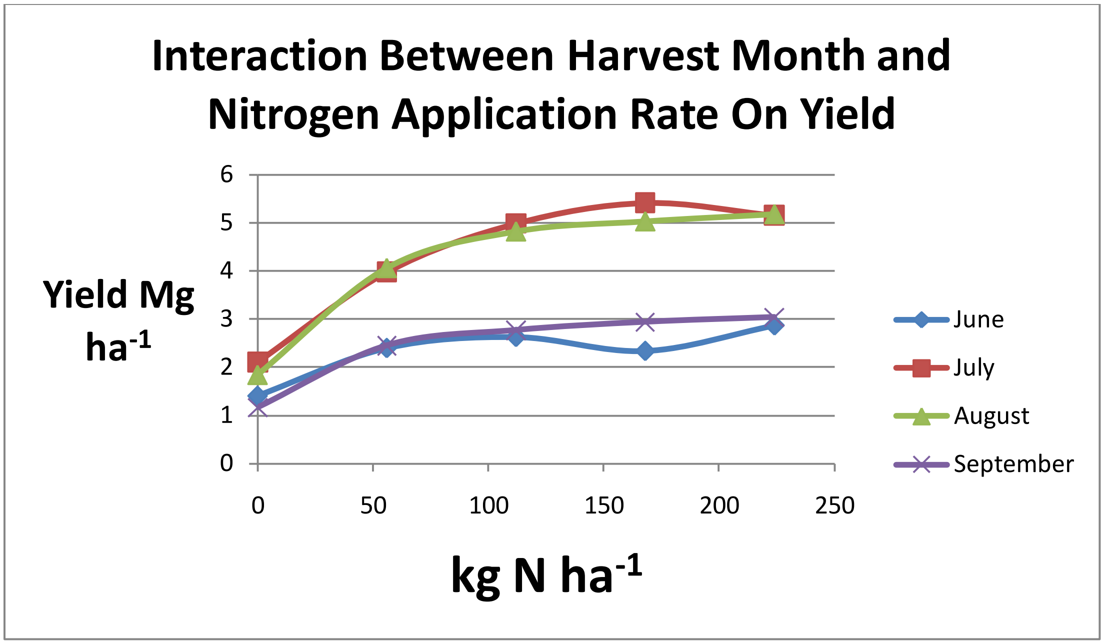

Figure 1 Interaction Between Harvest Month and Nitrogen Application Rate

Figure 1 displays the interaction between month and nitrogen application rate. Upon plotting the yields for each month, the interaction is caused by nitrogen application rates producing different yields in different months. The graph displays similar slopes and break points found in months June and September, and July and August. Table 1.6 summarizes the effects of nitrogen application rate on yield by month (harvest period) over three (3) years.

Table 1.6 Average Yield (Mg ha^{-1}) Response to Nitrogen by Harvest Month Over 3 Years

Nitrogen Rate (kg N ha^{-1})	June	Letter Group	July	Letter Group	August	Letter Group	September	Letter Group
0	1.41	FG	2.11	DEF	1.84	EF	1.16	G
56	2.40	CDE	3.98	B	4.06	B	2.45	CDE
112	2.63	CDE	4.98	A	4.82	A	2.77	CD
168	2.34	CDE	5.42	A	5.03	A	2.94	C
224	2.87	CD	5.16	A	5.18	A	3.04	C

Significance at $P<0.05$

Harvest period results of June and September show no yield response past the 56 kg N ha^{-1} rate, but harvest months July and August show no yield response past the 112 kg N ha^{-1} rate. From the results of the experiment, it appears that months June and September, and July and August, can be grouped together in order to evaluate appropriate nitrogen application rates.

Nitrogen Use Efficiency As Affected by Nitrogen Rates

Further evidence that suggests improved nitrogen efficiency by incorporating a combination of application rates would be that of the nitrogen use efficiency (NUE) for each of the application rates. Over the three years, lower applications of nitrogen are the most efficient (Table 1.7). Previous work done by Silveira et al. (2007) confirms higher efficiencies with lower rates of nitrogen applications. Table 1.7 summarizes NUE over the three (3) years of the study for each of the applied nitrogen rates.

Table 1.7 NUE for Total Nitrogen Recovered Annually at Each Application Rate Over 3 Years

Annual Nitrogen Application kg N ha^{-1}	2008	2009	2010
224	67.2	87.4	17.3
448	45.2	56.1	14.3
672	32.5	40.1	10.1
896	24.8	30.1	7.3

Nitrogen use efficiencies generally decrease as the growing season progressed (Table 1.8). Decreased nitrogen use efficiencies are due to the added nitrogen not producing ever increasing yields as the growing season progresses. With declining nitrogen use efficiencies progressing as the growing season progresses, less nitrogen needs to be applied in August. The highest NUE occur in June and the lowest NUE occurred in September (Table 1.8).

Table 1.8 NUE for Total Nitrogen Recovered at Each Application Rate by Harvest Month Over 3 Years

Annual Nitrogen Application kg/ha	June	July	August	September
224	42.2	33.2	26.1	11.3
448	26.7	26.1	17.6	7.1
676	15.7	19.5	12.5	5.2
696	16.0	13.9	9.9	4.1

Average Plant Tissue Nitrogen As Affected by Nitrogen Rate

Over the three (3) year period, irrigation (Table 1.9) did not have a significant effect on plant tissue nitrogen. Nitrogen application rates show a statistical difference ($p<0.0001$). The fixed effect by month (harvest date) is also significant ($p=0.0035$).

Table 1.9 Analysis of Variance of Average Plant Tissue Nitrogen Over 3 Years

Effect	Num DF	F Value	Pr>F
Irrigation	1	0.65	0.4199
N Application	**4**	**7.48**	**<0.0001**
Irrigation*N Application	4	0.44	0.7767
Month	**3**	**4.61**	**0.0035**
Irrigation*Month	3	0.07	0.9768
N Application*Month	12	0.86	0.5833
Irrigation*N Application*Month	12	0.79	0.6623

Significance at $P<0.05$

Percent plant tissue nitrogen generally increases with increased nitrogen inputs (Table 2.0). A plant tissue nitrogen response is not seen past the 56 kg N ha^{-1} rate. A minimum average of 2.2% tissue nitrogen is seen with the zero kg N ha^{-1} over the three (3) year experiment; whereas an average of 2.8% is observed as a maximum with the 168 kg N ha^{-1} rate. An optimum range of plant tissue nitrogen appears to be between 2.3 and 2.5%. Work performed by Johnson et al. (2001) shows a slightly lower optimum range of tissue nitrogen between 2.1 and 2.4%.

Table 2.0 Mean Separations of Tissue Nitrogen by Nitrogen Application Rate Over 3 Years

Nitrogen Application (kg N ha^{-1})	Estimate %	Letter Group
0	2.2	D
56	2.3	CD
112	2.5	BC
168	2.8	A
224	2.7	AB

Significance at $P<0.05$

There was little variation resulting in the plant tissue nitrogen concentrations as the growing season progresses (Table 2.1). The harvest month of September is significantly different from the June, July, and August harvest months. June, July, and August harvest months are not significantly different.

Table 2.1 Mean Separations of Tissue Nitrogen Over All Nitrogen Applications by Harvest Period Over 3 Years

Harvest Period	Estimate %	Letter Group
June	2.5	AB
July	2.5	B
August	2.4	B
September	2.8	A

Significance at $P<0.05$

With mean separations of nitrogen applications (Table 1.6) showing no response past the 112 kg N ha^{-1} rate in July and August, but not a response past the 56 kg N ha^{-1} rate in June and September, a producer can expect an optimum range of tissue nitrogen between 2.3 and 2.5%.

Yield Response and Profitability

In an effort to predict yields from different nitrogen rates, data collected from the three (3) year study is used to fit yield response functions. Based on significant values resulting from orthogonal contrasts and plotting fertility treatment yields, it is confirmed that a combination of linear and quadratic trends best described hybrid bermudagrass yields. This is consistent with models used by Fisher and Caldwell (1959) and Johnson et al. (2001). In order to best fit the data using both linear and quadratic elements, a linear plateau model is utilized. The PROC NLIN procedure in SAS v.9.2 is used to fit the linear plateau model to the data. The linear plateau model possesses an R-square of 0.2597. A maximum yield of 4.0 Mg ha^{-1} is estimated by the linear plateau model. The corresponding nitrogen application is 73 kg ha^{-1}. Figure 2 displays the linear plateau model description of yield over three (3) years as a function of individual plot yield.

