

SWITCHGRASS AS AN ENERGY CROP: FERTILIZATION, CULTIVAR, AND CUTTING MANAGEMENT

Roque W. Lemus

Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements of

Doctor of Philosophy
In
Crop and Soil Environmental Sciences

David. J. Parrish, Chair
Ozzie Abaye
Marcus Alley
Christine Anderson-Cook
Alex Niemiera

January 9, 2004
Blacksburg, Virginia

Keywords: switchgrass, *Panicum virgatum*, nitrogen, efficiency, mineralization,
volatilization, removal, translocation, biomass, management.

Copyright © Roque W. Lemus, 2004. All rights reserved.

SWITCHGRASS AS AN ENERGY CROP: FERTILIZATION, CULTIVAR, AND CUTTING MANAGEMENT

Roque W. Lemus

ABSTRACT

Switchgrass (*Panicum virgatum* L.) has potential as a biofuels feedstock. Major management questions include cultivar selection, cutting management, and optimizing N fertilization. Four cultivars of switchgrass were evaluated under two cutting regimes at eight locations within KY, NC, TN, VA, and WV in 2000 and 2001. Harvests were made once (in early November) or twice (midsummer and early November). Biomass yields averaged 15 Mg ha⁻¹ and ranged from 10 to 22 Mg ha⁻¹ across locations and years. There was no yield advantage to taking two harvests of the lowland cultivars ('Alamo' and 'Kanlow'). If harvested twice, the upland cultivars ('Cave-in-Rock' and 'Shelter') provided yields equivalent to the lowland ecotypes. A closer look at Alamo revealed much higher N removal in the midsummer harvests, late-season N translocation out of tillers, and fewer tillers developing under one-cut management. Switchgrass appears to be capable of truly perennial productivity in the upper Southeast USA with 50 kg N ha⁻¹ yr⁻¹ and a single harvest.

A second field study was conducted on 'Cave-in-Rock' switchgrass at Orange and Blacksburg, VA to examine N dynamics. For the 3-yr study, N fertilizer was applied once in May 2001 at 0, 90, 180, or 270 kg N ha⁻¹. Switchgrass was harvested once (early November) in 2001 and twice (early July and early November) in 2002 and 2003. Tissue, root, and soil samples were collected in May, July, September, and November each year. Nitrogen fertilization had no effect on yield in 2001 and small residual effects in 2002 and 2003. Higher N removal was observed with two-cut management, where a high-yielding July cut had high shoot N concentrations. The amount of N removed as

biomass from the 0 N treatments over 3 yr was 227 kg N ha⁻¹; obviously significant amounts of N can be made available by these soils without any fertilizer applied. During the growing season, higher mineral N in soil was observed in July and September, when warmer temperatures increase microbial activity and N mineralization. Nitrogen use efficiency declined with increasing N rates. The low N response could be due to “native” N, to microbiological interactions, and/or to the ability of the plants to create internal N reserves. Proper N management of switchgrass must take into account the dynamics of several N pools.

Greenhouse studies were conducted to establish switchgrass' responses to N and P under well-defined, soilless conditions and to examine two N sources. Shoot biomass increased with N fertilization with an observed inflection point at 210 kg N ha⁻¹. In these pot studies, root biomass increased with N only to 115 kg N ha⁻¹. No significant effect of P above 30 kg ha⁻¹ was observed in shoot or root biomass. Biomass yield and tiller number were highly correlated. Biomass production was two times greater with ammonium sulfate than with urea when each was applied at equivalent N rates.

Taken together, these findings suggest soils in the upper Southeast USA can supply significant amounts of the N needs of switchgrass, especially when harvested once at the end of the season.

ACKNOWLEDGMENTS

All my success in and out of the classroom has come because of the influence and support of a few great people. I want to start this section by expressing my deep appreciation and thankfulness to my parents, for giving me love and a strong will and ability to deal with the challenges of everyday life. Although they are 3,000 miles away, they have always taught me good morals and principles. I always look up to you both. Thank you and God bless you!

I want to thank my best friend Bryon Pepper for being there for me every time that I needed a shoulder to lean during the most difficult times. His words of encouragement made everything easier and his wise advises guided me to focus on a better understanding of where we come from, who we are, and where we go in the future. Your sincere, caring, and special friendship has and will always make me a better person. You have a very special place in my heart.

I have so many people that I want to express my gratitude for their help and support in making my college carrier at Virginia Tech so especial. I want to thank Dr. David Parrish and Dr. Ozzie Abaye for their unbelievable patience, time, belief, support, and friendship. Thank you for giving me the opportunity as a graduate student, and for the opportunity to develop a wide spread experience in the forage field, by allowing me to get involved in different projects and allowing me to pursue my interests. Your support and coaching made my research a positive reward for me. Your advice and academic training have prepared me well to for the agricultural challenges of the future. Your guidance and support were very helpful in achieving this goal.

Great thanks the rest of my committee members, Dr. Mark Alley, Dr. Christine Anderson-Cook, and Dr. Alex Niemiera, for advising me with ideas that will enrich my future carrier. Their contributions have been substantial and mere words cannot convey how much I appreciate them. Also, special thanks to Dr. Dale Wolf with whom I shared great times in the biomass project and gave me the opportunity to develop personally and professionally. His help and

encouragement has made my dream of achieving a higher education a reality. Thank you for being a role model of what a scientist should be. Working side by side with you was educational and appreciated.

I want to thank Dr. Gaber Hassan and W. T Price for putting long hours with me in the lab, organizing, preparing, and analyzing samples. You two were great at keeping me on task and expedient. Thank you for putting up with me on my difficult days. Finally, I would like to thank my colleague and friend Dr. Gregg Munshaw for his friendship and support throughout our times as grad students.

TABLE OF CONTENTS

Abstract.....	ii
Acknowledgments.....	iv
Table of Contents.....	vi
List of Tables	x
List of Figures	xiv
CHAPTER 1. Introduction.....	1
Background	1
Objectives	3
Dissertation Organization.....	4
Literature Cited.....	4
 CHAPTER 2. Literature Review.....	 6
Introduction	6
Switchgrass Background/Overview.....	8
Cutting Management and Implications for Biomass Production	9
Nitrogen as a Management Component	11
NUE: The Concept and Various Estimators	12
N Dynamics in the Field: Losses and Transformations	15
Nitrogen Inputs through Mineralization.....	17
N Losses through Volatilization	22
Nitrogen Dynamics in the Plant: Uptake, Content, Distribution, and Translocation.....	24
Phosphorus Requirements of Switchgrass.....	25
Summary/Rationale for Studies	26
Literature Cited.....	27

CHAPTER 3. Switchgrass for Biomass Production in the Upper Southeast USA:

Cultivar/Ecotype Selection and Cutting Management	41
Abstract	41
Introduction.....	42
Materials and Methods	44
Results and Discussion	46
Climatic Effects	46
Cultivar and Cutting Management Differences across Years and Sites.....	46
Ecotype Differences in Response to Cutting Management.....	48
Visual Stand Evaluation	49
Switchgrass Stability and Adaptation	50
Conclusions	51
Literature Cited	53

CHAPTER 4. Yield of and Nutrient Removal by ‘Alamo’ Switchgrass as Affected by Cutting Management.....

Abstract.....	66
Introduction	67
Materials and Methods	68
Results and Discussion	72
Climatic Effects.....	72
Biomass Yields	73
Nutrient Concentrations in Biomass	73
Nutrient Removal in Biomass	75
Nutrient Partitioning/Concentrations within Biomass	77
Soil Nutrient Levels.....	79
Conclusions.....	81
Literature Cited.....	83

CHAPTER 5. Evaluating N Dynamics to Improve Switchgrass Management in

Virginia.....	98
Abstract.....	98
Introduction	99
Materials and Methods.....	101
Biomass Yield Responses to N	101
Quantification of N-use Parameters.....	103
Soil N Pools and Dynamics: Total N, Mineral N, Organic N, and Potentially Mineralizable N	104
Statistical Analysis of Field Study	105
Results and Discussion.....	106
Biomass Yields and N-use efficiency.....	106
Roots Biomass and N Values	109
Sources of Available N	111
Total Soil N	111
Soil Mineral N (SMN).....	112
Potentially Mineralized N (PMN).....	113
Conclusions.....	115
Literature Cited.....	117

CHAPTER 6. Seedling switchgrass Response to N and P when Grown in a Soilless Substrate Growth.....	135
Abstract.....	135
Introduction	136
Materials and Methods.....	138
Experimental Design and Statistical Analysis.....	140
Results and Discussions	141
Study A: Responses to N and P fertilization	141
Study B: N sources comparison	143
Correlations among N applied and Yield Components.....	145
Conclusions.....	145
Literature Cited.....	146

CHAPTER 7. Summation/Conclusions	161
---	------------

APPENDIX. Ammonia Volatilization from Urea Applied to Soil under Switchgrass

Management	165
Introduction	165
Materials and Methods	166
Results and Discussion	169
Literature Cited	170
 Vita.....	 178

LIST OF TABLES

Table 2.1. Some Nitrogen Use Efficiency (NUE) variants. Adapted from Pandey et al. (2001)	13
Table 3.1. Location, elevation, soil series, pH, and class capability of sites where switchgrass varieties were evaluated as a biofuels crop in 2000 and 2001	55
Table 3.2. Description of switchgrass cultivars evaluated at eight locations in the upper Southeast USA in 2000 and 2001. (CIR = Cave-in-Rock).....	56
Table 3.3. Analysis of variance and mean squares for switchgrass biomass yields in response to two cutting managements during the growing season in 2000 and 2001 at eight different locations in the upper Southeast USA ..	57
Table 3.4. 2000, 2001, and long-term rainfall and mean temperature data for April through September (A-S) near sites on which switchgrass was grown in the upper Southeast USA. Departure from long-term (30-yr) normal is observed values minus long-term values	58
Table 3.5. Effect of cutting management, year, and cultivar on yield of switchgrass grown at eight locations in upper Southeast USA. (CIR = Cave-in-Rock)	59
Table 3.6. Effect of cutting management and cultivar on yield of switchgrass grown at eight locations in upper Southeast USA. Data are averaged across 2 yr. (CIR = Cave-in-Rock)	60
Table 3.7. Effect of harvest date (first and second harvest) and cultivar on switchgrass yields grown at eight locations across upper Southeast USA under two-cut management. Data are averaged across 2 yr. (CIR = Cave-in-Rock).....	61
Table 3.8. Effect of ecotype and cutting management on yield of switchgrass at eight locations across upper Southeast USA. Data are averaged across two cultivars and 2 yr	62
Table 3.9. Stand density ratings (0 = least dense, 10 = most dense) in November 2001 for four switchgrass cultivars grown at seven locations in upper Southeast USA when harvested once (in November) or twice (mid-summer and November). (CIR = Cave-in-Rock)	63

Table 4.1. Fertilization history during 10 yr (1992 to 2001) of Alamo switchgrass grown at eight locations in the upper Southeast. All fertilizer applications were made before growth began in any year	86
Table 4.2. Analysis of variance, mean squares, and F-values for Alamo switchgrass biomass yields in response to two cutting managements during the growing season in 2000 and 2001 at eight different locations. Years and locations were considered blocks	87
Table 4.3. Seasonal yields of Alamo switchgrass at eight locations when harvested once (in November) or twice (in June/July and one in November) in 2000 and 2001.....	88
Table 4.4. Analysis of variance and mean squares for Alamo switchgrass nutrient concentrations in response to two cutting managements.....	89
Table 4.5. Analysis of variance and mean squares for Alamo switchgrass total nutrient removals in response to two cutting managements. Years were considered blocks	90
Table 4.6. Nitrogen, P, K, and C concentrations (%) in whole-plant tissue collected at harvest of one- and two-cut managements of Alamo switchgrass. Data are averaged over eight locations and 2 yr	91
Table 4.7. Nitrogen, P, K, and Ca removals (kg ha ⁻¹) in whole-plant tissue collected at harvest of one- and two-cut managements of Alamo switchgrass. Data are averaged over eight locations and 2 yr	92
Table 4.8. Total K removals in whole-plant tissue and soil Ca concentrations of two cutting managements for Alamo switchgrass grown at eight locations. Data averaged over 2 yr.....	93
Table 4.9. Partitioning (by percentage and weight) of Alamo switchgrass tillers, nutrient element concentrations and content of each portion collected at the boot stage in late June 2000. Data are averaged across six locations.. ..	94
Table 4.10. Analysis of variance and mean squares for soil where Alamo switchgrass was grown under two cutting managements. Years were considered blocks	95
Table 4.11. Soil pH, P, K, and Ca in top 10 cm of Alamo switchgrass plots in 1992 (before planting) and in the fall of different years. Managements included one cut or two cuts per season	96
Table 4.12. Changes in soil K concentration with cutting managements among	

years. Data averaged over eight locations	97
Table 5.1. Observed and long-term (30-yr) monthly rainfall and mean emperatures for April through October at two locations at which switchgrass was grown in VA in 2001, 2002, and 2003	120
Table 5.2 Analyses of variance and mean squares for total switchgrass biomass yields, and total N removal in response to N applications in 2001 and residual N (2002 and 2003) at two locations in VA.....	121
Table 5.3. Nitrogen effects (applied in 2001 and residual in 2002 and 2003) on switchgrass total annual and cumulative (2001 + 2002 + 2003) yields averaged across two locations in VA	122
Table 5.4. Nitrogen removal by switchgrass when fertilized once (in 2001) and harvested once (2001) or twice (2002 and 2003) per year. Data are averaged over two locations in VA.....	123
Table 5.5. Nitrogen use estimators as affected by N rate for switchgrass production over 3 yr (2001 through 2003) when the N was applied only once (2001). Cumulative yields for the 3 yr are used in calculating the N- use estimators: N-use efficiency (NUE), apparent N recovery (ANR), and partial factor productivity (PFP). Data are averaged over two locations for ANR	124
Table 5.6. Changes in switchgrass root biomass in the upper 15 cm throughout the growing season. Data are averaged over two VA locations and four N rates. Data for 2001 are derived from 0.25 m ² quadrats. Data for 2002 and 2003 are based on smaller core samples subsequently corrected for nonrandom sampling.....	125
Table 5.7. Analysis of variance and mean squares for root N concentrations in response to N applications in 2001 and N residual (2002 and 2003) at two locations in VA.....	126
Table 5.8. Analysis of variance and mean squares for soil mineral N (SMN) and potentially mineralizable N (PMN) in response to N applications in 2001 and N residual (2002 and 2003) at two locations in VA.....	127
Table 5.9. Year, location, and sampling date effect on percent N and total soil under switchgrass management. Soil samples were collected to 15 cm and data are averaged over four N rates	128
Table 5.10. Locations and harvest effects on soil mineral N (SMN) and	

potentially mineralized N (PMN) in soils supporting switchgrass growth at two locations in VA during 2001, 2002, and 2003. Soil samples were collected to a 15 cm depth averaged over four N rates	129
Table 6.1. Changes in greenhouse-grown switchgrass seedling shoot and root biomass with applied N from two sources (Study B)	149
Table 6.2. Changes in greenhouse-grown switchgrass root and shoot N concentrations with N applied from two sources (Study B)	150
Table 6.3. Changes in greenhouse-grown switchgrass seedling root and shoot N content with N applied from two sources (Study B).....	151
Table 6.4. Correlations between N rate and switchgrass yield components for greenhouse-grown switchgrass seedlings in two studies (A and B) and two N sources (urea and ammonium sulfate)	152

LIST OF FIGURES

Fig. 2.1. Nitrogen inputs and effluxes in a plant-soil system.....	16
Fig. 3.1. Test locations in the upper Southeast USA	45
Fig. 3.2. Stubble density of 10-yr old switchgrass plots after fall harvest 2001 in Morgantown, WV.....	49
Fig. 3.3. Relationship between latitude of origin and yield of four switchgrass cultivars and biomass yields under two cutting systems in the upper Southeast USA. Data are the switchgrass cultivars averages from Table 3.5	64
Fig. 3.4. Regression of switchgrass cultivars means at each location on an environmental site yield variation for one- or two-cut systems. Site yield variation was calculated as the cultivar mean at each location minus the location grand mean. (Eberhart and Russell, 1996)	65
Fig. 4.1. Schematic of switchgrass tiller (drawing by Dale Wolf).....	70
Fig. 5.1. Switchgrass root biomass to 15 cm depth (0.25-m ² quadrat).....	102
Fig. 5.2. Correlation between root sampling methods (quadrat vs. core) to subsequently estimate corrected values for nonrandom sampling in 2002 and 2003 at different dates.....	130
Fig. 5.3. Effect of N rate on the relationship between cumulative response index (RI) and switchgrass cumulative NUE. Data are averaged over two locations	131
Fig. 5.4. Applied N, residual applied N, and date effects on switchgrass root N concentration during 2001, 2002, and 2003. Data averaged over two locations	132
Fig. 5.5. Soil mineral N test values at four sampling dates across the growing season for 3 yr in soils under switchgrass production in VA. Data are averaged over two locations and four N rates	133
Fig. 5.6. Potentially mineralizable N values at four sampling dates across the growing season for 3 yr in soils under switchgrass production in VA. Data are averaged over two locations and four N rates.....	134
Fig. 6.1. Effects of N fertilization rate on shoot and root biomass of greenhouse-	

grown switchgrass seedlings (Study A).....	153
Fig. 6.2. Effects of N fertilization rate on height and tiller number of greenhouse-grown switchgrass seedlings (Study A).....	154
Fig. 6.3. Changes on shoot and root N concentrations of greenhouse-grown switchgrass seedlings provided different N rates (Study A)	155
Fig. 6.4. Changes on shoot and root N content of greenhouse-grown switchgrass seedlings provided different N rates (Study A)	156
Fig. 6.5. Effect of N rate on N-use efficiency (NUE), apparent N recovery (ANR), and partial factor productivity (PFP) of greenhouse-grown switchgrass seedlings (Study A)	157
Fig. 6.6. Changes in tiller number with N applied from two sources to greenhouse-grown switchgrass seedlings (Study B).....	158
Fig. 6.7. Changes in height with N applied from two sources to greenhouse-grown switchgrass seedlings (Study B).....	159
Fig. 6.8. Effect of N rate on N-use efficiency (NUE), apparent N recovery (ANR), and partial factor productivity (PFP) of greenhouse-grown switchgrass seedlings (Study B)	160
Fig. A.1. Ammonia volatilization chambers, traps, and manifolds.....	167
Fig. A.2. Ammonia volatilization time course of two trials carried out in the greenhouse at different four N rates.....	173
Fig. A.3. Cumulative NH ₃ losses at different rates of N application. Uppercase letters are for comparison of N rates within experiment A and lowercase letters are from comparison of N rates within experiment B	175
Fig. A.4. Percent NH ₃ losses at different rates of N application. Uppercase letters are for comparison of N rates within experiment A and lowercase letters are from comparison of N rates within experiment B	176
Fig. A.5. Temperatures inside volatilization chambers at the time of collection where trials were carried out in the greenhouse.....	177

CHAPTER 1

INTRODUCTION

BACKGROUND

In the last few decades, interest in bioenergy crops has increased considerably. Based on a series of evaluation trials in VA, switchgrass (*Panicum virgatum* L.) has been identified as a promising species for development as a fuelcrop (Parrish et al., 2002); but information about cultivar choice, cutting management (once vs. twice), and the effects of N fertilization for optimizing yields is very limited. Interest in switchgrass for energy feedstock production has prompted questions about the appropriate management practices.

Across the upper Southeast, several factors have been shown to influence switchgrass biomass yields. These include ecotype (lowland vs. upland), cultivar, cutting management (once vs. twice), and environmental conditions. 'Cave-in-Rock' switchgrass (an upland cultivar) is widely recommended for forage management, but other cultivars (including lowland cultivars) have been tested in the upper Southeast for adaptability, perenniality, and biomass potential. The findings to be reported here suggest that lowland cultivars have greater potential than upland cultivars in the upper Southeast USA and that they are best managed with surprisingly low rates of N and a single harvest per year.

One of the goals of any herbaceous energy crop production system is to maximize or optimize biomass production. An appropriate harvest management is essential to optimizing production (Sanderson et al., 1999). Frequency and timing of harvests will likely have agronomic, quality, and ultimately economic consequences. Also, a cutting system that ensures maintenance of adequate plant energy reserves will be necessary for long-term productivity (Cuomo et al., 1996). Although most studies on switchgrass management have emphasized a

single harvest at the senescent stage (Sanderson et al., 1996), other harvest management practices could be desirable.

Basic agronomic requirements have been established for most warm-season grasses when managed for forage production (Metcalf and Bullard, 2001), but the capacity to produce high yields does not automatically make them suitable energy crops. Understanding the N cycle in switchgrass growth requires information about the seasonal dynamics of N in the various ecosystem components. It is essential to consider how soil-plant relationships can affect N dynamics, how yields are affected by N fertilization, and to quantify nutrient removal with various harvest management practices.

The determination of optimum N fertilizer rates for switchgrass is an unsolved problem. Nitrogen availability has been reported as the most frequently limiting factor in warm-season grass production (Berg, 1995). The assessment of optimum N fertilizer rates for switchgrass is important for economic and environmental reasons. Nitrogen fertilizer recommendations made without adequate knowledge of the N-supplying capability of soil can lead to inefficient use of N (Ziadi et al., 2000). Fertilizer recoveries by crops under field conditions rarely exceed 50 to 60%, even when soil immobilization is taken into account (Bock and Hergert, 1991). In order to optimize biomass production, developing precise N fertilizer rates requires a consideration of yield goals, N requirements of the crop, residual soil N availability, and tissue N contents that are observed when N is non-limiting (Baloch, 1998).

Although much of the land in VA is suited for agronomic crops, significant areas are limited by their topographic configuration, e.g., the southwestern part of the state. The main production limitations arise from soils with shallow horizons and steep terrains, making it difficult for farmers to find suitable crops for these conditions. When cropped, most of these areas are used in forage production, giving farmers the alternatives of pasture or hay management. Since switchgrass is a native species, it might readily function as one component in a multipurpose cropping system (forage and biofuels utilization). A series of studies by Parrish et al. (1999) has shown that switchgrass has high biomass

yield potential, wide adaptation to the upper Southeast, relatively low fertilization requirements, and compatibility with traditional forage management practices. A key component in establishing switchgrass as a bioenergy crop in VA and the upper Southeast is determining optimum N fertilization rates and cutting management practices that will optimize yield potentials.

OBJECTIVES

Information on cutting management, best cultivars, and optimal N fertilization for switchgrass grown as a biomass or bioenergy crop in VA and the upper Southeast is limited. Four studies were conducted to look more closely at switchgrass management. The first experiment evaluated the influence of cutting management and cultivar/ecotype in the upper Southeast (KY, NC, TN, VA, and WV) in 2000 and 2001. A second study was a subset of the first and looked more closely at 'Alamo' switchgrass yield and nutrient removal. A third field experiment evaluated the N requirement of 'Cave-in-Rock' in VA and residual N effects on yields under different cutting systems in 2001, 2002 and 2003. The fourth study was conducted in the greenhouse to determine N requirements under more highly defined, soilless conditions.

The objective of the large cutting management and cultivar response experiment was to generate detailed information on the performance of various switchgrass cultivars and to compare lowland and upland ecotypes in diverse environments and with two different cutting managements.

The objective of the Alamo study was to quantify nutrient content and nutrient removal of this cultivar as affected by site, year, and cutting management.

The objectives of the N fertilization field study in VA were: (1) to determine the effects of residual applied N on switchgrass biomass production; and (2) to study N accumulation and partitioning in switchgrass biomass.

The objectives of the greenhouse study were: (1) to measure switchgrass responses to N and P under defined conditions, and (2) to determine N use efficiency by switchgrass under various application rates.

DISSERTATION ORGANIZATION

This dissertation is organized into seven chapters. This first chapter includes the general statement on the research topics, the significance of the studies, and the objectives of the experiments. The second chapter is an in-depth literature review of concepts related to the study. The third, fourth, fifth, and sixth chapters are the four studies. The final chapter includes a general summary of the studies and applications to switchgrass management for biofuels production in VA and the upper Southeast. Finally, acknowledgements and appreciation to people who were of great support to the project are given.

LITERATURE CITED

- Baloch, D. M. 1998. Evaluation and use of soil mineralizable nitrogen test to determine the fertilizer nitrogen needs of winter wheat grown in western Oregon. Ph. D. Thesis. Oregon State University, Corvallis, OR.
- Berg, W. A. 1995. Response of a mixed native-warm season grass planting to nitrogen fertilization. *J. Range Manage.* 48: 64-67.
- Bock, B. R., and G. W. Hergert. 1991. Fertilizer nitrogen management. P. 139-164 *In* R. F. Follet, D. R. Keeney, and M. R. Cruse, eds. *Managing nitrogen for groundwater quality and farm profitability*. SSSA, Madison, WI.
- Cuomo, G. J., B. E. Anderson, L. J. Young, and W. W. Wilhelm. 1996. Harvest frequency and burning effects on monocultures of 3 warm-season grasses. *Range Manage.* 49 (2): 157-162.
- Metcalf, P., and M. J. Bullard. 2001. Life-cycle analysis of energy grasses. *Aspects of Applied Biology* 65: 29-37.
- Parrish, D. J., D. D. Wolf, J. H. Fike, and W. L. Daniels. 2002. Switchgrass as a

biofuels crop for the upper Southeast: variety trials and cultural improvements. Final report. Biofuels feedstocks development program. Oak Ridge National Laboratory. Oak Ridge, TN.

Parrish, D. J., D. D. Wolf, P. R. Peterson, and W. L. Daniels. 1999. Switchgrass as a biofuels crop for the upper Southeast: variety trials and cultural improvements. Annual report. Biofuels feedstocks development program. Oak Ridge National Laboratory. Oak Ridge, TN.

Sanderson, M. A., J. C. Read, and R. L. Reed. 1999. Harvest management of switchgrass for biomass feedstock and forage production. *Agron. J.* 91: 5-10.

Sanderson, M. A., R. L. Reed, S. B. McLaughlin, S. D. Wulfschleger, B. V. Conger, D. J. Parrish, D. D. Wolf, C. Taliaferro, A. A. Hopkins, W. R. Ocumpaugh, M. A. Hussey, J. C. Read, and C. R. Tischler. 1996. Switchgrass as a sustainable bioenergy crop. *Bioresource Technology* 56: 83-93.

Ziadi, N., R. R. Simard, G. Allard, and G. Parent. 2000. Yield response of forage grasses to N fertilizer as related to spring soil nitrate sorbed on anionic exchange membranes. *Can. J. Soil. Sci.* 80: 203-212.

CHAPTER 2

LITERATURE REVIEW

INTRODUCTION

Economic problems have led farmers and scientists to look for new crops to restore agricultural profitability. Concerns over global environmental problems, such as increased CO₂ in the atmosphere, have prompted a search for renewable energy sources that could replace fossil fuel resources. Energy crops—also called biofuels crops or simply biomass crops—have the potential to alleviate both problems by allowing diversification away from traditional crops and by cycling carbon in the biosphere, limiting the release of greenhouse gasses.

Producing economically competitive bioenergy depends on the availability of low-cost feedstocks from energy crops (Graham et al., 1997). Different grasses, such as elephantgrass (*Pennisetum purpureum* Schum.), kleingrass (*Panicum coloratum* L.), and buffalograss (*Buchloe dactyloides* Nutt.), have been identified as possible species for biofuel production (Madakadze et al., 1999); but, after a multi-year study of 35 perennial grasses, switchgrass was identified as the energy crop most likely to be widely successful (Vogel, 1996; Wulfschleger et al., 1996).

Biofuels production will generally be avoided on traditional croplands so as not to compete with food crops. This may provide one of the biggest challenges limiting the widespread use of switchgrass. The feasibility of bioenergy crops may vary from region to region because of differences in demand, land availability and management, and production costs (Tolbert and Wright, 1998). To optimize productivity, more information is needed on the establishment and management of biomass crops, especially N and P requirements (Bransby and McKenzie, 1997).

To meet future energy needs through converting crop biomass into bioenergy sources (electricity and liquid fuels), biofuels strategies will rely on species capable of high productivity on often-poor quality soils with minimum adverse effects to the environment (Kassel et al., 1985; Woolsey et al., 1992). The choice of switchgrass as a model herbaceous species for bioenergy production was based on its perenniality, wide geographic distribution, high nutrient use efficiency, relatively low fertilization requirements (a very important factor in reducing production costs), high biomass yield potential, and compatibility with conventional farm practices (McLaughlin et al., 1997; Vogel, 1996).

Switchgrass has promising biofuels attributes. It has excellent energy-use qualities, such as high lignin content and low chloride and ash contents; but it has yet to reach its productive potential (Lemus, 2000). Proper management practices such as harvest timing, amount of fertilizer applied, and harvesting methods that minimize dry matter loss and maximize biofuel quality need to be developed (Lemus, 2000). Although biomass crops, such as switchgrass, can be planted and harvested like traditional forage crops (Raneses et al., 1998), managing switchgrass for biomass production may be substantially different from managing switchgrass for livestock feed. The primary difference is because quality requirements differ for the two uses (Lowenberg-DeBoer and Cherney, 1989). Livestock feeding requires plant tissues high in crude protein and hemicelluloses, while bioenergy requirements are based in high cellulosic material. In addition, Radiotis et al. (1999) reported that switchgrass had lower ash content (1.7%) compared to other grass species, such as reed canarygrass (*Phalaris arundinacea* L.) (6.3%), prairie sandreed (*Calamovilfa longifolia* [Hook] Scribn.) (1.9%), and wheat (*Triticum aestivum* L.) straw (11.1%). Low ash content is an important concept, since minerals in the ash portion could contribute to corrosion of equipment during the combustion. Numerous variables affect biomass quality (high lignin and low mineral content), such as genetic variation, harvest management, storage conditions, and N fertilization (McLaughlin et al., 1996). Furthermore, the interactions between environmental

variation and management practices affect biomass quality and yield over years and/or locations (Brejda et al., 1997).

Switchgrass provides a year-round soil cover that reduces soil erosion and potential water contamination from fertilizer runoff (Redfearn et al., 1999; Woolsey et al., 1992). These benefits can be credited to the density of switchgrass stems and roots, which promote soil stability, increase infiltration, and slow runoff. Switchgrass also has low weed control requirements, since its canopy architecture allows for fast canopy closure. Switchgrass is also adapted to marginal sites, growing well in acid soils ($\text{pH} \leq 5.0$) with high exchangeable Al^{3+} concentrations (Hopkins and Taliaferro, 1997), water stressed regions, and under low soil nutrient concentrations (Sanderson et al., 1999; Sanderson et al., 1996; Vogel, 1996). Jung et al. (1988) reported dry matter yields of switchgrass in excess of 6 Mg ha^{-1} in highly acidic soils in Pennsylvania that received a moderate fertilization of 40 kg N ha^{-1} . Switchgrass' extensive root system also provides for considerable drought resistance, since it can extract water from deep within soil profiles (Kassel et al., 1985; Vogel, 1996).

Switchgrass Background/Overview

Switchgrass is a native, warm-season species found throughout much of the southern and central USA (Gettle et al., 1996; Graham et al., 1997). Across its wide native geographic range, switchgrass has evolved into locally adapted populations classified as ecotypes (Gunter et al., 1996). There are two distinctive general ecotypes, classified as lowland and upland (Gunter et al., 1996; Sladden and Bransby, 1992). The lowland ecotypes are vigorous, tall, thick-stemmed, and adapted to wetter conditions; whereas the upland ecotypes are shorter, rhizomatous, thinner-stemmed, and adapted to drier conditions (Gunter et al., 1996; Sladden and Bransby, 1992).

Switchgrass is a C_4 species that breaks dormancy (in late April in VA) under warm conditions and provides some grazing by late May (Gettle et al., 1996). However, 90% of its yield is produced from June through August, when

cool-season grasses are less productive (Hope and McElroy, 1990; Barnhart and Wedin, 1984; Roundtree et al., 1974). Switchgrass grows actively at warm temperatures and has a maximum photosynthetic rate at 35°C (Knapp, 1985; Hope and McElroy, 1990). This photosynthetic activity results in high biomass yields, particularly if cultivars have a long period of vegetative growth (Van Esbroeck et al., 1997). Sanderson et al. (1996) reported that late-flowering varieties produced higher biomass yields than early flowering varieties in IA and TX when harvested at maturity. This concept is important, because yield improvement has largely resulted from selecting late-flowering cultivars originating at lower latitudes and moving them to upper latitudes (Knapp, 1985). Also, delayed flowering thus prolongs vegetative growth and extends the period of biomass accumulation and therefore, a better nutrient use efficiency (Evans, 1993).

Cutting Management and Implications for Biomass Production

Managing perennial warm-season grasses as bioenergy crops has generally used a single harvest made at late maturity (Sanderson et al., 1996). Considering multiple harvests during the growing season will allow biomass producers to have more flexibility in their management systems and may allow a more efficient response to potential fluctuations in feedstock markets (Sanderson et al., 1999).

The timing of harvests greatly affects biomass yield and quality. Most studies have concluded that a late-season harvest of very mature and nearly senescent biomass is the most appropriate harvest management because of the accumulation of cellulosic material (Sanderson et al., 1996; Sanderson et al., 1999). However, in perennial ryegrass, Sibma and Alberda (1980) reported that higher N application rates increased yields more with reduced cutting frequencies. Nitrogen uptake was positively affected by the application rate, but only slightly by the cutting frequency. Vogel and Masters (1998) reported that delaying harvest until after a killing frost significantly reduced switchgrass yields

over all fertilizer levels in NE and IA. Cuomo et al. (1998) reported that greater harvest frequency increases tiller density.

Delaying harvest until after plant senescence allows translocation of nutrients from the aboveground biomass to the roots (Parrish et al., 1996). Parrish et al. (1999) suggested that this remobilization and translocation of dry matter can cause a yield reduction of approximately 10% between September and November. However, late harvests can improve both the biomass yield the following year and the biomass fuel quality due to a reduction in the mineral content of the harvested material. Potassium levels at late harvest were reduced up to 73% from those in earlier harvests (Parrish et al., 1996). Sanderson et al. (1999) also observed switchgrass yield decreases as the fall harvest was delayed from September to November. Some of the yield loss may have been due to leaf shattering or biomass decay (Sanderson et al., 1999; Sanderson et al., 1996).

Proper harvest management is essential to maintaining switchgrass stands and yields on a truly perennial basis. Anderson and Matches (1983) found that harvesting switchgrass three times per year reduced yield 34 to 60% during the second year in Nebraska. Stand reductions of up to 58% were reported with two or three annual harvests as compared to 39% with one annual harvest (Balasko et al., 1984). Ehrenreich (1957) concluded that decreased yields with frequent defoliation were a result of reduced photosynthetic area. Similarly, multiple harvests per season and delaying fall harvest past September reduced Alamo switchgrass yield in TX (Sanderson et al., 1996). In Louisiana, Pitman (2000) reported that Alamo switchgrass produced yields of 5.5 Mg ha⁻¹ from two harvests in 1996. While these studies suggest that a single harvest is most appropriate in most areas in the USA, two harvests per season were reported to yield more biomass than one in VA (Sanderson et al., 1996).

Griffin and Jung (1981) found that switchgrass leaf:stem ratios declined during plant maturation. Stems accounted for 63% of the total dry matter yield in November in late-season harvests. Additional leaf losses during harvest can account for up to 10% of the total biomass. The leaf biomass contains about 60%

of the total N. Although yield may be expected to decline if harvest is delayed too long, in VA biomass over-wintered in the field had no significant loss of yield from November to February during several seasons (Sanderson et al., 1996).

Nitrogen as a Management Component

Nitrogen is often considered the most important growth-limiting factor for biomass production, especially in warm-season grasses such as switchgrass (Ziadi et al., 2000). The N requirement for switchgrass, as for any other crop, is a function of the yield potential and the amount of N required per unit of yield. Stanford and Legg (1984) defined the N requirement as the minimum amount of N in the aboveground biomass associated with maximum production. Nitrogen rate experiments are generally considered the most effective way of determining the N requirement for a crop, but N-application rates should not confuse with N-use requirements. Only some portion of the applied N will actually be taken up by the crop and be present in the yield. Some of the applied N will be lost from the system, and some of the N in the yield may come from sources other than the applied fertilizer.

Reported annual rates of N use for switchgrass (70 to 100 kg ha⁻¹) are typically about half of those seen in corn (*Zea mays* L.) production (138 to 154 kg ha⁻¹) (McLaughlin and Walsh, 1998). Vogel and Masters (1998) indicated that N fertilizer rates of 120 to 180 kg ha⁻¹ are needed to obtain optimum switchgrass yields depending upon year and location (NE, IA, and IN). They also indicated that, at N rates of 120 kg ha⁻¹, most of the applied N was removed with the biomass. At higher fertilizer rates, N began to accumulate in the rooting zone, as leaf senescence and decomposition allowed N recycling into the soil (Sladden and Bransby, 1992).

Efficient use of N is important to reach high switchgrass biomass yields without jeopardizing water quality or economic returns (Anderson and Matches, 1983). Studies in the Midwest USA and elsewhere have shown that switchgrass yields typically increase with N applications (Lemus, 2000; Bredja et al., 1997).