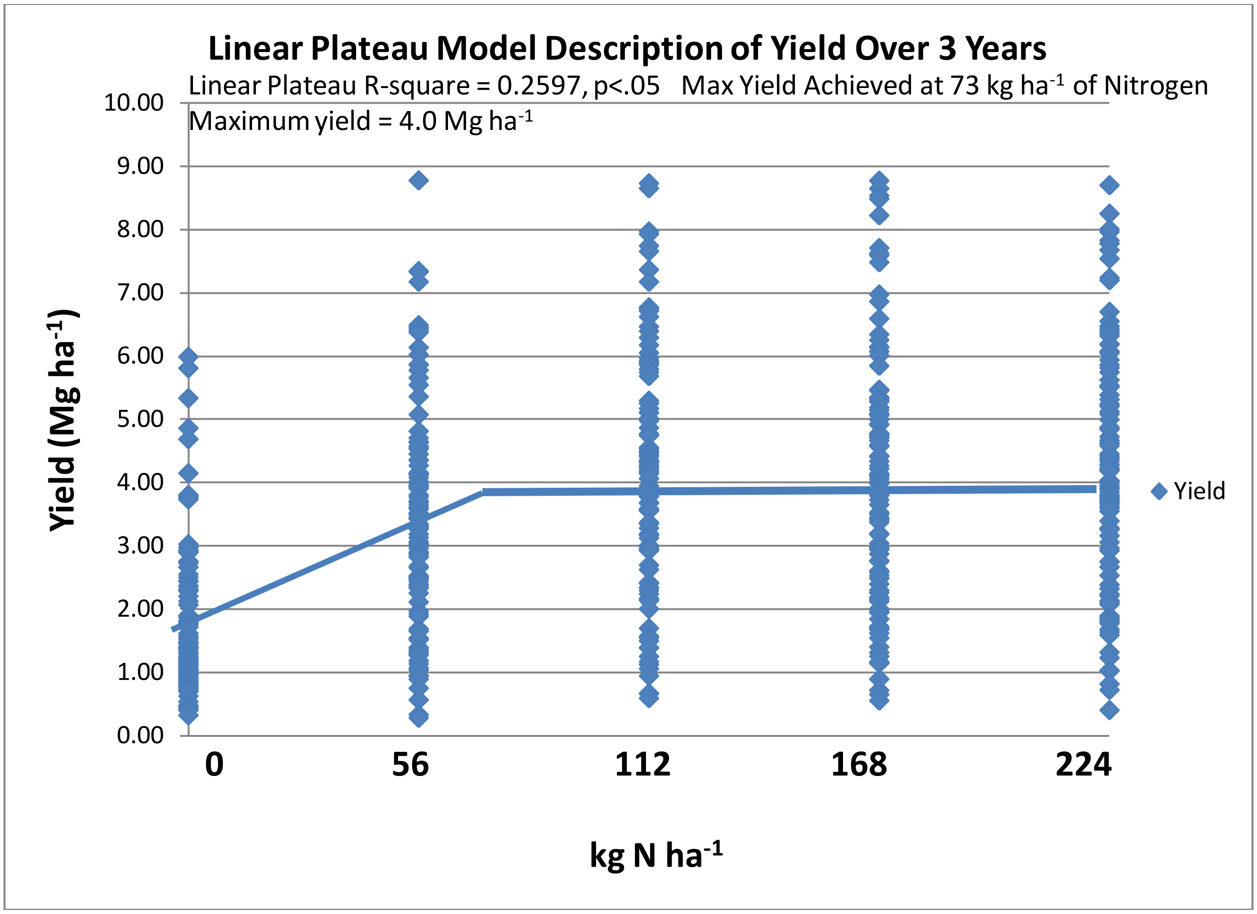

Figure 2 Linear Plateau Model Description of Individual Plot Yield Over 3 Years

Estimating plant yield response to nitrogen and determining economically optimal levels of nitrogen has been of interest for many decades (Tembo et al., 2008). Because the linear plateau model is used to obtain a plateau which optimizes an R-square for model explanation, it cannot be utilized for a profitability study. Table 2.2 clearly shows two harvest periods over the course of a growing season, with period one, being a low to medium yielding period, and period two being a medium to high yielding period. In period 1, yields resulting from added nitrogen are significantly lower than those resulting from added nitrogen in period 2. As opposed to current recommendations given by the University of Tennessee (448 kg N ha^{-1} annually in 4 equal split applications), by following recommendations suggested by the data in Table 2.2, a producer can a producer could save up to 126 kg N ha^{-1} annually.

Table 2.2 Most Profitable Nitrogen Rates Per Harvest and Yields Over 4 Harvest Periods (Linear Plateau)

Harvest Period	Month Nitrogen Applied	Harvest Month	Most Profitable N Rate (kg N ha^{-1})	Resulting Model Predicted Yield (Mg ha^{-1})	Most Profitable N Rate Over 3 Years (kg N ha^{-1}) (Linear Plateau)
Period 1	May	June	72	3.4	73
Period 2	June	July	94	5.6	
Period 2	July	August	80	5.2	
Period 1	August	September	76	2.9	

The derivative of the quadratic model can be set equal to a most profitable value of forage production. Traditionally it is used to determine profitability of each nitrogen application rate. The quadratic model is described in the following equation:

$$(1)\ Ax^2+Bx+C = Y,$$

where A = quadratic slope, x=nitrogen rate, kg ha^{-1}.net revenue, B=linear slope, and C= constant Y=yield of forage, Mg ha^{-1}.

Equation (2) states that net revenue minus total costs equals profit (Langemeier et al., 1992). Because all other input costs are constant as nitrogen changes, maximizing net revenue also maximizes profit. Profit is maximized by taking the derivative of net revenue with respect to nitrogen and setting it equal to zero, which is the first order condition for maximizing profit. The first order condition is: $d\Pi/dN=Pdy/dn-R=0$ (Akerlog et al., 1985).

$$(2)\ \Pi = PY\text{-}RN\ ,$$

where Π = net revenue, P= price/Mg of forage, Y=yield of forage, Mg ha^{-}1,R= price/kg N, and N= nitrogen rate, kg ha^{-1}.

The first derivative of equation (1) is:

$$(3)\quad 2Ax+B$$

Solving this first order condition for nitrogen gives the nitrogen rate that maximizes profit. In order to find the most profitable nitrogen rate with the quadratic model the derivative was set equal to R/P and solved with respect to x. With a current nitrogen price of $0.48/pound (Bowling et al., 2006), and a historical price (2001-2010) of bermudagrass hay of $107/ton (USDA, NASS, 2011), R/P=0.0045. Using the R/P value of 0.0045, and the quadratic model for profitability (Figure 3), the most profitable nitrogen application over the three (3) year period is 141 kg N ha^{-1} applied per harvest. This profitable nitrogen application resulted in a most profitable yield of 4.5 Mg ha^{-1}.

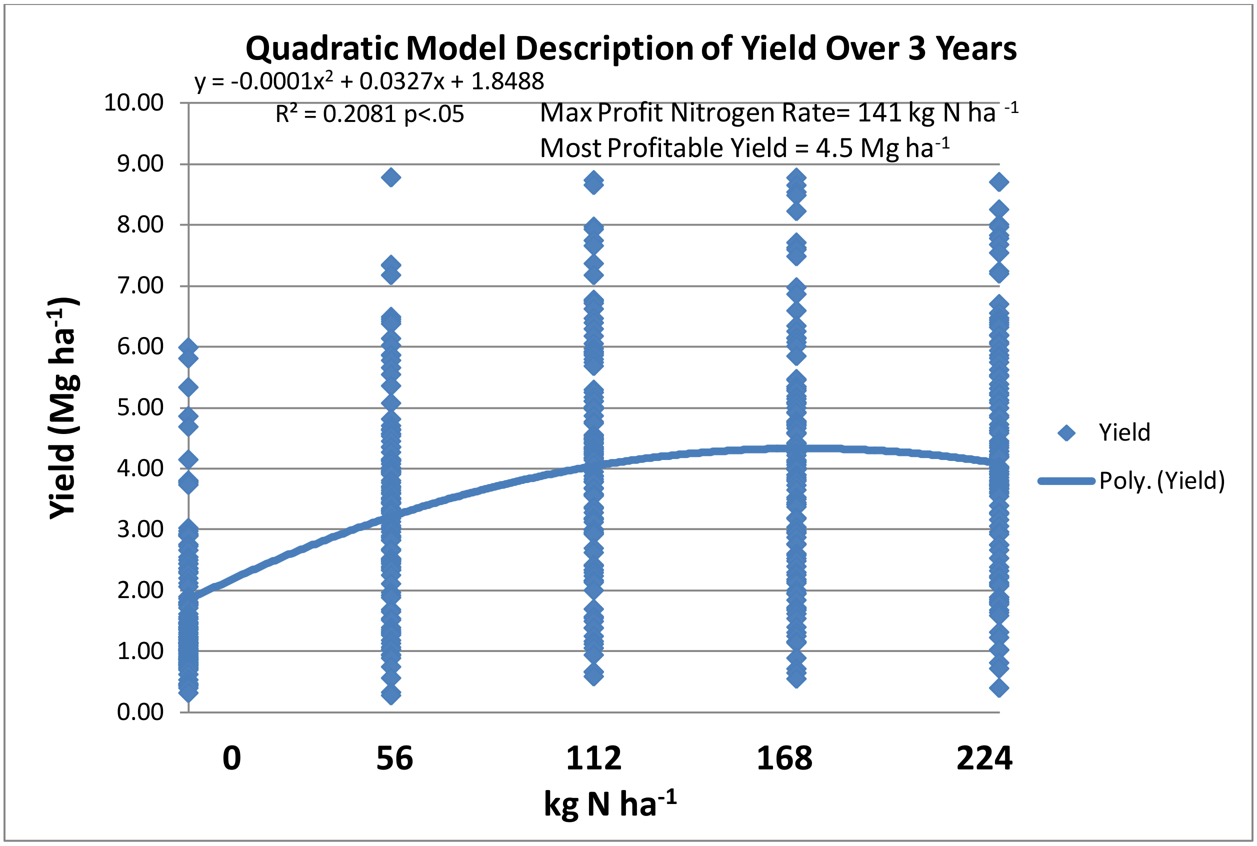

Figure 3 Quadratic Model Description of Individual Plot Yield Over 3 Years

Figure 3 displays the resulting profitable nitrogen application rates when using the quadratic model. When compared to the linear plateau model, the quadratic model suggests increased nitrogen application rates and predicted bermudagrass yields. Table 2.3 summarizes most profitable yields for the two (2) harvest periods resulting from the quadratic model.

Table 2.3 Most Profitable Nitrogen Rates and Yields Over 4 Harvest Periods (Quadratic Model)

	Month Nitrogen Applied	Harvest Month	Most Profitable N Rate (kg N ha^{-1})	Resulting Model Predicted Yield (Mg ha^{-1})	Most Profitable N Rate Over 3 Years (kg N ha^{-1})
Period 1	May	June	89	3.2	141
Period 2	June	July	135	5.2	
Period 2	July	August	134	5.0	
Period 1	August	September	106	2.7	

When comparing the two model results, the linear plateau model results in a more conservative approach to estimating profitability and yields. The quadratic model predicts higher yields and needed nitrogen fertilization rates. Nitrogen rates suggested by the quadratic model exceed rates observed to be adequate by an analysis of variance and mean separation approach.

NDVI and Soil Nitrate

NDVI and soil nitrate measurements are taken in 2010 in an effort to collect additional data pertaining to nutrient use and availability, as well as current plant health status. Table 2.4 summarizes the relationships between NDVI and soil nitrate with yield, tissue nitrate, and tissue nitrogen. Correlation values range from -1 to +1, with stronger relationships displaying correlation values closer to 1, and weaker relationships displaying correlations values closer to zero. Harvest NDVI measurements show a significant relationship between bermudagrass yield and tissue nitrate. Using polynomial regression methods, harvest NDVI measurements display significant linear and quadratic trends. NDVI measurements collected mid harvest are significant with respect to tissue nitrate, but not with yield or tissue nitrogen. Future research can investigate midseason tissue nitrate levels using NDVI, and as a result, producers can alter their nitrogen applications when critical NDVI measurements indicated possible increased nitrate accumulations. Soil nitrate is significantly related to tissue nitrogen, but not with yield or tissue nitrate. This may be due to the lack of response at one (1) harvest date during 2010. With only one (1) year of data, this is a preliminary look at soil nitrate and NDVI as plant nutrient status indicators.

Table 2.4 NDVI Correlation Values with Yield, Tissue Nitrogen, and Tissue Nitrate (2010)

Parameter	Dependent Variable	Pearson Correlation Coefficient	Linear Regression R-Square	Pr>F
Harvest NDVI	**Yield**	**0.88361**	**(*Quadratic) 0.5525**	**<.0001**
	Tissue Nitrate	**0.23012**	**0.2324**	**<.0001**
	Tissue Nitrogen	0.10684	0.0114	0.2025
NDVI Collected Mid Harvest	Yield	0.17567	0.0309	0.1317
	Tissue Nitrate	**-0.55149**	**0.2324**	**<.0001**
	Tissue Nitrogen	-0.51191	0.0114	0.2025
Soil Nitrate	Yield	-0.18433	0.0184	3.4
	Tissue Nitrate	0.17753	3.2	0.1250
	Tissue Nitrogen	**0.33387**	**0.1115**	**0.0034**

Significance at P<0.05

NDVI is highly correlated with yield. Worked performed by Xiong et al., (2007) also shows quadratic trends when comparing NDVI and bermudagrass yields. The polynomial regression R-square was 0.55. Figure 4 displays bermudagrass yields as a function of NDVI.

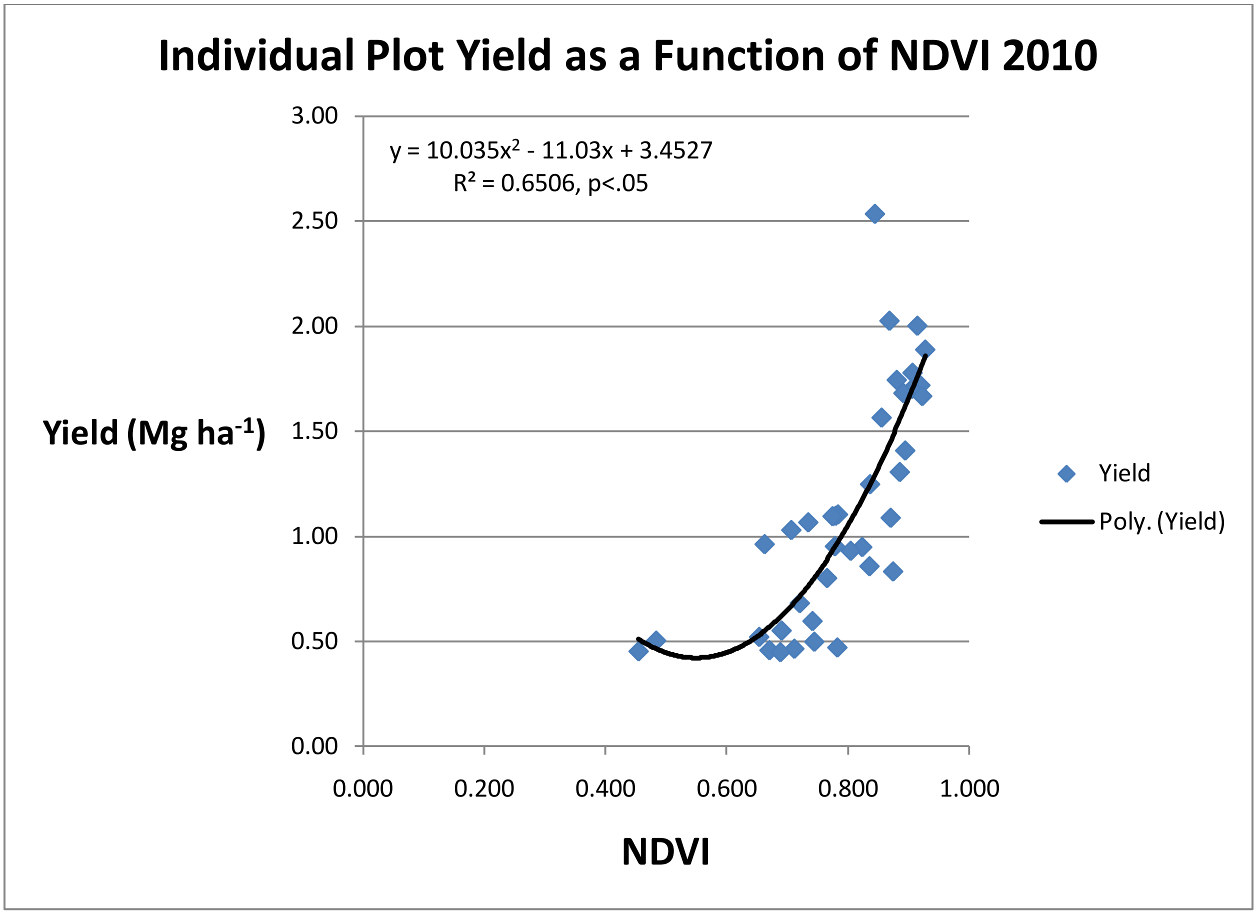

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Figure 4 Individual Plot Yield as a Function of NDVI

Looking at Figure 4, there is a significant quadratic relationship (R^2=.65) between individual plot yield and NDVI measurements taken on harvest date. When bermudagrass yields are averaged according to NDVI, NDVI displays a significant quadratic relationship. Figure 5 illustrates the quadratic relationship between NDVI means and nitrogen application. The quadratic model possesses an R-square of 0.9631 (p<.05).

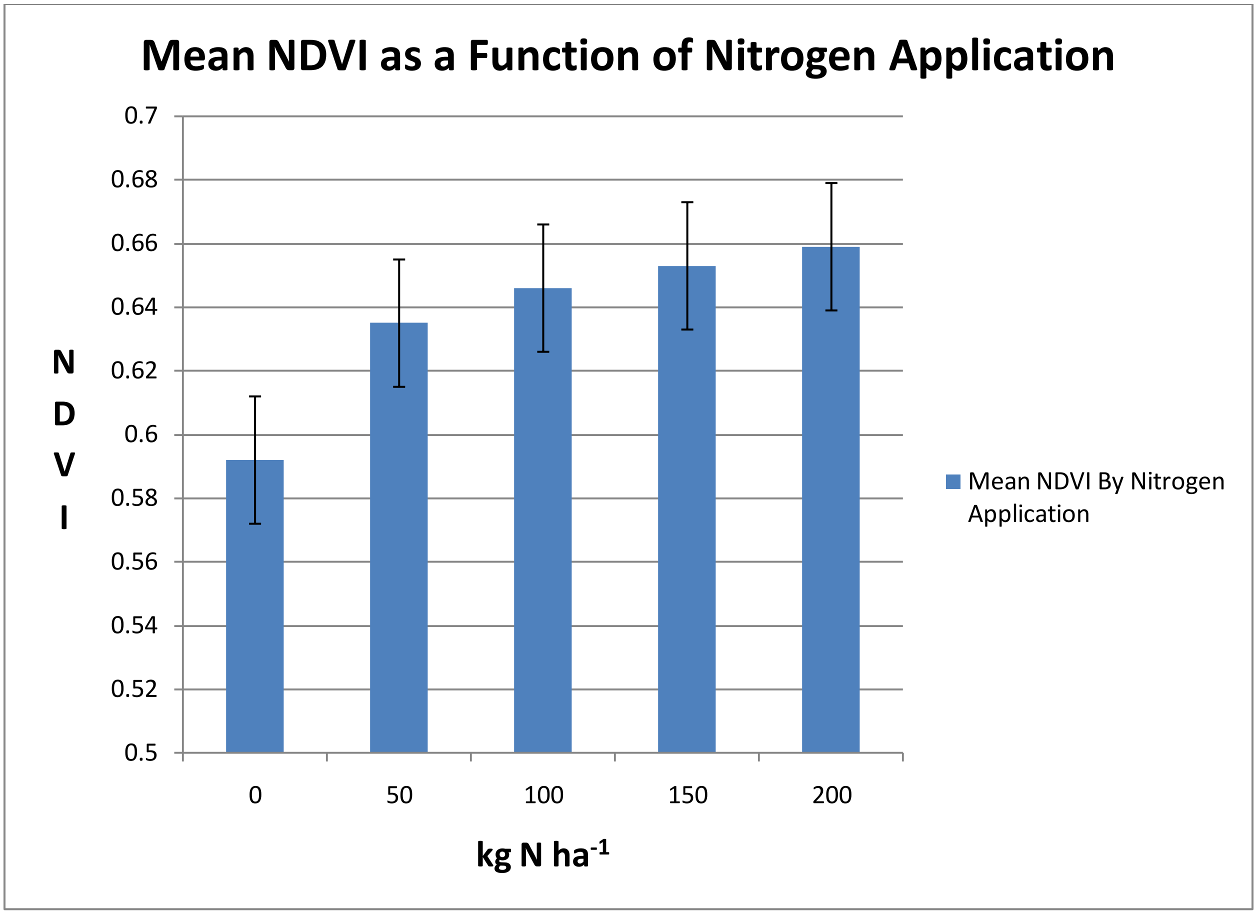

Figure 5 Mean NDVI as a Function of Nitrogen Application Rate

Past research done by Xiong et al., (2007) and this experiment suggest that NDVI can help adjust fertility programs based on seasonal changes in bermudagrass response to nitrogen fertilizer.