Although some studies have shown that yields improve linearly with N applications as high as 300 kg ha⁻¹ or more (Lutwick and Smith, 1979; Sanderson et al., 1996; Smith 1980), other studies have shown yield plateaus at N levels as low as 50 kg ha⁻¹ (Parrish and Wolf, 1992). The disparity in findings may result from harvest management (two vs. one cut) and especially from differences in N-supplying capacity of the soil. In the northern plains, McLaughlin et al. (1997) reported that fertilizer applications produced yield increases that were economically justifiable at applications of 60 to 120 kg ha⁻¹. In the deep-South, yield increases were observed in the range of 100 to 200 kg N ha⁻¹, and Alamo switchgrass responded to N fertilizer inputs up to 200 kg ha⁻¹ (Sanderson et al., 1999).

Although several studies have suggested that switchgrass has a relatively high N requirement for high yield (George et al., 1995; Lowenberg-DeBoer and Cherney, 1989), biomass yields exceeding 8 Mg ha⁻¹ of Alamo switchgrass have been reported in TX on unfertilized plots, where the initial N level was very low (<10 kg available N ha⁻¹ according to soil test) (Sanderson et al., 1996). The switchgrass yield improvements observed with N application may occur by increasing tiller density and stem development (Bredja et al., 1994). George et al. (1989) reported that N fertilization also increases leaf and stem weights and that the greater effect on stem weight resulted in lower leaf:stem mass ratios.

Any N in amounts exceeding the immediate requirements of the crop will remain unused in the soil, increasing potential for N leaching and groundwater contamination (Kanampiu et al., 1997). Nitrogen application to any crop is subject to leaching, denitrification, runoff, volatilization, and other mechanisms of loss. Therefore, N fertilization practices and other management decisions that influence N availability should take into consideration crop demand and uptake patterns (Sanchez and Doerge, 1999).

NUE: The Concept and Various Estimators

Nitrogen-use efficiency (NUE) is an important topic when discussing fertilizer applications and switchgrass biomass production. The term NUE has

been commonly used to describe the capacity of a plant to acquire and utilize N for making yield (Gourley et al., 1994). Definitions for NUE vary greatly (Clark, 1990). They generally can be divided into those emphasizing productivity (utilization efficiency) and those emphasizing the internal nutrient requirements of the plant (uptake efficiency) (Fiez et al., 1995). Uptake efficiency emphasizes the capacity of a plant to take up supplied N, while utilization efficiency shows the capability of the plants to utilize N by increasing yield. However, NUE definitions could be misleading in the search for increased productivity and identification of mechanisms that enhanced nutrient acquisition and utilization. With regard to yield parameters, nutrient efficiency has been defined as the ability to produce a high plant yield in a soil, or other substrate, that would otherwise limit production (Table 2.1) (Buso and Bliss, 1988).

Table 2.1. Some Nitrogen Use Efficiency (NUE) variants. Adapted from Pandey et al. (2001).

Component	Ratio ¹	Description	Source
Biomass NUE (kg kg ⁻¹)	$(B_X - B_C)/NA$	Increase in biomass yield due to applied N	Novoa and Loomis, 1981
Physiological NUE (kg kg ⁻¹)	$(B_X - B_C)/(PN_X - PN_C)$	Increase in biomass yield per increase in plant N removal	Craswell and Godwin, 1984
Recovery Efficiency or ANR (%)	$[(PN_X - PN_C)/NA] * 100$	Increase in plant N removal due to applied N	Craswell and Godwin, 1984
Partial factor productivity (kg kg ⁻¹)	$(B_O + \Delta B)/NA$	Total Biomass per unit applied N	Cassman et al., 1998

¹B_X=biomass in fertilizer treatment; B_C=biomass in control treatment; PN_X=N removal in fertilizer treatment; PN_C=N removal in control treatment; B_O=biomass yield without N input; ΔB=increase in yield that resulted from N application (B_X-B_C); NA= N applied.

Definitions of nutrient use efficiency, also referred to as “agronomic efficiency”, include harvestable product per unit of nutrient applied (Caradus,

1990). On the other hand, nutrient efficiency emphasizing utilization is sometimes defined as the total plant biomass produced per unit of nutrient absorbed, which is equivalent to the reciprocal of nutrient concentration in the entire plant. This is often called the nutrient-use efficiency ratio and has been used extensively to describe the internal nutrient requirement of many agronomic species (Godwin and Blair, 1991). Siddiqi and Glass (1981) argued that the reciprocal of nutrient concentration does not consider the yield of the crop. They suggested that a more appropriate measure of nutrient efficiency is the product of yield times the reciprocal of nutrient concentration, which they termed “utilization efficiency”. Other researchers have used “uptake efficiency”, defined as nutrient uptake per unit root length, surface area, or weight, as measures of nutrient-use efficiency (Buso and Bliss, 1988).

Calculated NUE can be affected by N-cycle processes in the soil, the form of N applied, and the growth stage of the plant (Wuest and Cassman, 1992). Switchgrass NUE has been reported as kg of biomass production per kg of N applied (Jacobsen et al., 1996; Gillard et al., 1995). Apparent N recovery (ANR) is an estimate of the amount of N that the fertilized crop uses relative to the amount applied. It is the amount of N in a fertilized crop minus the amount of N in an unfertilized crop, expressed as a percentage of the fertilizer applied (Zemenchik and Albrecht, 2002).

The efficiency of N absorption may be related to a plant’s growth characteristics, especially with switchgrass, which is a perennial, warm-season (C₄) grass (Jorgensen and Schelde, 2001). Switchgrass NUE could also be affected by cultivar, soil type, latitude, temperature, N fertilizer rate, precipitation, and soil moisture (Zemenchik and Albrecht, 2002). Nitrogen fertilizer recovery in switchgrass has been reported to be less than 20% of the amounts applied when Alamo switchgrass was harvested at full maturity after October 1 (Jones et al., 1993a).

Anderson et al. (1997) reported that Cave-in-Rock switchgrass harvested once per year, had a NUE of 19 to 37 kg kg⁻¹ compared with 39 to 50 kg kg⁻¹ for reed canarygrass, 39 to 54 kg kg⁻¹ for forage sorghum (*Sorghum vulgare* L.), 9 kg

kg⁻¹ for big bluestem (*Andropogon gerardii* Vitman), and 33 to 64 kg kg⁻¹ for corn. Gillard et al. (1995) reported that, in warm-season species such as corn grown for silage, NUE ranged from 43 to 47 kg kg⁻¹ at a N fertilizer rate of 112 kg N ha⁻¹, but decreased to a low 10 kg kg⁻¹ at 448 kg N ha⁻¹. Lemus (2000) reported NUE for switchgrass of 35 kg kg⁻¹, with higher NUE at 124 kg N ha⁻¹ than at 56 or 224 kg N ha⁻¹ over a 2-yr period. He concluded that the low NUE at the high N fertilization could be due to available soil N, mineralization rates, and changes in water availability. Thus, high rates allowed nitrate-N to accumulate in the soil, increasing the potential for leaching, which could decrease NUE (as well as water quality).

N Dynamics in the Field: Losses and Transformations

Soil N has a variety of pathways for input and efflux and can have important negative environmental impacts when lost from the production system (Fig. 2.1). Inputs (such as biological fixation, fertilization, or precipitation) and losses (such as denitrification, volatilization, leaching, and run-off) constitute processes that for the most part are amenable to direct measurement (Freney et al., 1990). The relative importance of these processes can vary widely, depending on the agricultural system and the environment. The major agronomic concern with NH₃ loss from urea-containing fertilizers is the effect of these losses on crop yield and NUE (Oberle and Bundy, 1987).

Precise fertilizer N recommendations for switchgrass require an accurate assessment of the soil N availability (Baloch, 1998). One of the primary goals of current biomass production systems is to improve the efficiency of N fertilization that could increase yields while reducing the risk of ground and surface contamination by NO₃. Despite complications such as mobility, leaching, nitrification, and volatilization, soil tests for residual NO₃-N have been found to be useful in determining N fertilizer needs of crops (Gelderman et al., 1988).

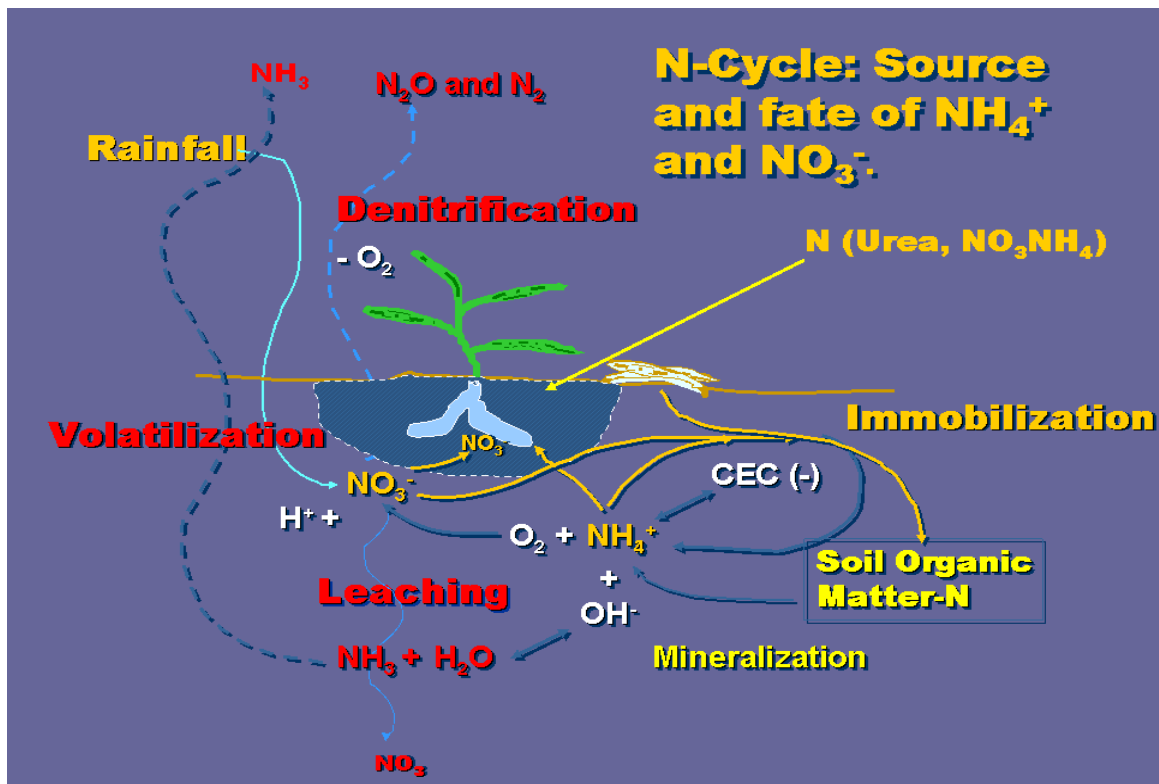


Fig 2.1. Nitrogen inputs and effluxes in a plant-soil system.

Several physical and biological processes can affect NUE in grassland systems: volatilization, leaching, mineralization, nitrification, denitrification, etc. Abbasi and Adams (2000) reported $> 50\%$ of the N applied as NH_4^+ disappeared over a period of 42 d in a grassland system, with some of this N evolved as N_2O . Marshall et al. (1999) found in pasture ecosystems that total losses of NH_3 were less than 6 kg ha^{-1} 150 d after N application, representing less than 5% of the total N applied. Denitrification is a form of anaerobic respiration that, in effect, reverses microbial N_2 fixation in the global N cycle.

Denitrification is characterized by a stepwise reduction of NO_3^- to N_2 . This process occurs under saturated conditions and will not be considered in this study, since most of the soils on which switchgrass grows are well drained. Another reason that denitrification will not be considered is because it has the largest temporal and spatial variability of all the N-cycle processes (Tiedje et al., 1989). Because of this variability and the problems of measuring N_2 production

against normal atmospheric background, quantifying denitrification is difficult and no standard or absolute methods are available (Moiser and Klemetsson, 1994).

Nitrogen Inputs through Mineralization

Fertilizer applications, precipitation and dry deposition, and biological fixation are the main N input sources for soils. On a global basis, within the natural and agricultural terrestrial system, soils are the major N reservoirs, containing 2.4×10^{11} Mg of N (Stevenson, 1982). But about 95% of the soil N is embedded in organic molecules, making it unavailable to plants (Tisdale et al., 1985). The mineralization of organic N into available inorganic N is carried out by soil microorganisms (Baloch, 1998). Nitrogen mineralization is affected by both abiotic and biotic factors (soil moisture, temperature, and texture) and by the supply of above- and belowground organic matter (OM) (Russelle, 1992).

Tyson et al. (1990) found an increase of only 0.001% per annum in the soil organic N to 15 cm depth (equivalent to $25 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) in the last 15 yr of a 30-yr study characterizing microbial activity on OM decomposition. The capacity of grassland soils to accumulate organic N can be large, equivalent to $160 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (Clement and Williams, 1967). Even though this rate of change represents an annual increase of about 0.5% of the total N present, much of which may be readily decomposable, such changes are still difficult to detect on short term, without a large scale soil sampling program and a high degree of analytical resolution.

Soil scientists have long been aware that a small percentage of organic N is mineralized in the course of the growing season and can significantly contribute to N requirements of the crop. Nitrogen mineralization is a complex process that depends on soil properties, crop residue quantity and quality, as well as climatic factors (temperature, soil water content, etc) (Cabrera et al, 1994). Foth and Ellis (1988) reported that, in a well-drained mineral soil, about 2% of the organic N is mineralized annually. Power and Doran (1984) reported that the mineralization process converts from 1 to 3% of total organic N in a soil

to inorganic N annually. Marumoto et al. (1982) argued that microorganisms may provide up to 40% of crop N need through mineralization.

Soils vary widely in their physical, chemical, and biological properties and in their inherent ability to support plant growth (Antil et al., 2001). Soil fertility can be considered as the relationship between the nutrient requirements of a crop and the ability of the soil to satisfy these requirements. Since the productivity of soil is often driven by the supply of N, an estimation of the release of N from soil OM may be regarded as a prime factor of soil fertility (Antil et al., 2001). At any time, only a small proportion (perhaps 2% of the total soil N) is present in available forms, but that can be a very significant amount (Bremner, 1965). Depending on soil conditions, the annual release of soil organic N can vary widely from <2% to >10% (Bartholomew and Kirkham, 1960). However, net mineralization (the difference between gross mineralization and gross immobilization) will indicate the capacity of the soil to satisfy the immediate requirements of the plant (Antil et al., 2001).

Nitrogen mineralization is a fundamental process in temperate areas, the understanding of which is critical for developing site management options. Although the factors controlling biological transformations of N in soil are many and complex, N mineralization is largely dependent on the quantity and quality (composition) of OM, soil moisture, and temperature (Goncalves and Carlyle, 1994). Although there are several thousands kilograms of N per hectare in most agricultural soils of temperate climates, only 1 to 2% of this becomes available to crops each year (Campbell et al., 1994).

Inorganic N can be easily extracted and measured, but establishing how much of that N came from the readily mineralized soil N pool is much more difficult (Cabrera et al., 2001). A major obstacle in achieving optimum N fertilization is the difficulty of predicting soil organic N mineralization under field conditions (Saint-Fort et al., 1990). Biological methods measure mineralizable N by incubating a sample anaerobically and measuring inorganic N released over a short time (Bitzer and Sims, 1988). Because soil N made available via mineralization may be inadequate to achieve optimum biomass yields, N

fertilization, based on soil tests and yield goals, allows producers to meet crop needs. A major problem in achieving optimum N fertilization rates is predicting soil N-supplying capacity.

Although N mineralization can supply significant quantities of N, biological immobilization also occurs simultaneously with mineralization. A significant proportion of mineralizable N is immediately assimilated into microbial biomass (Mary and Recous, 1994). In nonfertilized plots, the net mineralization rate is usually high, because plant roots compete with microbial populations for mineral N and effectively remove N from the soil and reduce the risk of immobilization (Wang and Bakken, 1989). During mineralization/immobilization processes, microbial biomass serves as a source and a sink of mineralizable N (Smith, 1994).

Fertilizer recommendations are usually based on soil mineral N ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$) measured before the growing season, or a combination of soil mineral N, mineralizable soil N, and the expected yield of the crop (Prins et al., 1988). Soil mineral-N testing before spring fertilization has proven a useful tool for adjusting N-fertilizer requirements (Cox, 1985).

Bonde and Rosswall (1987) reported a decrease in mineralization between April and August, followed by an increase in the fall. Groot and Houba (1995) also reported that soil mineralization rates measured in June were generally lower than in those samples taken in March, while rates measured in October samples were generally higher. They assumed that higher rates in March may have been a result of decomposing residues from the proceeding crop, which no longer contribute to mineralization in June; in October, residues from the current crop, presumably roots, were decomposing.

Under perennial grasslands, N contained in OM becomes available at varying rates via mineralization throughout the growing season (Collins and Allinson, 2002). Compounds rich in N (C/N of less than 15:1) favor mineralization, while compounds with low N contents (C/N of greater than 25:1) favor immobilization (Gil and Fick, 200; Schepers and Meisinger, 1994). Net mineralization is strongly dependent on the C/N ratio of OM (Whitmore and

Groot, 1994; Neve et al., 1994), where the amount of N returned to the soil from crop residues depends on the quality and quantity of the substrate (Baloch, 1998). Ajwa et al. (1998) reported that the cumulative N mineralized in a tallgrass prairie soil profile ranged from 218 mg N kg⁻¹ soil at 0.2 m to 8.2 mg N kg⁻¹ at 5.6 m. Decomposing soil OM can supply 30 to 100% of N nutritional needs for non-legume crops (Rasmussen et al., 1998) with the remainder supplied by organic residues, inorganic fertilizer, or manure. Warren and Whitehead (1988) suggested that the macro-organic matter (MOM) fraction in grassland soils may contribute substantially to the available N. This conclusion was derived from the observation that plant N uptake was significantly increased in soils where MOM was returned, compared with uptake where MOM had been removed.

The amount and rate of soil N mineralization can undoubtedly influence the productivity of switchgrass. Consistent and reasonably accurate estimates of net N mineralization rates in the field for switchgrass are needed to evaluate nutrient supply (Hook and Burke, 1995). Best estimates of N fertilizer requirements depend highly on an accurate estimation of the N that will be released during the growing season. Both the quantity of N present and its availability will influence decisions on N fertilizer recommendations.

Managed switchgrass fields that have been established for several years and that might have received fertilizer will likely have a high OM component capable of releasing considerable amounts of N upon mineralization. Whitmore et al. (1992) have estimated quantities of up to 4000 kg N ha⁻¹ can become available from long-term grasslands over several years after being ploughed.

In spite of the fact that N mineralization can occur in deeper soil horizons (Casman and Munns, 1980; Hadas et. al., 1986), most research has been limited to the upper layers. Soil layers vary in temperature, moisture, bulk density, aeration, and OM content, all of which may affect N mineralization at different depths. Federer (1983) reported that net mineralization of N decreased with depth. Cabrera and Kissell (1988) estimated that the top 5 cm of soil contributed 45 to 56% of the total N mineralized in 120-cm profiles of three Kansas soils and

that approximately 90% was mineralized in the top 45 cm. Patra et al. (1999) reported that mineralization in the bulk soil was greatest in the 0 to 10 cm layer and gradually decreased with depth. Depending on the soil and environmental conditions, the quantity of total soil N to maximum rooting depth (1 m) has been estimated to range from 1 to 10 Mg ha⁻¹, much of which is in the top 15 cm of the soil (Patra et al., 1999).

Being a biological process, N mineralization is highly affected by complex interactions among biological, chemical, and physical components of the soil and environmental factors (Loiseau et al., 1994). Soil mineralization is profoundly influenced by temperature within the range normally encountered under field conditions. Temperature greatly influences the microbial population, substrate composition, nutrient cycling and transport processes in the soil (Baloch, 1998). Stanford and Smith (1972) found that the N mineralization rate doubled with each 10 °C increase in temperature up to 35 °C.

Soil water availability and distribution are also prominent factors regulating N mineralization. The water status of soil affects biological activities and the products of the microbial activity by controlling diffusion and mass flow. Linn and Doran (1984) found that optimum N mineralization occurred when 60% of pore space was water filled. Stanford and Epstein (1974) reported that optimum net mineralization rates have been achieved between -0.033 and -0.01 MPa where water occupied 80 to 90 % of the pore space. Drying the soil below the optimum moisture content reduces mineralization and ultimately affects the amount of available N compared to N mineralized with optimum conditions (Seneviratne and Wild, 1984).

In Virginia, the amount of organic N potentially available has generally not been taken into account when adjusting N fertilizer needs for switchgrass production. The cool, humid conditions during the winter favor the decomposition of residual biomass; and, as temperatures increase during the early spring, mineralization of organic N can potentially supply a significant portion of the total N requirement for biomass production. Therefore, assessment of mineralizable

N at the beginning of the growing season could be helpful in improving fertilizer N recommendations.

N Losses through Volatilization

Soil N has a variety of pathways for input and outflow and can have important negative impacts on yields when lost from the production system (Gil and Fick, 2001). Investigations into N utilization by plants have indicated that a substantial portion of the N applied is apparently lost and that crop recovery is often less than 50% (Torello et al., 1983). One of the obstacles that limit N balance studies in the field is quantification of losses of nitrogenous gases.

Urea [$\text{CO}(\text{NH}_2)_2$] is an excellent N fertilizer source, but considerable inefficiencies have been observed due to volatilization. Urea is a popular N source of switchgrass producers because of its high N content, easy handling, and low cost. When surface broadcasting urea, ammonia (NH_3) volatilization becomes a major pathway for N loss, and losses reaching up to 50% (Roelcke et al., 1996) or even 80% (Ramos, 1996) of the applied N have been reported. Roelcke et al. (1996) reported that NH_3 volatilization is the major pathway for mineral N loss in calcareous soils, with maximum losses reaching 50% of the fertilizer-N applied, while up to 29% of the N in surface-applied urea has been lost to volatilization on acidic soils (Watson, 1990). An effective way to reduce NH_3 emissions after urea application is by injecting it into the soil (Ramos, 1996).

Nearly all direct measurements of NH_3 from bare soil have been done under laboratory or greenhouse conditions using chambers. Ammonia volatilization rates are controlled by many different processes, with significant interactions occurring between variables (Kirk and Nye, 1991). The potential for NH_3 volatilization following surface application of urea is influenced by several climatic and soil factors. Some of the properties, processes, and factors that influence NH_3 volatilization are soil type (cation exchange capacity, hydrogen-ion buffering capacity, pH, CaCO_3 content, urease activity, urea leaching, immobilization, nitrification, soil temperature, surface cover, and soil texture),

environmental conditions (temperature, atmospheric NH_3 concentration, soil water flux content, rainfall pattern, wind speed, and relative humidity), and fertilizer management (fertilizer type, timing, placement, and rate of application) (Lightner et al., 1990). Predicting appropriate agricultural practices is very difficult, because of the complex interactions of the processes involved in this phase of N movement into the soil (Ramos, 1996).

Nitrogen loss through NH_3 volatilization from surface-applied urea-containing fertilizers is a potential problem affecting NUE (Terman, 1979). Indirect evidence of lower crop yields and fertilizer N recovery due to NH_3 volatilization from surface-applied urea has been obtained in several field studies with corn (Bandel et al., 1984) and pasture grasses (Murdock and Frye, 1985). Direct losses of N sources applied to pasture grasses (Sherlock and Goh, 1984; Torello et al., 1983) have been reported, but no relationship between NH_3 losses in the field and yield was established. The amount of NH_3 loss detected in the experiments ranged from near 0 to 40% of the fertilizer N applied, probably because of the wide variety of experimental conditions in these studies. Titko et al. (1987) reported that NH_3 volatilization from urea applied to turfgrass ceased 5 d after treatment application and most of the NH_3 was usually lost within the first 2 d after treatment application, although this was somewhat treatment dependent. They also reported that NH_3 volatilization from both granular and dissolved urea was higher at 22.2 than at 10°C.

While a number of studies have cited inefficient use of urea-N when surface applied, few have actually measured N loss through NH_3 volatilization. Keller and Mengel (1986), studying no-till corn systems, observed losses as high as 31% of the N applied as granular urea. Hargrove and Kissel (1979) reported volatilization losses of only 3% of the urea applied to 'Coastal' bermudagrass.

Ammonia volatilization from soil following the application of urea has been studied both in the laboratory and in the field. Numerous studies have discussed the significance of these loss mechanisms in soils and the factors affecting the magnitude of NH_3 loss (Bouwmeester et al., 1985). The magnitude of NH_3 losses under laboratory conditions commonly range from 20 to 60% of the

applied N but can be as great as 90% when applied to the surface of sandy soils with low buffering capacity (Fenn and Hossner, 1985). However, losses under field conditions are generally less, ranging from 0 to 50% of applied N (Roelcke et al., 1996). The reason for greater losses in most reported laboratory studies is that the conditions of moisture, temperature, air exchange are often set to create an optimum environment for high rates of NH_3 loss. However, in a dynamic field environment, these conditions seldom exist for sustained periods (Hargrove, 1988). McInnes et al. (1986) reported that diurnal patterns of NH_3 loss coincided with fluctuations in soil temperature and water content. They reported that volatilization was low if urea was applied to dry soil. Following soil wetting, however, urea hydrolysis and the rate of NH_3 volatilization increased. Harper et al. (1983) found NH_3 volatilization from urea applications on pasture occurred at higher rates when the underlying soil was moist.

Nitrogen Dynamics in the Plant: Uptake, Content, Distribution, and Translocation

Nitrogen uptake is often approximated by measuring total N accumulation in aboveground biomass at intervals during the growing season (Jung et al., 1990). Despite the recognized importance of N in switchgrass production, there have been relatively few N studies in switchgrass and no emphasis on transfer and storage of N within the plant. Understanding the N economy of switchgrass will require information about the seasonal dynamics of N in the species (Risser and Parton, 1982), and the dynamics should be evaluated as switchgrass responds to harvest management and fertilization.

The differences among warm-season grasses in their ability to produce biomass may depend on differences in root uptake of nutrients. Such differences may be due to rooting depth and ability to extract soil N (Pandey et al., 2001). Root biomass of Cave-in-Rock, Alamo, and Kanlow in AL were 1.8, 1.5, and 1.4 Mg ha^{-1} respectively under various soil types (Ma et al., 2000b). Knowing root biomass is important in understanding the overall N economy of the plant,

because belowground biomass could serve as a C and N sink and to support high aboveground biomass yields (Sladden et al., 1991). Compared to other grass species such as orchardgrass, switchgrass has a high capacity to use N that is deeper in the soil profile. Nitrate removed by switchgrass was estimated to be as much as 20 kg ha⁻¹ from soil profiles deeper than 120 cm, about 22% of the total N requirement for switchgrass growth (Huang et al., 1996).

Plant tissue analysis at an early growth stage may be a valuable method of recommending optimum fertilizer N rates and has been used as an indicator of N fertilizer requirements for some crops. Total N content (the amount of N present in the above-ground portion of the plant) shows the plant's ability to accumulate N. Nitrogen uptake by plants depends on several factors, including NUE of the plant (yield per unit of N supply) and the state and morphology of roots (Karrou and Maranville, 1994).

Perennial C₄ grasses of tallgrass prairies have been reported to translocate as much as 30% of shoot N to roots and rhizomes in response to drought, and this stress-induced translocation can account for up to 70% of the 30 to 40% decline in shoot N concentration (Heckathorn and DeLucia, 1996). This might represent a compromise between C acquisition and N conservation, since photosynthetic activity during dry periods is affected considerably.

An understanding of the N uptake and movement patterns in switchgrass is needed to facilitate N management. Maximum efficiency should be expected when soil N availability is synchronized with the period of rapid N uptake by switchgrass. Scharf (1993) found that tissue N content in wheat was a useful tool in adjusting optimum N rate and suggested that total N should be calculated from the whole-plant samples.

Phosphorus Requirements of Switchgrass

At present, there are limited data on the effect of phosphorus (P) fertilization on switchgrass and/or P interactions with other nutrients such as N. Griffin and Jung (1983) reported that P levels in switchgrass and big bluestem

decreased with maturity. They found that stem tissue P content for the grasses declined from an average of 0.24% to 0.14% with increasing maturity. Smith and Greenfield (1979) reported high P concentrations in switchgrass compared to timothy (*Phleum pratense* L.), with the highest P accumulation in the inflorescence. Radiotis et al. (1999) reported switchgrass is 0.12% P at the reproductive stage, and it declined to 0.04% when grass was left to overwinter. Radiotis et al. (1999) further suggested that P is either transported to the roots or leached out. In either case, the return of nutrients to soil during the winter will assist farmers in maintaining soil quality, and reducing fertilizer requirements.

Warm-season grasses appear to be obligate mycotrophs and cannot grow to maturity in native prairie soils without the additional nutrients supplied by symbiosis (Hetrick and Wilson, 1993). Research with some forage species and grain crops indicates that rhizosphere microflora, particularly arbuscular mycorrhizae can enhance P uptake. Bredja et al. (1998) indicated that mycorrhizae in switchgrass increased P uptake by up to 37-fold when compared to controls.

Summary/Rationale for Studies

The development of switchgrass as a bioenergy crop in the upper Southeast could increase agricultural sustainability. Incorporating switchgrass into an energy system combined with proper N fertilization and cutting management practices could lead to major economic and environmental improvements to agroecosystems in the region.

Currently, fertilizer recommendations for switchgrass biomass in VA are based solely on yield potentials and fertilization studies done in other regions. Local studies are needed to improve N fertilizer recommendations. Such studies should take into account site-specific management approaches, soil-available N, mineralization potential, and nutrient removal.

The feasibility of switchgrass as a biomass crop may be enhanced if long-term and sustainable yields are increased with proper cultivar selection and optimal cutting management. The main objectives of this research were to

generate information on the performance of different switchgrass cultivars, to compare lowland and upland switchgrass ecotypes under different environments and cutting managements, and to consider more carefully N management. The data collected will allow modeling biofuel cropping systems for this region.

Improving the efficiency of N fertilization could improve the economics of switchgrass production and decrease the risk of surface and groundwater contamination. Correctly estimating the quantity of N needed by switchgrass requires an accurate assessment of the amount of organic N mineralized during the growing season as well as N dynamics overall.

Nitrogen recommendations made with adequate knowledge of plant removal and utilization can lead to optimizing yields. It is necessary to consider the nutrient supplying capability of the soil and to develop models that optimize fertilizer rates from switchgrass production in VA and the upper Southeast.

LITERATURE CITED

- Abbasi, M. K., and W. A. Adams. 2000. Estimation of simultaneous nitrification and denitrification in grassland soil associated with urea-N using ^{15}N and nitrification inhibitors. *Bio. Fertil. Soils*. 31 (1): 38-44.
- Ajwa, H. A., C. W. Rice, and D. Sotomayor. 1998. Carbon and nitrogen mineralization in tallgrass prairie and agricultural soil profiles. *Soil Sci. Soc. Am. J.* 62: 942-951.
- Anderson, I. C., D. R. Buxton, D. L. Karlen, and C. Cambardella. 1997. Cropping system effects on nitrogen removal, soil nitrogen, aggregate stability, and subsequent corn grain yield. *Agron. J.* 89: 881-886.
- Anderson, B., and A. G. Matches. 1983. Forage yield, quality and persistence of switchgrass and caucasian bluestem. *Agron. J.* 75: 119-124.
- Antil, R. S., R. D. Lovell, D. J. Hatch, and S. C. Jarvis. 2001. Mineralization of nitrogen in permanent pastures amended with fertilizer or dung. *Biol. Fertil. Soils* 33: 132-138.
- Balasko, J. A., D. M. Burner, and W. V. Thayne. 1984. Yield and quality of switchgrass grown without soil amendments. *Agron. J.* 76: 204-208.
- Baloch, D. M. 1998. Evaluation and use of soil mineralizable nitrogen test to

- determine the fertilizer nitrogen needs of winter wheat grown in western Oregon. Ph. D. Thesis. Oregon State University, Corvallis, OR.
- Bandel, V. A., F. R. Muldorf, and H. J. Bauer. 1984. Influence of fertilizer source and placement on no-tillage corn. *J. Fert. Issues* 1: 38-43.
- Banhart, S. K., and W. F. Wedin. 1984. Management and utilization of switchgrass (*Panicum virgatum*) by yearling steers in western Iowa. *Proceedings of the Forage and Grassland Conference*. Lexington, KY: American Forage and Grassland Council: 181-185.
- Bartholomew, W. V., and D. Kirkham. 1960. Mathematical descriptions and interpretations of culture induced soil nitrogen changes. 7th Int. Congr. oil Sci. Madison, WI Comm. III 2: 471-477.
- Bitzer, C. C., and J. Sims. 1988. Estimating the availability of nitrogen in poultry manure through laboratory and field studies. *J. Environ. Qual.* 17: 47-54.
- Black, A. S., R. R. Shelock, and N. P. Smith. 1987. Effect of urea granule size on ammonia volatilization from surface-applied urea. *Fert. Res.* 11: 87-96.
- Bonde, T. A., and T. Rosswall. 1987. Seasonal variation of potentially mineralizable nitrogen in four cropping systems. *Soil Sci. Soc. Am. J.* 51: 1508-1514.
- Bouwmeester, R. J. B., P. L. G. Vlek, and J. M. Stumpe. 1985. Effect of environmental factors on ammonia volatilization from urea-fertilized soil. *Soil Sci. Am. J.* 49: 376-381.
- Bransby, D. J., and R. L. McKenzie. 1997. Carbon sequestration by switchgrass managed as energy crop. *Exp. St. Auburn Univ., Auburn, Alabama*.
- Bredja, J. J., L. E. Moser, and K. P. Vogel. 1998. Evaluation of switchgrass rhizosphere microflora for enhancing seedling yield and nutrient uptake. *Agron. J.* 90: 753-758.
- Bredja, J. J., J. R. Brown, T. E. Lorenz, J. Henry, and S. R. Lowry. 1997. Variation in eastern gamagrass forage yield with environments, harvest, and nitrogen rates. *Agron. J.* 89: 702-706.
- Bredja, J. J., J. R. Brown, G. W. Wyman, and W. K. Schumacher. 1994. Management of switchgrass for forage and seed production. *J. Range Manage.* 47: 22-27.
- Bremner, J. M. 1965. Organic nitrogen in soils. p. 93-149. *In*: W. V

- Bartholomew and F. E. Clark (eds.) Soil nitrogen. Agronomy 10. Am. Soc. Agron., Madison, WI.
- Buso, G. S., and F. A. Bliss. 1988. Variability among lettuce cultivars grown at two levels of available phosphorus. *Plant and soil* 111: 67-73.
- Cabrera, M. L., D.E. Kissel, R. C. Davis, N. P. Qafoku, and W. I. Segars. 2001. Design and ammonia recovery evaluation of a wind speed sensitive chamber system. *Soil. Sci. Soc. Am. J.* 65: 1302-1306.
- Cabrera, M. L., D. E. Kissel, and M. F. Vigil. 1994. Potential nitrogen mineralization: laboratory and field evaluation. p. 15-30. *In* J. L. Havlin and J. S. Jacobsen (eds.) *Soil testing: Prospects for improving nutrient recommendations*. SSSA Spec. Publ. 40, Madison, WI.
- Cabrera, M. L. and D. E. Kissel. 1988. Potentially mineralizable nitrogen in disturbed and undisturbed soil samples. *Soil Sci. Soc. Am. J.* 52: 1027-1031.
- Campbell, C. A., Y. W. Jame, O. O. Akinremi, and H. J. Beckie. 1994. Evaluating potential nitrogen mineralization for predicting fertilizer requirements on long-term field experiments. p. 81-100. *In* J. L. Havlin and J. S. Jacobsen (eds.) *Soil testing: Prospects for improving nutrient recommendations*. SSSA Spec. Publ. 40, Madison, WI.
- Caradus, J. R. 1990. Mechanisms improving nutrient use by crop and herbage legumes. p. 253-311. *In* V. C. Baligar and R. R. Duncan (eds.) *Crops as enhancers of nutrient use*. Academic Press, San Diego, CA.
- Cassman, K. G., S. Peng, D. C. Olk, J. K. Ladha, W. Reichardt, A. Doberman, U. Sigh. 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crops Res.* 56: 7-39.
- Cassman, K. G., and D. N. Munns. 1980. Nitrogen mineralization as affected by moisture, temperature and depth. *Soil Sci. Soc. Am. J.* 44: 1233-1237.
- Clark, R. B. 1990. Physiology of cereals for mineral nutrient uptake, use, and efficiency. p. 131-209. *In* V. C. Baligar and R. R. Duncan (eds.) *Crops as enhancers of nutrient use*. Academic Press, San Diego, CA.
- Clement, C. R., and T. E. Williams. 1967. Leys and soil organic matter II: the accumulation of nitrogen in soils under different leys. *J. Agric. Sci.* 69: 133-138.
- Collins, A., and D. W. Allinson. 2002. Nitrogen mineralization in soil from

- perennial grassland measured through long-term laboratory incubations. *J. Agric. Sci.* 138: 301-310.
- Cox, F. 1985. Survey of state soil testing laboratories in the United States. *Soil Sci. Soc. Am.* Madison, WI.
- Crasswell, E. T. and D. C. Godwin. 1984. The efficiency of nitrogen fertilizers applied to cereals in different climates. Vol. 1 p. 1-55. In P. B. Thinker and A. Lauchli (eds.) *Advances in plant nutrition*. Praeger, New York.
- Cuomo, G. J., B. E. Anderson, and L. J. Young. 1998. Harvest frequency and burning effects on vigor of native grasses. *J. Range Manage.* 51 (1): 32-36.
- Ehrenreich, J. H., and J. M. Aikmann. 1957. Effect of burning on seed-stalk production of native prairie grasses. *Proc. Iowa Acad. Sci.* 64: 205-212.
- Evans, L. T. 1993. *Crop evolution, adaptation and yield*. Cambridge, UK: Cambridge University Press.
- Federer, C. A. 1983. Nitrogen mineralization and nitrification: Depth variation in four New England forest soils. *Soil Sci. Soc. Am. J.* 47:1008-1014.
- Fenn, L. B., and L. R. Hossner. 1985. Ammonia volatilization from ammonium or ammonium-forming nitrogen fertilizers. *In*: B. A. Stewart (ed.). *Adv. Soil. Sci.* 1: 123-169.
- Fiez, T. E., W. L. Pan, and B. C. Miller. 1995. Nitrogen use efficiency of winter wheat among landscape positions. *Soil Sci. Am. J.* 59: 1666-1671.
- Foth, D. H., and B. G. Ellis. 1988. The soil nitrogen cycle. *In*: *Soil fertility*. John Wiley & Sons Inc., pp. 69-73.
- Freney, J. R., A. C. F. Trevitt, S. K. De Datta, W. N. Obcemea, and J. G. Real. 1990. The interdependence of ammonia volatilization and denitrification as nitrogen loss processes in flooded rice fields in the Philippines. *Biol. Fert. Soils* 9: 31-36.
- Gelderman, R. H., W. C. Dahnke, and L. Swenson. 1988. Correlation of several N indices for wheat. *Commun. Soil. Sci. Plant Anal.* 19 (6): 755-772.
- George, J. R., K. M. Blanchet, R. M. Gettle, D. R. Buxton, and K. J. Moore. 1995. Yield and botanical composition of legume-interseeded vs. nitrogen-fertilized switchgrass. *Agron. J.* 87: 1147-1153.
- George, J. R., D. J. Oberman, and D. D. Wolf. 1989. Seasonal trends for

- nonstructural carbohydrates in stem bases of defoliated switchgrass. *Crop Sci.* 29: 1282-1287.
- Gettle, R. M., J. R. George, K. M. Blanchet, D. R. Buxton, and K. J. Moore. 1996. Frost-seeding legumes into established switchgrass: Forage yield and botanical composition of the stratified canopy. *Agron. J.* 88: 855-860.
- Gil, J. L., and W. H. Fick. 2001. Soil nitrogen mineralization in mixtures of eastern gammagrass with alfalfa and red clover. *Agron. J.* 93: 902-910.
- Gillard, K., G. F. Griffin, D. W. Allinson, M. M. Rafey, W. R. Yamartino, and S. W. Pietrzyk. 1995. Nitrogen utilization of selected cropping systems in the U.S Northeast: I. Dry matter yield, N uptake, apparent N recover, and N use efficiency. *Agron J.* 87: 193-199.
- Goncalves, J. L. M., and J. C. Carlyle. 1994. Modeling the influence of moisture and temperature on net mineralization in forested sandy soils. *Soil Biol. Biochem.* 26: 1557-1564.
- Goodwin, D. C., and G. J. Blair. 1991. Phosphorus efficiency in pasture species. V. A comparison of white clover accessions. *Aust. J. Agric. Res.* 42: 531-540.
- Gourly, C. J. P., D. L. Allan, and M. P. Russelle. 1994. Plant nutrient efficiency: A comparison of definitions and suggested improvements. *Plant and Soil* 158: 29-37.
- Graham, R. L., B. C. English, C. E. Noon, H. I. Jager, and M. J. Daly. 1997. Predicting switchgrass farmgate and delivered costs: An 11 state analysis. P. 121-129. *In* R. P. Overend and E. Chornet (eds). *Making a business from Biomass in energy, environment, chemicals, fibers, and materials. Proceedings of the 3rd Biomass Conference of the Americas.* 24-29 Aug. 1997. Montreal, Quebec, Canada.
- Griffin, J. L., and G. A. Jung. 1983. Leaf and stem forage quality of big bluestem and switchgrass. *Agron. J.* 75: 723-726.
- Griffin, J. L., and G. A. Jung. 1981. Yield and forage quality of *Panicum virgatum*: Grazing switchgrass, cows and cattle. p. 491-494. *Proceedings of the XVI International Grassland Congress, Lexington, Kentucky: June 15-24, 1981.* J. Allan Smith and Virgil W. Hays (eds) . Boulder, Colo. : Westview Press, 1983.
- Groot, J. J. R., and V. J. G. Houba. 1995. A comparison of different indices of nitrogen mineralization. *Biol. Fertil. Soils* 19: 1-9.