Soil nitrate is weakly correlated with both yield and tissue nitrate, however, soil nitrate is correlated with tissue nitrogen (Table 2.4). Neither of the regression models for soil nitrate with respect to yield are significant. NDVI values collected mid harvest are less correlated with yield than NDVI measurements collected on harvest dates. An interesting note is the correlation values between mid harvest NDVI values and tissue nitrogen and tissue nitrate, which are higher than those taken on date of harvest. This observation can be investigated further to allow NDVI to be a mid season yield indicator. Possibly due to the low yields of 2010, soil nitrate shows no correlation with bermudagrass yields. The analysis of variance of soil nitrate with respect to yield (Table 2.5) reveal a significant effect of nitrogen application, month, and the interaction between nitrogen application and month.

Table 2.5 Analysis of Variance of Soil Nitrate With Respect to Yield (2010)

Effect	Num DF	F Value	Pr>F
N Application	4	15.23	**<.0001**
Month	2	5.13	**0.0090**
N Application*Month	8	2.33	**0.0312**

Significance at P<0.05

The interaction between soil nitrate and month reveals soil nitrate means increasing as nitrogen inputs increased (Table 2.6). Soil nitrate concentrations by month are not significantly different, as soil nitrate concentrations by nitrogen application were also not significant. Generally, soil nitrate concentrations increase as the growing season progressed.

Table 2.6 Mean Separations of Soil Nitrate (mg kg^{-1}) by Nitrogen Application and Harvest Period (2010)

Application kg/ha	July	August	September
0	11.0 F	35.5 BCDE	8.9 F
56	11.0 F	20.2 EF	29.0 DEF
112	24.7 DEF	17.5 EF	34.8 CDE
168	30.3 DEF	39.4 BCDE	58.6 B
224	57.6 BC	45.4 BCD	85.2 A

Significance at P<0.05

Since no significant difference occurs between the concentrations of soil nitrate and month, soil nitrate cannot be used to predict bermudagrass yields so far using this preliminary data. Historically, soil nitrate can only be used to reveal a possible response to added nitrogen.

Nitrate Toxicity

Applying high rates of nitrogen to hybrid bermudagrass plots can result in toxic levels of nitrate accumulation for hay production. The analysis of variance with respect to tissue nitrate (Table 2.7) reveals significant effects resulting from nitrogen applications, as well as month, and the interaction between month and nitrogen application. Irrigation shows no significant effect on plant tissue nitrate in this three (3) year study.

Table 2.7 Analysis of Variance of Tissue Nitrate Over Three Years

Effect	Num DF	F Value	Pr>F
Irrigation	1	0.24	0.6229
N Application	**4**	**82.97**	**<0.0001**
Irrigation*N Application	4	0.54	0.7093
Month	**3**	**53.06**	**<0.0001**
Irrigation*Month	3	1.46	0.2240
N Application*Month	**12**	**5.72**	**<0.0001**
Irrigation*N Application*Month	12	0.26	0.9943

Significance at $P<0.05$

Over the three (3) year experiment, higher rates of nitrogen applications result in higher levels of nitrate accumulation (Table 2.8). This is consistent with past research by Westerman et al., (1983) and Osborne et al., (1999).

Table 2.8 Mean Separations of Nitrogen Application by Tissue Nitrate (mg kg^{-1}) and by Harvest Period Over 3 Years

Nitrogen Rate (kg N $ha^{-1)}$	June	Letter Group	July	Letter Group	August	Letter Group	September	Letter Group
0	1164	HI	1491	HI	251	I	1272	HI
56	2389	EFGH	2286	GH	468	I	1554	HI
112	4316	CD	6114	B	2407	FGH	3301	DEFG
168	6577	B	3258	DEFG	3258	DEFG	3938	CDEF
224	9843	A	10358	A	4010	CDE	5084	BC

Significance at $P<0.05$

Higher levels of nitrate accumulation are also observed in the months of June and July as opposed to August and September. This is consistent with work done by Bergareche and Simon (1989) and Veen and Kleinendorst (1985) with rye grass. Illustrating how nitrogen applications resulted in tissue nitrate accumulation, Figure 6 displays tissue nitrate as a result of each nitrogen application.

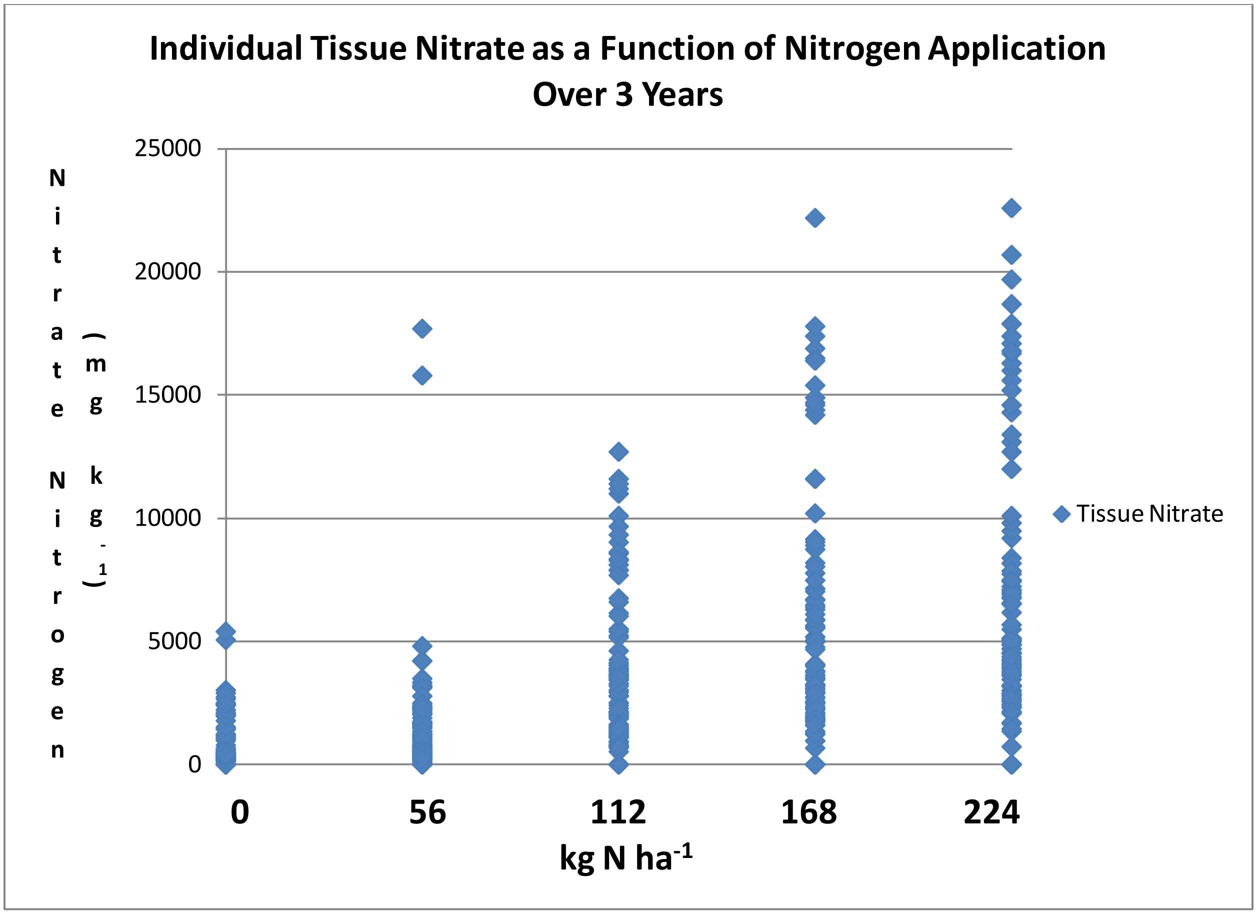

Figure 6 Tissue Nitrate as a Function of Nitrogen Application Over 3 Years

Figure 6 clearly shows a relationship between increased nitrogen applications and increased tissue nitrate concentrations. Over the three (3) year period, applications of 112, 168, and 224 kg N ha^{-1} consistently result in toxic levels of tissue nitrate accumulation.

By looking at each individual year, more analytical assumptions pertaining to tissue nitrate can be made with respect to the interaction between month and nitrogen application. Figure 7 summarizes tissue nitrate concentrations for non-irrigated plots in 2008.

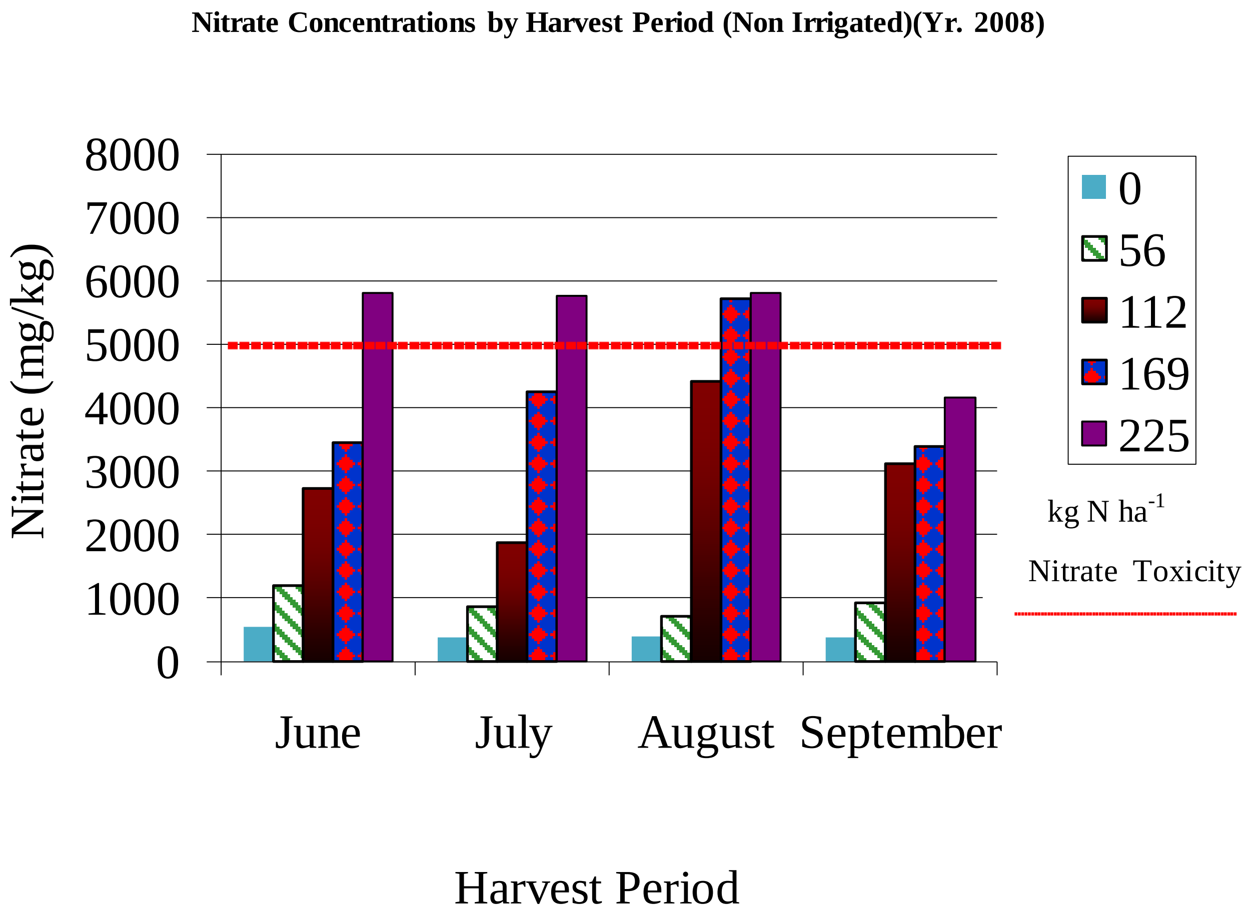

Figure 7 Nitrate Concentrations by Harvest Period (Non Irrigated) 2008

In figure 7, nitrogen applications of 225 kg N ha^{-1} are consistently approaching (September) or above the toxic level of 5,000 ppm. Only in August, did the 169 kg N ha^{-1} rate exceed this toxic level. The September harvest shows no tissue nitrate accumulation reaching toxic levels. Figure 8 summarizes tissue nitrate concentrations for non-irrigated plots in 2009.

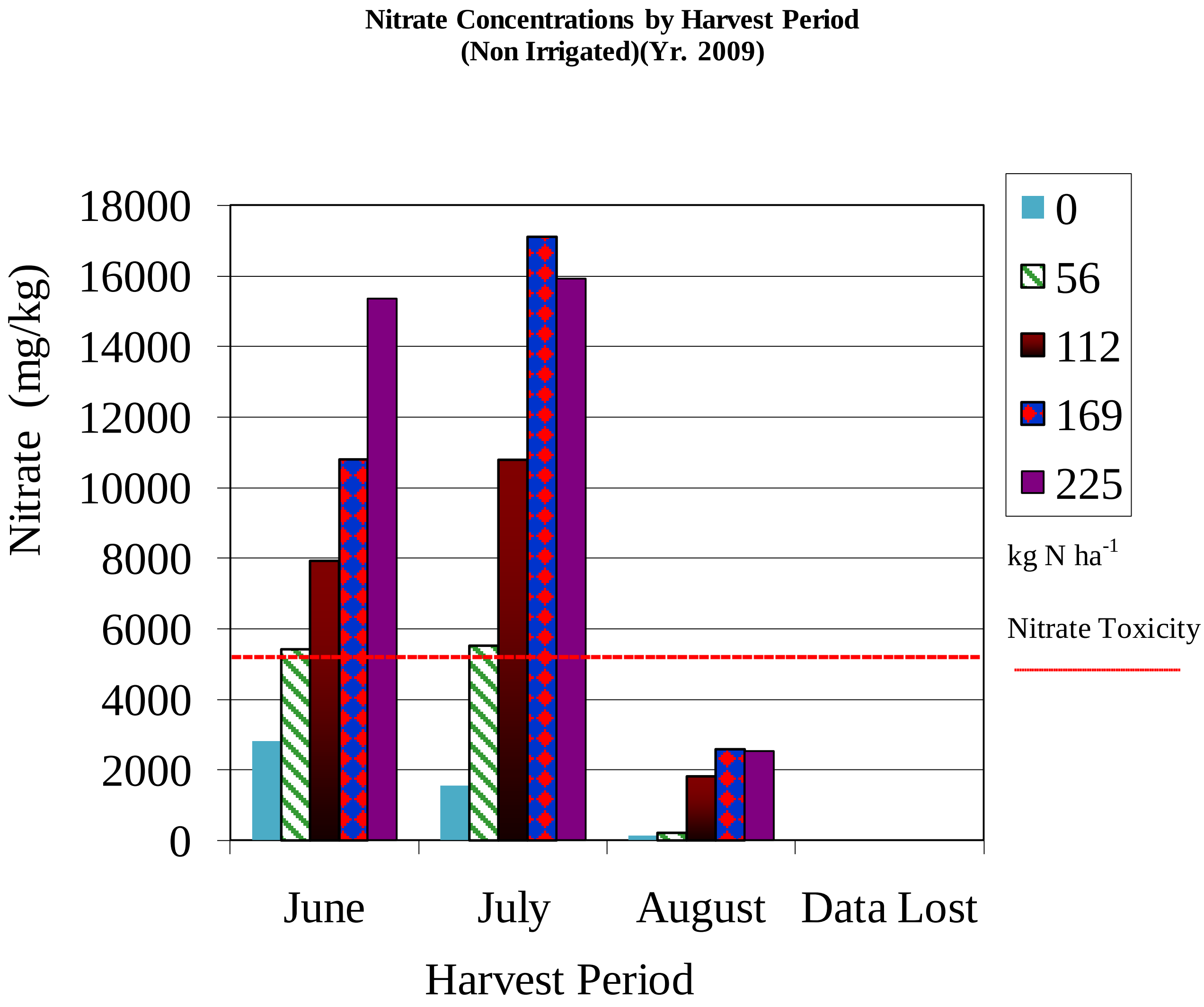

Figure 8 Nitrate Concentrations by Harvest Period (Non Irrigated) 2009

In Figure 8, months of June and July reveal toxic levels of tissue nitrate accumulation. However, in those months, rates of 56, 112, 169, and 225 kg N ha^{-1} all exceed the toxic level of 5,000 ppm. Figure 9 shows a different story for nitrate accumulation in 2010.

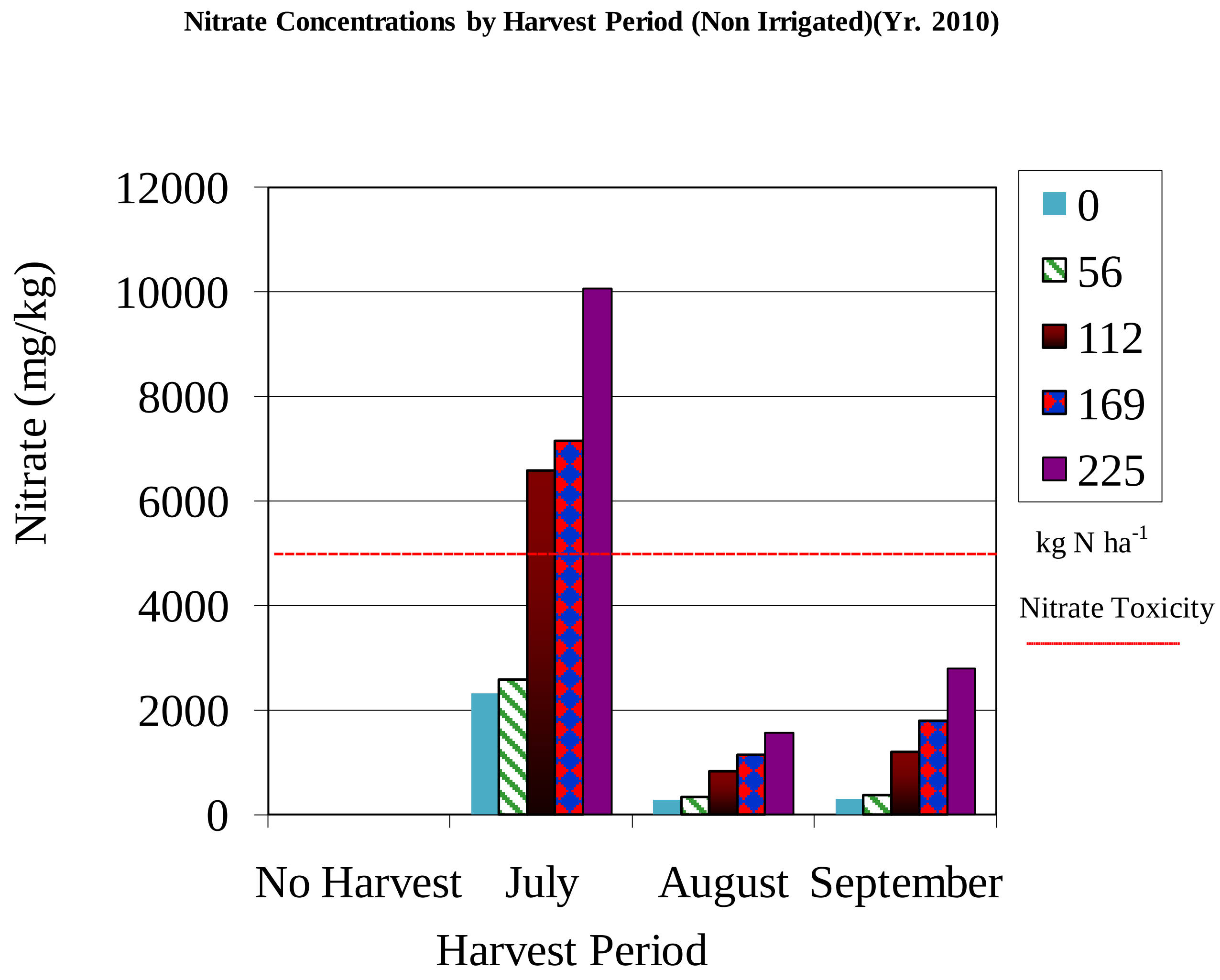

Figure 9 Nitrate Concentrations by Harvest Period (Non Irrigated) 2010

In Figure 9, July indicates toxic levels of tissue nitrate by the 112, 169, and 225 kg N ha^{-1} applications. With the lowest yields occurring in 2010, nitrate accumulation may be less frequent in years with increased yields.