- Gunter, L. E., G. A. Tuskan, and S. D. Wulfschleger. 1996. Diversity among populations of switchgrass based on RAPD markers. *Crop Sci.* 36: 1017-1022.
- Hadas, A., S. Feigenbaum, A. Feigin, and R. Portnoy. 1986. Nitrogen mineralization rate in profile of differently managed soil types. *Soil Sci. Am. J.* 50: 314-319.
- Hargrove, W. L. 1988. Evaluation of ammonia volatilization in the field. *J. Prod. Agric.* 1 (2): 104-111.
- Hargrove, W. L., and D. E. Kissel. 1979. Ammonia volatilization from surface applications of urea in the field and laboratory. *Soil Sci. Soc. Am. J.* 43: 359-363.
- Harper, L. A., V. R. Catchpoole, R. Davis, and K. L. Weir. 1983. Ammonia volatilization: Soil, plant, and microclimate effects on diurnal and seasonal fluctuations. *Agron. J.* 75: 212-218.
- Heckathorn, S. A., and E. H. Delucia. 1996. Retranslocation of shoot nitrogen to rhizomes and roots in prairie grasses may limit loss of N to grazing and fire during drought. *Functional Ecology* 10: 396-400.
- Hetrick, B. A. D., and G. W. T. Wilson. 1993. Mycorrhizal activity in warm- and cool-season grasses: variation in nutrient-uptake and strategies. *Can. J. Bot.* 72: 1002-1008.
- Hook, P. B., and I. C. Burke. 1995. Evaluation of methods for estimating net nitrogen mineralization in a semiarid grassland. *Soil Sci. Soc. Am. J.* 59: 831-837.
- Hope, H. J., and A. McElroy. 1990. Low-temperature tolerance of switchgrass (*Panicum virgatum* L.). *Can. J. Plant Sci.* 70: 1091-1096.
- Hopkins, A. A., and C. M. Taliaferro. 1997. Genetic variation within switchgrass populations for acid soil tolerance. *Crop Sci.* 37: 1719-1722.
- Huang, Y., D. H. Rickerl, and K. D. Kephart. 1996. Recovery of deep-point injected soil nitrogen-15 by switchgrass, alfalfa, ineffective alfalfa, and corn. *J. Environ. Qual.* 25: 1394-1400.
- Jacobsen, J. S., S. H. Lorbeer, H. A. R. Houlton, and G. R. Carlson. 1996. Nitrogen fertilization of dryland grasses in the northern great plains. *J. Range Manage.* 49: 340-345.
- Jones, M.B. and Carter, T.R. 1993a. European grassland production in a

- changing climate. Proceedings of the 14th General Meeting of the European Grassland Federation, Lahti, Finland. pp. 97-110.
- Jones, M. B., S. P. Long, and U. Jorgensen. 1993b. C₄ perennial rhizomatous grasses as low input cellulose biomass crops in the north of the European community. JOUB-0069. Final report.
- Jorgensen, U., and K. Schelde. 2001. Energy crop water and nutrient use efficiency. The International Energy Agency IEA Bioenergy task 17, Short rotation crops. Annual report.
- Jung, G. A., J. A. Shafer, W. L. Stout, and M. J. Panciera. 1990. Warm-season grass diversity in yield, plant morphology, nitrogen concentration, and removal in the northeastern USA. Agron. J. 82: 21-26.
- Jung, G. A., J. A. Shaffer, and W. L. Stout. 1988. Switchgrass and big bluestem responses to amendments on strongly acid soils. Agron. J. 80: 669-676.
- Kanampiu, F. K., W. R. Raun, and G. V. Johnson. 1997. Effect of nitrogen rate on plant nitrogen loss in winter wheat varieties. J. Plant Nutr. 20 (2&3): 389-404.
- Karrou, M., and J. W. Maranville. 1994. Response of wheat cultivars to different soil nitrogen and moisture regimes: II. Nitrogen uptake, partitioning, and influx. J. Plant Nut. 17: 745-761.
- Kassel, P. C., R. E. Mullen, and T. B. Bailey. 1985. Seed yield response of three switchgrass cultivars for different management practices. Agron. J. 77: 214-218.
- Keller, G. D., and D. B. Mengel. 1986. Ammonia volatilization from nitrogen fertilizers surface applied to non-till corn. Soil Sci. Soc. Am. J. 50: 1060-1063.
- Kirk, G. J., and P. H. Nye. 1991. A model of ammonia volatilization from applied urea. V. The effects of steady-state drainage and evaporation. VI. The effects of transient-state water evaporation. J. Soil Sci. 42: 103-125.
- Knapp, A. K. 1985. Effect of fire and drought on the ecophysiology of *Andropogon gerardii* and *Panicum virgatum* in tall grass prairie. Ecology 66: 1309-1320.
- Lemus, R. W. 2000. Cultivar and fertility effects on switchgrass biofuel production in southern Iowa. M.S. Thesis. Iowa State University.
- Lightner, J. W., D. B. Mengel, and C. L. Rhykerd. 1990. Ammonia volatilization

- for nitrogen fertilizer surface applied to orchardgrass sod. Soil Sci. Am. J. 54: 1478-1482.
- Linn, D. M., and J. W. Doran. 1984. Effect of waterfilled pore and space on CO₂ and NO₂ production in tilled and non-tilled soils. Soil Sci. Soc. Am. J. 48: 267-272.
- Lutwick, L.E., and A. D. Smith. 1979. Yield and N uptake by seven perennial grass species as affected by high rates of N fertilization. J. Range Manage. 32 (6): 433-436.
- Loiseau, P., R. Chaussod, and R. Delpy. 1994. Soil microbial biomass and *in situ* nitrogen mineralization after 20 years of different nitrogen fertilization and forage cropping systems. Eur. J. Agron. 3: 327-332.
- Lowenberg-DeBoer, J., and J. H. Cherney. 1989. Biophysical simulation for evaluating new crops: The case of switchgrass biomass energy feedstock. Agricultural Systems 29: 233-246.
- Ma, Z., C. W. Wood, and D. I. Bransby. 2000. Impacts of soil management on root characteristics of switchgrass. Biomass and Bioenergy 18: 105-112.
- Madakadze, I. C., K. A. Stewart, P. R. Peterson, B. E. Coulman, and D. L. Smith. 1999. Switchgrass biomass and chemical composition for biofuel in eastern Canada. Agron. J. 91: 696-701.
- Marshall, S. B., M. L. Cabrera, L. C. Braun, C. W. Wood, M. D. Mullen, and E. A. Guertal. 1999. Denitrification from fescue pastures in the Southeastern USA fertilized with broiler litter. J. Environ. Qual. 28 (6): 1978-1983.
- Marumoto, T., J. P. Anderson, and K. H. Domsch. 1982. Mineralization of nutrients from soil microbial biomass. Soil Biol. Biochem. 14: 469-475.
- Mary, B., and S. Recous. 1994. Measurement of nitrogen mineralization and mobilization fluxes in soil as a mean of predicting net mineralization. Eur. J. Agron. 3: 291-300.
- McInnes, K. J., R. B. Ferguson, D. E. Kissel, and E. T. Kanemasu. 1986. Field measurements of ammonia loss from surface applications of urea solution to bare soil. Agron. J. 78: 192-196.
- McLaughlin, S. B., and M. E. Walsh. 1998. Evaluating environmental consequences of producing herbaceous crops for bioenergy. Biomass and Bioenergy 14: 317-324.
- McLaughlin, S., J. Button, D. Bransby, R. Conger, W. Ocumpaugh, D. Parrish, C.

- Taliaferro, K. Vogel, and S. Wulschleger. 1997. Evaluating and improving switchgrass as a bioenergy crop. Proceedings of the 3rd Biomass Conference of the Americas. August 24-29. Montreal, Quebec, Canada 1: 137-143.
- McLaughlin, S. B., R. Samson, D. Bransby, and A. Wiselogle. 1996. Evaluating physical, chemical and energetic properties of perennial grasses as biofuels. Proceedings of Bioenergy '96-The seventh national Bioenergy Conference: Partnerships to develop and apply biomass technologies, September 15-20, Nashville, TN.
- Moiser, A. R., and L. Klemetsson. 1994. Measuring denitrification in the field. p. 1047-1065. In Methods of Soil Analysis. Part 2: Microbiological and Biochemical Properties. J. M. Bigham (ed). Soil Sci. Soc. Am., Inc. Madison, WI.
- Murdock, L. W., and W. W. Frye. 1985. Comparison of urea and urea-ammonium polyphosphate with ammonium nitrate in production of tall fescue. Agron. J. 77: 630-633.
- Neve, S. D., J. Pannier, and G. Hofman. 1994. Fraction of vegetable crop residues in relation to *in situ* N mineralization. Eur. J. Agron. 3: 267-272.
- Novoa, R., and R. S. Loomis. 1981. Nitrogen and Plant Production. Plant and Soil 58: 177-204.
- Oberle, S. L., and L. G. Bundy. 1987. Ammonia volatilization from nitrogen fertilizers surface-applied to corn (*Zea mays*) and grass pasture (*Dactylis glomerata*). Biol. Fertil. Soils. 4: 185-192.
- Pandey, R. K., J. W. Maranville, and Y. Bako. 2001. Nitrogen fertilizer response and use efficiency for three cereal crops in Niger. Commun. Soil Sci. Plant. Anal. 32 (9 & 10): 1465-1482.
- Parrish, D. J., D. Wolf, P.R. Peterson, and W. L. Daniels. 1999. Switchgrass as a biofuel crop for the upper Southeast: variety trials and cultural improvements. Semi-annual report. Biofuels feedstock development program. Oak Ridge National Laboratory. Oak Ridge, TN.
- Parrish, D. J., D. Wolf, P.R. Peterson, and W. L. Daniels. 1996. Switchgrass as a biofuel crop for the upper southeast: variety trials and cultural improvements. Annual report. Biofuels feedstock development program. Oak Ridge National Laboratory. Oak Ridge, TN.
- Parrish, D. J., and D. D. Wolf. 1992. Managing switchgrass for sustainable biomass production. p. 34-39. In J. S. Cundiff (ed). Liquid fuels from

- renewable resources. Proc. of an Alternative Energy Conf., 14-15 December 1992, Nashville, TN. Am. Soc. Agric. Eng.
- Patra, A. K., S. C. Jarvis, and D. J. Hatch. 1999. Nitrogen mineralization in soil layers, soil particles, and macro-organic matter under grassland. *Biol. Fertil. Soils* 29: 38-45.
- Pitman, W. D. 2000. Adaptation of tall-grass prairie cultivars to West Louisiana. *J. Range Manage.* 53 (1): 47-51.
- Power, J. F., and J. W. Doran. 1984. Nitrogen use in organic farming. *In* R. D. Hauck (ed.) *Nitrogen in crop production*. Am. Soc. Agron. Madison, WI.
- Prins, W. H., K. Dilz, and J. J. Neetson. 1988. Current recommendations for nitrogen fertilization within the EEG in relation to nitrate leaching. *Proc.* 276, Fert. Soc., London.
- Radiotis, T., J. Li, K. Goel, and R. Eisner. 1999. Fiber characteristics, pupability, and bleachability of switchgrass. *Tappi J.* 82: 100-105.
- Ramos, C. 1996. Effect of agricultural practices on the nitrogen losses to the environment. *Fert. Res.* 43: 183-189.
- Ranases, A., K. Hanson, and H. Shapouri. 1998. Economic impacts from shifting cropland use from food to fuel. *Biomass and Bioenergy* 15: 417-422.
- Rasmussen, P. E., C. L. Douglas Jr., H. P. Collins, and S. L. Albrecht. 1998. Long-term cropping system effects on mineralizable nitrogen in soil. *Soil Biol. Biochem.* 30 (13): 1829-1837.
- Redfearn, D. D., K. J. Moore, K. P. Vogel, S. S. Waller, and R. B. Mitchell. 1999. Canopy architecture and morphology of switchgrass populations differing in forage yield. *Agron. J.* 89: 262-269.
- Risser, P. G., and W. J. Parton. 1982. Ecosystem analysis of the tallgrass prairie: nitrogen cycle. *Ecology* 63(5): 1342-1351.
- Roelcke, M., Y. Han, S. X. Li, and J. Ritcher. 1996. Laboratory measurements and simulations of ammonia volatilization from urea applied to calcareous Chinese loess soils. *Plant and Soil* 181: 123-129.
- Roundtree, B. H., A. G. Matches, and F. A. Martz. 1974. Season too long for your grass pastures? *Crops Soils* 26 (7): 7-10.
- Russelle, M. P. 1992. Nitrogen cycling in pasture and range. *J. Prod. Agric.* 5:

13-23.

- Saint-Fort, R., K. D. Frank, and J. S. Schepers. 1990. Role of nitrogen mineralization in fertilizer recommendations. *Commun. Soil Sci. Plant Anal.* 21: 1945-1958.
- Sanchez, C. A., and T. A. Doerge. 1999. Using nutrient uptake patterns to develop efficient nitrogen management strategies for vegetable. *HortTechnology* 9(4): 601-606.
- Sanderson, M. A., J. C. Read, and R. L. Reed. 1999. Harvest management of switchgrass for biomass feedstock and forage production. *Agron. J.* 91: 5-10.
- Sanderson, M. A., R. L. Reed, S. B. McLaughlin, S. D. Wulschleger, B. V. Conger, D. J. Parrish, D. D. Wolf, C. Taliaferro, A. A. Hopkins, W. R. Ocumpaugh, M. A. Hussey, J. C. Read, and C. R. Tischler. 1996. Switchgrass as a sustainable bioenergy crop. *Bioresource Technology* 56: 83-93.
- Scharf, P. 1993. Development of field-specific spring N recommendations for winter wheat. Ph. D Thesis. Virginia Polytechnic Institute and State University. Blacksburg, Virginia.
- Schepers, J., and J. J. Meisinger. 1994. Field indicators of nitrogen mineralization. p. 31-47. *In* J. L. Havlin and J. S. Jacobsen (eds.) *Soil esting: Prospects for improving nutrient recommendations*. SSSA Special Publication 40. Madison, WI.
- Seneviratne, R., and A. Wild. 1984. Effect of mild drying on the mineralization of soil nitrogen. *Plant and Soil* 84: 175-179.
- Sibma, L., and T. H. Alberda. 1980. The effect of cutting frequency and nitrogen fertilizer rates on dry matter production, nitrogen uptake, and herbage nitrate content. *Neth. J. Agric. Sci.* 28: 243-251.
- Siddiqi, M. Y., and A. D. Glass. 1981. Utilization index: A modified approach to the estimation and comparison of nutrient utilization efficiency in plants. *J. Plant Nutr.* 4: 289-302.
- Sherlock, R. R., and K. M. Goh. 1984. Dynamics of ammonia volatilization from simulated urine patches and aqueous urea applied to pasture I. Field experiments. *Fert. Res.* 5: 181-185.
- Sladden, S. E., and D. I. Bransby. 1992. Genetic variation in morphology, yield

- and quality of switchgrass. Proceedings of the Forage and Grassland Conference. Georgetown, TX: American Forage and Grassland Council 1: 175-179.
- Sladden, S. E., D. I Bransby, and G. E. Aiken. 1991. Biomass yield, composition, and production costs for eight switchgrass varieties in Alabama. *Biomass and Bioenergy* 1(2): 119-122.
- Smith, J. L. 1994. Cycling of nitrogen through microbial activity. *In* J. L. Hatfield and B. A. Stewart (eds). *Advances in Soils Science*. Lewis Publishers, pp. 91-119.
- Smith, J. L., R. I. Papendick, D. F. Besdick, and L. M. Lynch. 1993. Soil organic matter dynamics and crop residue management. p. 65-94. *In*: F. B. Meeting, Jr. (ed.). *Soil applications in agricultural and environmental management: Microbial Ecology*. New York: Marcel Dekker Inc.
- Smith, M. A. 1980. Nitrogen requirements and yield performance of seven switchgrass (*Panicum virgatum* L.) varieties. Master's Thesis. Iowa State Univ., Ames, Iowa.
- Smith, D., and S. B. Greenfield. 1979. Distribution of chemical constituents among shoot parts of timothy and switchgrass at anthesis. *J. Plant Nutrition* 1: 81-99.
- Stanford, G., and J. O. Legg. 1984. Nitrogen and yield potential. p. 263-293. *In* R. D. Hauck (ed.). *Nitrogen in crop production*. ASA Spec. Publ., Madison, WI.
- Stanford, G., and E. Epstein. 1974. Nitrogen mineralization-water relations in the soils. *Soil Sci. Soc. Am. Proc.* 38: 103-107.
- Stanford, G., and S. J. Smith. 1972. Nitrogen mineralization potentials of soils. *Soil Sci. Soc. Am. Proc.* 36: 465-472.
- Stevenson, F. J. 1982. Origin and distribution of nitrogen in soils. p. 1-42. *In* *Nitrogen in agricultural soils*. ASA, CSSA, SSSA, Madison, WI.
- Terman, G. L. 1979. Volatilization losses of nitrogen as ammonia from surface-applied fertilizers, organic amendments, and crop residues. *Adv. Agron.* 31: 189-223.
- Tiedje, J. M., S. Simkins, and P. M. Groffman. 1989. Perspectives on measuring denitrification in the field including recommended protocols for acetylene based methods. p. 217-240. *In* M. Clarholm and L. Bergstrom (eds). *Ecology of arable land*. Dordrecht, Holland: Kluwer Academic Publ.

- Tisdale, S. L., W. L. Nelson, and J. D. Beaton. 1985. Soil fertility and fertilizers. New York: MacMillan Publishing Co.
- Titko, S. III, J. R. Street, and T. J. Logan. 1987. Volatilization of ammonia from granular and dissolved urea applied to turfgrass. *Agron. J.* 79: 535-540.
- Tolbert, V. R., and L. L. Wright. 1998. Environmental enhancement of U. S. biomass crop technologies: Research results to date. *Biomass and Bioenergy* 15: 93-100.
- Torello, W. A., D. J. Wehner, and A. J. Turgeon. 1983. Ammonia volatilization from fertilized turfgrass stands. *Agron. J.* 75: 454-456.
- Tyson, K.C., D. H. Roberts, C. R. Clement, E. A. Garwood. 1990. Comparison of crop yields and soil conditions during 30 years under annual tillage and grazed pasture. *J. Agric. Sci.* 115: 29-40.
- Van Esbroeck, G. A., M. A. Hussey, and M. A. Sanderson. 1997. Leaf appearance rate and final leaf number of switchgrass cultivars. *Crop Sci.* 37: 864-870.
- Vogel, K. P., and R. A. Masters. 1998. Developing switchgrass into a biomass fuel crop for the Midwest USA. Bioenergy Conference: Expanding bioenergy partnerships. Madison, WI. October 4-8.
- Vogel, K. P. 1996. Energy production from forages (or American agriculture-back to the future). *J. Soil and Water Conservation* 51 (2): 137-139.
- Wang, J. G., and R. L. Bakken. 1989. Nitrogen mineralization in the rhizosphere and non-rhizosphere soil, effect of spatial distribution of N-rich and N-poor plant residue. p. 81-97. *In*: J. A. Hansen and K. Henriksen (eds.) Nitrogen in organic wastes applied to soils. London: Academic Press.
- Warren, G. P., and D. C. Whitehead. 1988. Available soil nitrogen in relation to fractions of soil nitrogen and other soil properties. *Plant Soil* 112: 155-165.
- Watson, C. J. 1990. The influence of soil properties on the effectiveness of phenylphosphorodiamidate (PPD) in reducing ammonia volatilization from surface applied urea. *Fert. Res.* 24: 1-10.
- Whitemore, A. P., and J. R. Groot. 1994. The mineralization of N from finely or coarsely chopped crop residues: measurement and modeling. *Eur. J. Agron.* 3: 367-373.
- Whitemore, A. P., N. J. Bradbury, and P. A. Johnson. 1992. Potential

- contribution of ploughed grassland to nitrate leaching. *Agriculture, Ecosystems, and Environment* 39: 221-233.
- Woolsey, E. L. 1992. Switchgrass--Back to the future. *Energy Crop Forum-Spring 1992*. U.S. Department of Energy, Biofuels Feedstock Development Program at Oak Ridge National Laboratory.
- Wright, M. J., and K. L. Davison. 1964. Nitrate accumulation in crops and nitrate poisoning in animals. *Adv. Agron.* 16: 197-247.
- Wuest, S. B., and K. G. Cassman. 1992. Fertilizer-nitrogen efficiency of irrigated wheat: I. uptake efficiency of preplant versus late-season application. *Agron. J.* 84: 682-688.
- Wullschlegel, S. D., M. A. Sanderson, S. B. McLaughlin, D. P. Biradar, and A. L. Rayburn. 1996. Photosynthetic rates and ploidy levels among populations of switchgrass. *Crop Sci.* 36: 306-312.
- Zemenchick, R. A., and K. A. Albrecht. 2002. Nitrogen use efficiency and apparent nitrogen recovery of Kentucky bluegrass, smooth brome grass, and orchardgrass. *Agron. J.* 94: 421-428.
- Ziadi, N., R. R. Simard, G. Allard, and G. Parent. 2000. Yield response of forage grasses to N fertilizer as related to spring soil nitrate sorbed on anionic exchange membranes. *Can. J. Soil. Sci.* 80: 203-212.

CHAPTER 3

SWITCHGRASS FOR BIOMASS PRODUCTION IN THE UPPER SOUTHEAST USA: CULTIVAR/ECOTYPE SELECTION AND CUTTING MANAGEMENT

ABSTRACT

Switchgrass (*Panicum virgatum* L.), a perennial warm-season grass indigenous to the upper Southeast, has potential as a biofuels feedstock. The objectives of this study were to investigate the performance of different switchgrass cultivars and to compare lowland and upland ecotypes under different environments and cutting managements. Four cultivars of switchgrass were evaluated in 2000 and 2001 under two cutting regimes in plots established in 1992 at eight locations within KY, NC, TN, VA, and WV. Harvests were made once (in November) or twice (in mid-summer and November). The experiment at each location was a randomized complete block replicated four times. Biomass yields averaged 15 Mg ha⁻¹ and ranged from 10 to 22 Mg ha⁻¹ across locations and years. There was no yield advantage to taking two harvests of the lowland cultivars ('Alamo' and 'Kanlow'). If harvested twice, the upland cultivars ('Cave-in-Rock' and 'Shelter') provided yields equivalent to the lowland ecotypes. Tiller density was 36% lower in stands cut only once, but the stands appeared vigorous and were quite productive after 9 yr of such management. Switchgrass shows good potential for truly perennial biomass production in the upper Southeast. Lowland cultivars and a one-cut management (after the tops have senesced) using low rates of applied N (50 kg ha⁻¹) are recommended.

INTRODUCTION

Herbaceous biomass has been investigated in the search for renewable energy alternatives. Switchgrass is a perennial, C₄ grass, with an energy ratio of 29 MJ kg⁻¹ (Metcalf and Bullard, 2001), and indigenous to the upper Southeast. It has been studied for ethanol, fiber, electricity, and heat production in the USA. Biofuels production systems seek to optimize yields through proper harvest management and economic fertilizer inputs. Currently there is limited information on the adaptation and management of different ecotypes and cultivars in the upper Southeast.

One factor determining variety adaptation to a specific region is the origin of the genotype (Elbersen et al., 2001). Switchgrass cultivars belong to two ecotypes based on their geographical and morphological characteristics. Lowland ecotypes are tetraploid, taller, thicker-stemmed, and more adapted to wet conditions. Upland ecotypes are hexaploid or octaploid, shorter, rhizomatous, thinner-stemmed, and more adapted to drier conditions (Lemus et al., 2002). Elbersen et al. (2001) reported that yield of cultivars are correlated with the origin of the ecotype, with lowland ecotypes having higher yield potential. Various ecotypes are grown throughout the upper Southeast, but their yield capability under different management systems has not been studied.

A goal of herbaceous energy crop production is to optimize switchgrass production (high yields with economic inputs). A possible avenue to greater efficiency is harvest management (Sanderson et al., 1999b). Frequency and timing of harvests will likely have agronomic, processing, quality, and ultimately, economic consequences. Also, a cutting system that ensures maintenance of adequate energy reserves in roots will be necessary for plant survival and long-term productivity (Cuomo et al., 1996). An annual cutting in the late fall or early spring has been considered suitable for biomass production, since the value of switchgrass is based on amount of biomass produced and not on its feed quality (Sanderson et al., 1996). However, other harvest management practices could

be better for producing switchgrass feedstock, potentially increasing production and reducing storage requirements by harvesting more than once a year.

Switchgrass is commonly harvested using conventional haying techniques, but management practices for switchgrass bioenergy production may differ from forage management. Reduction of switchgrass stands associated with frequent harvests has been reported. Cuomo et al. (1996) estimated that three annual harvests of switchgrass decreased yield 34 to 60% the following year in Nebraska. Switchgrass stand reductions of up to 58% were reported with two or three annual harvests as compared to 39% with one annual harvest in the Midwest (Balasko et al. 1984; Anderson and Matches, 1983). Similarly, multiple harvests per season and delaying fall harvest past September reduced Alamo switchgrass yields in TX (Sanderson et al., 1996). In OK, switchgrass stands were severely reduced when cut two or four times each season instead of once, and stand losses were lower when a 10-cm of stubble was left instead of 5-cm (Dwyer et al., 1963).

Harvest management is essential to maintaining long-term switchgrass stands and yields, but it can have effects within the season as well. Delaying harvest until after frost allows translocation of materials from the above-ground biomass to the roots (Parrish et al., 1996). Parrish and Wolf (1993) suggested that this remobilization and translocation cause a yield reduction in above-ground biomass of approximately 10%. Sanderson et al. (1999b) also observed switchgrass yields decreased if the fall harvest was delayed from September to November. They attributed yield losses to leaf shattering. While these studies suggest that a single harvest is most appropriate in most areas in the USA, two harvests per season were reported to yield more biomass than one in a study in VA (Sanderson et al., 1996).

The profitability of switchgrass as a biomass crop may be enhanced if long-term and sustainable yields are increased with proper cultivar selection and optimal cutting management. The main objectives of this research were: (1) to measure yields of different switchgrass cultivars; and (2) to compare lowland and upland switchgrass ecotypes under different environments and cutting

managements to provide data for recommending biofuels cropping systems for the upper Southeast USA.

MATERIALS AND METHODS

The study was conducted during 2000 and 2001 on existing switchgrass stands planted in 1992 at eight different sites across five states in the upper Southeast USA (Table 3.1 and Fig. 3.1). Experimental plots were 6.1 X 2.4 m at all locations except at the Blacksburg site B where plots were 6.1 X 2.1 m. The cultivars utilized included lowland and upland ecotypes (Table 3.2). The lowland cultivars were 'Alamo' and 'Kanlow'. The upland cultivars were 'Cave-in-Rock' (CIR) and 'Shelter.' The switchgrass stands were managed with two harvest systems: one-cut or two-cut. Plots were cut once (in November) or twice (in mid-summer and November). First harvest in the two-cut system was taken in mid-summer when Shelter and Cave-in-Rock were in early head emergence stage and the lowland varieties were jointing or early boot stage. A 1-m wide strip was harvested from the center of each plot at a height of 10-cm using a flail type forage harvester (Carter Manufacturing Co., Brookston, IN) equipped with an electronic scale. Biomass sub-samples were collected and dried for dry matter determination. After each harvest, all border material in each plot was mowed and residue removed. Stand densities were determined after the November 2001 harvest by visually evaluating stubble density. All visual ratings were made by a single individual at all locations to maintain consistency of the rating. Plots were visually ranked from 0 = no stubble to 10 = a dense stubble (very little soil surface visible).

Nitrogen fertilizer was applied as ammonium nitrate (34-0-0). For the one-cut management, 50 kg N ha⁻¹ was surface broadcasted in late May. The two-cut management received a split application with 50 kg N ha⁻¹ applied in May and 50 kg N ha⁻¹ applied after the first cut. Phosphorus and K were applied as needed

to maintain a medium level of fertility based on soil testing recommendations from each geographic location.

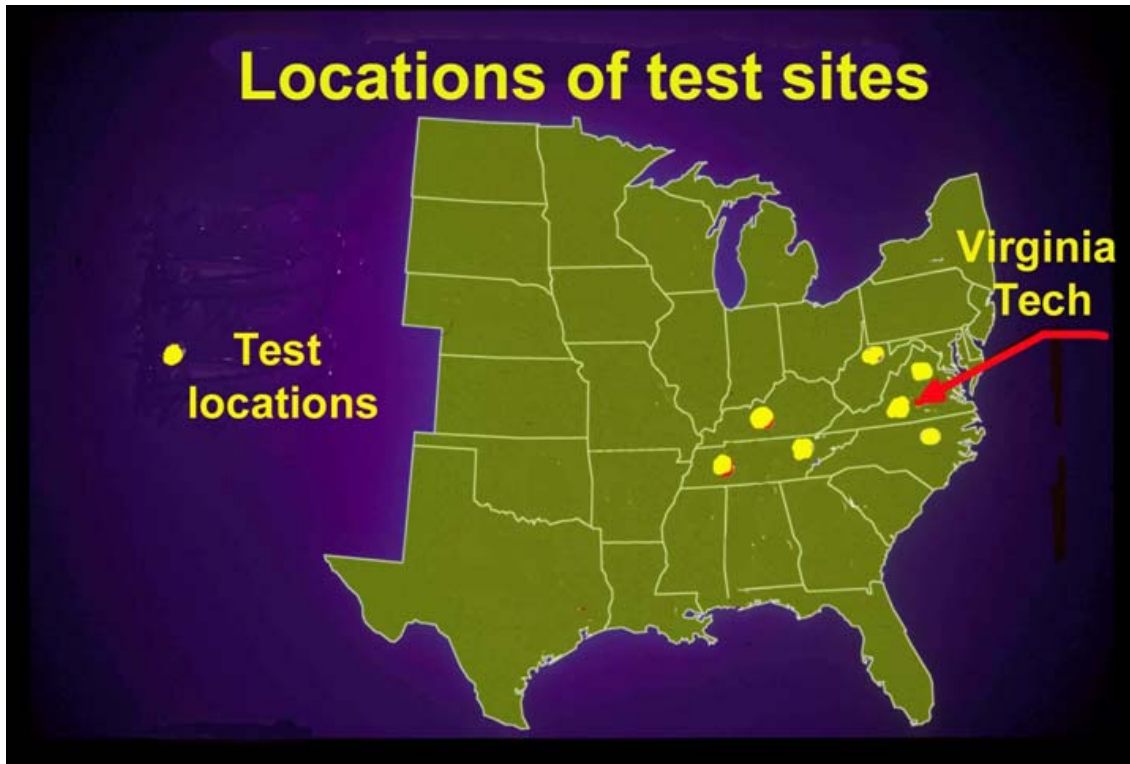


Fig. 3.1. Test locations in the upper Southeast USA.

The experimental design at each location was a randomized complete block, replicated four times. The treatments included four cultivars and two cutting managements. Yield data were initially analyzed in a combined analysis using a split-plot arrangement in which years and locations were considered the main plots and cultivars and cutting managements the sub-plots. The location x variety x management x year interaction was highly significant for biomass yields (Table 3.3); therefore, data were analyzed separately for each location. Appropriate F-test followed the procedure outline in Steel and Torrie (1980). A site yield variation index, for cultivars in each cutting management, was calculated as the cultivar mean at each location minus the location grand mean (Eberhart and Russel, 1996). Mean separations were done by the protected Least Significance Difference (LSD) test. All statistical analyses were conducted

by SAS General Linear Model procedure (SAS, 2003) at the 0.05 probability level unless otherwise noted.

RESULTS AND DISCUSSION

Climatic Effects

Essentially all aboveground switchgrass growth occurs between April and September. Rainfall patterns during this period varied between the 2 yr, but switchgrass productivity was not significantly affected. While some locations experienced below-normal rainfalls in 2000, rainfalls above 30-yr averages were seen at all locations in 2001 (Table 3.4). The April-to-September weather data had very small deviation from long-term means in both years for precipitation and temperature. Comparisons with long-term average rainfall at all locations between April and September showed that precipitation was below normal at KY and TN₁ in both years and at Orange in 2001. North Carolina had the highest amount of precipitation in both years. Mean temperatures in 2001 were cooler than in 2000, especially at VA₃ and KY locations; but both years were above long-term averages overall, and especially in NC.

Cultivar and Cutting Management Differences Across Years and Sites

There was a significant cut x year x cultivar interaction, which make interpretations very challenging (Table 3.5). Because of this, data analysis has been divided into main effects and two-way interactions for discussion purposes. The two-cut system yields (averaging 15.3 Mg ha⁻¹ yr⁻¹) provided a 12% mean yield advantage over the one-cut system (13.6 Mg ha⁻¹ yr⁻¹). Most of that yield advantage occurred in 2000, when the two-cut system had a 21% higher yield. The one-cut system produced higher yields than the one-cut system at VA₃ and TN₁ in 2001 and at VA₂ in 2002. With the two-cut system, yields were higher at VA₂ in 2000 and 2001 (data not shown).