Evaluating Factors Contributing to High Forage Nitrate

In summary, forage becomes toxic to beef cattle when nitrate levels approach 5,000 ppm. Over the three (3) year study, the 56 kg N ha^{-1} rate is consistently much lower than 5,000 ppm, with the 112 kg N ha^{-1} rate reaching this toxic level during the July harvest. Toxic nitrate accumulation occurs in the 169 and 225 kg N ha^{-1} rate respectively throughout the growing season. Comparing the zero nitrogen application rate with added nitrogen, an initial significant nitrate accumulation response ($P<0.05$) is observed with the 112 kg N ha^{-1} application. Mean nitrate levels peaked in July over the course of the study.

Table 2.9 ranks each variable according to both R-square and Cp value. Table 2.9 illustrates how well the variables explain variability with respect to tissue nitrate. Generally, tissue nitrogen is the single greatest factor in explaining tissue nitrate, with soil nitrate explaining the least. Other important factors which explain variability among tissue nitrate are NDVI, nitrogen application, and rainfall. Soil nitrate is not a determining factor in tissue nitrate accumulation in this study. However, with the addition of each of the variables into the model, the R-square reaches 0.7175.With important factors such as nitrogen application and NDVI appearing near the top of the list; it is possible for producers to control and monitor tissue nitrate accumulating in the forage.

Table 2.9 Factors Determining Tissue Nitrate As Ranked by Model R-Square

Number of Variables In Model	R-Square	C(p)	Variables
1	0.42	68.3027	Tissue N
1	0.30	97.8512	NDVI
1	0.20	122.4319	Nitrogen Trt
1	0.10	146.7393	Rainfall
1	0.03	165.8901	Soil Nitrate
2	0.64	17.3022	NDVI Tissue N
2	0.48	56.6714	NDVI Nitrogen Trt
2	0.47	58.5935	NDVI Rainfall
2	0.44	67.6468	Tissue N Fertility Trt
2	0.43	68.1695	Tissue N Rainfall
2	0.43	69.7369	Tissue N Soil Nitrate
2	0.41	74.8146	NDVI Soil Nitrate
2	0.31	97.9313	Rainfall Fertility Trt
2	0.22	121.2934	Soil Nitrate Fertility Trt
2	0.12	143.7159	Rainfall Soil Nitrate
3	0.68	9.9528	NDVI Tissue N Rainfall
3	0.65	16.1688	NDVI Tissue N Fertility Trt
3	0.65	16.6465	NDVI Tissue N Soil Nitrate
3	0.65	18.1911	NDVI Rainfall Fertility Trt
3	0.56	39.2578	NDVI Rainfall Fertility Trt
3	0.49	57.2499	NDVI Soil Nitrate Fertility Trt
3	0.45	65.7286	Tissue N Rainfall Fertility Trt
3	0.45	66.3016	Tissue N Soil Nitrate Fertility Trt
3	0.44	69.6768	Tissue N Rainfall Soil Nitrate
3	0.33	94.2805	Rainfall Soil Nitrate Fertility Trt
4	0.71	4.4060	NDVI Tissue N Rainfall Fertility Trt
4	0.70	8.0546	NDVI Tissue N Rainfall Soil Nitrate
4	0.62	17.4973	NDVI Tissue N Soil Nitrate Fertility Trt
4	0.65	19.6364	NDVI Rainfall Soil Nitrate Fertility Trt
4	0.47	63.3545	Tissue N Rainfall Soil Nitrate Fertility Trt
5	0.71	6.0000	NDVI Tissue N Rainfall Soil Nitrate Ferttrt

Protein Content

Besides toxic nitrate accumulation, protein content of the forage is the second quality consideration facing hay producers. Over the three (3) year experiment, nitrogen application and month show a significant effect on protein content of the forage. Table 3.0 summarizes the analysis of variance for protein content over three (3) years.

Table 3.0 Summary of Analysis of Variance of Protein Content Over Three Years

Effect	Num DF	F Value	Pr>F
Irrigation	1	0.72	0.3979
N Application	**4**	**7.58**	**<0.0001**
Irrigation*N Application	4	0.28	0.8914
Month	**3**	**2.76**	**0.0421**
Irrigation*Month	3	0.14	0.9371
N Application*Month	12	0.77	0.6823
Irrigation*N Application*Month	12	0.97	0.4760

Significance at $P<0.05$

Over the three (3) year experiment increased nitrogen also results in increased protein content up to 682 kg N ha^{-1} annually (Table 3.0). This is higher than reported by Silveira et al. (2007) which reports increased protein was achieved by applying up to 450 kg N ha^{-1}. A response in percent protein is not seen past the 112 kg N ha^{-1} rate application (Table 3.1).

Table 3.1 Summary of Protein Content by Nitrogen Application Over Three Years

Nitrogen Rate (kg N ha^{-1})	Mean Estimate (%)	Letter Group
0	13.6	D
56	14.6	CD
112	15.6	BC
169	17.3	A
225	16.9	AB

Significance at $P<0.05$

Quality forage contains anywhere from 9 to 13% protein. There is little variability in percent protein in the forage when compared by harvest month (Table 3.2). June, July, and August display no significant difference in protein content. September is not significantly different from June.

Table 3.2 Summary of Protein Content by Harvest Month Over Three Years

Month	Mean Estimate (%)	Letter Group
June	15.6	AB
July	15.3	B
August	15.3	B
September	16.1	A

Significance at $P<0.05$

Higher levels of protein content are achieved by applying higher levels of nitrogen. This is consistent with previous work performed by Prine and Burton (1956).

Soil PH

Mean soil ph declines as nitrogen inputs increased (Table 3.3). This is consistent with past research performed by Walker et al., (1979) which also observes a decline in soil ph with added nitrogen. Over the three (3) years of the experiment, average soil ph values decline as nitrogen applications increase. With increased levels of nitrogen inputs, an additional cost of liming needs will further affect a producer's profit margin. Nitrogen applications beginning at the 112 kg N ha^{-1} rate produce a significant decrease in soil ph. In 2008, individual plots are limed as part on the initiation of the study. Table 3.3 also shows a three (3) year buffer, in which the added lime stablizes the increased acidity resulting from nitrogen applications.

Table 3.3 Average Soil PH by Nitrogen Application Over 3 Years

Nitrogen Application kg/ha	Mean Estimate	Spring 2008 Mean PH	Spring 2009 Mean PH	Spring 2010 Mean PH	Spring 2011 Mean PH	Change in PH 2008 - 2011
0	6.4 A	6.06	6.28	6.60	6.52	+0.24
56	6.2 B	5.94	6.08	6.56	6.25	+0.17
112	5.9 C	5.82	5.88	6.28	5.55	-0.27
168	5.8 CD	5.88	5.78	6.10	5.45	-0.33
225	5.7 D	5.82	5.55	6.02	5.19	-0.36

Significance at $P<0.05$

Chapter V: Summary and Conclusions

This three (3) year study (2008-2010) performed at the Highland Rim Research and Education Center near Springfield, Tennessee studied Vaughn's hybrid bermudagrass hay production with five (5) different nitrogen application rates applied in late April and at the completion of each harvest in June, July, and August. The last year of the study, NDVI and soil nitrate sampling were added to investigate their relationship with hybrid bermudagrass yields, tissue nitrate, and tissue nitrogen.

Average hybrid bermudagrass yields over the course of the experiment are achieved by applying increasing levels of nitrogen. The results of the experiment show yields similar to historical results with total average annual yields for each of the five (5) nitrogen application rates being 2.8, 6.5, 12.9, 15.2, and 16.3 Mg ha^{-1} of dry matter forage respectively. The significant interaction between month and nitrogen application rate reveal similar yields in July and August and similar yields in June and September. The results show irrigation to have no effect on hybrid bermudagrass yields in this three (3) year experiment.

A linear plateau model and a quadratic model suggest a maximum profit nitrogen rate for each harvest period. Both models explain variability among bermudagrass yields similarly, possessing an R-square between 0.20 and 0.25. Over the three (3) year experiment, the linear plateau model estimates a nitrogen application rate of 73 kg N ha^{-1} per harvest which produces a maximum harvest yield of 4.0 Mg ha^{-1}. With respect to profitability, the quadratic model over the three (3) year period produces a most profitable nitrogen application of 141 kg N ha^{-1}. Looking at month separately, the most profitable nitrogen rates resulting from the linear plateau model for harvests in June, July, August, and September are 72, 94, 80, and 76 kg N ha^{-}

^{1}respectively, significantly lower than the most profitable nitrogen application produced when looking at the experiment over three (3) years (73 kg N ha^{-1}).

Analysis of variance with respect to protein reveals significant effects including nitrogen application and month. Percent protein is not significantly increased past the 169 kg N ha^{-1} rate (17.3%). There is no significant difference among the monthly averages of percent protein. Average annual percent protein content resulting from the nitrogen applications are 12.2, 13.4, 13.1, 14.2, and 14.0 respectively.

Analysis of variance with respect to tissue nitrogen reveals significant fixed effects including nitrogen application and month. No tissue nitrogen response is seen past the 112 kg N ha^{-1} application. The 112 kg N ha^{-1}application results in an average of 2.5% tissue nitrogen over (3) years. Nitrogen use efficiency (NUE) in the forage is observed to be higher in the lower nitrogen applications as oppose to the higher nitrogen applications. Average annual NUE for the four (4) application rates are 57, 38, 28, and 21% respectively. As the growing season progressed, NUE declines.

A significant interaction between month and nitrogen application occurs when analyzing fixed effects pertaining to tissue nitrate. Looking at Table 2.6, it is hard to summarize the interaction between month and nitrogen application with respect to tissue nitrate. In general, higher nitrogen applications result in higher accumulations of tissue nitrate. By looking at each individual year, June and July appear to have more nitrate accumulation occurring than August and September. However, 2008 appears to have a more even distribution among months of the growing season.

NDVI measurements indicate a strong correlation with hybrid bermudagrass hay yields (Pearson Coefficient = 0.88), as did the mid season NDVI values with tissue nitrate and tissue nitrogen. Further research can create NDVI crop indicators that can allow for the implementation of in-season NDVI parameters which could alert producers of potential nitrate toxicities and changing periods of maximum bermudagrass yields. Soil nitrate is not strongly correlated with yield or tissue nitrate.

The interaction between month and nitrogen application is significant with respect to bermudagrass yields and tissue nitrate. With previous historical studies not investigating this relationship, assumptions pertaining to nitrogen applications are not accurate.

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APPENDIX

Appendix I: Additional Tables

Harvest Date	Rainfall Between Harvests (Inches)
6-01-08	3.03
7-16-08	4.13
8-20-08	7.13
9-25-08	3.18
6-09-09	8.89
7-08-09	5.95
8-11-09	6.60
9-22-09	4.44
7-07-09	3.77
8-11-09	1.89
9-27-09	4.08

Table A-1 Inches of Rainfall Between Harvest Dates

Appendix 2

Highland Rim 2008 Month	Ave Max Daily Temp ˚F	Dept from Normal	Ave Min Daily Temp ˚F	Dept from Normal	Total Precip (Inches)	Dept from Normal
May	75	-1	53	0	5.92	+0.39
June	87	+3	66	+4	1.81	-2.7
July	89	+1	67	+1	5.83	+1.71
August	86	-1	65	+1	1.52	-1.67
September	83	+2	61	+4	1.93	-1.77
2009						
May	74	-2	56	+3	8.42	+2.89
June	86	+2	66	+4	5.32	+0.81
July	83	-5	64	-2	4.68	+0.56
August	86	-1	65	+1	2.23	-0.96
September	79	-2	62	-2	5.51	+1.81
2010						
May	78	+2	58	+5	10.34*	+4.81
June	90	+6	69	+7	3.77	-0.74
July	92	+4	71	+5	1.31	-2.81
August	92	+5	69	+5	2.91	-0.28
September	86	+5	59	+2	1.75	-1.95
*6.61 inches precip from 5-01 5-03						

(Tennessee climate data, 2011)

Table A-2 Weather Data.

Month	N Rate	Year	Estimate (Tons/Acre)	Year	Estimate (Tons/Acre)	Year	Estimate (Tons/Acre)	All 3 Years	Estimate (Tons/Acre)
June		2008		2009		2010	N/A		
	1	C	0.39	C	0.82			B	0.75
	2	B	0.83	B	1.60			A	1.32
	3	A	1.33	AB	1.74	No Harvest		A	1.44
	4	AB	1.17	AB	1.84			A	1.43
	5	AB	1.09	A	2.09			A	1.65
	Significance at P<0.05								
July									
	1	C	1.86	C	0.53	C	0.39	C	0.93
	2	B	2.80	B	1.63	B	0.83	B	1.75
	3	AB	3.11	A	2.11	A	1.33	A	2.18
	4	A	3.63	A	2.35	AB	1.17	A	2.39
	5	A	3.46	A	2.13	AB	1.09	A	2.24
	Significance at P<0.05								
August									
	1	C	1.12	C	0.39	*Not Sig	0.91	C	0.81
	2	B	2.42	B	1.75		1.20	B	1.79
	3	A	2.87	A	2.17		1.33	A	2.12
	4	A	3.15	A	2.14		1.36	A	2.21
	5	A	3.13	A	2.28		1.43	A	2.28
	Significance at P<0.05								
September									
	1	B	0.52	C	0.56	C	0.45	C	0.51
	2	A	1.28	B	1.46	BC	0.49	B	1.08
	3	A	1.45	AB	1.62	BC	0.59	AB	1.22
	4	A	1.51	A	1.75	AB	0.61	A	1.29
	5	A	1.51	A	1.77	A	0.73	A	1.34

Table A-3 Annual Harvest Mean Separation Summary

Outline of 2008 Yield MMAOV

```
                 Class Level Information

  Class       Levels    Values

  yr               1    8
  irrtrt           2    1 2
  rep              5    1 2 3 4 5
  plot             5    1 2 3 4 5
  ferttrt          5    1 2 3 4 5
  mongroup         4    6 7 8 9

              Type 3 Tests of Fixed Effects

                         Num     Den
Effect                    DF      DF    F Value    Pr > F

irrtrt                     1    20.4       0.33    0.5743
ferttrt                    4    19.9      25.82    <.0001
irrtrt*ferttrt             4    20.3       0.28    0.8863
mongroup                   3     113     188.41    <.0001
irrtrt*mongroup            3     113       0.91    0.4385
ferttrt*mongroup          12     113       4.67    <.0001
irrtrt*ferttr*mongro      12     113       0.29    0.9901
```

Outline of 2009 Yield MMAOV

```
                 Class Level Information

  Class       Levels    Values

  yr               1    9
  irrtrt           2    1 2
  rep              5    1 2 3 4 5
  plot             5    1 2 3 4 5
  ferttrt          5    1 2 3 4 5
  mongroup         4    6 7 8 9

              Type 3 Tests of Fixed Effects

                         Num     Den
Effect                    DF      DF    F Value    Pr > F

irrtrt                     1     135       1.74    0.1897
ferttrt                    4      11     121.34    <.0001
irrtrt*ferttrt             4     135       0.38    0.8258
mongroup                   3     136      10.04    <.0001
irrtrt*mongroup            3     135       4.14    0.0077
ferttrt*mongroup          12     136       2.71    0.0026
irrtrt*ferttr*mongro      12     135       0.77    0.6798
```

Outline of 2010 Yield MMAOV

```
                   Class Level Information

     Class       Levels    Values

     yr               1    10
     irrtrt           2    1 2
     rep              5    1 2 3 4 5
     plot             5    1 2 3 4 5
     ferttrt          5    1 2 3 4 5
     mongroup         3    7 8 9

                Type 3 Tests of Fixed Effects

                          Num     Den
Effect                     DF      DF    F Value    Pr > F

irrtrt                      1     113       0.03    0.8557
ferttrt                     4     113       7.76    <.0001
irrtrt*ferttrt              4     113       0.92    0.4525
mongroup                    2     113     214.70    <.0001
irrtrt*mongroup             2     113       0.05    0.9530
ferttrt*mongroup            8     113       6.99    <.0001
irrtrt*ferttr*mongro        8     113       0.87    0.5444
```

Yield MMAOV Over 3 Years

```
                   Class Level Information

     Class       Levels    Values

     yr               3    8 9 10
     irrtrt           2    1 2
     rep              5    1 2 3 4 5
     plot             5    1 2 3 4 5
     ferttrt          5    1 2 3 4 5
     mongroup         4    6 7 8 9

                Type 3 Tests of Fixed Effects

                          Num     Den
Effect                     DF      DF    F Value    Pr > F

irrtrt                      1     368       0.11    0.7425
ferttrt                     4    51.6      31.37    <.0001
irrtrt*ferttrt              4     368       0.12    0.9766
mongroup                    3     370      88.55    <.0001
irrtrt*mongroup             3     367       1.95    0.1216
ferttrt*mongroup           12     398       2.87    0.0008
irrtrt*ferttr*mongro       12     368       0.24    0.9961
```

Outline of Tissue Nitrate MMAOV Over 3 Years

```
                 Class Level Information

  Class       Levels    Values

  yr               3    8 9 10
  irrtrt           2    1 2
  rep              5    1 2 3 4 5
  plot             5    1 2 3 4 5
  ferttrt          5    1 2 3 4 5
  mongroup         4    6 7 8 9

              Type 3 Tests of Fixed Effects

                         Num     Den
Effect                    DF      DF    F Value    Pr > F

irrtrt                     1     439       0.24    0.6229
ferttrt                    4     439      82.97    <.0001
irrtrt*ferttrt             4     439       0.54    0.7093
mongroup                   3     440      53.06    <.0001
irrtrt*mongroup            3     439       1.46    0.2240
ferttrt*mongroup          12     439       5.72    <.0001
irrtrt*ferttr*mongro      12     439       0.26    0.9943
```

Outline of Protein MMAOV Over 3 Years

```
                 Class Level Information

  Class       Levels    Values

  yr               3    8 9 10
  irrtrt           2    1 2
  rep              5    1 2 3 4 5
  plot             5    1 2 3 4 5
  ferttrt          5    1 2 3 4 5
  mongroup         4    6 7 8 9

              Type 3 Tests of Fixed Effects

                         Num     Den
Effect                    DF      DF    F Value    Pr > F

irrtrt                     1     318       0.72    0.3979
ferttrt                    4    71.7       7.58    <.0001
irrtrt*ferttrt             4     318       0.28    0.8914
mongroup                   3     321       2.76    0.0421
irrtrt*mongroup            3     317       0.14    0.9371
ferttrt*mongroup          12     329       0.77    0.6823
irrtrt*ferttr*mongro      12     317       0.97    0.4760
```