Of the commercially available cultivars used in this study, Alamo and Kanlow were generally the highest yielding across the varied geographical locations and years and within cutting managements. Alamo and Kanlow produced their highest yields at VA₃. These yields were dramatically higher than at VA₂, located approximately 100 m away. The physical differences between these two sites included soil, slope, and aspect – but clearly not temperature (except micro-environmentally) or rainfall. Mean yields by site ranged from 10.9 Mg ha⁻¹ in NC to 18.5 Mg ha⁻¹ in VA₂. Shelter was the least productive cultivar at all locations, having 30% lower yield than Alamo. All cultivars had generally lower yields in TN₁ and NC. Although there was no correlation of cultivar yields with growing season rainfall (April thru September), there is the possibility that wetter, warmer conditions at NC and drier conditions at TN₁ might have affected cultivar performance in these specific locations. One of the reasons for the generally better performance of lowland cultivars among locations might be related to their response to day length and their later maturity. Alamo and Kanlow matured in late August to mid September. Under these circumstances, lowland cultivars have a prolonged vegetative growth, which usually results in yield increases (Lemus et al., 2002).

The predominant factor affecting switchgrass cultivar productivity at all locations, other than cultivar itself, was cutting frequency (Table 3.5). Yield differences between cutting managements were observed at VA₁, KY, WV, and NC. The two-cut management showed yield advantages ranging from 7% in KY to 40% in VA₁ when compared to the one-cut system; but in WV, the two-cut management had a 12% yield reduction. Cutting management had differential effects on cultivar performance. Although no yield advantage was observed for the two lowland cultivars (Alamo and Kanlow) under the two-cut management, differences were observed for CIR and Shelter. Cave-in-Rock and Shelter mean yields were increased by approximately 30% when cut twice. Cave-in-Rock yields under the two-cut system were equivalent to lowland cultivars. Alamo and Kanlow yields were significantly reduced when cut twice at several locations, with the highest reductions at in TN₂ (~16%) and WV (~24%). Our data agree with

others' findings, in which Alamo yields decreased greatly with increasing harvest frequency (Sanderson et al., 1999b); Kanlow showed the same results at some locations (VA₂, VA₃, and WV).

One of the goals of the two-cut management was to time the first harvest such that about 50% of seasonal production was harvested in the first cut. Data showed that more yield was removed in June harvests than in November when averaged over all locations (Table 3.7). Analysis of the two-cut management revealed cultivar differences in amount of biomass removed at each harvest and location. When averaged across cultivars, no yield differences between harvests were observed at any site in VA, i.e., each harvest was about 50% of the seasonal total. Relative to other locations, lower yields in June were observed in KY and during the November harvest at NC. The upland cultivars (CIR and Shelter) had 62% and 63% of their total yield removed in June under the two-cut management when averaged across locations and years. On the other hand, Alamo and Kanlow had 51% and 59% removed in June. These data indicate that, by mid-summer, CIR and Shelter had produced more than half of their seasonal yield. Most of the first harvests occurred in the late boot (R₀) to early seed head emergence (R₁) stage (Moore et al., 1991). Since the upland cultivars developed seed heads earlier, this harvest date might have given some advantage to the lowland cultivars due to their extended vegetative growth. Also, switchgrass has a slow recovery time for regrowth, which might be different for each cultivar, affecting yield sustainability. Energy resources that might have been dedicated to increase total biomass yield will have to be expended for regrowth.

Ecotype Differences in Response to Cutting Management

Ecotypes were compared in further analyses. The lowland ecotype was represented by Alamo and Kanlow and the upland ecotype by CIR and Shelter. Harvest management differentially affected ecotype yields in several locations (Table 3.8). The general pattern was that the cultivars of the upland ecotype produced greater yields with two cuts, while the lowland ecotype cultivars did not.

Yields at VA₃ and TN₁ were not different between ecotypes, but that was because the lowland ecotype responded atypically, showing a yield increase with two cuts. The lowland ecotype had no yield response to cutting management at several locations (VA₂, VA₃, and KY). On the other hand, yield reductions were observed in TN₂ (23%) and WV (21%). By contrast, the upland ecotype increased yield when harvested twice at all locations except in WV. The two-cut management produced about 31% more biomass than the single-cut of the upland ecotype across locations. This positive yield response of the upland ecotype to two cuts ranged from 15% in WV to 65% in NC. No yield responses to cutting management were observed for the upland ecotype in WV.

Visual Stand Evaluation



Fig. 3.2. Stubble density of 10-yr old switchgrass plots after fall harvest 2001 in Morgantown, WV.

Stand densities were visually estimated after the November 2001 harvest (Fig. 3.1). Cutting management played a major role in stand density. Plots cut twice during the season had more stubble than plots cut once (Table 3.9). Plots that received one cut had a 36% decline in stand density. The lower densities observed at VA₂ were produced by low values under the one-cut management. Stands of one-cut management seemed sparse for most locations in VA for both ecotypes, but yields were not reduced: VA₂ and VA₃ were among the highest yielding locations. The increase in stand density with the two-cut management is likely due to increased tiller development following the June cutting. We also speculate that midsummer cutting could affect apical dominance, stimulating axillary buds on the 10-cm stubble to become active. This would produce additional stubble – if not true tillers.

Switchgrass Stability and Adaptation

Cultivar x environment interaction is of major importance when trying to determine adaptability of switchgrass cultivars to specific areas because of their latitude of origin and maturity rating. When comparing switchgrass cultivars over a series of locations and years, their relative rankings usually change, making it difficult or impossible to identify a “best” cultivar. To determine yield stability and cultivar adaptation, the mean biomass yields at all locations for each cultivar from the 2-yr study were plotted against the latitude of origin of each cultivar (Fig. 3.3). This showed a significant relationship with cutting management. This is an indication that delayed maturity along with cutting management might be responsible for the yield advantage seen with lowland cultivars. The relationship was similar to the relationship found by Sanderson et al. (1999a) in TX, with the exception that our data had a lower relationship compared to their findings. This difference could be due to our broader range of environmental conditions compared to the ones studied in TX.

Data across locations demonstrated that the lowland cultivars (Alamo and Kanlow) performed well at all locations. The reason for the poorer performance of the upland cultivars may be related to their response to photoperiod and timing of harvest as related to their developmental stage as indicated previously by Sanderson et al. (1999a). Maximum yields were mainly observed with the lowland cultivars, late-flowering ecotypes that have an extended duration of vegetative growth. This is an indication that moving northern adapted cultivars (upland ecotypes generally) to lower latitudes could trigger a more rapid flowering, and probably result in lower yield potentials.

Plotting the means of individual cultivars on a site yield variation index [calculated as the location mean minus the grand mean (Eberhart and Russel, 1996)] indicated that Alamo and Kanlow were more stable across locations [Slope (b_1) ≥ 1] than CIR and Shelter under both cutting managements (Fig. 3.4). Cave-in-Rock did not have a response to location under either cutting system, while Shelter slightly improve performance with the two-cut system. This supports findings discussed earlier, in which the upland cultivars had an improved performance under the two-cut system. Data suggest that the upper Southeast USA has a great window to utilize lowland switchgrass cultivars in a multipurpose cropping system that will satisfy biofuels feedstock availability in the region. These recommendations might not hold true for all the geographic regions where soils and microclimatic conditions could play a major role, since Stout (1992) indicated that soil physical and chemical properties can affect switchgrass productivity in the northeastern USA. The dramatic differences between two closely located sites in VA (VA₁ and VA₂) certainly bear this out.

CONCLUSIONS

Switchgrass demonstrated high productivity across a wide geographic region in the upper Southeast USA. Alamo and Kanlow (lowland ecotype) produced higher yields in the upper Southeast than two upland cultivars.

Differences in yield among cultivars were mainly related to cutting management and ecotype. The results indicate that both switchgrass ecotypes can be sustainably harvested once or twice per year in the upper Southeast. For the upland ecotype, a two-cut system will maximize yields without affecting stand persistence. For the lowlands, a single cut at the end of the growing season will provide maximum yields. Yield differences among cultivars at each location suggest that management may need to be site-specific.

Ecotype, cultivar, cutting management, and location have been shown to be important factors in switchgrass biomass production. Total seasonal yields increased with two cuts, especially for upland cultivars. Lowland ecotypes were shown to have a broader response to cutting management and higher biomass yields. Effects of cutting management on plant morphology could be observed in stand density. Although stand thickness will not always be related to biomass production, a good stand may enhance the competitive status in the ecosystem to which it is adapted. There was an excellent performance of the lowland ecotypes under the different microclimates found in this study.

Incorporating switchgrass into an energy system could lead to major improvements in the sustainability of agroecosystems. Developing harvest management practices that maximize yield, with the least impact on environmental quality and with the greatest economic return, will require a greater understanding of the interaction between the environment, ecotypes, and soil dynamics. Further testing of these and other cultivars under a combination of cutting frequencies and N fertilization rates should be performed in the upper Southeast. This will establish how these variables may affect switchgrass development and persistence. The results of these studies could also be used to develop an index of selection for cultivars and sites that will maximize biofuels production and help identify new cultivars or lines more adapted to the upper Southeast.

LITERATURE CITED

- Alderson, J., and W. C. Sharp. 1994. Grass varieties in the United States. USDA Handbook No. 170. CRC Press, Boca Raton, FL.
- Anderson, B., and A. G. Matches. 1983. Forage yield, quality and persistence of switchgrass and caucasian bluestem. *Agronomy J.* 75: 119-124.
- Balasko, J. A., D. M. Burner, W. V. Thayne. 1984. Yield and quality of switchgrass grown without soil amendments. *Agronomy J.* 76: 204-208.
- Cuomo, G. J., B. A. Anderson, L. J. Young, and W. W. Wilhem. 1996. Harvest frequency and burning effects on mono-cultures of three warm-season grasses. *J. Range Manage* 49: 157-162.
- Dwyer, D. D., W. C. Elder, and G. Singh. 1963. Effects of height and frequency of clipping on pure stands of range grasses in North Central Oklahoma. *Oklahoma Agric. Exp. Stn. Bull.* B-614.
- Eberhart, S. A., and W. A. Russell. 1966. Stability parameters for comparing varieties. *Crop Sci.* 6: 36-40.
- Elbersen, H. W., D. G. Christian, N. El Bassen, W. Bacher, G. Sauerbeck, E. Aleopoulou, N. Sharma, I. Piscioneri, P. De Visser, and D. Van Den Berg. 2001. Switchgrass variety choice in Europe. *Aspects of Applied Biology* 65: 21-28.
- Hopkins, A. A., C. M. Taliaferro., C. D. Murphy, and D. Christian. 1996. Chromosome number and nuclear DNA content of several switchgrass populations. *Crop Sci.* 36: 1192-1195.
- Hultquist, S. J., K. P. Vogel, D. J. Lee, K. Arumuganathan, and S. Kaeppler. 1996. Chloroplast DNA and nuclear DNA content variations among cultivars of switchgrass *Panicum virgatum* L. *Crop Sci.* 36: 1049-1052.
- Lemus, R., E. C Brummer, K. J. Moore, N. E. Molstad, C. L. Burras, and M. F. Baker. 2002. Biomass yield and quality of 20 switchgrass populations in southern Iowa, USA. *Biomass and Bioenergy* 23: 433-442.
- Metcalfe, P. and M. J. Bullard. 2001. Life cycle analysis of energy grasses. *Aspects of Applied Biology* 65: 29-37.
- Moore, K. J., L. E. Moser, K. P. Vogel, S. S. Waller, B. E. Johnson, and J. F. Pedersen. 1991. Describing and quantifying growth stages of perennial forage grasses. *Agron J.* 83: 1073-1077.

- Parrish, D. J., D. D. Wolf, and W. L. Daniels. 1996. Switchgrass as biofuels crop for the upper Southeast: Variety trial and cultural improvement. Annual report to Oak Ridge National Laboratory, Biofuels Feedstock Development Program, 44 p.
- Parrish, D. J., and D. D. Wolf. 1993. Switchgrass as a biofuels crop for the upper Southeast. P. 248-253. In: Proc. Biomass Conf. of the Americas, 1st, Burlington, VT. 30 Aug-2 Sept. 1993. Natl. Renewable Energy Lab., Golden, CO.
- Sanderson, M. A., R. L. Reed, W. R. Ocumpaugh, M. A. Hussey, G. Van Esbroeck, J. C. Read, C. R. Tischler, and F. M. Hons. 1999a. Switchgrass cultivars and germplasm for biomass feedstock production in Texas. *Bioresource Technology* 67: 209-219.
- Sanderson, M. A., J. C. Read, and R. L. Reed. 1999b. Harvest management of switchgrass for biomass feedstock and forage production. *Agron. J.* 91: 5-10.
- Sanderson, M. A., R. L. Reed, S. B. McLaughlin, S. D. Wulschleger, B. V. Conger, D. J. Parrish, D. D. Wolf, C. Taliaferro, A. A. Hopkins, W. R. Ocumpaugh, M. A. Hussey, J. C. Read, and C. R. Tischler. 1996. Switchgrass as a sustainable bioenergy crop. *Bioresource Technology* 56: 83-93.
- SAS[®] User's Guide: Statistics, Version 8.02. 2003. SAS Institute Inc., Cary, NC.
- Steel, R. G. D., and J. H. Torrie. 1980. Principles and procedures of statistics. 2nd ed. McGraw Hill, New York.
- Stout, W. L. 1992. Water-use efficiency of grasses as affected by soil, nitrogen, and temperature. *Soil Sci. Am. J.* 56: 897-902.

Table 3.1. Location, elevation, soil series, pH, and class capability of sites where switchgrass varieties were evaluated as a biofuels crop in 2000 and 2001.

State	Town	Location		Elev.	Soil Series	pH
		Lat. N	Long. W			
		--Degree, Min-	-m-			
KY	Princeton	37°06'	87°49'	173	Tilsit, 2 to 6% slope (Fine-silty, mixed, mesic, Ultic, Hapludalf)	6.8
NC	Raleigh	35°43'	78°40'	120	Cecil, 5 to 10% slope (Clayey, kaolinitic thermic, Typic Kanhapludult)	6.3
TN	Jackson (TN ₁)	35°37'	88°55'	120	Deanburg, 2 to 5% slope (Fine-loamy, mixed, thermic, Ultic Hapludalf)	5.7
	Knoxville (TN ₂)	35°53'	83°57'	250	Etowah, 5 to 12% slope (Fine-loamy, siliceous, thermic, Typic Paleudult)	5.5
VA	Blacksburg Site A (VA ₁)	37°11'	80°25'	600	Chatter, 2 to 5% slope (Clayey, kaolinitic, mesic, Typic Paleudult)	6.2
	Site B (VA ₂)				Shottower, 10 to 15 % (Clayey, kaolinitic, mesic, Typic Paleudult)	6.2
	Orange (VA ₃)	38°13'	78°07'	156	Davidson, 10% slope (Clayey, kaolinitic, thermic, Rhodic Kandudult)	5.6
WV	Morgantown	39°37'	79°55'	378	Dormont, 2 to 5% slope (Fine-loamy, mixed, mesic, Ultic, Hapludalf)	6.2

Table 3.2. Description of switchgrass cultivars evaluated at eight locations in the upper Southeast USA in 2000 and 2001. (CIR = Cave-in-Rock).

Cultivar	Ecotype ¹	Ploidy level ¹	Origin ²	Released	
				Year ²	By ²
CIR	Upland	Octaploid	Southern Illinois	1973	NRCS PMC, Elsberry, MO
Shelter	Upland	Octaploid	St. Mary's, WV	1986	NRCS PMC, Big Flats, NY
Alamo	Lowland	Tetraploid	South Texas	1978	NRCS PMC, Kox City, TX
Kanlow	Lowland	Tetraploid	Central Oklahoma	1963	NRCS PMC, Manhattan, KS

¹Hultquist et al. (1996) and Hopkins et al. (1996).

²Alderson and Sharp (1994).

Table 3.3. Analysis of variance and mean squares for switchgrass biomass yields in response to two cutting managements during the growing season in 2000 and 2001 at eight different locations in the upper Southeast USA.

Source	df	Mean Square	F Value
Block (Blk)	3	19.7	4.0
Year (Yr)	1	13.3	0.6
Location (Loc)	7	434.3	18.1*
Yr*Loc	7	123.6	5.1*
Error a	45	24.0	--
Cut	1	363.1	73.5*
Yr*Cut	1	150.1	30.4*
Loc*Cut	7	77.6	15.7*
Yr*Loc*Cut	7	29.5	6.0*
Cultivar (Cul)	3	387.6	78.4*
Yr*Cul	3	5.1	1.0
Loc*Cul	21	25.6	5.2*
Yr*Loc*Cul	21	11.9	2.4*
Cut*Cul	3	143.7	29.1*
Yr*Cut*Cul	3	5.6	1.1
Loc*Cut*Cul	21	11.7	2.4*
Yr*Loc*Cut*Cul	21	9.7	2.0*
Error b	336	4.9	--

Table 3.4. 2000, 2001, and long-term rainfall and mean temperature data for April through September (A-S) near sites on which switchgrass was grown in the upper Southeast USA. Departure from long-term (30-yr) normal is observed values minus long-term values.

Location	Long-term	Observed		Departure from Long-term	
	A-S	2000	2001	2000	2001
----- Precipitation (cm) -----					
KY	64.3	62.1	62.2	-2.2	-2.1
NC	58.6	101.3	78.3	42.7	19.7
TN ₁	57.9	74.0	63.3	16.1	5.4
TN ₂	65.6	54.2	60.5	-11.4	-5.1
VA _{1,2}	51.6	66.2	61.9	14.6	10.3
VA ₃	58.7	62.3	53.4	3.6	-5.3
WV	58.5	62.6	62.0	4.1	3.5
Mean	59.3	69.0	63.1	9.6	3.8
----- Mean Temperature (°C) -----					
KY	21.6	25.7	22.3	4.2	0.8
NC	18.7	24.2	21.6	5.5	2.9
TN ₁	21.0	23.8	21.2	2.9	0.2
TN ₂	22.1	25.6	22.7	3.5	0.5
VA _{1,2}	17.8	20.4	18.0	2.6	0.2
VA ₃	20.0	22.4	19.9	2.4	-0.1
WV	18.5	20.4	18.3	1.9	-0.2
Mean	19.9	23.2	20.6	3.3	0.6

Table 3.5. Effect of cutting management, year, and cultivar on yield of switchgrass grown at eight locations in upper Southeast USA. (CIR = Cave-in-Rock).

Cut	Year	Cultivar	Location								Mean	LSD _{0.05} ²
			KY	NC	TN ₁	TN ₂	VA ₁	VA ₂	VA ₃	WV		
Once	2000	Alamo	15.5	14.7	7.8	20.8	9.5	17.1	19.8	15.5	15.1	4.5
		CIR	10.1	10.5	8.3	14.4	14.2	11.9	15.0	13.6	12.2	3.1
		Kanlow	16.4	14.8	11.0	15.5	11.1	18.9	16.6	18.3	15.3	3.7
		Shelter	8.4	8.3	7.9	11.8	10.3	12.0	11.2	12.8	10.3	3.0
		Mean	12.6	12.1	8.7	15.6	11.3	15.0	15.6	15.1	13.2	2.0
		LSD _{0.05} ¹	2.3	3.7	2.8	3.1	4.2	4.9	5.2	3.4	1.4	--
	2001	Alamo	13.6	7.4	11.6	24.9	10.6	27.4	17.6	18.2	16.4	4.9
		CIR	13.2	6.2	8.2	13.8	9.6	18.4	12.6	15.7	12.2	3.6
		Kanlow	14.8	6.9	12.7	22.4	13.7	22.2	20.0	20.5	16.8	5.3
		Shelter	10.6	5.1	8.7	11.2	9.7	11.7	12.2	16.7	10.7	3.4
		Mean	13.1	6.4	10.3	18.1	10.9	19.9	15.6	17.8	14.0	2.4
		LSD _{0.05} ¹	3.1	1.8	3.0	4.7	3.6	8.0	6.4	3.2	1.7	--
	Mean		12.8	9.2	9.5	16.9	11.1	17.4	15.6	16.4	13.6	2.1
	Twice	2000	Alamo	17.0	16.7	10.2	16.9	15.8	22.4	20.4	15.2	16.8
CIR			13.4	16.7	14.2	16.7	17.2	20.5	19.6	16.4	16.8	3.3
Kanlow			15.8	15.7	11.7	14.1	16.1	21.3	19.4	15.4	16.2	3.7
Shelter			11.4	13.9	9.8	14.2	16.8	17.4	15.7	14.3	14.2	3.6
Mean			14.4	15.7	11.5	15.5	16.5	20.4	18.7	15.3	16.0	1.8
LSD _{0.05} ¹			2.5	1.9	ns	1.9	ns	3.2	ns	0.8	1.2	--
2001		Alamo	15.2	9.7	16.6	17.9	13.7	19.7	15.1	13.0	15.1	4.6
		CIR	13.6	10.2	16.9	17.0	14.6	16.7	15.5	15.7	15.1	3.4
		Kanlow	14.7	9.1	15.5	15.0	16.5	19.9	14.2	13.8	14.8	4.4
		Shelter	10.7	8.8	12.9	15.2	13.2	18.0	13.6	14.7	13.4	3.0
		Mean	13.6	9.5	15.5	16.3	14.5	18.6	14.6	14.3	14.6	1.9
		LSD _{0.05} ¹	1.7	ns	ns	2.4	3.2	ns	ns	1.4	1.3	--
Mean		14.0	12.6	13.5	15.9	15.5	19.5	16.7	14.8	15.3	0.9	
LSD _{0.05} ³		ns	1.9	1.7	ns	1.2	ns	ns	1.2	1.3	--	

¹LSD for comparison of cultivars within cut, year, and location; ²LSD for comparison of locations within a cut, year, and cultivar; ³LSD for comparison of means between cutting managements.

Table 3.6. Effect of cutting management and cultivar on yield of switchgrass grown at eight locations in upper Southeast USA. Data are averaged across 2 yr. (CIR = Cave-in-Rock).

Cut	Cultivar	Location								Mean	LSD _{0.05} ²
		KY	NC	TN ₁	TN ₂	VA ₁	VA ₂	VA ₃	WV		
----- Yield (Mg ha ⁻¹) -----											
Once	Alamo	14.5	11.0	9.7	22.8	10.1	22.2	18.7	16.9	15.7	4.1
	CIR	11.7	8.3	8.3	14.1	11.9	15.1	13.8	14.7	12.2	2.9
	Kanlow	15.6	10.9	11.9	19.0	12.4	20.6	18.3	19.4	16.0	3.7
	Shelter	9.5	6.6	8.3	11.5	10.0	11.8	11.7	14.7	10.5	2.3
	LSD _{0.05} ¹	2.1	3.7	2.1	3.3	2.8	5.3	3.8	2.5	1.6	--
Twice	Alamo	16.1	13.2	13.4	17.4	14.7	21.1	17.7	14.1	16.0	3.7
	CIR	13.5	13.4	15.6	16.8	15.9	18.6	17.5	16.0	15.9	2.8
	Kanlow	15.2	12.4	13.6	14.5	16.3	20.6	16.8	14.6	15.5	3.1
	Shelter	11.0	11.3	11.4	14.7	15.0	17.7	14.6	14.5	13.8	2.5
	LSD _{0.05} ¹	1.4	ns	4.1	ns	2.6	ns	2.1	1.0	1.3	--

¹LSD for comparison of cultivars within a cut and location.

²LSD for comparison of locations within each cut and cultivar

Table 3.7. Effect of harvest date (first and second harvest) and cultivar on switchgrass yields grown at eight locations across upper Southeast USA under two-cut management. Data are averaged across 2 yr. (CIR = Cave-in-Rock).

Harvest	Cultivar	Location								Mean	LSD _{0.05} ²
		KY	NC	TN ₁	TN ₂	VA ₁	VA ₂	VA ₃	WV		
----- Yield (Mg ha ⁻¹) -----											
June (first)	Alamo	7.1	8.9	7.7	10.4	6.8	9.3	7.8	7.7	8.2	2.1
	CIR	8.2	8.9	10.7	11.7	9.3	10.7	9.7	10.7	10.0	2.1
	Kanlow	8.3	8.7	9.0	9.8	8.5	10.3	9.1	9.4	9.1	2.0
	Shelter	6.3	7.6	8.0	10.4	8.9	10.0	8.6	10.0	8.7	1.9
	Mean	7.5	8.5	8.8	10.6	8.3	10.1	8.8	9.4	9.0	1.7
	LSD _{0.05} ¹	1.2	0.8	2.7	1.0	0.8	1.2	1.0	0.6	0.5	--
November (second)	Alamo	9.0	4.3	5.7	7.0	7.9	11.8	9.9	6.4	7.8	2.4
	CIR	5.3	4.6	4.9	5.2	6.6	7.9	7.9	5.3	6.0	1.8
	Kanlow	6.9	3.7	4.6	4.7	7.8	10.3	7.7	5.2	6.4	2.4
	Shelter	4.7	3.7	3.3	4.3	6.1	7.7	6.1	4.5	5.1	1.4
	Mean	6.5	4.1	4.6	5.3	7.1	9.4	7.9	5.4	6.3	1.8
	LSD _{0.05} ¹	1.1	0.9	1.4	0.5	1.4	1.4	1.6	0.7	0.5	--
LSD _{0.05} ³		0.4	1.4	1.2	1.0	ns	ns	ns	1.3	0.4	--

¹LSD for comparison of cultivars within a harvest and location.

²LSD for comparison of locations within a harvest and cultivar.

³LSD for comparison of means within a location.

Table 3.8. Effect of ecotype and cutting management on yield of switchgrass at eight locations across upper Southeast USA. Data are averaged across two cultivars and 2 yr.

Ecotype	Cut	Location								Mean	LSD _{0.05} ²
		KY	NC	TN ₁	TN ₂	VA ₁	VA ₂	VA ₃	WV		
Yield (Mg ha ⁻¹)											
Lowland	Once	15.1	11.0	10.8	20.9	11.2	21.4	18.5	18.1	15.9	2.7
	Twice	15.7	12.8	13.5	16.0	15.5	20.8	17.2	14.3	15.7	2.3
	Mean	15.4	11.9	12.2	18.5	13.4	21.1	17.9	16.2	15.8	1.9
	LSD _{0.05} ¹	ns	ns	2.6	2.7	1.9	ns	ns	1.6	ns	--
Upland	Once	10.6	7.5	8.3	12.8	11.0	13.5	12.7	14.7	11.4	1.9
	Twice	12.2	12.4	13.5	15.8	15.4	18.2	16.1	15.3	14.9	2.0
	Mean	11.4	10.0	10.9	14.3	13.2	15.9	14.4	15.0	13.1	1.6
	LSD _{0.05} ¹	1.6	21.2	1.7	1.3	1.3	2.3	1.7	ns	0.7	--
	LSD _{0.05} ³	1.0	ns	ns	1.7	ns	2.2	2.3	1.2	0.8	--

¹LSD for comparison of cuts within a location.

²LSD for comparison of locations within an ecotype and cut.

³LSD for comparison of means within a location.

Table 3.9. Stand density ratings (0 = least dense, 10 = most dense) in November 2001 for four switchgrass cultivars grown at seven locations in upper Southeast USA when harvested once (in November) or twice (mid-summer and November). (CIR = Cave-in-Rock).

Cut	Cultivar	Location								Mean	LSD _{0.05} ²
		KY	NC	TN ₁	TN ₂	VA ₁	VA ₂	VA ₃	WV		
----- Stand Rating (0 to 10) -----											
Once	Alamo	9.8	6.8	6.2	7.0	4.8	2.9	6.2	8.0	6.4	2.6
	CIR	9.5	7.8	8.0	6.5	6.6	4.2	7.1	5.5	6.9	1.6
	Kanlow	10.0	8.2	8.2	7.5	6.8	3.5	6.6	9.5	7.5	1.9
	Shelter	8.2	6.8	8.2	7.2	7.0	3.9	5.6	6.5	6.6	2.4
	Mean	9.4	7.4	7.7	7.0	6.3	3.6	6.4	7.4	6.9	0.8
	LSD _{0.05} ¹	1.1	ns	ns	ns	1.0	ns	ns	2.3	0.6	--
Twice	Alamo	10.0	9.5	8.8	9.2	9.8	8.6	8.9	10.0	9.4	0.9
	CIR	10.0	9.5	9.2	9.5	9.6	8.6	9.2	8.5	9.2	1.0
	Kanlow	10.0	8.8	9.0	9.8	10.0	9.3	9.6	9.5	9.5	1.2
	Shelter	10.0	9.2	9.5	9.8	9.8	9.1	9.1	9.8	9.5	0.7
	Mean	10.0	9.2	9.1	9.6	9.8	8.9	9.2	9.4	9.4	0.4
	LSD _{0.05} ¹	ns	0.5	ns	ns	ns	ns	ns	0.8	ns	--
LSD _{0.05} ³		0.4	0.7	1.1	1.3	0.4	0.6	0.9	0.9	0.3	--

¹LSD for comparison of cultivars within a cut and location.

²LSD for comparison of locations within each cut and cultivar.

³LSD for comparison of cuts within a location.

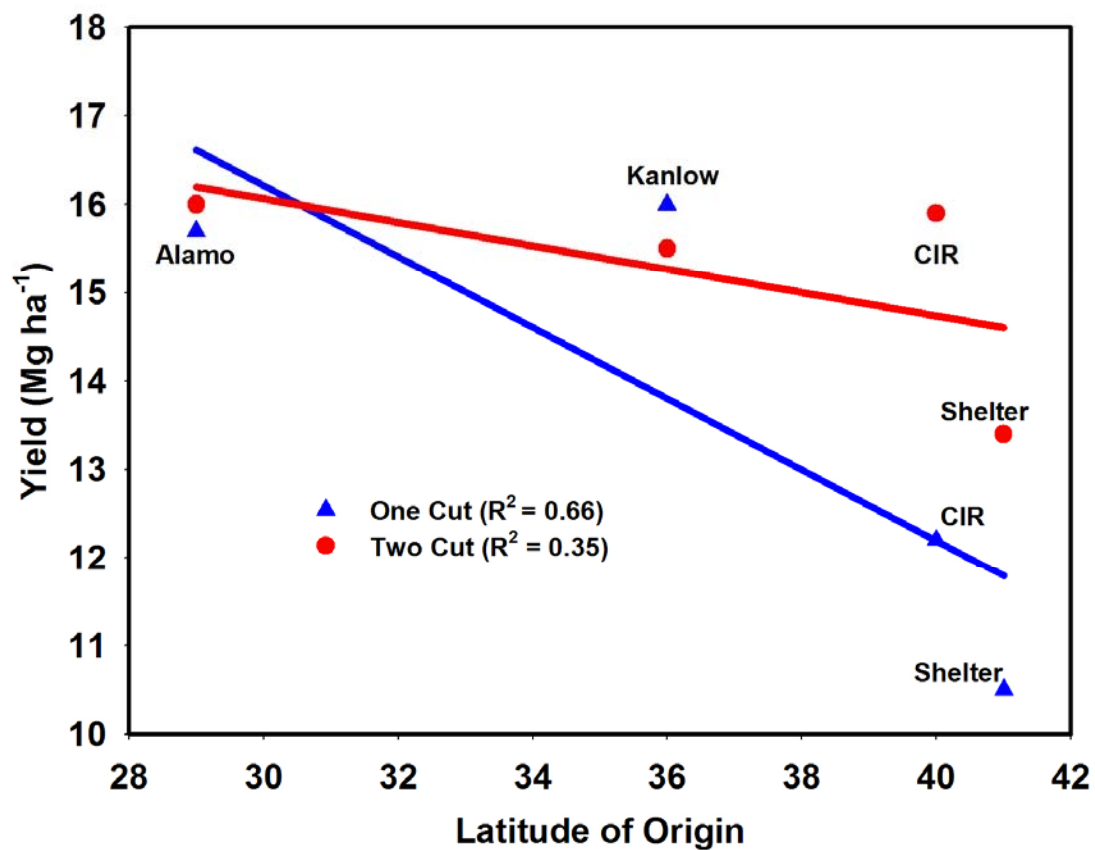


Fig. 3.3. Relationship between latitude of origin and yield of four switchgrass cultivars and biomass yields under two cutting systems in the upper Southeast USA. Data are the switchgrass cultivars averages from Table 3.5.

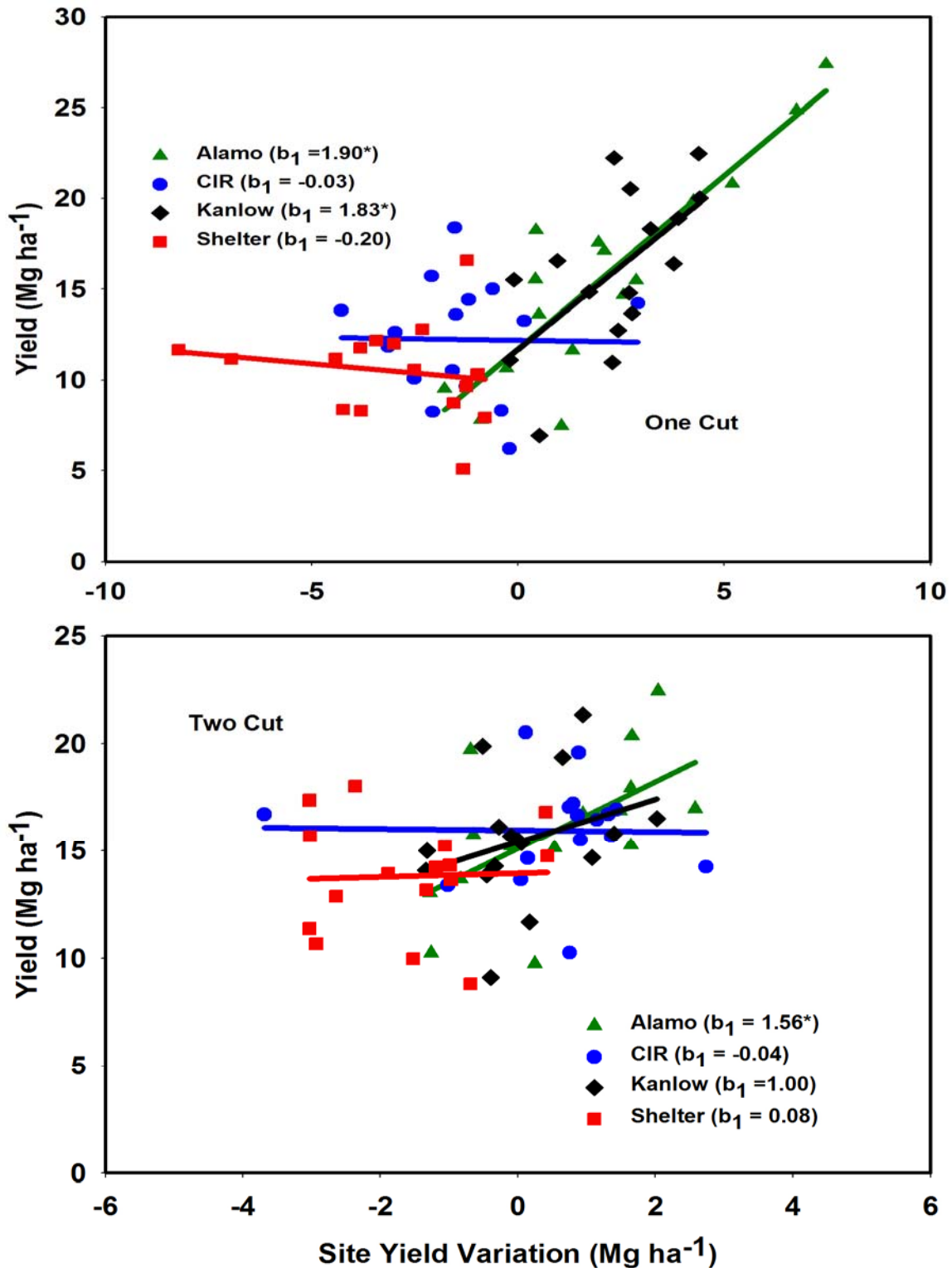


Fig. 3.4. Regression of switchgrass cultivars means at each location on an environmental site yield variation for one- or two-cut systems. Site yield variation was calculated as the cultivar mean at each location minus the location grand mean. (Eberhart and Russell, 1996).

CHAPTER 4

YIELD OF AND NUTRIENT REMOVAL BY 'ALAMO' SWITCHGRASS AS AFFECTED BY CUTTING MANAGEMENT

ABSTRACT

Field studies were conducted in 2000 and 2001 to examine the yield of and nutrient removal by Alamo switchgrass (*Panicum virgatum* L.) grown at eight locations in the upper Southeast USA. Plots were cut either once (in early November) or twice (mid-summer and in November). Partition of nutrients into leaf and stem fractions was determined at the time of the first harvest in 2000. Biomass production during 2000 and 2001 averaged approximately 16 Mg ha⁻¹ yr⁻¹ and was as high as 21.7 Mg ha⁻¹ at one site. Nitrogen removal with the two-cut system was much higher than with a single cut because of the higher N content in the first, midsummer harvest of actively growing, vegetative tissue. Removal over 2 yr showed twice as much N removed with the two-cut system as with the one-cut system. Annual N removal exceeded the amounts of N applied, suggesting N was being supplied via mineralization and or other processes. Phosphorus removal also increased significantly with the two-cut management. Potassium and Ca removal were similar between the two cutting managements. Tillers sampled in June were about 60% leaf and 40% stem. Nitrogen and P concentrations generally declined basipetally, with older leaves and internodes having lower concentrations. Potassium was more uniformly distributed than N throughout the tiller components (leaf and stem). Calcium was highest for older leaf blades. Adequate levels of soil P, K, and Ca at most locations were not limiting biomass production and were adequate for long-term productivity.