PROC NLIN Output for Linear Plateau Model

```
      Source                    DF     Squares      Square     F Value    Pr > F

Model                      2     87.1732     43.5866       72.09    <.0001
Error                    525       317.4      0.6046
Corrected Total          527       404.6


                                    Approx
      Parameter      Estimate    Std Error    Approximate 95% Confidence Limits

      alpha            0.7624       0.0762      0.6126      0.9122
      beta             0.0150      0.00214      0.0108      0.0192
      x0              70.2754       7.8650     54.8246     85.7262


                     Approximate Correlation Matrix
                          alpha            beta              x0

          alpha       1.0000000      -0.7137464       0.2619816
          beta       -0.7137464       1.0000000      -0.8110940
          x0          0.2619816      -0.8110940       1.0000000

                        x0=70.275407286 plateau=.
```

PROC NLIN Output for Quadratic Plateau Model

```
                                 Sum of        Mean                Approx
Source                    DF     Squares       Square    F Value    Pr > F

Model                      2     87.1891     43.5945       72.11    <.0001
Error                    525       317.4      0.6046
Corrected Total          527       404.6

                                    Approx
      Parameter      Estimate    Std Error    Approximate 95% Confidence Limits

      alpha            0.7632       0.0761      0.6138      0.9126
      beta             0.0194      0.00351      0.0125      0.0263
      gamma          -0.00009     0.000030    -0.00015    -0.00003


                     Approximate Correlation Matrix
                          alpha            beta           gamma

          alpha       1.0000000      -0.6222098       0.4605669
          beta       -0.6222098       1.0000000      -0.9741354
          gamma       0.4605669      -0.9741354       1.0000000

                        x0=109.09818597 plateau=.
```

PROC NLIN Output for Logistic Model

```
                                Sum of        Mean                Approx
Source                    DF    Squares      Square    F Value    Pr > F

Model                      3     1422.5       474.2     694.00    <.0001
Error                    530      362.1      0.6832
Uncorrected Total        533     1784.6

                                   Approx
      Parameter      Estimate    Std Error    Approximate 95% Confidence Limits

      a                1.8979       0.0569      1.7862      2.0097
      c                0.0347      0.00656      0.0219      0.0476
      b                0.3926       0.1779      0.0431      0.7422
```

PROC NLIN Output for Exponential Model

```
                                 Sum of        Mean                Approx
Source                    DF    Squares      Square    F Value    Pr > F

Model                      2    96.3651     48.1826      70.53    <.0001
Error                    530      362.1      0.6831
Corrected Total          532      458.4

                                   Approx
      Parameter      Estimate    Std Error    Approximate 95% Confidence Limits

      a                1.9315       0.0748      1.7846      2.0784
      c                1.1701       0.1048      0.9644      1.3759
      b               -0.0209      0.00513     -0.0310     -0.0108
```

Polynomial Regression of Yield by NDVI

```
                                 The GLM Procedure

                              Dependent Variable: yld

                                        Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        2     25.90208183     12.95104091      84.89    <.0001

Error                      144     21.96964002      0.15256694

Corrected Total            146     47.87172185


                R-Square     Coeff Var      Root MSE      yld Mean

                0.541073      41.95220      0.390598      0.931055


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

ndvi                         1     22.69647769     22.69647769     148.76    <.0001
ndvi*ndvi                    1      3.20560414      3.20560414      21.01    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

ndvi                         1      1.46036887      1.46036887       9.57    0.0024
ndvi*ndvi                    1      3.20560414      3.20560414      21.01    <.0001


                                           Standard
         Parameter         Estimate           Error    t Value    Pr > |t|

         Intercept      1.581656313      0.48917949       3.23      0.0015
         ndvi          -5.021319631      1.62299360      -3.09      0.0024
         ndvi*ndvi      5.862727979      1.27901319       4.58      <.0001
```

Polynomial Regression of Yield by Nitrogen Application

```
                                    The GLM Procedure

Dependent Variable: yld

                                                Sum of
       Source                      DF          Squares     Mean Square    F Value    Pr > F

       Model                        2       94.2994351      47.1497176      68.62    <.0001

       Error                      530      364.1710173       0.6871151

       Corrected Total            532      458.4704524


                       R-Square     Coeff Var      Root MSE      yld Mean

                       0.205683      52.54795      0.828924      1.577462


       Source                      DF        Type I SS     Mean Square    F Value    Pr > F

       ferttrt                      1      74.35867923     74.35867923     108.22    <.0001
       ferttrt*ferttrt              1      19.94075589     19.94075589      29.02    <.0001


       Source                      DF      Type III SS     Mean Square    F Value    Pr > F

       ferttrt                      1      36.51766341     36.51766341      53.15    <.0001
       ferttrt*ferttrt              1      19.94075589     19.94075589      29.02    <.0001


                                                        Standard
             Parameter                Estimate             Error    t Value    Pr > |t|

             Intercept            -.0376806973        0.17374811      -0.22      0.8284
             ferttrt              0.9626764143        0.13205158       7.29      <.0001
             ferttrt*ferttrt      -.1161587701        0.02156234      -5.39      <.0001
```

Polynomial Regression of Yield by Tissue Nitrate

```
                                The GLM Procedure

Dependent Variable: yld

                                            Sum of
        Source                      DF         Squares     Mean Square    F Value    Pr > F

        Model                        3      38.6603694      12.8867898      16.09    <.0001

        Error                      331     265.0548260       0.8007699

        Corrected Total            334     303.7151953


                        R-Square     Coeff Var      Root MSE      yld Mean

                        0.127292      47.54500      0.894857      1.882127


        Source                      DF       Type I SS     Mean Square    F Value    Pr > F

        no3                          1     18.77708463     18.77708463      23.45    <.0001
        no3*no3                      1     13.89507926     13.89507926      17.35    <.0001
        no3*no3*no3                  1      5.98820549      5.98820549       7.48    0.0066


        Source                      DF     Type III SS     Mean Square    F Value    Pr > F

        no3                          1     22.32548711     22.32548711      27.88    <.0001
        no3*no3                      1     10.39404960     10.39404960      12.98    0.0004
        no3*no3*no3                  1      5.98820549      5.98820549       7.48    0.0066


                                                     Standard
                Parameter           Estimate            Error    t Value    Pr > |t|

                Intercept        1.276702984       0.10336077      12.35      <.0001
                no3              0.000314253       0.00005952       5.28      <.0001
                no3*no3         -0.000000029       0.00000001      -3.60      0.0004
                no3*no3*no3      0.000000000       0.00000000       2.73      0.0066
```

Polynomial Regression of Plant Nitrate by NDVI

```
                                        The GLM Procedure

Dependent Variable: no3

                                               Sum of
       Source                        DF         Squares     Mean Square    F Value    Pr > F

       Model                          3       594219851       198073284      34.69    <.0001

       Error                        142       810873423         5710376

       Corrected Total              145      1405093274


                       R-Square     Coeff Var      Root MSE      no3 Mean

                       0.422904      85.35867      2389.639      2799.527


       Source                        DF       Type I SS     Mean Square    F Value    Pr > F

       ndvi                           1     324745156.8     324745156.8      56.87    <.0001
       ndvi*ndvi                      1     230345992.1     230345992.1      40.34    <.0001
       ndvi*ndvi*ndvi                 1      39128702.4      39128702.4       6.85    0.0098


       Source                        DF     Type III SS     Mean Square    F Value    Pr > F

       ndvi                           1     13336603.89     13336603.89       2.34    0.1287
       ndvi*ndvi                      1     23235646.27     23235646.27       4.07    0.0456
       ndvi*ndvi*ndvi                 1     39128702.42     39128702.42       6.85    0.0098


                                                    Standard
             Parameter              Estimate           Error    t Value    Pr > |t|

             Intercept            -9893.7005     10117.15247      -0.98      0.3298
             ndvi                 78882.6176     51616.79661       1.53      0.1287
             ndvi*ndvi          -170356.3553     84452.65801      -2.02      0.0456
             ndvi*ndvi*ndvi      116597.4278     44542.39940       2.62      0.0098
```

Polynomial Regression of Tissue Nitrate by Nitrogen Application

```
                                   The GLM Procedure

Dependent Variable: no3

                                              Sum of
       Source                      DF        Squares     Mean Square    F Value    Pr > F

       Model                        3     2764982230       921660743      68.00    <.0001

       Error                      477     6465160169        13553795

       Corrected Total            480     9230142399


                        R-Square     Coeff Var      Root MSE      no3 Mean

                        0.299560      95.34253      3681.548      3861.391


       Source                      DF      Type I SS     Mean Square    F Value    Pr > F

       ferttrt                      1     2706639985      2706639985     199.70    <.0001
       ferttrt*ferttrt              1        2564636         2564636       0.19    0.6638
       ferttr*ferttr*ferttr         1       55777608        55777608       4.12    0.0431


       Source                      DF    Type III SS     Mean Square    F Value    Pr > F

       ferttrt                      1    25430149.01     25430149.01       1.88    0.1714
       ferttrt*ferttrt              1    57788326.84     57788326.84       4.26    0.0395
       ferttr*ferttr*ferttr         1    55777608.18     55777608.18       4.12    0.0431


                                                       Standard
          Parameter                   Estimate            Error    t Value    Pr > |t|

          Intercept                2469.038081      1845.554613       1.34      0.1816
          ferttrt                 -3289.030251      2401.175316      -1.37      0.1714
          ferttrt*ferttrt          1836.279496       889.301817       2.06      0.0395
          ferttr*ferttr*ferttr     -199.035689        98.114110      -2.03      0.0431
```

VITA

Timothy Donald Carter was born in Dublin, Georgia on August 3, 1983. He attended public school in Laurens County and graduated from Dublin High School in May of 2002. He then attended the University of Georgia in Athens, Georgia where he graduated in May of 2006 with a Bachelor of Science degree in Environmental Health Science. After graduating from UGA, he began his environmental career with Earth Consulting Group, Inc. in 2007. He worked as a staff scientist for EarthCon for 2.5 years. He then entered graduate school at the University of Tennessee, Knoxville. While a graduate assistant, he assisted in nitrogen, phosphorous, and potassium studies involving corn and forage under the direction of Dr. Hugh Savoy, and with his guidance, learned how to analyze results obtained from field trials of hybrid bermudagrass. He anticipates a Master of Science degree in Biosystems Engineering Technology in May 2011.