INTRODUCTION

In the previous chapter, we looked at performance, production, and adaptability of several switchgrass cultivars over a range of environments. In this chapter, we shall look more closely at the performance of one cultivar.

Alamo switchgrass is native to TX in the southwestern USA and is a tetraploid ($2n = 4x = 36$). lowland ecotype (Hultquist et al., 1996; Hopkins et al., 1996). Alamo has been predominantly used in the southern region because of its long vegetative growth (flowers one or two months later than Cave-in-Rock) and tolerance of wet environments (Lemus et al., 2002a). Alamo is considered a good forage producer, with moderate tolerance to salinity, and grows well in most soils when it receives 63 cm or more annual precipitation (Alderson and Sharp, 1995).

Producing economically competitive bioenergy depends on keeping production costs low. High productivity with low inputs is obviously desirable. Biomass with low mineral content is also preferred for bioenergy production, especially with regards to nitrogen (N), potassium (K), and calcium (Ca). Those three elements are of major interest in combustion processes due to their potential for producing air pollution (NO_x) and the alkali minerals potential for corrosion, ash slagging, and fouling (Jorgensen, 1997). However, these and other elements are important nutrients required for optimal plant growth and biomass yield.

Knowing the quantity of nutrients removed by the biomass can be helpful in determining fertilization needs for yield sustainability and nutrient management in bioenergy crops. The suitability of switchgrass as a biomass crop could be enhanced if nutrient management could be designed to avoid soil nutrient deficiencies that impair future optimum yield and stand persistence. Among other things, harvest management is essential to maintaining switchgrass stand and yields; but it also affects nutrient removal and subsequent nutrient availability.

Extensive evidence had shown that the key soil nutrient for biomass production is N (Jacobsen et. al., 1996). Nitrogen fertilization has been shown to

increase production in many settings (McLaughlin et al., 1997), but no measurements have been made of P, Ca, and K removal and how depletions of these nutrients could affect biomass yield under different cutting management systems.

Most fertility recommendations for switchgrass are based on its use in forage production or grazing systems, where the aim is to find a compromise between maximum forage quality and maximum biomass production (Muir et al., 2001). Achieving this balance should presumably not be necessary for bioenergy production, since the main goal in energy cropping is to increase lignocellulosic material (Muir et al., 2001). Typical recommendations of N applications for switchgrass (50 to 90 kg ha⁻¹) are considered very low relative to many other crops (Bredja, 2000). Phosphorus fertilizer recommendations for switchgrass range from 0 to 35 kg ha⁻¹ yr⁻¹, depending on the soil supplying capability, soil pH, and soil test data (Bredja, 2000). While there have been reports of responses to P fertilization in low-P soils in TX, the information on switchgrass P responses is minimal (Mangaroo, 1983). Many soils in the upper Southeast are moderate in available P, which suggests minimal need for P fertilization (Parrish et al., 2002).

Few data are available on the productivity of Alamo switchgrass grown in the upper southeastern USA, especially on “marginal” sites with low nutrient inputs. The objectives of this study, then, were to: (1) determine the influence of nutrient availability on Alamo biomass production and its nutrient content, and (2) measure nutrient removal by Alamo switchgrass under adequate levels of fertilization.

MATERIALS AND METHODS

This study, which is an expanded subset of the study described in the previous chapter, was conducted during 2000 and 2001 on Alamo switchgrass stands planted in 1992 at eight sites across five states in the upper Southeast

(Table 3.1). Experimental plots were 6.1 x 2.4 m. The study employed two harvest/management systems. Plots were cut either once (in early November) or twice (mid-summer and in early November). First harvest in the two-cut system was taken in mid-summer when the Alamo switchgrass was at the jointing stage. A 1-m wide strip was harvested from the center of each plot at a height of 10 cm using a flail-type forage harvester (Carter Manufacturing Co., Brookston, IN) equipped with an electronic scale. Biomass subsamples were collected and dried at 60°C in forced air for 48 hr for dry matter determination. Border material in harvested plots was mowed and residue removed after each harvest.

Nitrogen fertilizer had been applied annually to these plots beginning in 1993. For the one-cut management, fertilizer was applied in May at 50 kg N ha⁻¹. The two-cut management received a split application, with 50 kg N ha⁻¹ applied in May and 50 kg N ha⁻¹ applied immediately after the first cut. Potassium and phosphorus were applied as needed to reach a moderate level of fertility based on soil test recommendations from each geographic location. Rates of P and K applied since the year of establishment are presented in Table 4.1. No limestone needed to be applied at any location.

Subsamples of the biomass harvested in midsummer and November of 2000 and 2001 were used for tissue analysis. Elemental analyses included N, P, K, and Ca. Tissue samples were oven dried at 60 °C for 48 h and ground in a Wiley Mill (Thomas Manufacturing, Philadelphia, PA) to pass a 8-mm screen and then in a UDY Cyclone Mill (UDY Corp., Fort Collins, CO) to pass a 1-mm screen. Samples of homogenized tissue were stored in sealed plastic bottles until analyses were performed. Plant tissue was ashed at 550 °C for 4 h, and the ash was eluted with 5 mM HCL (Basta and Tabatabai, 1985). Samples were filtered and analyzed for P, K, and Ca using the ICP mass spectrometry unit at the Virginia Tech soil testing lab. Total N was determined on non-ashed samples using the Kjeldahl procedure for measuring total sample N (Bremner and Breitenbeck, 1983). Quantities of elements removed in biomass were determined by multiplying aboveground biomass yield by the element concentration in plant tissue.

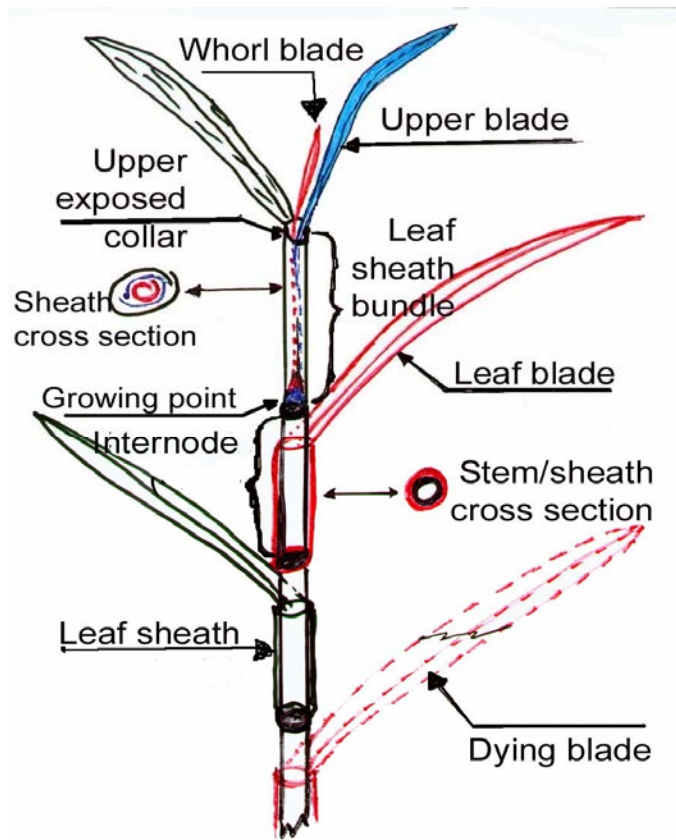


Fig. 4.1. Schematic of switchgrass tiller (drawing by Dale Wolf).

Ten switchgrass tillers (in a mid-boot growth stage) per plot were randomly collected from two-cut management plots at the KY, TN1, TN2, VA1, VA2, and VA3 sites at the time of the first harvest in June 2000. Tillers were separated into leaf and culm (stem). Each leaf, with a fully exposed collar, was separated into blade and sheath components (Fig. 4.1). Sheaths of leaves with exposed collars were combined. The first leaf was always attached to the uppermost palpable node. Within the sheath of this leaf were the growing point and newly developing, partially exposed leaves. Because of difficulty in separating the parts within this bundle of sheaths, one of the component parts was collectively called the “upper bundle of sheaths” and included the sheath from the leaf with the first exposed collar, the growing point, possibly some leaves that had not begun to expand, and sheaths of the whorl leaves. There

were generally two new leaf blades emerging from the uppermost bundle of leaf sheaths, and these are referred to as “whorl” leaf blades. The first leaf was attached to the top of first internode. Thus, internode (stem portion) number one was immediately below the growing point (between the uppermost two palpable nodes). Only the upper three fully expanded leaves and upper three internodes were considered, even though some tillers had four or five leaves and internodes. The rationale for this was based on the assumed synchrony in the younger developing tissues.

Tissue was dried (in moving air at 60 °C for 48 h) and weighed to determine weight proportions and total tiller mass. Tissue was ground and tested as above for P, K, and Ca concentrations using the ICP mass spectrometry unit at the Virginia Tech soil testing lab. Total N was determined using Kjeldahl procedures as above. Elemental concentrations of leaf, stem, and whole tiller were calculated using weighted values of mass and concentration. Soil samples (0 to 10 cm) were also collected from each plot in which tillers were sampled in June 2000. Soil P concentrations were obtained using the Melich I soil testing procedure (Donahue, and Heckendorn, 1994).

Soil samples were collected in 2001 at the end of the growing season from each cutting management to a depth of 15 cm with a Hoffer tube (1 cm diameter). Five cores per plot were collected, composited, and analyzed for P, K, and Ca using the ICP mass spectrometry unit at the Virginia Tech soil testing lab. Soil P concentrations were obtained using the Melich I soil testing procedure (Donahue and Heckendorn, 1994). Soil nutrient values were compared to soil values previously collected in 1992 (prior to switchgrass establishment), 1996 and 1998 (Parrish et al., 2002).

The experimental design at each location was a randomized complete block replicated four times with two cutting treatments. Yield data were analyzed as a split-plot in which years and locations were considered the main plots and cutting managements were considered the subplots. For total nutrient removal and soil nutrient analyses, years were considered blocks. The locations were considered the main plots and cutting managements the subplots. For tiller

nutrient analyses, only two replications at each location were used. Soil test and yield data from each location were averaged over replications. Mean separation was by the protected Least Significance Difference (LSD) test at $P < 0.05$. All statistical analyses were conducted by SAS General Linear Model procedure (SAS, 2003).

RESULTS AND DISCUSSION

Climatic Effects

Weather conditions during the growing season varied between years, but switchgrass productivity was minimally affected. The April to September precipitation, when most switchgrass growth occurred, had relatively small deviations from long-term means in both years (Table 3.4). The long-term average rainfall at each location between April and September showed that precipitation was somewhat below normal at KY and TN1 in both years and at VA3 in 2000. North Carolina had the highest amounts of precipitation in both years. Temperatures higher than normal temperatures were observed at most locations in 2000 (Table 3.4).

An analysis of yields versus growing season rainfall (April thru September) showed no significant correlations for either the one-cut or two-cut management when considering data for all eight locations in 2000 and 2001 (data not shown). Since switchgrass does not develop foliage to use soil water until late April (Knapp et al., 1985), there is usually adequate moisture in the soil profile to sustain growth without drought stress at least through the first portion of the growing season.

Biomass Yields

Significant ($P < 0.05$) location x cutting management, location x year, cutting management x year, and location x cutting management x year interactions were observed for mean yields (Table 4.2). Biomass production during 2000 and 2001 averaged approximately 16 Mg ha⁻¹ (Table 4.3). Total Alamo biomass yields across the 2 yr and two cutting managements were higher in VA2 (21.7 Mg ha⁻¹) than at several other sites. The NC, TN1, and VA1 sites had generally lower yields.

When averaged across locations and years, there was no effect of cutting management on yield. This is to be expected for a lowland cultivar, based on findings from the previous chapter. Cutting effects were observed sporadically, e.g., in TN2 and VA1 in 2000, but not in 2001. In 2001, the two-cut management had a yield advantage in KY and NC, but the single cut produced more yield in TN2 and WV. Yields in NC in 2001 were significantly lower than the rest of the locations. This was likely related to the weather conditions, where high precipitation (78 cm) and winds in mid-June caused lodging at the boot stage.

Nutrient Concentrations in Biomass

A location, cutting management, and harvest date effect was observed for each nutrient concentration with the exception of Ca, where no harvest date effect was observed (Table 4.4). No location x cutting management or location x harvest date interactions were observed for any nutrient.

Nitrogen is necessary for—among other vital processes—chlorophyll synthesis; and, as a part of the chlorophyll molecule and chloroplast enzymes, it is vitally involved in photosynthesis. It is especially important in plant regrowth and protein formation. The concentration of N in biomass differed between locations among cutting managements (Table 4.6). A higher N level was present in the midsummer harvest versus the senescent November biomass in the two-

cut system. In November, N concentrations were lower in the one-cut management than in the two-cut management. This could be due to more advanced senescence of the older tillers in the one-cut management. In the two-cut system, all tillers had been produced since July (versus April for the one-cut system). After the midsummer harvest, N reserves in the roots presumably would have to be used to support biomass regrowth.

Phosphorus concentrations within biomass harvested from the two-cut system were lower in June when averaged across locations and years (Table 4.6), an indication that more soil P was being removed with that management, and perhaps reducing P availability. In November, tissue P concentrations were very similar between cutting managements, with a slight increase in the two-cut management. As with N, the increase may have been due to the fact that the November-harvested material was younger and less senescent in the two-cut system.

Potassium concentrations varied among harvests. Potassium concentrations were higher in June than in November under the two-cut system (Table 4.6). Mean K concentration across locations in November was higher for the one-cut management. This is consistent with the notion that K accumulates throughout the growing season but may be somewhat mobile (or leached) as leaves senesce and die.

Calcium concentrations in biomass were different between cutting managements (Table 4.6). Calcium concentrations were very similar in June and November harvests in the two-cut system, with a slight increase in the November biomass. When comparing the November harvests of each cutting management, higher Ca concentrations were observed in the two-cut system. This higher concentration in younger biomass was unexpected. Older leaves, i.e., those from one-cut management, might be expected to have higher Ca concentrations. The transpiration stream moves Ca into a leaf over the leaf's lifetime and should have moved more into the older leaves. However, in the one-cut system, most plants might be more senescent, and dead tissues may have been leached. This

difference in Ca concentrations was unlikely due to soil Ca depletion via biomass removal, since all the soils have a medium to high Ca availability.

Nutrient Removals via Biomass

Analysis of variance showed, as would be expected, that nutrient removal followed the same pattern observed with nutrient concentrations. Nutrient removal via biomass was calculated by multiplying nutrient concentration times yield. Cutting management clearly affected total nutrient removal (Table 4.5). Total K removal also reflected year x cutting management and location effects.

Total N removal was 51% greater with two cuts than with one cut (Table 4.6). Within the two-cut system, 64% of the N removal occurred during the midsummer harvest. At the time of the midsummer harvest, Alamo switchgrass is in a late vegetative stage, where its predominantly leafy vegetation has a higher N concentration. After the first cut, any N available to the plant (soil supply or root reserves) has to be allocated to new vegetative growth (organic components), which might be expected to reduce overall N accumulation in plant tissue. Removal of less N in biomass from the one-cut system than was applied might be due to senescence/translocation processes in the fall, leaching, and leaf loss as has been suggested by Parrish et al. (2002).

Phosphorus provides plants with, among other things, a means of using the energy harnessed by photosynthesis to drive its metabolism. Total P removal was 55% with the two-cut management (Table 4.6). A year x cut interaction showed also that total P removal was 45% higher in 2000 and 35%

higher in 2001 with two cuts than once cut (data not shown). Comparison of harvests for the two-cut system also showed that the larger portion of P removal occurred in the midsummer harvest. Comparisons of November harvests of each cutting management showed a 43% larger P removal under the one cut. This suggests greater P accumulation over the course of a longer leaf duration.

Potassium rivals N as the nutrient element absorbed in greatest amounts by plants. Like N, a relatively large proportion of plant-available K is taken up by crops each growing season. Total K removal was 25% greater with the two-cut system (Table 4.7). More K was removed than applied, indicating that soils at these study sites might have large pools of K available to the plants, possibly replenished from the cation exchange capacity. Year x cutting management and a location x cutting management interactions were observed for total K removal. Large differences in K removal were also observed within cutting managements. The midsummer harvest had a 62% greater K removal than the November harvest. Although large quantities of K could have been absorbed after the first cut, most of the K could have been utilized for cellular functions and making it difficult to measure. A location x cut interaction ($P < 0.05$) was also observed for total K removal (Table 4.8). Most of differences observed were among locations within each cutting management. No significant differences were observed between cutting managements within any specific location.

Calcium is essential for the proper functioning of plant cell walls and membranes. Total Ca removal differed among locations with larger removals in the two-cut system. Total Ca removal was 25% higher with two cuts than with one cut in 2000, but 49% lower than the one cut in 2001 (data not shown).

Differences in annual/cumulative transpiration (along with yield differences) might account for the year reversals in amount of Ca removed by each cutting management. When comparing the November harvests of both cutting systems, Ca removal was 18% greater under the two-cut system. These differences in November are a function of yield. Although higher Ca concentration was observed in the November harvest of the two-cut system, lower yields tended to decrease N removal.

Nutrient Partitioning/Concentrations within Biomass

Tillers of Alamo switchgrass in June were about 60% leaf and 40% stem, and the average weight of a tiller was about 3.8 g (Table 4.9). The whorl leaf blades and upper bundle of sheaths represented about 20% of the total tiller mass. Nutrient concentration and content of each tiller component were determined. Calculated concentrations of N, P, K, and Ca for the whole tiller were very similar to the concentrations found in the whole plant tissue taken at the midsummer harvest (Table 4.6).

Tiller N and P concentrations generally declined basipetally, with older leaves and internodes having less (Rao et al., 1996; Sharpley et al., 1993). Also, leaf blades had higher N, P, K, and Ca concentrations, leaf sheaths being intermediate, and internodes lower. Sampling the uppermost leaf blade with an exposed collar would be recommended for testing tissue N concentration for possible deficiencies, since the newly emerging whorl-leaf blades had slightly lower N than the uppermost fully expanded leaf blade. Sampling whorl leaves might cause more variability in values, since some leaf blades can be very long before the collar emerges. All leaf blades had similar P concentrations regardless of location. Sampling the uppermost fully expanded leaf blade would be suitable for testing tiller P concentration as well as N.

Potassium was more uniformly distributed than N throughout the tiller components. Leaf sheaths had the highest concentration, followed by the

internodes and the leaf blade. Potassium concentration decreased with the age of the leaf and internode, suggesting mobilization of K into younger tissue. The whorl leaf blades and the upper bundle of leaf sheaths had highest K levels. Due to the difficulty for defining and obtaining a sample above the upper-most leaf collar, the uppermost leaf blade would be recommended for testing tiller K concentration.

Calcium is a relatively immobile element once deposited, and the concentration that develops in tissue is largely dependent on the transpiration rate (White, 2001). Thus, Ca concentration was highest for older leaf blades. Calcium concentration in the leaf increased with age (and therefore longer transpiration duration). Since Ca is most likely to be limiting in regions of the tiller where cell division and expansion (above the growing point) are occurring, that is the tissue that should be sampled for diagnostic tests. The whorl leaf blades and the uppermost bundle of sheaths had the lowest Ca concentration and the least opportunity to accumulate Ca. Calcium dissolves in water and moves through the plant in the vascular system to the leaves. Leaves are the primary sink for movement of water. Under high moisture stress, the dissolved Ca and other minerals move rapidly to the leaves. This might result in a localized Ca deficiency. Also, fluctuations in soil moisture during periods of rapid plant growth can create moisture stress and limit Ca distribution to the plant.

When sampling plant tissue for nutrient concentration to predict yield or relate to plant growth response, considering the specific plant part that could give the most sensitive value will be important. The plant part selected will depend on factors such as mobility of the element and the site of maximum physiological activity. A wise compromise for tissue sampling that would give an adequate sample for these elements would be the blade of the uppermost leaf with an exposed collar. Such a sample is easy to describe and select, and it is possibly best related to soil test and yield differences. These data indicate that progressive morphological development, such as leaf appearance and stem elongation, could be used to determine critical periods of fertilizer requirement to

maintain optimal yields when switchgrass plants partition nutrients to compensate for physiological needs.

Soil Nutrient Levels

The goal of soil testing in this study was to provide guidelines for the efficient use of soil nutrients. Soil test values collected in 2001 were compared to data collected in 1992 previous to the switchgrass establishment and to data collected in 1996 and 1998 (Parrish et al., 2002). Data analyses showed significant differences in soil nutrient levels between locations and among years within locations (Table 4.10). Declines in soil pH were observed over the years at most locations, but the declines did not appear to influence switchgrass productivity.

At most locations, soil P reflected P removal during this long-term study (Table 4.11). There was no statistical correlation between soil P and yields over a wide range of soil P values. Detailed sampling of the NC site showed that a P source was apparently applied some years prior to switchgrass establishment. Soil P data from this location were omitted in the statistical analysis; but it was observed that, despite the high soil P concentration, the plant tissue P in the June harvest was adequate when compared to other locations having lower P. Soil P exists in a wide range of forms. Some is present as part of soil organic matter and becomes available to plants as the organic matter decomposes. Most inorganic soil Phosphorus is bound tightly to the surface of soil mineral particles. Warm, moist, well aerated soils at about pH 6.5 optimize the release of both these forms. This indicates that the switchgrass requirements for P might be adequate if supplied by the soil instead of being applied. This suggests that available soil P levels of 2 to 15 ppm are adequate for optimum switchgrass yields. Soil P was very NC and did not appear to increase the tissue concentration.

Soil K and Ca levels declined similarly to pH during the 10-yr period but did not become yield limiting (Table 4.11), an indication that K and Ca required for switchgrass production were generally available in these soils. A location x cutting management interaction showed differences in soil K among locations within each cutting management, but no significant differences were observed between cutting managements within any of the specific locations. Soil K ranged from 314 to 763 ppm in the one-cut system and 341 to 394 ppm in the two-cut system. A closer look at the year x cutting management interaction showed a decline in available soil K with the two-cut system (4.12). This indicates that the two-cut system was more quickly depleting the soil K pool. (The one- and two-cut plots were fertilized at the same rate, although nutrients were being removed at differing rates, creating the greater reduction with two cuttings. The K is highly mobile in the phloem and is redistributed from older leaves to young leaves or growing organs. This leaves space to speculate that translocation into roots or leaching out (in November of the one-cut system) into the soil pool might replenish the necessary pool to sustain productivity. Also, most available K exists as an exchangeable cation. The slow release of K from native soil minerals can replenish some of the K lost by biomass removal and leaching. This ability, however, could be limited and variable.

Levels of Ca in plant tissue did not reflect soil Ca levels (no correlation between tissue concentration and soil concentration), despite the 212 to 1123 ppm range observed in the 2001 soil tests. Depleting the active pool through crop uptake may cause some of the fixed Ca to slowly be released from the parent material. The conversion of fixed Ca to available Ca may be the reason for the slow rate of available nutrient depletion since these soils were never limed. Adequate rainfall at most of the locations might have also helped to maintain Ca levels since soils with a constant and adequate moisture will normally supply sufficient calcium to plants.

As with tissue analysis, annual soil test measurements are helpful for making adjustments in fertilization. Changes in nutrients should be interpreted with caution however. Hart et al. (2002) reported that soil test K and tissue K

concentrations provide support for the use of 100 ppm K as the soil test level below which K fertilizer application is recommended in perennial ryegrass (*Lolium perenne* L.). A soil test value of “medium-minus” for K (44 ppm according to the Virginia Tech soil testing lab) was apparently inadequate for maximum yields of corn (Hart et al., 2002), but a soil P level of “low-plus” (8 ppm) was more than adequate based on comparisons made by Hue et al. (1997) across different crops.

CONCLUSIONS

This multi-state study has shown that Alamo switchgrass, when harvested once at the end of the growing season, produces high sustainable yields if nutrients are properly managed. Means yields were slightly higher overall if harvested twice, indicating that multiple harvests could only be significant depending on location and year. The differences in nutrient removal between locations were more dependent on yield differences than on tissue concentration differences. Most elements were removed at rates higher than applied in both years.

Fertilizer recommendations for Alamo switchgrass should be based on soil and environmental conditions. Nitrogen can be used at somewhat limiting rates as far as short-term yield goals are concerned. Many of these locations may not need any N for 2 or 3 yr after planting when using a one-cut management. There is some indication that switchgrass might obtain sufficient N from mineralized forms and/or might be able to conserve/recycle N during its annual growth cycle. No more than 50 kg N ha⁻¹ may need to be applied to achieve optimal, sustained productivity with a one-cut management system.

Nitrogen removal studies show that the needs of switchgrass for N are relatively small. The fact that only 50 kg N ha⁻¹ yr⁻¹ were applied and slightly more removed suggests that N can be applied at a low rate and perhaps only in alternate years. Significant amounts of the N located in the biomass are

translocated to the crown/root system at the end of the growing season under one-cut management (Lemus et al., 2000b; Parrish et al., 2002). Thus, no more than 50 kg N ha⁻¹ may be needed to sustain yields (Bredja, 2000). In a two-cut system, split applications of 50 kg N ha⁻¹ in the spring and after the first harvest should supply adequate N and minimize potential adverse effects of over-application.

Average annual applications of 22 kg P ha⁻¹ and 30 kg K ha⁻¹ during the 10-yr study increased soil P but resulted in decreased soil K content relative to initial values measured in 1992. Soil K was in a medium productivity soil test range at the end of the 10 yr. Soil data show that P and K recommendations should be at moderate levels (20 kg P ha⁻¹ and 45 kg K ha⁻¹) based on soil tests over the 10-yr period. Soil pH declined steadily during the 10 yr, yet yield remained high. Yields were not affected by soil pH, an indication that lime may not need to be applied unless soil pH is under 5.

Higher nutrient removal for the two-cut system was due to higher nutrient concentrations in the midsummer harvest. If low nutrient concentrations are desired for biofuels quality, a one-cut system with a late fall harvest would be preferable for economic, environmental, and processing/quality reasons. A delay in harvest until the end of the growing season will also enable nutrient remobilization to be completed. Also, leaching by natural weathering processes can help to reduce nutrient concentrations in the biomass while increasing soil availability in the following season. These data indicate that soil P, K, and Ca at levels found in these locations were not limiting biomass yields nor were they being depleted.

An adequate supply of nutrients is only one of the factors that determine crop yield, and the application of fertilizers is not the sole means of correcting nutrient deficiencies in soils under switchgrass production. Equal attention must be paid to the other soil and biofuels management practices such as harvest frequency and nutrient removals to ensure long-term sustainability. Each one of these plays a vital role in determining the feasibility of switchgrass for biofuels purposes.

LITERATURE CITED

- Alderson, J., and W. C. Sharp. 1995. Grass Varieties in the United States. Boca Raton, NY: Lewis Publishers, p. 194.
- Basta, N. T., and M. A. Tabatabai. 1985. Determination of total potassium, calcium, and magnesium in plant materials by ion chromatography. Soil ci. Soc. Am. J. 49: 76-81.
- Bredja, J. J. 2000. Fertilization of native warm-season grasses. p. 177-200. *In*: K. J. Moore and B. E. Anderson (eds.) Native warm-season grasses: Research trends and issues. CSSA Spec. Publ. 30. CSSA and ASA, Madison, WI.
- Bremmer, J. M., and G. A. Breitenbeck. 1983. A simple method for determination of ammonium in semimicro-Kjeldhal analysis for soils and plant materials using a block digester. Commun. Soil Sci. Plant Anal. 14: 905-913.
- Donahue, S.J., and S.E. Heckendorn. 1994. Soil test recommendations for Virginia. Virginia Cooperative Extension, Virginia Tech, Blacksburg, VA.
- Hart, J., N. Christensen, and R. McReynolds. 2002. Potassium and production of perennial ryegrass for seed- Part 1. Oregon State University: Corvallis, OR. Crop and soil news/notes. Vol. 16 (7): 9-11.
- Hopkins, A. A., C. M. Taliaferro., C. D. Murphy, and D. Christian. 1996. Chromosome number and nuclear DNA content of several switchgrass populations. Crop Sci. 36: 1192-1195.
- Hue, N. V., H. Ikawa, and X. Huang. 1997. Predicting phosphorus requirements of some Hawaii soils. University of Hawaii at Manoa. Agronomy and soils AS-2: 1-4.
- Hultquist, S. J., K. P. Vogel, D. J. Lee, K. Arumuganathan, and S. Kaeppler. 1996. Chloroplast DNA and nuclear DNA content variations among cultivars of switchgrass *Panicum virgatum* L. Crop Sci. 36: 1049-1052.
- Gunter, L. E., G. A Tuskan, and S. D. Wulschleger. 1996. Diversity among populations of switchgrass based on RAPD markers. Crop Sci. 36: 1017-1022.
- Jacobsen, J. S., S. H. Lorbeer, H. A. R. Houlton, and G. R. Carlson. 1996. Nitrogen fertilization of dryland grasses in the northern great plains. J. Range Manage. 49: 340-345.

- Jorgensen, U. 1997. Genotypic variation in dry matter accumulation and content of N, K, and Cl in *Miscanthus* in Denmark. *Biomass and Bioenergy* 12 (1): 155-169.
- Knapp, A. K. 1985. Effect of fire and drought on the ecophysiology of *Andropogon gerardii* and *Panicum virgatum* in tall grass prairie. *Ecology* 66: 1309-1320.
- Lemus, R., E. C. Brummer, K. J. Moore, N. E. Molstad, C. L. Burras, and M. F. Baker. 2002a. Biomass yield and quality of 20 switchgrass populations in southern Iowa, USA. *Biomass and Bioenergy* 23: 433-442.
- Lemus, R., D. Parrish, and D. Wolf. 2002b. Estimating N dynamics under field conditions to improve switchgrass production in Virginia. *Proceedings of the Third Eastern Native Grass Symposium*. Chapel Hill, NC: October 1-3, 2002.
- Mangaroo, A. S. 1983. Soil fertility management for selected forages: The effect of nitrogen and phosphorous fertilization on the performance of improved forage cultivars. p. 169-173. *In* Forage Res. Texas CPR. Publ. 4141.
- McLaughlin, S., J. Button, D. Bransby, R. Conger, W. Ocumpaugh, D. Parrish, C. Taliaferro, K. Vogel, and S. Wullschleger. 1997. Evaluating and improving switchgrass as a bioenergy crop. *Proceedings of the 3rd Biomass Conference of the Americas*. Augsut 24-29. Montreal, Quebec, Canada 1: 137-143.
- Muir, J. P., M. A. Sanderson, W. R. Ocumpaugh, R. M. Jones, and R. L. Reed. 2001. Biomass production of 'Alamo' switchgrass in response to nitrogen, phosphorus, and row spacing. *Agron. J.* 93: 896-901.
- Parrish, D. J., D. D. Wolf, J. H. Fike, and W. L. Daniels. 2002. Switchgrass as a biofuel crop for the upper southeast: variety trials and cultural improvements. Final Report. Biofuels feedstock development program. Oak Ridge National Laboratory. Oak Ridge, TN.
- Parrish, D. J., D. D. Wolf, and W. L. Daniels. 1997. Switchgrass as a biofuel crop for the upper southeast: variety trials and cultural improvements. Annual Report. Biofuels feedstock development program. Oak Ridge National Laboratory. Oak Ridge, TN.
- Rao, I.M., V. Borrero, J. Ricaurte, R. Garcia, and M.A. Ayarza. 1996. Adaptive attributes of tropical forage species to acid soils. II. Differences in shoot and root growth responses to varying phosphorus supply and soil type. *J. Plant Nutrition* 19:323-352.

SAS® User's Guide: Statistics, Version 8.02. 2002. SAS Institute Inc., Cary, NC.

Sharpley, A.N., T.C. Daniels, and D.R. Edwards. 1993. Phosphorus movement in the landscape. J. Prod. Agric. 6:492-500.

White, P. 2001. The pathways of calcium movement in the xylem. J. Exp. Bot. 52 (358): 891-899.

Table 4.1. Fertilization history during 10 yr (1992 to 2001) of Alamo switchgrass grown at eight locations in the upper Southeast. All fertilizer applications were made before growth began in any year.

Locations	Fertilizer amount (and year)	
	P	K
KY		
Princeton	44 (1993)	60 (1993)
	48 (1994)	72 (1994)
	92 Total	132 Total
NC		
Raleigh	60 (1993)	82 (1993)
	50 (1997)	50 (1997)
	110 Total	132 Total
TN		
Jackson (TN ₁)	40 (1992)	--
	18 (1999)	116 (1999)
	58 Total	116 Total
Knoxville (TN ₂)	33 (1992)	--
	50 (1994)	50 (1994)
	45 (1997)	135 (1997)
	128 Total	185 Total
VA		
Blacksburg	63 (1993)	--
Site A (VA ₁)	82 (1998)	200 (1998)
	145 Total	200 Total
Site B(VA ₂)	63 (1993)	--
	82 (1998)	200 (1998)
	145 Total	200 Total
Orange (VA ₃)	35 (1993)	34 (1993)
	19 (1994)	140 (1994)
	19 (1995)	140 (1995)
	22 (1998)	30 (1998)
	22 (1999)	30 (1999)
	22 (2000)	30 (2000)
	22 (2001)	30 (2001)
	161 Total	434 Total
WV		
Morgantown	44 (1993)	76 (1993)
	53 (1994)	52 (1994)
	50 (1997)	50 (1997)
	147 Total	178 Total

Table 4.2. Analysis of variance, mean squares, and F-values for Alamo switchgrass biomass yields in response to two cutting managements (Cut) during the growing season in 2000 and 2001 at eight different locations. Years and locations were considered blocks.

Source	df	Mean Square	F Value
Block (Blk)	3	12.6	1.7
Year (Yr)	1	1.0	0.1
Location (Loc)	7	232.9	17.6***
Loc*Yr	7	65.6	5.0***
Error a	45	13.2	--
Cut (Ct)	1	1.7	0.2
Ct*Yr	1	72.6	9.9***
Loc*Ct	7	46.6	6.4***
Loc*Ct*Yr	7	22.1	3.0**
Error b	48	7.3	--

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

Table 4.3. Seasonal yields of Alamo switchgrass at eight locations when harvested once (in November) or twice (in midsummer and in November) in 2000 and 2001.

Year	Cut	Locations									LSD _{0.05} ²
		KY	NC	TN ₁	TN ₂	VA ₁	VA ₂	VA ₃	WV	Mean	
		----- Yield (Mg ha ⁻¹) -----									
2000	Once	15.5	14.6	7.8	20.8	9.5	17.1	19.8	15.5	15.1	4.6
	Twice	17.0	16.7	12.0	17.0	15.7	22.4	20.4	15.9	16.8	4.4
	Mean	16.3	15.7	9.9	18.9	12.6	19.8	20.1	15.7	16.0	3.5
	LSD _{0.05} ¹	ns	ns	ns	2.7	4.2	ns	ns	ns	ns	--
2001	Once	13.6	7.4	11.6	24.8	10.6	27.4	17.6	18.2	16.4	5.1
	Twice	15.2	9.7	16.6	18.1	13.7	19.7	15.1	13.0	15.1	4.6
	Mean	14.4	8.6	14.1	21.5	12.2	23.6	16.4	15.6	15.8	4.2
	LSD _{0.05} ¹	1.4	2.1	ns	6.1	ns	ns	ns	2.3	ns	--
	LSD _{0.05} ³	ns	1.2	3.2	ns	ns	ns	3.2	ns	ns	--
Mean	Once	14.5	11.1	9.7	22.8	10.1	22.2	18.7	16.9	15.8	4.1
	Twice	16.1	13.2	13.4	17.4	14.7	21.1	17.8	14.1	16.0	4.1
	LSD _{0.05} ⁴	0.7	ns	ns	4.2	ns	ns	ns	ns	ns	--
	Mean	15.3	12.1	11.5	20.1	12.3	21.7	18.2	15.6	15.9	2.2

¹LSD for comparison of cutting systems within year and location.

²LSD for comparison of locations within cutting system and year.

³LSD for comparison year means within location.

⁴LSD for comparison of cutting management means within location.

Table 4.4. Analysis of variance and mean squares for Alamo switchgrass nutrient concentrations in response to two cutting managements.

Source	df	Nutrient Concentration			
		N	P	K	Ca
Year (Yr)	1	0.0287	0.0011	0.0737	0.0023
Location (Loc)	7	0.1562***	0.0032***	0.1919***	0.0183**
Cut (Ct)	1	1.9323***	0.0271***	0.4214***	0.0298
Loc*Ct	7	0.0360	0.0005	0.0189	0.0024
Error a	15	0.0139	0.0003	0.0256	0.0043
Harvest (H) (Ct)	1	1.5312***	0.0422***	4.5602***	0.0109
Loc*H (Ct)	7	0.0658	0.0014	0.0604	0.0018
Error b	8	0.0304	0.0005	0.0167	0.0049

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

Table 4.5. Analysis of variance and mean squares for Alamo switchgrass total nutrient removals in response to two cutting managements. Years were considered blocks.

Source	df	Total Nutrient Removed			
		N	P	K	Ca
Year (Yr)	1	88	95	3062**	136
Location (Loc)	7	6732***	33*	9431***	1321**
Yr*Loc	7	725	13	720	333
Cut (Ct)	1	40115***	675***	10189***	800*
Yr*Ct	1	1391	43*	4778***	242
Loc*Ct	7	987	13	1038*	116
Error	7	461	6	258	140

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

Table 4.6. Nitrogen, P, K, and C concentrations in whole-plant tissue collected at harvest of one- and two-cut managements of Alamo switchgrass. Data are averaged over eight locations and 2 yr.

Nutrient	Harvest	Cut		LSD _{0.05} ²
		Once	Twice	
		----- % -----		
N	June	--	1.08	--
	November	0.43	0.64	0.09
	LSD _{0.05} ¹	--	0.12	--
P	June	--	0.18	--
	November	0.09	0.11	0.01
	LSD _{0.05} ¹	--	0.02	--
K	June	--	1.26	--
	November	0.69	0.51	0.07
	LSD _{0.05} ¹	--	0.12	
Ca	June	--	0.33	--
	November	0.28	0.37	0.05
	LSD _{0.05} ¹	--	ns	--

¹LSD for comparison of harvests within the two-cut management.

²LSD for comparison of cuts with the November harvest.

Table 4.7. Nitrogen, P, K, and Ca removals (kg ha^{-1}) in whole-plant tissue collected at harvest of one- and two-cut managements of Alamo switchgrass. Data are averaged over eight locations and 2 yr.

Nutrient	Harvest	Cut		$\text{LSD}_{0.05}^2$
		Once	Twice	
		----- kg ha^{-1} -----		
N	June	--	89	--
	November	69	51	14
	Total	69	140	18
	$\text{LSD}_{0.05}^1$	--	2	--
P	June	--	15	--
	November	14	8	2
	Total	14	23	2
	$\text{LSD}_{0.05}^1$	--	2	--
K	June	--	105	--
	November	109	40	20
	Total	109	145	13
	$\text{LSD}_{0.05}^1$	--	10	--
Ca	June	--	28	--
	November	47	29	9
	Total	47	57	10
	$\text{LSD}_{0.05}^1$	--	ns	--

¹LSD for comparison of harvests within the two-cut management.

²LSD for comparison of cuts.

Table 4.8. Total K removals in whole-plant tissue and soil Ca concentrations of two cutting managements for Alamo switchgrass grown at eight locations. Data averaged over 2 yr.

Location	Cutting Management			
	One	Two	One	Two
	-- Removal (Kg ha ⁻¹) --		-- Soil K (ppm) --	
KY ¹	101	113	--	--
NC	74	128	763	791
TN1	59	132	767	794
TN2	134	104	486	484
VA1	76	135	621	524
VA2	219	259	314	341
VA3	137	167	669	670
WV	77	122	659	689
LSD _{0.05} ²	55	50	74	94

¹Ca from Princeton, KY not included in averages because of atypical values.

²LSD for comparison of locations within a cutting management.

Table 4.9. Partitioning (by percentage and weight) of Alamo switchgrass tillers, nutrient element concentrations and content of each portion collected at the boot stage in late June 2000. Data are averaged across six locations.

Tiller Portion	Tiller Partition		Concentration			
	mg tiller ⁻¹	%	N	P	K	Ca
			-----%			
Leaf Blades						
Whorl	325	8.6	1.66	0.21	1.44	0.19
First	385	10.2	1.86	0.22	1.23	0.39
Second	361	9.6	1.76	0.21	1.10	0.53
Third	311	8.3	1.60	0.19	1.00	0.67
Total	1382	36.7	--	--	--	--
Mean	346	--	1.72	0.21	1.19	0.44
Leaf Sheathes						
Upper Bundle	383	10.2	1.02	0.22	2.83	0.20
All Others	505	13.4	0.52	0.12	2.00	0.40
Total	887	23.6	--	--	--	--
Mean	444	--	0.77	0.17	2.41	0.30
Leaf (blade + sheath)	2269	60.2	1.25	0.19	1.80	0.37
Stem/Internode						
First	387	10.3	0.66	0.16	2.46	0.10
Second	564	15.0	0.39	0.11	1.35	0.06
Third	546	14.5	0.31	0.08	0.91	0.06
Total	1497	39.8	--	--	--	--
Mean	499	--	0.45	0.12	1.57	0.07
Total Tiller and mean conc.	3766	100.0	0.93	0.15	1.61	0.25
LSD _{0.05} ¹	163	--	0.13	0.03	0.34	0.23

¹LSD for comparison of tiller portions within each nutrient.

Table 4.10. Analysis of variance and mean squares for soil test values where Alamo switchgrass was grown under two cutting managements. Years were considered blocks.

Source	df	Soil Nutrient	
		pH	K
Year (Yr)	3	1.7414***	5019***
Location (Loc)	7	1.7907***	965***
Yr*Loc	21	0.0621***	491***
Cut (Ct)	1	0.0039	3600***
Yr*Ct	3	0.0039	446**
Loc*Ct	7	0.0475	180
Error	21	0.0151	94
		P ¹	Ca ²
Year (Yr)	3	157***	149433***
Location (Loc)	6	124***	215304***
Yr*Loc	18	101***	4963**
Cut (Ct)	1	7	46
Yr*Ct	3	1	1076
Loc*Ct	6	3	4145
Error	18	2	1522

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

¹P from Raleigh, NC is not included in averages because of atypical values

²Ca from Princeton, KY is not included in the analysis because of atypical values.

Table 4.11. Soil pH, P, K, and Ca in top 10 cm of Alamo switchgrass plots in 1992 (before planting) and in the fall of different years. Managements included one cut or two cuts per season.

Location	Year	pH	P	K	Ca
			----- ppm -----		
KY ²	1992 ¹	6.7	15	101	1720
	1996 ¹	6.8	6	29	1268
	1998 ¹	6.4	7	37	1270
	2001	6.2	7	37	1100
NC ³	1992	6.3	420	70	100
	1996	6.3	137	51	643
	1998	5.7	170	58	870
	2001	5.9	107	29	599
TN ₁	1992	5.8	12	90	900
	1996	5.4	8	64	764
	1998	5.3	8	79	777
	2001	5.2	7	59	683
TN ₂	1992	5.6	7	62	594
	1996	5.4	4	32	477
	1998	5.2	6	43	513
	2001	5.2	3	27	356
VA ₁	1992	6.5	3	60	651
	1996	6.2	8	41	606
	1998	6.0	30	87	599
	2001	6.0	13	32	434
VA ₂	1992	6.0	4	80	402
	1996	5.2	7	60	315
	1998	5.2	32	107	368
	2001	4.8	25	43	227
VA ₃	1992	5.7	2	77	798
	1996	5.2	6	61	669
	1998	5.0	6	48	651
	2001	4.8	16	56	561
WV	1992	6.3	12	95	801
	1996	5.9	8	34	690
	1998	5.5	10	42	669
	2001	5.2	12	37	536
LSD _{0.05} ⁴		0.2	3	19	78

¹Data adapted from Parrish et al., 2002; ²Ca from Princeton, KY is not included in averages because of unusually high values; ³P from Raleigh, NC is not included in averages because of unusually high values; ⁴Least significant differences for comparison of soil nutrients between years and within location and among locations.

Table 4.12. Changes in soil K concentration with cutting managements among years. Data from soil test values are averaged over eight locations.

Year	Cutting Management		LSD _{0.05} ²
	One	Two	
	----- K (ppm) -----		
1992	79	79	--
1996	56	36	14
1998	80	51	20
2001	48	32	6
LSD _{0.05} ¹	21	14	--

¹LSD for comparison of years with a cutting management.

²LSD for comparison of cutting managements with a year.

CHAPTER 5

EVALUATING N DYNAMICS TO IMPROVE SWITCHGRASS MANAGEMENT IN VIRGINIA

ABSTRACT

Determining an N budget (inputs, outputs, and internal fluxes) for a crop can improve management and lower production costs. The objectives of this study were to examine some dynamics of applying N to switchgrass (*Panicum virgatum* L.) and to consider the effects of residual N on biomass production. This 3-yr study was conducted on two well-established 'Cave-in-Rock' switchgrass stands in the Piedmont and the Ridge and Valley regions of VA. Treatments of 0, 90, 180, or 270 kg N ha⁻¹ were applied once in May 2001. No N was applied in 2002 or 2003, when residual effects were assessed. Biomass was harvested once (in November) in 2001 and twice (July and November) in 2002 and 2003. Biomass production, N removal, and N-use efficiency (NUE) were compared at each N rate. Root and soil samples were analyzed for N in May, July, September, and November. Nitrogen applications did not increase yields in 2001. A positive residual N effect on yield was seen, but only for the highest N rate, in 2002 and 2003. The amount of N removed in biomass increased with N applied and with two cuttings. More N was removed in biomass than was applied. Even with no N added, 100 kg N ha⁻¹ yr⁻¹ were removed – suggesting mineralized N or other sources must be contributing substantially to yields. Mineralizable N was high throughout the growing season and likely provided substantial quantities of N to maintain yields. Net N flux from shoots to roots was observed between July and November. Lower NUE was generally associated with higher application rates. Taken together, these data

suggest that switchgrass biomass production can be sustained in some soils with relatively low levels and infrequent applications of N.

INTRODUCTION

Based on a series of evaluation trials in VA, switchgrass has been identified as a promising species for development into a biofuels crop (Parrish et al., 2002); but one of the major problems with its management is optimizing N requirements. Nitrogen is the fertilizer element required in the greatest quantities by most crops. The feasibility of switchgrass as a bioenergy crop could be enhanced if its yield could be increased without having to increase nutrient inputs, especially N. Information about the effects of N fertilization on yield, N uptake, and N-use efficiency (NUE) is very limited and/or inconclusive.

Interest in the use of switchgrass for energy purposes has prompted questions about best management practices for this use, especially in VA, where little or no yield response to N has been observed in the past. One goal in bioenergy crop production is to design management systems that use N efficiently. A management system will take into account the N available to the crop (from soil and fertilizer) as well as other factors, such as drought and other limitations to plant growth (Kowalenko and Bittman, 2000).

Nitrogen uptake dynamics and NUE are often examined by measuring total N accumulation in aboveground biomass and comparing that to N applied. Studies of grasses under conditions of low responsiveness to N have shown that N uptake and retranslocation are influenced more by yield removal than by N applications (Kowalenko and Bittman, 2000). Huang et al. (1996) reported that switchgrass can remove as much as 20 kg ha⁻¹ of NO₃-N from soil profiles deeper than 120 cm, accounting for about 22% of the total switchgrass N requirement. Such deep N would obviously not have been applied in the current growing season. These and other dynamics make N removal vs. N applied studies difficult to interpret.

Switchgrass NUE could be affected by cultivar, ecotype, soil type, latitude, temperature, N fertilizer rate, and soil moisture. Any N applied or made available from the soil (by various chemical and/or microbiological processes) in amounts exceeding the immediate requirements of the switchgrass will remain unused in the soil and be potentially subject to losses by leaching, denitrification, in this way reducing N-use and recovery. Staley et al. (1991) reported a low 29% fertilizer NUE in warm-season grasses. Therefore, N fertilization practices and other management decision that influence N availability should take into consideration N-use and recovery.

The translocation of N prior to senescence is one of the key processes by which plants might achieve greater efficiency in the use of this element. Heckathorn and Delucia (1996) reported that perennial C₄ grasses of the tallgrass prairie translocate up to 30% of shoot N to rhizomes and roots in response to water stress. Parrish et al. (1996) have reported significant redistribution of N into belowground biomass at the end of the growing season. Nitrogen uptake studies could help to identify the total amount of N needed by switchgrass and the periods of peak demand. This information could be used to devise N management strategies. More research is needed to quantify these inputs and outputs.

The supply of soil nutrients largely determines the productivity of any crop. Nitrogen is of particular interest, because it is usually the most limiting nutrient for switchgrass production. Nitrogen has a variety of pathways for input and outflow (Fig. 2.1) of the soil-plant system and can have important negative environmental impacts when lost from the production system. The N inputs, from the crop's perspective, include nutrients mineralized in the soil profile, fertilizer applied, precipitation, and N fixation. Nutrient effluxes from the system occur as biomass removal, soil erosion, runoff, leaching, denitrification, and volatilization, etc. In addition to yield improvement efforts in switchgrass related to fertilizer N applications, losses from N applications need to be considered to maximize N use.

Nutrient depletion can occur if there is a deficit between influx and efflux. Maintenance of proper nutrient status in soil is critical. Soil testing can be used to adjust N recommendations for optimum yields. Under- or over-fertilization is apt to occur in any given season if soil N availability is not taken into account. Estimation of plant-available N is complicated enormously by the dynamic nature of soil N, owing largely to the effects of temperature and moisture supply on N-cycle processes. Numerous biological and chemical methods have been proposed as measures of soil N availability but they have been of limited value because of low correlations with crop N uptake (Khan et al., 2001).

In-season measurements of the soil's N status, biomass accumulation rates, and N uptake patterns could provide the basis for determining N requirements throughout the growing season. Soil mineral N and potentially mineralizable N measurements are needed. To properly manage nutrient balance of a soil system in a sustainable way, knowledge of the availability, depletion, and balance of N in the soil system is necessary. The main objectives of this research were (1) to examine immediate and residual responses of switchgrass to N fertilization; (2) to study N allocation patterns in roots and shoots; (3) to quantify N removal by switchgrass biomass; (4) to consider possible alternative sources for N (besides the N applied); and (5) to evaluate various N-use estimators and the effect of N rate on their values.

MATERIALS AND METHODS

Biomass Yield Responses to N

Experiments were conducted on well-established (>5-yr old) stands of Cave-in-Rock switchgrass at the Northern Piedmont Agricultural Research and Extension Center (NPAREC) (Orange, VA) and at Kentland Farm (Blacksburg, VA). Soil at Blacksburg was a Chatter soil (Clayey, kaolinitic, mesic, Typic Paleudult) with 2 to 5% slope. Soil at Orange was a Davidson soil (Clayey,

kaolinitic, thermic, Rhodic Kandudult) with 10% slope. Plots at NPAREC were 2X7 m, and plots at Kentland farm were 3X6 m. A 0.9 m buffer strip between plots reduced the potential for N runoff from one plot to another. Nitrogen was applied once at 0, 90, 180, or 270 kg N ha⁻¹ as urea (46-0-0) in mid-May 2001. Plots were not fertilized in 2002 or 2003. Switchgrass was harvested once (in early November) in 2001 and twice (early July and early November) in 2002 and 2003. Switchgrass maturity was determined using the system of Moore et al., 1991. Biomass was harvested using a flail harvester at a cutting height of 7 cm. Biomass samples were weighed fresh and dried for 48 hr at 60 °C for dry matter determinations.



Fig. 5.1. Switchgrass root biomass to 15 cm depth (0.25-m² quadrat).

Root and soil samples were collected across the growing season to determine N status and plant utilization. The soil depth considered was 15 cm due to the very high root concentrations in that layer (Fig. 5.1) (Ma et al., 2000).

Belowground biomass samples (crown, rhizomes, and roots) were taken to a 15-cm depth within a 0.25-m² quadrat before fertilizer was applied in May 2001 and at sampling periods in July, September, and November of 2001. In 2002 and 2003, a core sampling method was used in May, July, September, and November (Ma et al., 2000). One belowground biomass sample was taken per plot at each sampling date with a 4.5 cm diameter hydraulic corer to a 15-cm depth (Ma et al., 2000). Root samples (whether quadrat or core) were washed by submerging in water and allowing them to elute onto a 2-mm screen (Smucker et al., 1982). Most roots were retained on the screen, although some very fine materials passed through. Roots were then oven-dried at 60 °C for 48 h and

weighed for determination of root mass. Root N concentrations were determined using the Vario Max CN Analyzer (Elementar Analysensysteme GmbH).

The core sampling method used in 2002 and 2003 yielded ~ 7X higher root weight density and root mass than found in the quadrats in 2001. The differences were attributed to a nonrandom sampling method. The 0.25-m²-quadrat sampled better for spatial variability, since large portions of the quadrat would not be as densely populated by roots as the core samples, which were collected not randomly but from the center of plant crowns. It is expected that a higher root density and more mature/larger roots will occur in the crown zone. In order to make comparisons between sampling methods (quadrat vs. core), root samples were collected at both locations in late 2003 using both methods to develop an equation (Fig. 5.2) that corrected the values obtained from the nonrandom core sampling during the 2002 and 2003 seasons. To make sampling comparisons, the quadrat was randomly dropped in each plot. From the center of the quadrat, a core sample was collected prior to the removal of the root biomass within the quadrat to a 15 cm depth. Once samples were oven-dried and root biomass was determined, biomass collected with the core was added to back the biomass values obtained from quadrat method to have the total biomass. The equation was developed by using REG procedures of SAS (SAS Institute, 2003).

Root mass in the top 15 cm was calculated using a formula described by Ma et. al. (2000): $RM = RWD \cdot CL \cdot 10$; where RM=root mass (mg); RWD= root weight density (mg cm⁻³). Root weight density was calculated as $RWD = RDM / (\pi \cdot CR^2 \cdot CL)$ where: CR =core radius (2.3 cm) and CL= core length (15 cm). The value of 10 is a conversion factor for area and mass. Root weight density and mass calculations in 2001 were calculated or extrapolated from 0.25-m² quadrat.

Quantification of N-use Parameters

Nitrogen use in relation to crop response was evaluated using three different parameters that take into account biomass yields, N removal, and

biomass increments due to N applications. Nitrogen-use efficiency (kg kg^{-1}) for each harvest was calculated as $\text{NUE} = [(\text{yield at } N_x - \text{yield at } N_0)/\text{kg of N applied at } N_x]$, where $x = \text{N rate} > 0$ (Zemenchik and Albretch, 2002; Novoa and Loomis, 1981).

The apparent N recovery (ANR) (%) in the biomass was calculated using the difference method: $\text{ANR} = [(\text{kg of N removed at } N_x - \text{kg of N removed from } N_0)/\text{kg N applied at } N_x] \times 100$, where $x = \text{N rate} > 0$ (Crasswell and Godwin, 1984). Nitrogen removal was calculated by multiplying plant biomass times the concentration of N in the harvested switchgrass.

Partial factor productivity (PFP) (kg kg^{-1}) was calculated as $\text{PFP} = (Y_0 + \Delta Y)/N_x$, where Y_0 is the biomass yield at N_0 and ΔY is the increment in biomass yield that resulted from N application (Cassman et al., 1998). Values of ANR, NUE, and PFP were calculated for seasonal as well as the cumulative (2001 + 2002 + 2003) yields.

Soil N Pools and Dynamics: Total N, Mineral N, and Potentially Mineralizable N

Soil samples were taken for N analysis in May, July, September, and November of 2001, 2002, and 2003 to a 15-cm depth. Three core soil samples were collected from each plot, bulked, and dried at room temperature to prevent further mineralization (Collins and Allinson, 2002). After drying, the roots were removed mechanically, and the soil was sieved to pass a 2-mm screen. Soil N concentration, which is a measure of N in all forms, was determined using the Vario Max CN analyzer (Elementar Analysensysteme GmbH). Soil N concentrations were multiplied by soil bulk density at each location to obtain total soil N (TSN) on a mass per area basis.

Soil mineral N (SMN) ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$) was determined using a modified 1:5 KCl extraction method described by Keeney and Nelson (1982). Two-gram soil samples were placed in 50-ml test tubes, and 10 ml 2 M KCl extracting

solution were added. Tubes were shaken for 1 h. The extraction solution was filtered through 0.45 μm nitrocellulose membrane filters (Millipore Co., Bedford, MA) under suction. Nitrate and $\text{NH}_4\text{-N}$ were determined colorimetrically on a Lachat Instruments Automated Analyzer using QuikChem Methods 12-107-04-1-B and 12-107-06-2-A, respectively (Lachat Instruments, Milwaukee, WI). Soil mineral N concentrations were multiplied by soil bulk density and values expressed on a kg ha^{-1} basis.

Potentially mineralizable N (PMN) in soil samples collected in May through November was estimated using a short-term anaerobic incubation method described by Bundy and Meisinger (1994). The incubation procedure was slightly modified by decreasing the sample size (Gordillo and Cabrera, 1997). Ten-gram soil samples were placed in a 250-ml extraction bottles to which 25 ml distilled water were added. Bottles were sealed and place in an incubator for 7 d (168 h) at 40 ± 1 °C. Following the incubation, 25 ml of 2 M KCl were added and bottles were shaken for 1 h. Extracts were filtered through a 0.45 μm nitrocellulose membrane filter (Millipore Co., Bedford, MA). Nitrate and $\text{NH}_4\text{-H}$ were determined colorimetrically on a Lachat Instruments Automated Analyzer using QuikChem Methods 12-107-04-1-B and 12-107-06-2-A, respectively (Lachat Instruments, Milwaukee, WI). Ammonium and $\text{NO}_3\text{-N}$ concentrations before incubation were subtracted from $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations after incubation to estimate the amount of N mineralized (Christensen et al., 1999). Potentially mineralizable N was calculated as the difference between the final and initial total extractable N ($\text{NH}_4\text{-N}$) and expressed as mass of N per unit area (kg ha^{-1}) to a 15-cm depth using the soil bulk density at each location.

Statistical Analysis

The experimental design was a randomized complete block replicated four times. The main treatments were N rates, cutting managements, and soil sampling dates within each year. Because of the change in cutting management for 2002 and 2003, data collected in 2001 were analyzed separately. Data from

the four sampling dates in 2002 and in 2003 were analyzed in a combined analysis for root biomass changes with time. Analysis of variance (ANOVA) procedures were conducted using the GLM procedure of SAS (SAS Inst., 2003) at $P_{0.05}$ to test the effects of year, location, N treatment, and all interactions in the models for biomass yield, NUE, ANR, and PFP. Means were separated by the least significant difference (LSD) at $P_{0.05}$ probability level.

RESULTS AND DISCUSSION

Biomass Yields and N-Use Efficiency

Total seasonal yields varied with year and were confounded by the change in harvest pattern after 2001. Therefore, total yield data, N concentrations, and N removal will be discussed as separate analyses for each year (Table 5.2) and then cumulatively. The effects of N rate on biomass produced are presented in Table 5.3. Switchgrass did not respond to N applications in 2001. It was due to this non-response in 2001 that no further N was applied and a two-cut system was imposed. Lower yields were observed in 2002 compared to a wetter 2003, with significant differences within N treatments. Residual N effects on biomass yields were evident in 2002 and 2003, with the effects being more prominent in 2003. The year X N rate interaction could be related to a higher precipitation in 2003 (Table 5.1). Application of 270 kg N ha^{-1} had the largest residual effect in 2003. Interestingly there was no yield difference between the control (0 N) and the two intermediate N rates in this productive year. Cumulative biomass yields (2001 through 2003) showed a clear, positive response to N.

Plant N removal is often used to assess implicit availability of soil and fertilizer N. Very significant amounts of N were removed with the biomass harvests (Table 5.4). Approximately 80% of the annual N removal occurred during the July harvest in 2002 and 2003. Cumulative N removal was 45%

higher in Blacksburg than in Orange. As would be expected, N removal differences reflected both yield and N concentration differences. With a single harvest (2001), N removal increased with N applications and ranged from 26.3 at 0 N to 57.9 at 270 N. With two cuts (2002 and 2003), the largest N removal occurred in the July harvests. The November harvest had lower N removals for all N treatments, reflecting the overall lower N values for late-season material and an indication of the translocation or leaching of N out of the shoots toward the end of the season.

Tracking cumulative N removal in biomass harvests indicated that only a fraction of the applied N was recovered in 2001. Over the next 2 yr, however, when no new N was applied, much additional N was removed. Eventually, more N was removed than applied in all plots. Sladden et al. (1994) reported that more N was removed in switchgrass biomass than was applied as fertilizer. Collins (1994) has reported that, under switchgrass with no fertilization, N removal ranged from 41 to 83 kg N ha⁻¹. The removal of more N than was applied must be explained by uptake of non-fertilizer sources. Indeed, the 0-N plots provided over 100 kg N ha⁻¹ to the biomass removed from them over the 3 yr of this study.

Nitrogen-use is an important area when discussing fertilizer applications and switchgrass growth. In these discussions, we shall focus on N use over time, i.e., the 3 yr following the single N application. Cumulative yields over those 3 yr have been used to calculate N-use parameters. Trends of diminishing returns with increasing N application rates were observed. Nitrogen-use efficiency decreased linearly as N rate increased when data were averaged across the two locations, but no significant differences between N rates were observed for NUE at Orange (Table 5.5).

A response index (calculated as the yield obtained from the applied N divided by the control yield) was used to determine the degree to which N, external to the switchgrass environment, might be needed to support yield potential (Thomason et al., 2002). The response index was plotted against NUE to determine the responses (Fig. 5.3). The results showed N applications

beyond 90 kg N ha⁻¹ might not provide a yield advantage in VA. Based on this, NUE may be improved and at the same time excess fertilizer applications could be avoided. It is wise to note that the responses seen here may be peculiar to these VA soils and sites.

Knowledge of the fate of the unaccounted-for N is very important in attempts to improve NUE and avoid environmental degradation. In order to gain more insight into comparative removal and the likelihood of fertilizer carry-over from one season to another, fertilizer N-use estimates based on cumulative (2001 to 2003) values were calculated for two more parameters: ANR and PFP. Apparent N recovery, which discounts any N removed in the control (0 N), followed the same trends observed with NUE, in which ANR decreased with increased applied N (Table 5.5). Cumulative values of ANR showed that about 83% of the applied N appeared to be recovered over a 3-yr period at the 90 kg N ha⁻¹ rate, while approximately 57 or 25% was recovered as N rates increased. Stout and Jung (1995) reported that fertilizer N recovery was about 31% and 23% for the 90 and 180 kg N ha⁻¹ yr⁻¹. The 3-yr cumulative analysis is consistent with their findings.

Partial factor productivity was calculated using cumulative yields. This formula also discounts (as does ANR) the biomass produced with 0 N input (Y_0) and looks at the yield increments that result from N increment (ΔY) (Cassman et al., 1998). As with other N-use parameters, PFP decreased with increasing N rates. Partial factor productivity was higher at Blacksburg within each N rate (Table 5.5), perhaps reflecting greater N availability at the Orange site (and less response to the applied N). Differences between the two locations were highest at the 90 kg N ha⁻¹ with no differences at the 270 kg N ha⁻¹. These data show that efficiency of N-use depends on site-specific N management strategies that are responsive to soil N supply and plant N status.

Roots Biomass and N Values

Root biomass collected to 15 cm using the quadrat method showed higher biomass in Blacksburg (6.8 Mg ha^{-1}) than in Orange (5.7 Mg ha^{-1}), and a similar pattern of increase during the 2001 season (data not shown). Root biomass increased 79% increase from May to November in 2001 (Table 5.6). This is a very surprising finding. We suspected a burst of shallow root growth following fertilization after several years of no fertilization for these plots, but the same pattern of increased biomass was evident in the 0 N plots. It would appear, then, that there was a significant turnover and regrowth of roots in 2001. We cannot conclude that new, long-lived roots are added at the 2001 rate every year.

Because the quadrat method was quite destructive in our plots, raising questions about possible effects on yields, root sampling in 2002 and 2003 was done by a core sampling method as described by Ma et al. (2000). The core sampling method, however, yielded $\sim 7\text{X}$ higher root biomass than the quadrat method. The differences were attributed in retrospect to nonrandom core sampling method. Utilization of the 0.25-m^2 quadrat compensates for spatial variability in root distribution, since large portions of the area where roots were collected would not be as densely populated by roots as the core samples, which were collected from the center of plant crowns. A higher root density and more mature and developed roots are expected to populate the crown zone. We believe that data collected in 2001 were more accurate estimates of switchgrass root biomass in the top 15 cm.

In order to make comparisons between years in which root biomass data were collected by the two different methods, root samples were collected at both locations and in all plots in late season 2003 using both methods (quadrat and crown core) to develop an equation (Fig. 5.2) ($Y = 0.094X + 3.38$, $r = 0.38$, $P < 0.001$) that allowed estimated values during the 2002 and 2003 seasons comparable to those observed in 2001.

A year $\times$ date interaction ($P < 0.05$) revealed fluctuations in root biomass across the season (Table 5.6). Estimated values showed that root biomass

decrease from May to July 2002, but values spiked in September and then declined in November. During the 2003 season, the early increase in root biomass was followed by a decrease after the first harvest (July). We speculate that the increase in root mass observed in September of 2002 is related to increases in root branching to cope with drought stress, especially when water availability was crucial for shoot regrowth. Our data also suggest that the increase in root mass throughout the season in 2001 may be atypical and could have been affected by management in previous 3 or 4 yr, when the stands were not fertilized or harvested for biomass.

Nitrogen application rate and sampling date affected root N concentrations (Table 5.7). Root N concentrations generally increased with applied N in 2001 (Fig. 5.4). Higher root N concentrations were observed only at the 270 kg N ha⁻¹ rate in the “residual years” of 2002 and 2003. An overall decrease in N concentration in roots was observed from 2001 to 2003, an indication that the amount of N reserves was being depleted by the greater N removals occurring under the two-cut system.

Sampling dates also revealed fluctuations in root N concentrations during the growing season (Fig. 5.4). Nitrogen concentrations in roots in the top 15 cm increased with sampling date during the 2001 season. Highest root N concentrations were observed in May (before fertilizer was applied), with a decline as the season progressed until N translocation after September increased root reserves.

When examined during the “residual years” (2002 and 2003), root N concentrations were highest in May followed by November values. Decreases in root N content in July could be attributed to N translocation from the roots to shoots during the spring growth. Values might be expected to decrease further in September as roots had to supply the regrowing shoots with N. Since there was a 2-month window between July and September, there is the possibility that roots had enough time to replenish their storage reserves from the soil. Those root N reserves were 33% less in November 2003 compared to 2002, indicating that low or no fertilization in combination with high N removal under the two-cut

management could have considerable impact on N retained and recycled within the plants. Without additional N inputs, it appeared that the plants' internal N supplies were being depleted.

Sources of Available N

Nitrogen supply has a strong impact on the productivity of all agroecosystems. To date, N fertilization studies with switchgrass have not paid particular attention to possible N cycle contributions and the effects that N already present in the soil could have on productivity. Consistent and reasonably accurate estimates of soil N supplying capacity are needed to evaluate nutrient supply for switchgrass production. Fertilizer recommendations for switchgrass are usually based on the assumption that fertilizer N must be supplied (with some excess to account for inevitable losses/inefficiencies) at rates equivalent to the rate of removal via the harvests. Recommendations that take into account soil mineral N currently available, potentially mineralized N, and the expected biomass yields would be more useful.

Analysis of variance showed that soil mineral N (SMN) and potentially mineralizable N (PMN) could play a major role in plant nutrient requirements throughout the switchgrass growing season. Significant differences in sampling date and location x sampling date interactions were observed in the 3 yr of this study (Table 5.8).

Total Soil N (TSN)

Total soil N (TSN) was calculated by multiplying the CN-analyzer-derived soil N concentrations times the soil bulk density. The TSN is expressed as a mass of N per unit area (kg ha^{-1}) in the top 15 cm. Total soil N varied by surprisingly large amounts across sampling dates (Table 5.9). Total soil N was

higher at Orange, especially in 2003. There was generally an increase in TSN with date from May to September. During the 2003 season, a decline in TSN was observed from May to September at Blacksburg, while total soil N values followed the opposite trend at Orange.

The TSN values should largely reflect the organic matter (OM) content of the soil, i.e., TSN is almost entirely organic N. It is not likely that the OM (and therefore the TSN) of these soils changed significantly across the growing season. Therefore, we put minimal value on the changes reported. Rather we note that the average TSN values for each site were 2300 to 2700 kg N ha⁻¹ and that some portion of this N must potentially be mineralizable, about which more will be said below.

Soil Mineral N (SMN)

Measurement of SMN in the soil profile is the best way to estimate the amount of soil N readily available for crop uptake, since it takes account of the most common sources of N for plants (NO₃ and NH₄). The amount of N available to plants depends on N cycling, i.e., on the rate of N uptake by plants and soil organisms, on the rate of release of inorganic N due to mineralization processes, as well as on the amount of N lost from the system (by leaching, denitrification, and volatilization) and on N fertilization.

Determination of plant-available N, i.e., SMN, helps in evaluating N carryover from the previous season. Tests for SMN (NO₃-N + NH₄-N) by KCl extractions revealed significant differences among sampling dates and years. The influence of N fertilization on SMN was evident in 2001 (Fig. 5.5). Soil mineral increased considerably in July after N fertilization. More than 100 kg of soil-available N ha⁻¹ were present in the 2001 growing season. Higher levels of mineral N during the growing season might not be the main reason for plant uptake, but possibly symbiotic relationship that could facilitate N uptake.

The amounts of soil mineral N decreased considerably during the 2002 and 2003 season, but a seasonally higher availability was observed in July and

September of 2002. The reduction in mineral N during the 2002 and 2003 growing seasons could be related to N removal rates. These data suggest that, under the two-cut system, N fertilization may be needed every few years to replenish the soil supplying capacity. Based on data from Chapter 4, it may be possible that cutting biomass once at the end of the season could be a more sustainable system (one which removes less N annually) – one that benefits from N-recycling within the soil-plant system and perhaps inputs such as N deposition.

Differences between locations for mineral N were also observed at sampling dates for each year (Table 5.10). Soil samples collected in July 2001 after N fertilization showed a ~31 and 54% increase in SMN in Blacksburg and Orange, respectively (Table 5.9). Soil mineral N was highest in July and September at Blacksburg and Orange in 2001 and 2002. During the 2003 season, soil mineral N has declined considerably. This location x date interaction supports the data presented in Fig. 5.5. These lower values in 2003 might indicate depletion of soil available due to N removal in biomass under two cuts.

One supposes that SMN reflects N applied in fertilizer as well as N mineralized from the TSN pool. We cannot tell which sources are contributing how much for any particular sampling date, but mineralization must be the more important contributor at least in 2002 and 2003. It would seem to be the primary (if not sole) source of N for the 0 N treatments, which were not significantly different from any other N rate at any sampling date (data not shown). This observation makes it all the more important to look at mineralization processes.

Potentially Mineralized N (PMN)

Predicting potential N mineralization from soil OM, because N mineralization is affected by several environmental factors, while being the net outcome of concurrent N processes that produce and consume mineral N. Nitrogen mineralization in the field can be better estimated using a sequential soil sampling procedure, which enables measurements with minimum soil disturbance and under field moisture and temperature regimes throughout the growing season, but soil dynamics make these estimations very difficult. To

compensate for those limitations, incubations under controlled conditions have been used to determine the potential mineralization process.

Potentially mineralized N (PMN), based on anaerobic incubations and NH_4 released, varied with year and across sampling dates within a season (Fig. 5.6). Most of the mineralization potential was observed in samples between September and November. The amounts of N that could be mineralized in 2001 and 2002 were very repeatable across sampling dates. Potential mineralization was highest at all sampling dates in 2003. Under field conditions this could be related to higher precipitations, but under control conditions could be related to temperature fluctuations or higher microbial activity than expected in the field.

Mineralization potential peaked in July at Orange and in September at Blacksburg in 2001 (Table 5.10). During the residual years (2002 and 2003), there was variability in PMN between locations and dates. Higher rates of PMN were observed in July and September at all locations. Potentially mineralized N was higher at both locations in 2003 than 2002. This is attributed to above normal rainfall patterns at both locations during the 2003 sampling dates (Table 5.1). Records of the growing season (April to October) of 2002 showed that precipitation was below normal. Because N mineralization is influenced by soil water content (Kladravko and Keeny, 1987), we would expect lower rates of N mineralization during the growing season of 2002. Patterns of PMN are likely to vary with a season due to biological transformations that depend on temperature and moisture, fertilization, and management practices (White et al., 1987).

We should note that PMN does not report actual N mineralized – on the potential that a soil sample exhibits for mineralizing N when put under the “unnatural” conditions used in the procedure (anoxic, saturated, suspensions, 40°C). The values produced in the procedure do not reflect actual N releases in the field. They are probably not even close approximations. However, they do reflect some sort of changes in the soils over the course of the growing season that might result in higher rates of N mineralization. Those higher rates (and subsequent denitrification activity) are quite likely the cause of the changes in SMN noted above.

CONCLUSIONS

Consideration of yields over the 3 yr of this study revealed no yield increase due to N fertilization in 2001 and small increases in 2002 and 2003. Cumulative yields showed a clearer fertilization effect over the 3-yr. Application of all N in May 2001 provided residual effects on yield in subsequent years. This suggests that N applications might be required only every 3 yr or even at longer time intervals, but there are clear indications that external N will likely need to be supplied periodically if biomass (and N) is removed twice per year.

Nitrogen removal from an agroecosystem will be a function of biomass yield and N concentration in the biomass. It is logical, then, that the magnitude and duration of any residual-N effects will be influenced by the rate at which N is removed. Higher N removal was observed in 2002 and 2003 than in 2001. This was partially due to a change to two-cut management, where a July cutting had high N concentrations in leafy biomass. Over the 3 yr, more N than was applied was removed from all plots. In fact, the amount of N removed from the unfertilized plots was 60% as great as that removed from plots receiving 270 kg N ha⁻¹. This means, among other things, that applied N was not as major a factor in yield generation as might have been supposed. This also means that N is being taken from the system and that less N is carried forward to the next season, increasing the risk that the long-term soil N supply will be depleted by N removal. Only if other factors, such as N deposition, can offset the losses will the system ultimately be sustainable.

A trend of decline in NUE with increasing N rates was observed. This is similar to trends found by Staley et al. (1991). Apparent N recovery followed the same trend, with highest N recovery at 90 kg N ha⁻¹. The PFP estimator also showed significant differences among treatments, with a decrease in production efficiency at 270 kg N ha⁻¹ rate. These data suggest that N rates no greater than 90 kg ha⁻¹ should be applied to improve switchgrass N uptake and utilization in VA. Switchgrass biomass yields could be maximized with low N levels or even no applied N. The lack of N response could be due to adequate “native” N,

possible microbiological interactions, and/or the ability of the plants to create internal N reserves in the roots.

The great ability of switchgrass to capitalize on non-fertilizer N sources, e.g., recently mineralized N, deposition, mycorrhizae, or other pools, tends to negate the value of NUE, ANR, PFP, and similar estimators of N use. Those estimators key on the amounts of N supplied as fertilizer and implicitly or explicitly assume that such N is the primary factor that is driving yield. These data suggest otherwise. We do not put great stock in these estimators for establishing the efficiency with which fertilizer N is used in this crop in soils which can obviously provide very significant amounts of N.

Biomass and N allocation patterns to aboveground and belowground biomass were different at all harvest dates and locations. The low concentration of N in the roots in May probably reflected translocation from roots to shoots during the period of new shoot growth. The seasonal changes in N content in shoots showed the extent of N translocation from roots to shoots and back.

Soil mineral N could be a good indicator of switchgrass yield potential. Levels of mineral and mineralizable N contributed to yield and plant uptake, especially in the third year after N application. Further studies will need to account for deeper root zones to quantify available N. Soil mineral N and PMN were greatest in July and September but decreased sharply by the end of the season, likely a function of less microbial activity due to decrease in soil temperatures.

Soil mineral N and seasonally mineralized N will vary with the season and year as well as soil, because of biological transformations that depend on temperature, moisture, fertilization, and management practices (White et al., 1987). Mineral N was generally lower in May and increased through the growing season, probably due increases in N mineralization rates. The general conclusion from laboratory incubations was that PMN increased at the same time SMN increased. It was also observed that potentially mineralized N was lower in drier 2002, indicating, as is known to be the case in other studies, that soil moisture had an effect on N availability. There is also the possibility that

switchgrass roots may gain direct access to the mineralizable N pool through mycorrhizal symbiosis (Bredja et al., 1998).

Switchgrass can be highly productive under VA conditions with minimal or no N inputs. We speculate that is possible because of the plants' ability to capitalize on mineralized N and also to develop mobile N reserves that can be sequestered prior to late-fall harvests. The translocation of N out of the aboveground biomass prior to senescence apparently allows switchgrass to achieve great efficiency in its use of N. This information should be factored into N management strategies, especially in energy-cropping systems – where N content of the biomass may be a liability, not an asset. Further studies are needed on nutrient removal and nutrient efficiency. Every strategy to improve recycling and N use needs to be evaluated in a model system analysis, taking into account all the insights that have been gained from this study.

LITERATURE CITED

- Bredja, J. J., L. E. Moser, and K. P. Vogel. 1998. Evaluation of switchgrass rhizosphere microflora for enhancing seedling yield and nutrient uptake. *Agron. J.* 90: 753-758.
- Bundy, L. G., and J. J. Meisinger. 1994. Nitrogen availability indices. p. 951-984. *In* R. W. Waver, S. Angle, P. Bottomley, D. Bezdicek, S. Smith, A. Tabatabai, and A. Wollum (eds). *Methods of soil analysis. Part 2. Microbial and biochemical properties.* Book Series No. 5. SSSA, Madison, WI.
- Cassman, K. G., S. Peng, D. C. Olk, J. K. Ladha, W. Reichardt, A. Doberman, U. Sigh. 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crops Res.* 56: 7-39.
- Christensen, N. W., M. H. Qureshi, D. M. Baloch, and R. S. Karow. 1999. Assessing nitrogen mineralization in a moist xeric environment. *Proceedings of the Western Nutrient Management Conference* 3: 83-90. March 4-5. Potash & Phosphate Institute: Salt Lake City, UT.
- Collins, A., and D. W. Allinson. 2002. Nitrogen mineralization in soil from

- perennial grassland measured through long-term laboratory incubations. *J. Agric. Sci.* 138: 301-310.
- Collins, M. 1994. Biomass production by fescue and switchgrass alone and in mixed swards with legumes. Final Report to Oak Ridge National Laboratory ORNL/Sub/88-SC617, 86 p.
- Crasswell, E. T. and D. C. Godwin. 1984. The efficiency of nitrogen fertilizers applied to cereals in different climates. Vol. 1 p. 1-55. In P. B. Thacker and A. Lauchli (eds.) *Advances in plant nutrition*. Praeger, New York.
- Gordillo, R. M., and M. L. Cabrera. 1997. Mineralizable nitrogen in broiler litter. I. Effect of litter chemical characteristics. *J. Environ. Qual.* 26: 1672-1679.
- Heckathorn, S. A. and E. H. Delucia. 1996. Retranslocation of shoot nitrogen to rhizomes and roots in prairie grasses may limit loss of N to grazing and fire during drought. *Functional Ecology* 10: 396-400.
- Huang, Y., D. H. Rickerl, and K. D. Kephart. 1996. Recovery of deep-point injected soil nitrogen-15 by switchgrass, alfalfa, ineffective alfalfa, and corn. *J. Environ. Qual.* 25: 1394-1400.
- Keeney, D. R., and D. W. Nelson. 1982. Nitrogen inorganic forms. In A. L. Page, R. H. Miller, and D. R. Keeney (eds). *Methods of soil analysis: Part 2. Agron. Monogr.* 9. 2nd ed. ASA and SSSA, Madison, WI.
- Khan, S. A., R. L. Mulvaney, and R. G. Hoelt. 2001. A simple soil test for detecting sites that are not responsive to nitrogen fertilization. *Soil Sci. Soc. Am. J.* 65: 1751-1760.
- Kladivko, E. J., and D. R. Keeney. 1987. Soil nitrogen mineralization as affected by water and temperature interactions. *Biol. Fertil. Soils* 5: 248-252.
- Kowalenko, C. G., and S. Bittman. 2000. Within-season grass yield and nitrogen uptake, and soil nitrogen as affected by nitrogen applied at various rates and distributions in a high rainfall environment. *Can. J. Plant. Sci.* 80: 287-301.
- Ma, Z., C. W. Wood, and D. I. Bransby. 2000. Impacts of soil management on root characteristics of switchgrass. *Biomass and Bioenergy* 18: 105-112.
- Moore, K. J., L. E. Moser, K. P. Vogel, S. S. Waller, B. E. Johnson, and J. F. Pedersen. 1991. Describing and quantifying growth stages of perennial forage grasses. *Agron J.* 83: 1073-1077.

- Novoa, R., and R. S. Loomis. 1981. Nitrogen and Plant Production. *Plant and Soil* 58: 177-204.
- Parrish, D. J., D. D. Wolf, J. H. Fike, and W. L. Daniels. 2002. Switchgrass as a biofuels crop for the upper Southeast: variety trials and cultural improvements. Final report. Biofuels feedstocks development program. Oak Ridge National Laboratory. Oak Ridge, TN.
- Parrish, D. J., D. Wolf, P.R. Peterson, and W. L. Daniels. 1996. Switchgrass as a biofuel crop for the upper southeast: variety trials and cultural improvements. Annual report. Biofuels feedstock development program. Oak Ridge National Laboratory. Oak Ridge, TN.
- SAS Institute. 2003. SAS User's Guide: Statistics. Version 8.2. SAS Inst., Cary, NC.
- Sladden, S. E., D. I. Bransby, D. D. Kee. 1994. Changes in Yield and forage quality with time for two switchgrass varieties. *Proceedings of American Forage and Grassland Council*, Vol 3: 242-246.
- Smuker, A. J. M., S. L. McBurney, and A. K. Srivastava. 1982. Quantitive separation of roots from compacted soil profiles by the hydropneumatic elutriation system. *Agron J.* 74: 500-503.
- Staley, T. E., W. L. Stout, and G. A. Jung. 1991. Nitrogen use by tall fescue and switchgrass established on acidic soils of varying water holding capacity. *Agron. J.* 83: 732-738.
- Stout, W. L., and G. A. Jung. 1995. Biomass and nitrogen accumulation in switchgrass: Effects of soil and environment. *Agron. J.* 87: 663-669.
- Thomason, W.E., W.R. Raun, G.V. Johnson, K.W. Freeman, K.J. Wynn, and R.W. Mullen. 2002. Production system techniques to increase nitrogen use efficiency in winter wheat. *J. Plant Nutr.* 25:2261-2283.
- White, R. E., R. A. Haigh, and J. H. Macduff. 1987. Frequency distributions of spatially dependent variability of ammonium and nitrate concentrations in soil under grazed and ungrazed grasslands. *Fert. Res.* 11: 193-208.
- Zemenchick, R. A. and K. A. Albrecht. 2002. Nitrogen use efficiency and apparent nitrogen recovery of Kentucky bluegrass, smooth brome grass, and orchardgrass. *Agron. J.* 94: 421-428.

Table 5.1. Observed and long-term (30-yr) monthly rainfall and mean emperatures for April through October at two locations at which switchgrass was grown in VA in 2001, 2002, and 2003.

Month	Blacksburg				Orange			
	Long-term	2001	2002	2003	Long-term	2001	2002	2003
----- Precipitation (cm) -----								
April	7.1	1.6	4.8	8.6	6.5	1.8	9.0	8.0
May	9.7	18.5	0.7	15.0	8.3	11.8	4.8	16.3
June	8.6	8.9	7.0	19.0	13.0	21.0	7.0	18.3
July	10.2	16.1	11.2	17.1	13.8	10.3	13.0	11.3
August	8.4	5.4	1.8	10.6	7.3	7.5	6.8	10.0
September	7.6	4.5	12.6	13.2	12.5	2.0	6.3	26.5
October	8.4	2.1	10.5	3.4	7.5	3.0	14.0	8.5
Total	60.0	57.1	48.6	86.9	68.9	57.4	60.9	98.8
----- Temperature (°C) -----								
April	10.5	11.4	12.3	11.2	15.2	12.6	14.0	12.1
May	15.7	15.2	8.0	13.0	20.1	18.2	17.2	16.2
June	19.8	19.6	20.5	18.9	25.3	22.8	22.4	20.8
July	21.8	19.9	22.2	21.3	27.8	22.0	24.4	24.2
August	21.2	21.0	21.6	22.0	26.9	23.6	24.8	24.6
September	17.6	15.5	19.3	17.0	22.8	18.6	20.3	19.8
October	11.7	9.4	12.5	10.8	16.0	14.2	15.3	12.8
Mean	16.9	16.0	16.6	16.3	22.0	18.8	19.7	16.9

Table 5.2 Analyses of variance and mean squares for total switchgrass biomass yields, and total (2001 to 2003) N removal in response to N applications in 2001 at two locations in VA.

Year	Source	df	Yield	N Removal
2001	Replication (Rep)	3	4.3	192
	Location (Loc)	1	0.3	4580*
	Error a	3	1.7	232
	N Treatment (Trt)	3	2.2	1345**
	Loc*Trt	3	3.3	750*
	Error b	18	1.8	235
2002	Replication (Rep)	3	7.0	1142
	Location (Loc)	1	38.6*	31916*
	Error a	3	3.2	2036
	N Treatment (Trt)	3	9.0*	8943***
	Loc*Trt	3	3.0	898
	Error b	18	2.0	714
2003	Replication (Rep)	3	7.8	1592
	Location (Loc)	1	402.2*	58886*
	Error a	3	30.3	5819
	N Treatment (Trt)	3	17.7***	3899*
	Loc*Trt	3	2.7	1161
	Error b	18	2.7	1063

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

Table 5.3. Nitrogen effects (applied in 2001 and residual in 2002 and 2003) on switchgrass seasonal and 3-yr cumulative (2001 to 2003) yields averaged across two locations in VA.

N Rate kg ha ⁻¹	Year			Cumulative
	2001	2002	2003	
	----- Mg ha ⁻¹ -----			
0	9.7	9.9	13.3	33.0
90	10.6	11.5	14.3	36.4
180	10.9	11.2	13.9	36.1
270	10.8	12.4	16.7	40.0
LSD _{0.05} ¹	ns	1.4	1.8	3.0

¹LSD for comparison of N treatments within each year and cumulative values.

Table 5.4. Annual and 3-yr cumulative N removal by switchgrass when fertilized once (in 2001) and harvested once (2001) or twice (2002 and 2003) per year. Data are averaged over two locations in VA.

Year	Harvest Date	Applied N (kg ha ⁻¹)				LSD _{0.05} ²
		0	90	180	270	
----- N Removal (kg ha ⁻¹) -----						
2001	Nov.	26.4	40.5	44.6	57.9	15.2
2002	July	70.3	97.5	104.2	141.0	26.8
	Nov.	24.0	31.0	22.7	34.6	11.8
	Total	94.3	128.5	126.9	175.6	29.9
	LSD _{0.05} ¹	20.1	30.9	29.6	33.5	--
2003	July	86.6	113.5	82.8	121.2	35.5
	Nov.	19.7	19.7	18.0	26.1	5.7
	Total	106.3	133.2	100.8	147.3	34.4
	LSD _{0.05} ¹	26.1	54.1	27.1	48.1	--
2001-03	----	227.0	302.3	272.4	380.7	66.2

¹LSD for comparison of harvest dates within a year and N rate.

²LSD for comparison of N rates within a year and harvest date.

Table 5.5. Nitrogen use estimators as affected by N rate for switchgrass production over 3 yr (2001 through 2003) when the N was applied only once (2001). Cumulative yields for the 3 yr are used in calculating N-use efficiency (NUE), apparent N recovery (ANR), and partial factor productivity (PFP). Data are averaged over two locations for ANR.

N Treatment	NUE		LSD _{0.05} ²	ANR	PFP		LSD _{0.05} ²
	Blacksburg	Orange			Blacksburg	Orange	
	----- kg kg ⁻¹ -----			---- % ----	----- kg kg ⁻¹ -----		
90	66	11	ns	83	478	331	143
180	11	23	ns	57	217	183	23
270	30	22	ns	25	167	129	ns
LSD _{0.05} ¹	53	ns	--	43	70	17	--

¹LSD for comparison of N treatments within a location.

²LSD for comparison of locations within a N treatment.

Table 5.6. Changes in switchgrass root biomass in the upper 15 cm throughout the growing season. Data are averaged over two VA locations and four N rates. Data for 2001 are derived from 0.25 m² quadrats. Data for 2002 and 2003 are based on smaller core samples subsequently corrected for nonrandom sampling.

Sampling Date	Year		
	2001	2002	2003
	----- Root Biomass (Mg ha ⁻¹) -----		
May	1.7	7.9	7.0
July	4.1	7.0	7.3
Sep.	7.0	8.1	6.7
Nov.	8.0	7.9	6.7
LSD _{0.05} ¹	0.8	0.8	ns

¹LSD for comparison of harvests within a year.

Table 5.7. Analysis of variance and mean squares for root N concentrations in response to N applications in 2001 and residual N (2002 and 2003) at two locations in VA.

Source	df	2001	2002	2003
Replication (Rep)	3	0.0074	0.0270	0.0086
Location (Loc)	1	0.0704	0.2476	0.1372*
N Treatment (Trt)	3	0.7385***	0.4654**	0.0933*
Loc*Trt	3	0.0036	0.0474	0.0417
Error a	21	0.0686	0.0971	0.0240
Date (Dt)	2	0.9327***	0.3874***	0.0887***
Loc*Dt	2	0.0035	0.1214***	0.0033
Dt*Trt	6	0.0157	0.0300	0.0187
Loc*Dt*Trt	6	0.0107	0.0385	0.0111
Error b	48	0.0164	0.0199	0.0154

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

Table 5.8. Analyses of variance and mean squares for soil mineral N (SMN) and potentially mineralizable N (PMN) in response to N applications in 2001 and N residual (2002 and 2003) at two locations in VA.

Year	Source	df	MN	PMN
2001	Replication (Rep)	3	378	408
	Location (Loc)	1	1423	19303***
	N Treatment (Trt)	3	576	2138
	Loc*Trt	3	172	797
	Error a	21	776	1669
	Date (Dt)	2	64060***	114905***
	Dt*Loc	2	15522***	14626***
	Dt*Trt	6	247	1342
	Dt*Loc*Trt	6	674	2174
	Error b	48	738	990
2002	Replication (Rep)	3	178	715
	Location (Loc)	1	1809***	5876***
	N Treatment (Trt)	3	93	1109
	Loc*Trt	3	149	329
	Error a	21	125	410
	Date (Dt)	3	13167***	100650***
	Dt*Loc	3	689***	1752*
	Dt*Trt	9	46	711
	Dt*Loc*Trt	9	86	862
	Error b	72	89	508
2003	Replication (Rep)	3	19	1315
	Location (Loc)	1	19	4896
	N Treatment (Trt)	3	62	830
	Loc*Trt	3	70	1100
	Error a	21	62	1492
	Date (Dt)	3	1183***	8427***
	Dt*Loc	3	163**	4778***
	Dt*Trt	9	45	761
	Dt*Loc*Trt	9	14	1394
	Error b	72	39	777

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

Table 5.9. Year, location, and sampling date effect on total soil N in two VA soils under switchgrass management. Soil samples were collected to 15 cm and data are averaged over four N rates.

Year	Location	Sampling Date				LSD _{0.05} ²
		May	July	Sep.	Nov.	
		----- TSN (kg ha ⁻¹) -----				
2001	--	1910.7	3291.8	3502.9	3322.6	145.0
2002	Blacksburg	2357.6	2501.0	2296.3	2451.0	ns
	Orange	2564.9	2598.4	2654.6	2369.1	213.6
	LSD _{0.05} ¹	ns	ns	154.4	ns	--
2003	Blacksburg	2527.4	2429.5	2334.1	2385.3	144.6
	Orange	2581.4	2967.8	2907.2	3632.0	265.0
	LSD _{0.05} ¹	ns	154.7	205.3	469.4	--

¹LSD for comparison of locations within a year and sampling date.

²LSD for comparison of sampling dates within a year and location.

Table 5.10. Location and harvest effects on soil mineral N (SMN) and potentially mineralized N (PMN) in soils supporting switchgrass growth at two locations in VA during 2001 to 2003. Values from soil samples (collected to a 15-cm depth) were averaged over four N rates.

Year	Location	Sampling Date				LSD _{0.05} ²
		May	July	Sep.	Nov.	
		----- SMN (kg ha ⁻¹) -----				
2001	Blacksburg	90	132	101	58	20
	Orange	50	108	154	36	18
	LSD _{0.05} ¹	--	21	18	16	--
2002	Blacksburg	31	62	55	31	7
	Orange	37	74	72	26	7
	LSD _{0.05} ¹	ns	6	8	ns	--
2003	Blacksburg	22	21	16	14	5
	Orange	29	21	12	10	4
	LSD _{0.05} ¹	ns	ns	3	ns	--
----- PMN (kg ha ⁻¹) -----						
2001	Blacksburg	94	78	117	18	20
	Orange	111	154	130	14	27
	LSD _{0.05} ¹	--	27	ns	ns	--
2002	Blacksburg	10	125	122	18	17
	Orange	11	97	98	15	14
	LSD _{0.05} ¹	ns	23	19	ns	--
2003	Blacksburg	152	169	154	141	24
	Orange	104	164	154	145	19
	LSD _{0.05} ¹	15	ns	ns	ns	--

¹LSD for comparison of locations within a sampling date and year.

²LSD for comparison of sampling dates within a location and year.

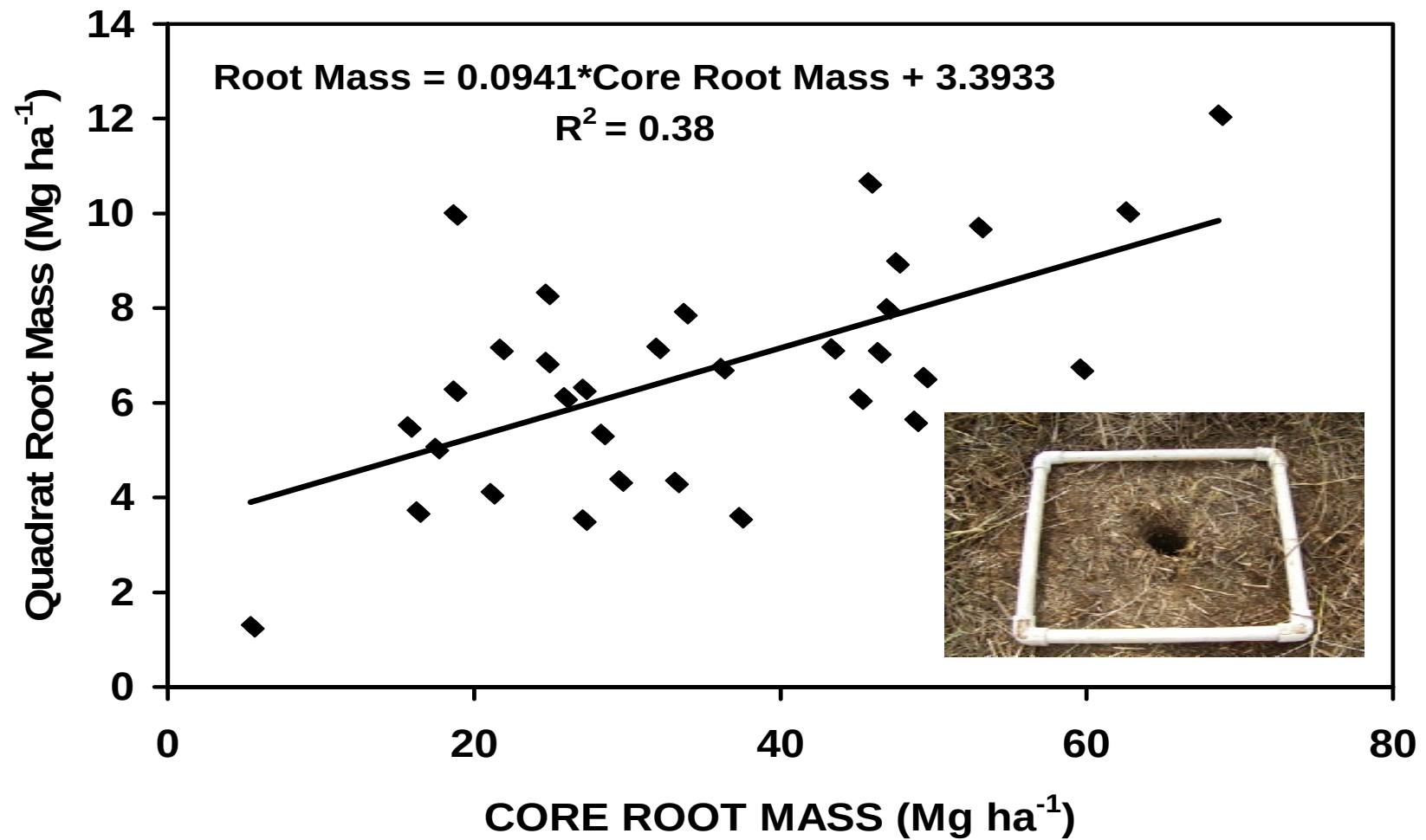


Fig. 5.2. Correlation between root sampling methods (quadrat vs. core) to subsequently estimate corrected values for nonrandom sampling in 2002 and 2003 at different dates.

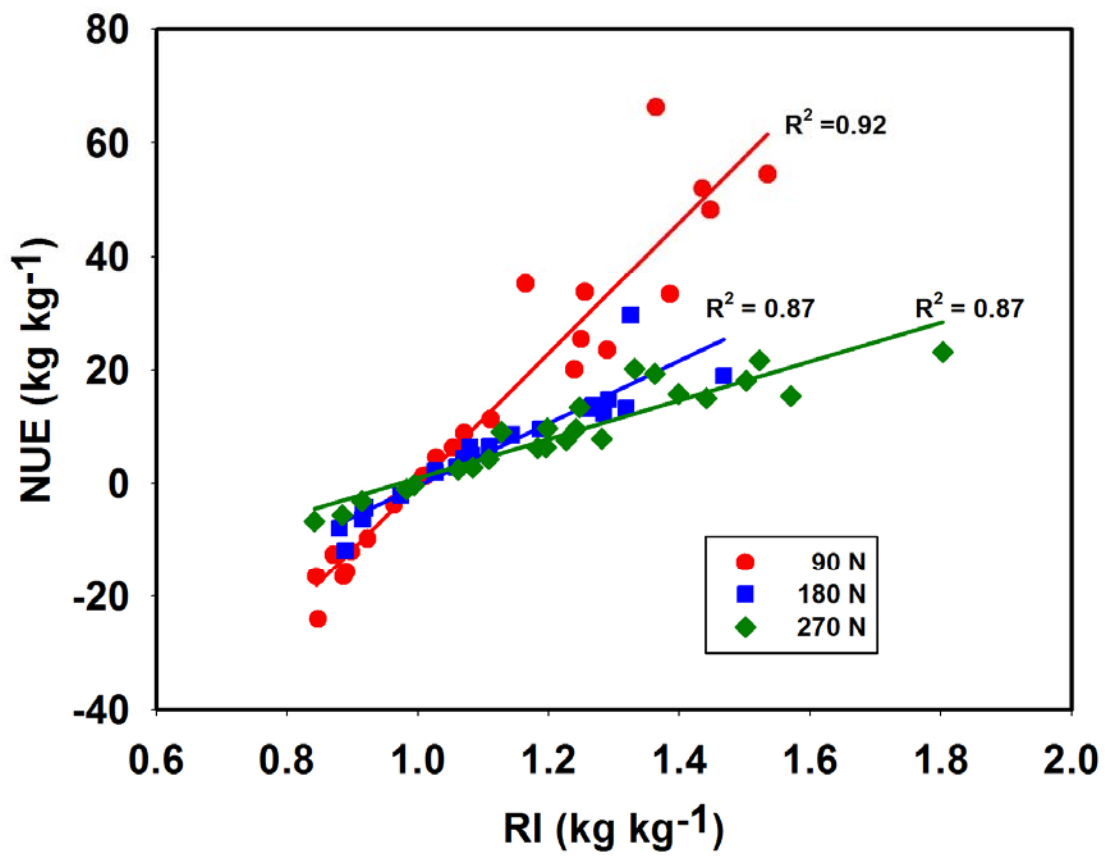


Fig. 5.3. Effect of N rate on the relationship between cumulative response index (RI) and switchgrass cumulative NUE. Data are averaged over two locations.

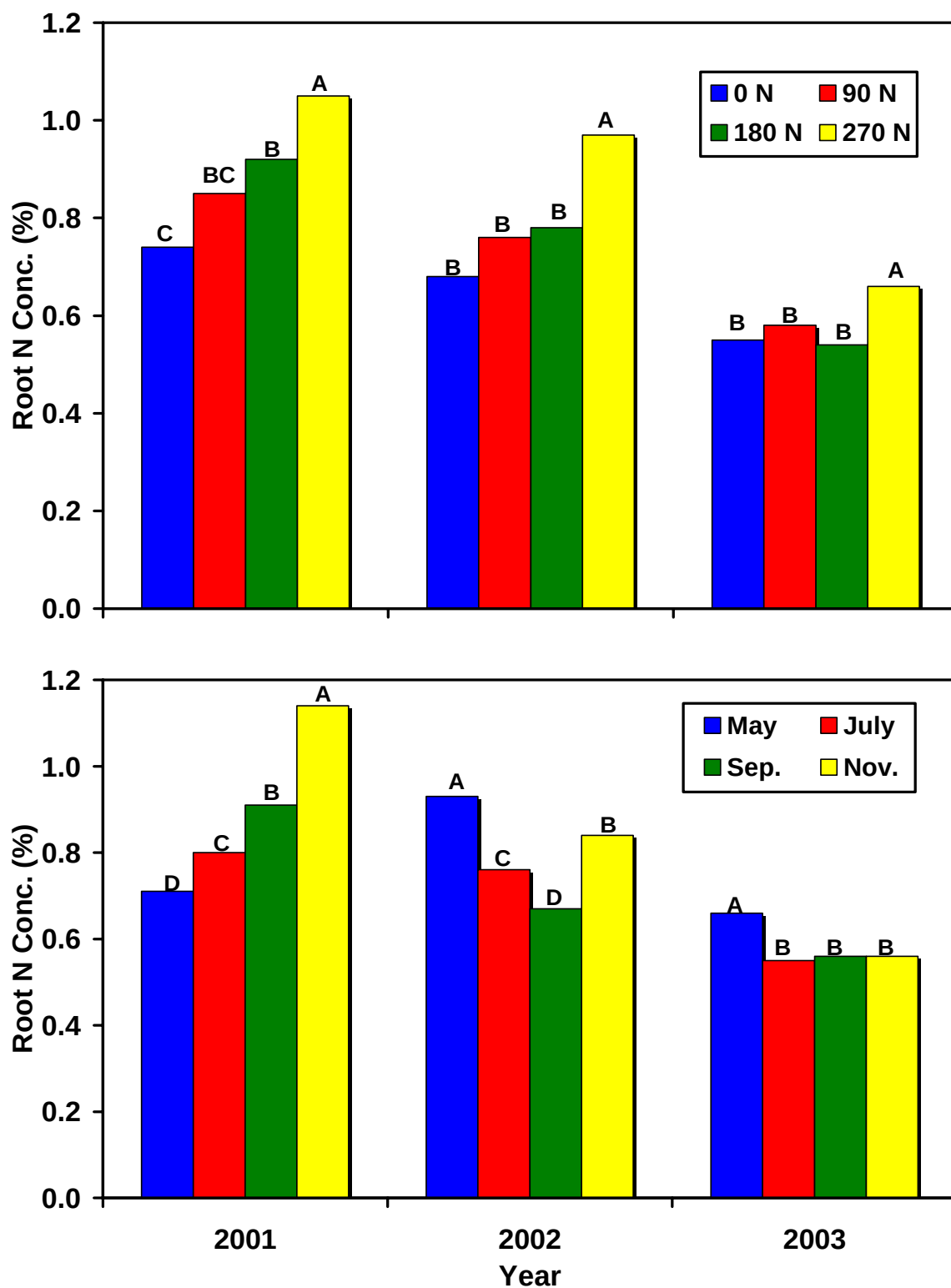


Fig. 5.4. Applied N and date effects on switchgrass root N concentrations during 2001, 2002, and 2003. Data are averaged over two locations.

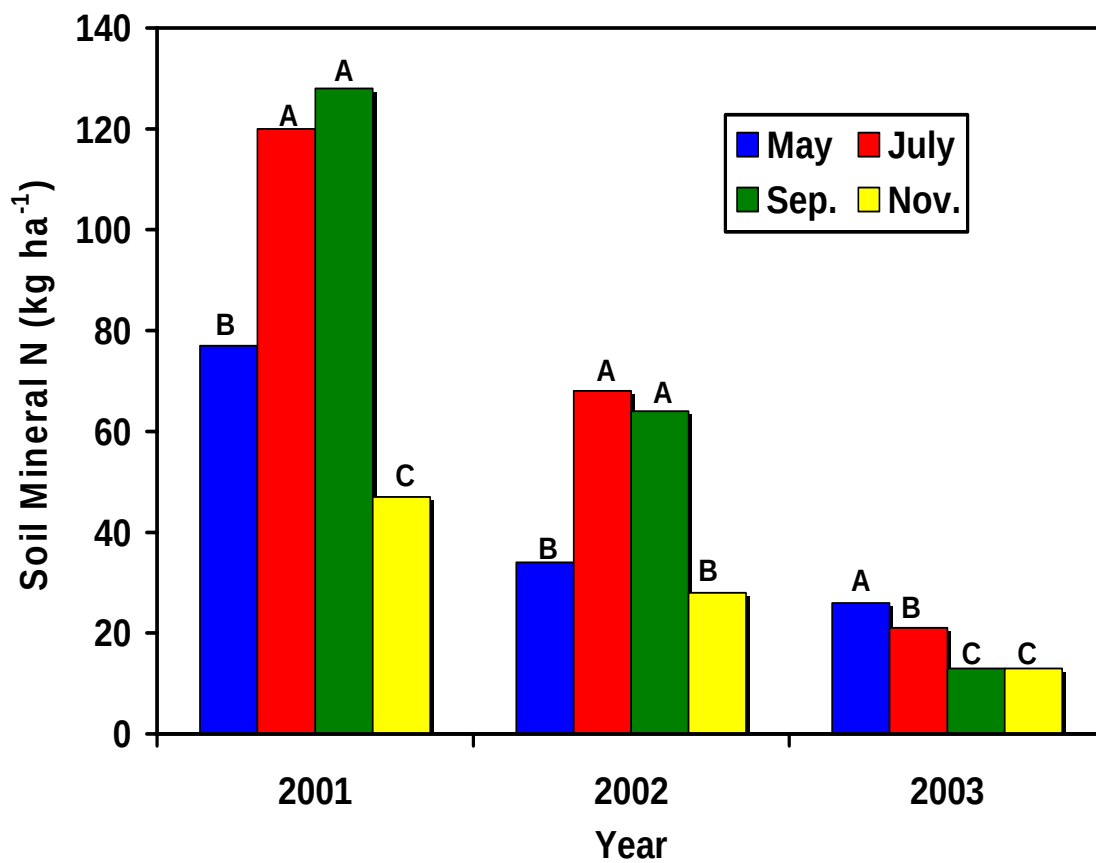


Fig. 5.5. Soil mineral N test values at four sampling dates across the growing season for 3 yr in soils under switchgrass production in VA. Data are averaged over two locations and four N rates.

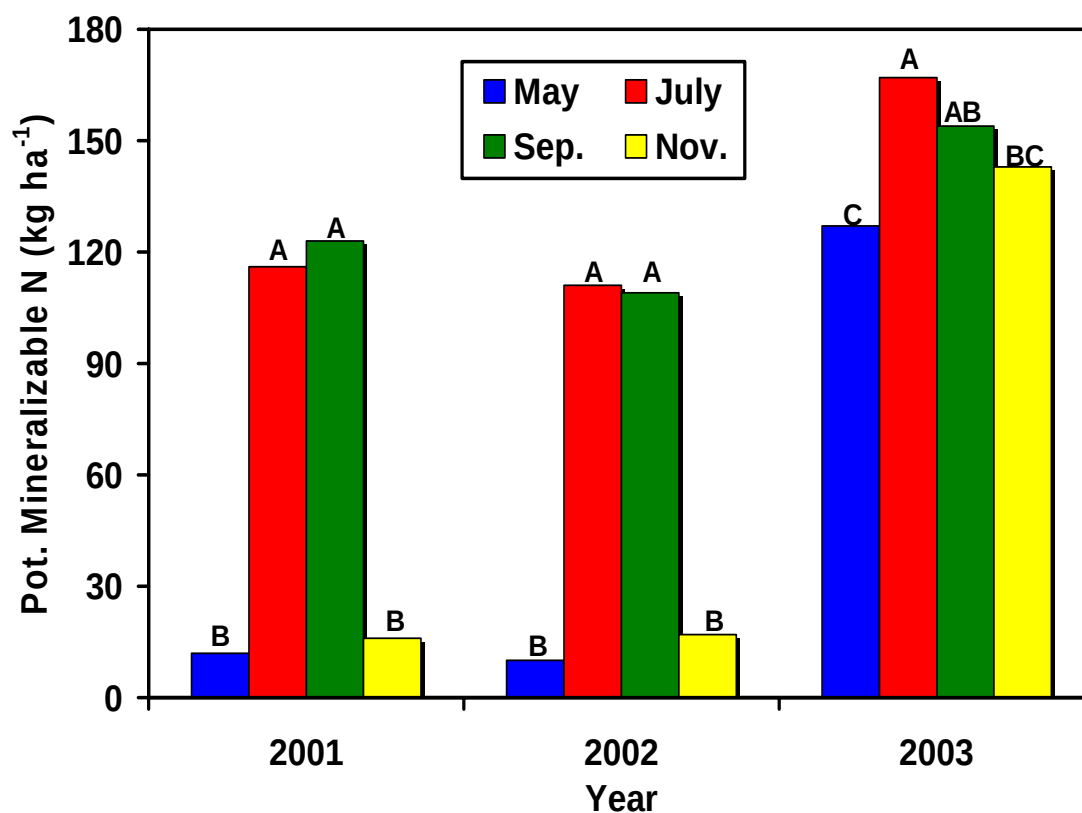


Fig. 5.6. Potentially mineralizable N values at four sampling dates across the growing season for 3 yr in soils under switchgrass production in VA. Data are averaged over two locations and four N rates.

CHAPTER 6

SEEDLING SWITCHGRASS RESPONSE TO N AND P WHEN GROWN IN A SOILLESS SUBSTRATE

ABSTRACT

Switchgrass (*Panicum virgatum* L.) is a high-yielding, native perennial that could serve as a biofuels feedstock. In field studies, maximum yields have been obtained by adding as little as 50 kg N ha⁻¹ to as much as 744 kg N ha⁻¹. The objectives of this research were to establish switchgrass' responses to N and P under well-defined, soilless conditions and to measure its fertilizer recovery. 'Cave-in-Rock' switchgrass was grown from seed in the greenhouse in a 2:1 (v/v) vermiculite:perlite substrate. Treatments (nine rates of N up to 400 kg N ha⁻¹ and four rates of P up to 90 kg ha⁻¹) were replicated three times in a randomized complete block design. In a second study, treatments from two N sources (ammonium sulfate and urea) were applied at rates up to 270 kg N ha⁻¹. In both studies, plants were harvested 12 wk after germination, dried, weighed, and analyzed for tissue N and P concentrations. Shoot biomass increased with N fertilization with an observed inflection point at 210 kg N ha⁻¹. In these pot studies, root biomass increased with N only to 115 kg N ha⁻¹. No significant effect above 30 kg P ha⁻¹ was observed in shoot or root biomass. Biomass and tiller number were highly correlated. Increases in tillers plant⁻¹ were observed up to 116 kg N ha⁻¹. Shoot and root N concentrations generally increased with fertilization. Ammonium sulfate had a greater effect than urea on shoot and root biomass. These data suggest switchgrass can maximize biomass production with ~200 kg available N ha⁻¹.

INTRODUCTION

Switchgrass (*Panicum virgatum* L.), a native, warm-season species found throughout much of the southern and central USA, has potential as a biofuels feedstock; but information is scarce on nutrient management for the species as an energy crop. Fertility recommendations for switchgrass apply mainly to forage production (Muir et al., 2001), where there is a compromise between maximum biomass production and peak forage quality. In energy cropping, this compromise is unnecessary, because the main goal is to maximize production of lignocellulose (Sanderson et al., 1999a). Producing optimum switchgrass yields requires applying sufficient N for switchgrass growth without over-fertilizing. Too little N will not allow the crop to take full advantage of all other resources. Too much N may reduce yields by making plants more susceptible to diseases and insects and by increasing lodging.

Although switchgrass has demonstrated high productivity across a wide geographic area, there is no consensus on fertilizer recommendations that would maximize yields (while ideally minimizing nutrient losses). Reported annual rates of N use for switchgrass (70 to 100 kg ha⁻¹) are typically about half of those required for corn production (138 to 154 kg ha⁻¹) (McLaughlin and Walsh, 1998). Several authors make N recommendations as low as 50 to 100 kg N ha⁻¹ yr⁻¹ (Wolf and Fiske, 1994; Bredja, 2000). In TX, Sanderson et al. (1999b) reported that the annual yield of several cultivars fertilized with 134 kg N ha⁻¹ ranged from 8 to 20 Mg ha⁻¹. Others have shown responses in the field at up to 744 kg N ha⁻¹ yr⁻¹ (Lutwick and Smith, 1979).

The precise N needs of switchgrass cannot be determined from field data because of, among other things, the great variability of soils in supplying “endogenous” N. Nitrogen, which is highly mobile in the soil, is constantly undergoing transformations such as mineralization, leaching, volatilization, and immobilization. These dynamics undoubtedly contribute to the confusion in the literature regarding switchgrass’ N response. Estimations of N requirements under soilless conditions will provide a more precise way to determine

switchgrass N needs.

Warm-season grasses generally have a lower N requirement and are more efficient users of P (Balasko et al., 1984). There are limited data on the effect of P fertilization on switchgrass and/or P interactions with other nutrients such as N. Depending on soil test and pH, P recommendations for switchgrass range from 0 to 35 kg ha⁻¹ (Bredja, 2000). Griffin and Jung (1983) reported P levels in switchgrass and big bluestem (*Andropogon gerardii* Vitman) decreased from 0.24% to 0.14% with increasing maturity. Radiotis et al. (1999) reported that P levels of the whole switchgrass plant fraction was 0.12% at the reproductive stage but declined to 0.04% when standing biomass was left to over-winter. They suggested that P is either transported or leached out of the shoots. Smith and Greenfield (1979) reported high P concentrations in switchgrass compared to timothy (*Phleum pratense* L.), with the highest P accumulation in the inflorescence. Research with some forage species and grain crops also indicates that rhizosphere microflora, particularly mycorrhizae, can enhance P uptake. Bredja et al. (1998) indicated that mycorrhiza populations collected in switchgrass fields increased P uptake by 37-fold across lowland and upland switchgrass ecotypes when compared to controls.

The N requirement for any crop is a function of the yield potential and the amount of N required per unit of yield. Stanford and Legg (1984) defined the N requirement as the minimum amount of N in the aboveground biomass associated with maximum production. Nitrogen use efficiency (NUE) provides a framework for evaluating variation in N-use factors as related to major plant physiological processes. Nitrogen-use efficiency is an important topic when discussing fertilizer applications and switchgrass biomass production. The term NUE has been commonly used to describe the capacity of a plant to acquire and utilize N for making yield (Gourley et al., 1994). Definitions of NUE vary greatly (Clark, 1990). They generally can be divided into those emphasizing productivity (utilization efficiency) and those emphasizing the internal nutrient requirement of the plant (uptake efficiency) (Fiez et al., 1995). Uptake efficiency emphasizes the ability of a plant to take up supplied N, while utilization efficiency highlights

the ability of N to increase yield. However, various N-use parameters could be misleading in the search for increased productivity and identification of mechanisms that enhanced nutrient acquisition and utilization. With regard to yield parameters, nutrient efficiency has been defined as the ability to produce a high plant yield in a soil, or other media, that would otherwise limit production (Buso and Bliss, 1988).

The feasibility of switchgrass as a biomass crop will be enhanced if high yields can be produced while holding N use to the minimum required for such yields. The main objectives of this research with greenhouse-grown seedling switchgrass were: (1) to measure responses to N and P under well-defined conditions, (2) to look at the effect of two different N sources on biomass production, (3) to examine NUE under different N sources and application rates, and (4) to compare NUE parameters that as aids to making N recommendations.

MATERIALS AND METHODS

Two N fertilizations studies (A and B) were conducted in a greenhouse setting. Study A was conducted from early-July to October 2002, and study B was conducted from late-July to November 2003. A 2:1 (v/v) mix of vermiculite and perlite was used as substrate in both studies. This artificial substrate contained no N and very low levels of extractable P. To determine water-holding capacity, pots (4.5 L) were filled with the substrate, saturated with tap water, and allowed to drain overnight. The drained weight was used to establish “field capacity.” The moisture content of the substrate during the course of the study was adjusted by using time domain reflectrometry (TDR) (ESI, Vancouver, BC, Canada). Pots were weighed as soil water content of the substrate (as indicated by TDR readings) fell to about 80% of field capacity, and water was added to adjust moisture content to 80% of field capacity. About 500 ml of water per pot needed to be added every 2 d to maintain moisture once plants attained full size.

The range of fertilization rates for these studies was established based on recommendations for grasses and warm-season grasses from several states

(ND, SD, KY, IA, VA, NY, and NC). The treatments for Study A included nine N rates (0, 50, 100, 150, 200, 250, 300, 350, or 400 kg N ha⁻¹), combined factorially with four P rates (0, 30, 60, or 90 kg P ha⁻¹) applied on a substrate-surface-area basis. Ammonium sulfate [(NH₄)₂SO₄] and sodium phosphate (NaPO₄ · 7H₂O) were used as N and P sources, respectively. Pots were rotated periodically within blocks in both studies.

In Study B, urea (46-0-0) or ammonium sulfate [(NH₄)₂SO₄] was applied at 0, 45, 90, 180, or 270 kg N ha⁻¹. A uniform 50 kg P ha⁻¹ (as NaPO₄ · 7H₂O) was applied at time of N applications.

All fertilizer sources in both studies were dissolved in distilled H₂O and applied in solution. Plants of each study were watered once a week with 200 ml of a Peter's No-N/P (0-0-50) soluble trace element mix (STEM) (Peter's Co, Allentown, PA) to maintain an adequate level of K and micronutrients. The solution contains approximately 2 ppm K per application.

In both studies, Cave-in-Rock seeds collected in 1998 at the Virginia Tech turf grass research center were planted directly into 4.7 L undrained pots. A germination test (30°C for 72 hr) conducted in July 2002 showed that seeds were 74% germinable. Approximately 30 seeds were planted in each pot and thinned to eight plants per pot 3 wk after planting in Study A. For Study B, pots were thinned to ten plants per pot. Switchgrass plants were maintained in a 14-hr photoperiod in the greenhouse (using natural sun light as well as fluorescent light) and adequate temperature range. Some temperature fluctuations were observed in the greenhouse, since the cooling system was unable to maintain the set maximum temperature of 25°C.

For both studies, biomass yields were determined at the heading stage [R1 (Moore et al., 1991)] (approximately 12 wk after planting). Shoots were harvested at the substrate surface. Roots were separated from the substrate by washing with water. All plant materials (above and belowground) were dried at 60°C for 72 hr in a forced air oven for dry weight determinations. Tiller number per pot was divided by plant number to obtain mean tillers per plant. Plant materials were ground to pass a 2 mm screen in a Wiley mill before extraction.

Total N in aboveground and belowground samples was determined using the Vario Max CN analyzer (Elementar Analysensysteme GmbH, 2000).

Nitrogen content in biomass fractions was calculated by multiplying biomass by the concentration of N. Nitrogen-use efficiency (g g^{-1}) was calculated as $\text{NUE} = [(\text{yield at } N_x - \text{yield at } N_0) / \text{g of N applied at } N_x]$, where $x = \text{N rate} > 0$ (Zemenchik and Albretch, 2002; Novoa and Loomis, 1981). The apparent N recovery (ANR) was calculated using the difference method: $\text{ANR} = [(\text{g of N recovered at } N_x - \text{g of N recovered from } N_0) / \text{g N applied at } N_x] \times 100$, where $x = \text{N rate} > 0$ (Crasswell and Godwin, 1984). Partial factor productivity (PFP) (g g^{-1}) was calculated as $(Y_0 + \Delta Y) / N_x$, where Y_0 is the biomass yield at N_0 and ΔY is the increment in biomass yield that resulted from N application (Cassman et al., 1998).

Experimental Design and Statistical Analysis

The experimental design in Study A was a randomized complete block in factorial arrangement with three replications or blocks. The second study was a randomized complete block with a split-plot design replicated four times. Fertilizer sources were considered the main plots, and fertilizer rates were considered the sub-plots. Nitrogen rates were randomized within each block by following the PLAN procedure of SAS (SAS Institute, 2003).

Analyses of variance (ANOVA) were conducted using the GLM procedure of SAS (SAS Inst., 2001) at $P < 0.05$ to test the effects of fertilizer sources and rates. Means were separated by the least significant difference (LSD) at 0.05 probability level. The REG and CORR procedures of SAS (SAS Institute, 2003) were utilized to determine relationships between switchgrass components (yield, N concentration and content, tiller number, height, and N-use parameters) and N rates. A nonlinear, linear-plateau model that follows the NLIN procedure and the NEWTON method was also used for data analysis. The linear-plateau model is a manifestation of Liebig's law of the minimum, where the rate of change in plant

responses to changes in N applications is constant until a certain yield level or N concentration is reached, at which point other nutrients become limiting and the response attains a plateau (Schabenberger and Pierce, 2002). The linear-plateau model calculates the inflection point at which the relationship is no longer linear, which is called the join point of the model. Significance of both the linear and non-linear regression models was tested, and the models with the strongest coefficients of determination were fitted to the data.

RESULTS AND DISCUSSION

Study A: Responses to N and P Fertilization

Plants receiving no P were extremely small and obviously stressed. By contrast, plants receiving 30 kg P ha⁻¹ and adequate N were quite vigorous. There were no differences in root or shoot biomass between plants receiving P rates of 30 kg ha⁻¹ or more and no N x P interaction (data not shown). Accordingly, data for the N treatments were combined across P rates (except for the 0 P rate). Nitrogen fertilization dramatically increased biomass yields in both shoots and roots (Fig. 6.1). Differences in shoot biomass were observed past 250 kg N ha⁻¹. At 400 kg N ha⁻¹, there seemed to be a plateau in the response curve according to the linear-plateau model. Root biomass yield did reach a plateau, and much earlier, at 114 kg N ha⁻¹. This could be related to roots growing in a restricted (pot) environment, which might have affected their developmental physiology.

Applied N promoted switchgrass height and tiller density (Fig. 6.2). Height increased up through a rate of 113 kg N ha⁻¹ and plateaued across higher N rates. Nitrogen had a linear effect on tiller number. Tillers increase up to at least 300 kg N ha⁻¹, and the linear-plateau model did not show a clear break point there. In this greenhouse setting and soilless substrate, increased biomass productivity at higher N rates was largely a function of increased tillering of the seedlings.

Nitrogen concentration in switchgrass tissues averaged about 90% higher in shoots than roots, but both increased linearly with applied N (Fig. 6.3). This difference between shoot and root is expected for leafy material, which is inherently higher in protein.

Nitrogen content (mg N in biomass) in shoots increased steadily with increasing N applied up to and past 300 kg N ha⁻¹ (Fig 6.4). Roots had a similar, if less dramatic, pattern. Especially at higher N rates, shoots had a much greater N content than roots, reflecting both greater biomass and higher N concentrations in the shoots. Also, since roots were growing in a restricted environment, root biomass and nutrient absorption could have been affected. Roots might become a greater sink for N accumulation in a field situation, where they might grow more and “compete” accordingly with shoots for dry matter and N partitioning.

Efficient use of N is important to reach an optimum switchgrass biomass yield. Different N-use parameters (NUE, ANR, and PFP) were calculated to determine productivity (utilization efficiency) and internal nutrient requirements of the plant (uptake efficiency). Nitrogen-use efficiency, ANR, and PFP were significantly different across N application rates (Fig. 6.5). Nutrient-use efficiency, which was maximal at 100 kg N ha⁻¹, and PFP tended to decline with increased N applications. These results are consistent with field studies in IA in which highest NUE was reached at 112 kg N ha⁻¹ (Lemus, 2000). In the current study, less than 20% of the applied N was present in biomass. Maximal ANR occurred at 200 kg N ha⁻¹, with its lowest values at 50 and 400 kg N ha⁻¹. These values are very similar to ANR values reported by Weiser and Smith (1988). Calculated PFP values followed the same trend as those observed with NUE. Partial factor productivity was maximal at 100 kg ha⁻¹.

Nitrogen-use parameters are a good measure of switchgrass' ability to produce yields with low N inputs. For switchgrass, ANR should be considered the best measure of N use to assess its ability to produce feedstock. Apparent N recovery measures the amount of N removed in biomass. A bioenergy crop with low N and high biomass production will be preferable, since less NO_x

compounds will be released in the combustion process and less N is needed in fertilizers. On the other hand, NUE or PFP do not take into account nutrient losses from the production system, which can be significant; especially for N, which can easily be volatilized, leached, or lost by surface run-off (Gerber, 2000). The evaluation of N use in switchgrass should therefore be based on a value that includes total removals from the system. Apparent N recovery provides that capability, since it considers N removal from applied fertilizer or that provided by endogenous soil N sources.

Study B: N Sources Comparison

Biomass yields of shoots and roots were much lower with urea (U) than with ammonium sulfate (AS) at each N rate (Table 6.1). Since this study was carried out using undrained pots, a lower U response could be related to N losses in a saturated, anoxic zone through denitrification. Hauck (1981) estimated that 30% of added N fertilizer could be lost by denitrification, especially in saturated conditions. Ammonium sulfate applications increased shoot biomass up to 90 kg AS ha⁻¹. Shoot biomass with U applications increased up to 180 kg ha⁻¹. The distinct plateaus in shoot biomass (even with AS, as was used in Study A) – well before the 400 kg N ha⁻¹ maximum observed in Study A – are surprising and not readily explained. Root biomass for the U application followed the same pattern as shoot biomass; and again, AS produced much more biomass than an equivalent rate of U, but not so much as in Study A. We suspect possible temperature and or irradiance differences between the two studies affected biomass production. Differences between the two N sources – AS vs. U – almost appeared to be due to some sort of toxic effects in the U treatments. It is possible that pH was affected adversely. In retrospect, it would have been very good to look at N and pH values in the substrate at the end of the study.

Nitrogen sources had an effect on tiller density and height that mirrored shoot biomass data (Fig. 6.6). Tiller density was 35% higher greater overall with

AS applications. There were consistently more tillers at any rate with AS than with U. Within each N source, no differences were observed in tiller density above 180 kg N ha⁻¹, but a plateau was reached at 116 kg N ha⁻¹ for U and 85 kg N ha⁻¹ for AS. Height plateaued at 60 kg AS ha⁻¹, while no height increased was observed past 150 kg U ha⁻¹ (Fig. 6.7). No height differences were observed between the 45 and 90 kg U ha⁻¹. Both biomass and morphological parameters suggest AS was a much better N source than U in the soilless substrate of this experiment.

Plant components differed in N concentrations depending on N source and rate of application (Table 6.2). Nitrogen concentration in roots averaged 13% higher under U application than AS and 34% higher with U than AS in shoots. Increases in N concentrations were observed up to 270 kg N ha⁻¹ with AS. Based on Study A (Fig. 6.3), we would expect a lower maximum value. The 3% N value is very high for switchgrass. Urea applications had no effect on tissue N levels beyond the 90 kg U ha⁻¹. Roots showed increases in N concentration with the highest AS application. No increases in root N concentration were observed past 90 kg U ha⁻¹. Again, this may be some indication of phytotoxic conditions in the U treatments.

Nitrogen content followed the expected pattern, given the yields and N concentrations seen. Differences due to N source and application rate were large (Table 6.3). Switchgrass N content was many-fold higher with AS application. Nitrogen content in the shoots was ~5X higher with AS application. Ammonium sulfate increased shoot N content at the highest rate of application. No differences in shoot N content were observed with U application past the 180 kg U ha⁻¹ rate. In the roots, N content plateaued at 180 kg N ha⁻¹ under both N sources. Either major volatilization losses of N from U or U toxicity would seem to be at play.

Nutrient-use efficiency, ANR and PFP did not differ with N source. Mean NUE, ANR and PFP were 16.6 g g⁻¹, 7.6%, and 8 g g⁻¹, respectively. As in Study A, significant differences were observed between N rates (Fig. 6.8). All N-use factors were negatively correlated with increase in N application rates [NUE ($r = -$

0.44, $P < 0.001$), ANR ($r = -0.67$, $P < 0.001$), and PFP ($r = -0.71$, $P < 0.001$)). Nutrient use-efficiency was highly correlated with ANR ($r = 0.85$, $P < 0.001$) and PFP ($r = 0.84$, $P < 0.001$). Apparent N recovery was highly correlated also with PFP ($r = 0.99$, $P < 0.001$). N-use parameters in study B were comparable to those values observed in study A, when averaged over N source, except PFP. Partial factor productivity was ~4X lower in study B. These lower PFP values are directly related to the lower yields with U.

Correlations Among N Applied and Yield Components

Several parameters examined were very highly correlated with N rates (Table 6.1). Correlation of each N source with the different yield variables measured in switchgrass showed that biomass yield was better correlated with AS in Study A but yet better correlated with U in Study B (Table 6.4). Nitrogen concentration was highly correlated with yield for the AS in both studies. Also, N content had a high correlation with N rates in both studies. Nitrogen rate also had a great influence on tiller development. Nitrogen concentration had a somewhat lower correlation with N rate. A lower correlation between height and AS was a reflection of the linear plateau reached at lower N rates in both studies (Figs. 6.2 and 6.7). The data in both studies showed very high correlations with yield components, but greater influences were not reflected in the yields as expected. This means that, although switchgrass has the ability to absorb N in large quantities, the utilization efficiency of such N is limited.

CONCLUSIONS

Management of switchgrass greatly depends on fertilization strategies. Our data showed a lower response of switchgrass to urea applications. If urea is to be used, it will be necessary to determine how it might affect plant growth, especially under field conditions. The poor response to urea could have been

related to some unknown form of toxicity or to higher rates of urea-N loss, via denitrification or volatilization.

While our results suggest that, under well-defined substrate conditions, seedling switchgrass can respond to up to 400 kg N ha⁻¹. Recommendations of 50 to 100 kg N ha⁻¹ yr⁻¹ are usually made under field conditions (Wolf and Fiske, 1994). This is an indication that soil N dynamics and/or microbiological processes play an important role in switchgrass N uptake and utilization. Microbial symbioses, N mineralization, and internal N “reserves” translocated between roots and shoots throughout the season could explain why switchgrass in a field setting is often less N-responsive than were these greenhouse-grown seedlings. Taking into consideration the N cycle as a dynamic model to better understand switchgrass nutrient use efficiency will be important. Further studies that incorporate both approaches (greenhouse and field settings) will be beneficial in developing more precise recommendations.

LITERATURE CITED

- Balasko, J. A., D. M. Burner, W. V. Thayne. 1984. Yield and quality of switchgrass grown without soil amendments. *Agron. J.* 76: 204-208.
- Bredja, J. J. 2000. Fertilization of native warm-season grasses. p. 177-200. *In*: K. J. Moore and B. E. Anderson (eds.) *Native warm-season grasses: Research trends and issues*. CSSA Spec. Publ. 30. CSSA and ASA, Madison, WI.
- Bredja, J. J., L. E. Moser, and K. P. Vogel. 1998. Evaluation of switchgrass rhizosphere microflora for enhancing seedling yield and nutrient uptake. *Agron. J.* 90: 753-758.
- Buso, G. S., and F. A. Bliss. 1988. Variability among lettuce cultivars grown at two levels of available phosphorus. *Plant and soil* 111: 67-73.
- Clark, R. B. 1990. Physiology of cereals for mineral nutrient uptake, use, and efficiency. p. 131-209. *In* V. C. Baligar and R. R. Duncan (eds.) *Crops as enhancers of nutrient use*. Academic Press, San Diego, CA.
- Cassman, K. G., S. Peng, D. C. Olk, J. K. Ladha, W. Reichardt, A. Doberman, U.

- Sigh. 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crops Res.* 56: 7-39.
- Crasswell, E. T. and D. C. Godwin. 1984. The efficiency of nitrogen fertilizers applied to cereals in different climates. Vol. 1 p. 1-55. In P. B. Thinker and A. Lauchli (eds.) *Advances in plant nutrition*. Praeger, New York.
- Fiez, T. E., W. L. Pan, and B. C. Miller. 1995. Nitrogen use efficiency of winter wheat among landscape positions. *Soil Sci. Am. J.* 59: 1666-1671.
- Griffin, J. L., and G. A. Jung. 1983. Leaf and stem forage quality of big bluestem and switchgrass. *Agron. J.* 75: 723-726.
- Gourley, C. J. P., D. L. Allan, and M. P. Russelle. 1994. Plant nutrient efficiency: A comparison of definitions and suggested improvement. *Plant and Soil* 158: 29-37.
- Lemus, R. W. 2000. Cultivar and fertility effects on switchgrass biofuel production in southern Iowa. M.S. Thesis. Iowa State University.
- Lutwick, L.E., and A. D. Smith. 1979. Yield and N uptake by seven perennial grass species as affected by high rates of N fertilization. *J. Range Manage.* 32 (6): 433-436.
- McLaughlin, S. B., and M. E. Walsh. 1998. Evaluating environmental consequences of producing herbaceous crops for bioenergy. *Biomass and Bioenergy* 14: 317-324.
- Moore, K. J., L. E. Moser, K. P. Vogel, S. S. Waller, B. E. Johnson, and J. F. Pedersen. 1991. Describing and quantifying growth stages of perennial forage grasses. *Agron J.* 83: 1073-1077.
- Muir, J. P., M. A. Sanderson, W. R. Ocumpaugh, R. M. Jones, and R. L. Reed. 2001. Biomass production of 'Alamo' switchgrass in response to nitrogen, phosphorus, and row spacing. *Agron. J.* 93: 896-901.
- Novoa, R., and R. S. Loomis. 1981. Nitrogen and Plant Production. *Plant and Soil* 58: 177-204.
- Radiotis, T., J Li, K. Goel, and R. Eisner. 1999. Fiber characteristics, pupability, and bleachability of switchgrass. *Tappi J.* 82: 100-105.
- Sanderson, M. A., J. C. Read, and R. L. Reed. 1999a. Harvest management of switchgrass for biomass feedstock and forage production. *Agron. J.* 91: 5-10.

- Sanderson, M. A., R. L. Reed, W. R. Ocampo, M. A., Hussey, G. Van Esbroeck, J. C. Read, C. R. Tisher, and F. M. Hons. 1999b. Switchgrass cultivars and germplasm for biomass feedstock production in Texas. *Bioresour. Technol.* 67: 209-219.
- SAS Institute. 2003. SAS User's Guide: Statistics. Version 8.2. SAS Inst., Cary, NC.
- Schabenberger, O., and F.J. Pierce. 2002. Contemporary Statistical Models for the Plant and Soil Sciences. CRC Press, Boca Raton, FL.
- Smith, D., and S. B. Greenfield. 1979. Distribution of chemical constituents among shoot parts of timothy and switchgrass at anthesis. *J. Plant Nutrition* 1: 81-99.
- Stanford, G., and J. O. Legg. 1984. Nitrogen and yield potential. p. 263-293. *In* R. D. Hauck (ed.). Nitrogen in crop production. ASA Spec. Publ., Madison, WI.
- Weiser, G. C., and R. L. Smith. 1988. Nitrogen related characteristics of switchgrass and bahiagrass in Folorida. *Soil and Crop Sci. Soc. Fla. Proc.* 47: 161-164.
- Wolf, D. D., and D. A. Fiske. 1994. Planting and managing switchgrass for forage, wildlife and conservation. Publ. 418-013. Virginia Coop. Ext., Blacksburg.
- Zemenchick, R. A. and K. A. Albrecht. 2002. Nitrogen use efficiency and apparent nitrogen recovery of Kentucky bluegrass, smooth brome grass, and orchardgrass. *Agron. J.* 94: 421-428.

Table 6.1. Changes in greenhouse-grown switchgrass seedling shoot and root biomass with applied N from two sources (Study B).

Part	Source	N (kg ha ⁻¹)					LSD _{0.05} ³
		0	45	90	180	270	
		----- Biomass (g pot ⁻¹) -----					
Shoot	AS ¹	0.2	8.8	15.4	15.6	17.2	2.9
	Urea	0.2	1.6	1.8	3.8	4.2	1.3
	LSD _{0.05} ²	--	2.2	3.7	3.8	4.2	--
Root	AS	0.1	3.4	4.4	4.4	3.7	1.0
	Urea	0.1	0.6	0.7	1.3	1.2	0.4
	LSD _{0.05} ²	-	1.4	1.4	1.9	0.6	--
	LSD _{0.05} ⁵	-	1.2	2.5	1.6	5.1	--
	LSD _{0.05} ⁶	-	0.7	ns	1.3	1.1	--

¹Ammonium sulfate

²LSD for comparison of N sources within N rate and part.

³LSD for comparison of N rates within part and N source

⁴LSD for comparison of N sources within N rate.

⁵LSD for comparison of parts within AS and N rate.

⁶LSD for comparison of parts within Urea and N rate.

Table 6.2. Changes in greenhouse-grown switchgrass root and shoot N concentrations with N applied from two sources (Study B).

Part	Source	N (kg ha ⁻¹)					LSD _{0.05} ³
		0	45	90	180	270	
		----- N Conc. (%) -----					
Shoot	AS ¹	1.44	1.44	1.90	2.68	3.09	0.17
	Urea	1.44	2.00	2.63	2.71	2.66	0.41
	LSD _{0.05} ²	--	ns	ns	ns	0.21	--
Root	AS	0.91	0.67	1.01	1.65	2.09	0.26
	Urea	0.91	1.08	1.91	2.09	2.18	0.44
	LSD _{0.05} ²	--	ns	0.84	ns	ns	--
	LSD _{0.05} ⁵	--	0.16	0.17	0.23	0.42	--
	LSD _{0.05} ⁶	--	0.23	0.47	0.19	0.10	--

¹Ammonium sulfate

²LSD for comparison of N sources within N rate and part.

³LSD for comparison of N rates within part and N source

⁴LSD for comparison of N sources within N rate.

⁵LSD for comparison of parts within AS and N rate.

⁶LSD for comparison of parts within Urea and N rate.

Table 6.3. Changes in greenhouse-grown switchgrass seedling root and shoot N content with N applied from two sources (Study B).

Part	Source	N (kg ha ⁻¹)					LSD _{0.05} ³
		0	45	90	180	270	
----- N Content (mg pot ⁻¹) -----							
Shoot	AS ¹	2.3	126.2	290.6	418.4	532.6	82.1
	Urea	2.3	29.7	43.1	101.9	111.3	30.5
	LSD _{0.05} ²	--	21.1	67.5	97.7	150.6	--
Root	AS	0.9	22.7	43.5	72.7	77.0	12.4
	Urea	0.9	6.1	11.2	26.5	27.4	4.7
	LSD _{0.05} ²	--	7.8	12.7	26.9	26.7	--
Total	AS	3.2	148.9	334.1	491.0	609.6	87.1
	Urea	3.2	35.8	54.4	128.4	138.7	33.9
	LSD _{0.05} ²	--	28.8	74.8	121.1	163.7	--
	LSD _{0.05} ⁵	--	8.4	57.6	53.4	172.0	--
	LSD _{0.05} ⁶	--	12.5	30.3	38.8	33.4	--

¹Ammonium sulfate

²LSD for comparison of N sources within N rate and part.

³LSD for comparison of N rates within part and N source

⁴LSD for comparison of N sources within N rate.

⁵LSD for comparison of parts within AS and N rate.

⁶LSD for comparison of parts within Urea and N rate.

Table 6.4. Correlations between N rate and switchgrass yield components for greenhouse-grown switchgrass seedlings in two studies (A and B) and two N sources (urea and ammonium sulfate).

	N Rate		
	Study A	Study B	
		Urea	Ammonium Sulfate
N Rate	--	--	--
Yield	0.92*	0.87*	0.80*
% N	0.94	0.72*	0.97*
N Content	0.99*	0.90*	0.94*
Tiller	0.94*	0.81*	0.84*
Height	0.76*	0.81*	0.67*

*Significant at $P_{0.001}$.

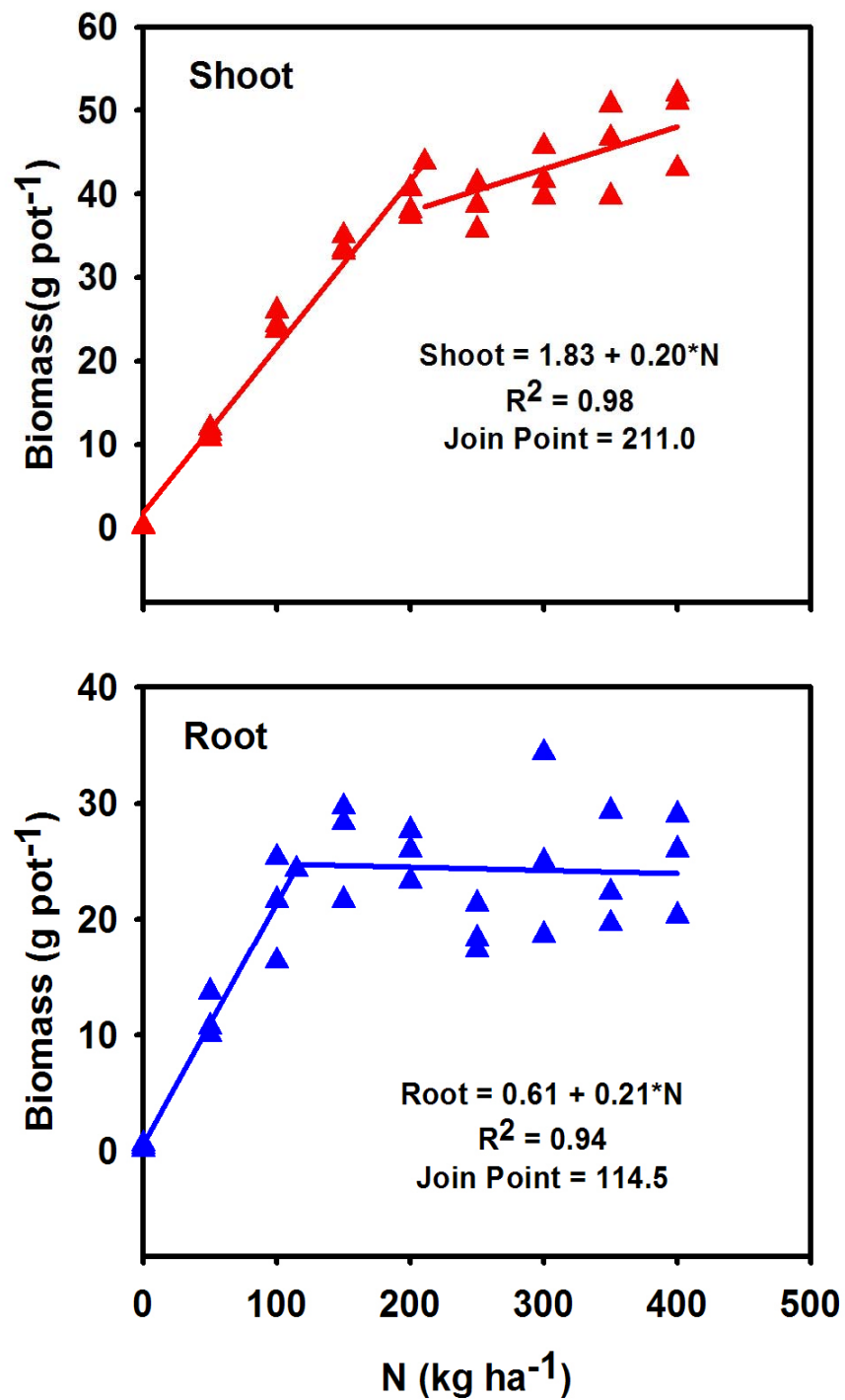


Fig. 6.1. Effects of N fertilization rate on shoot and root biomass of greenhouse-grown switchgrass seedlings (Study A).

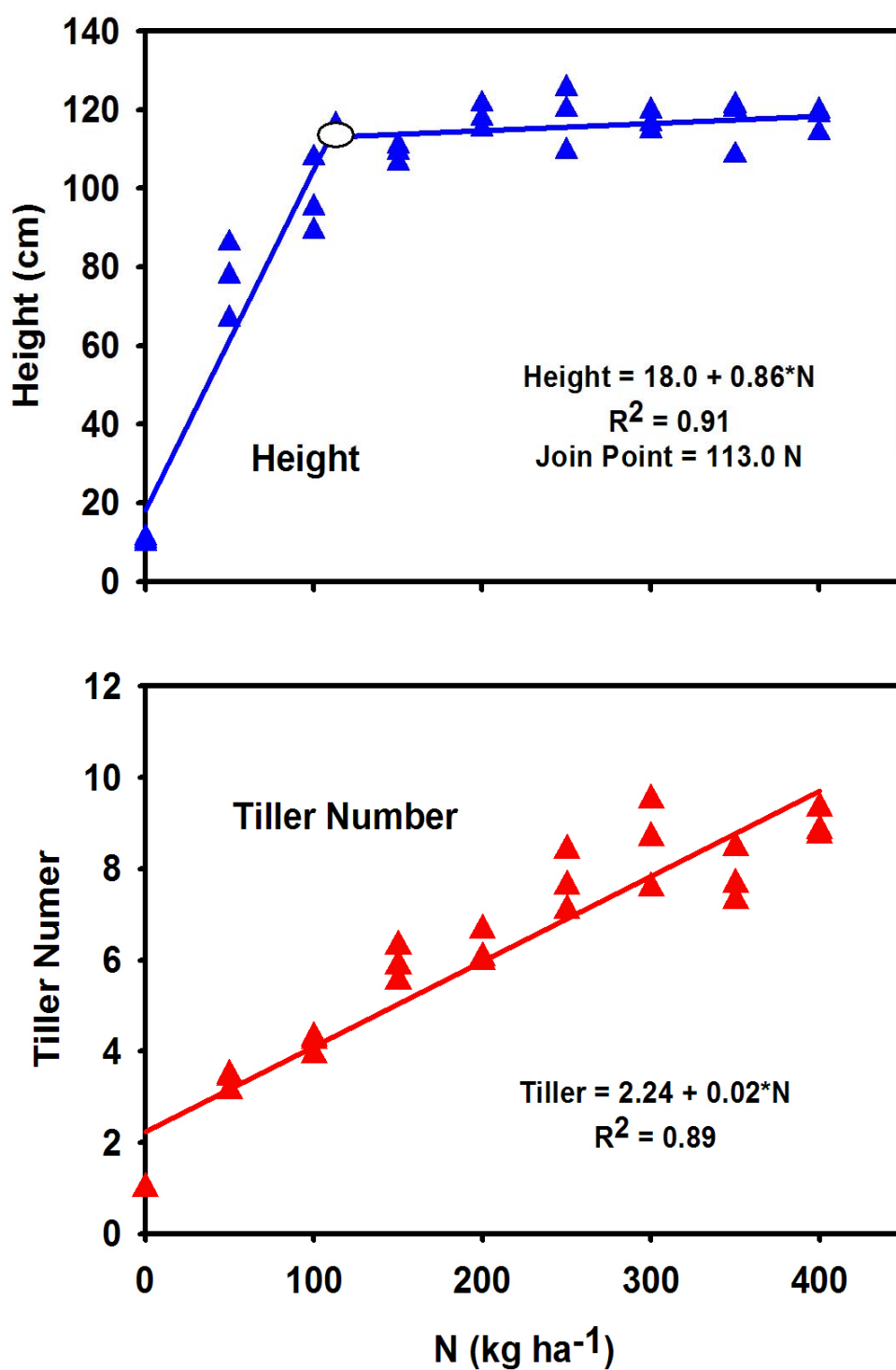


Fig. 6.2. Effects of N fertilization rate on height and tiller number of greenhouse-grown switchgrass seedlings (Study A).

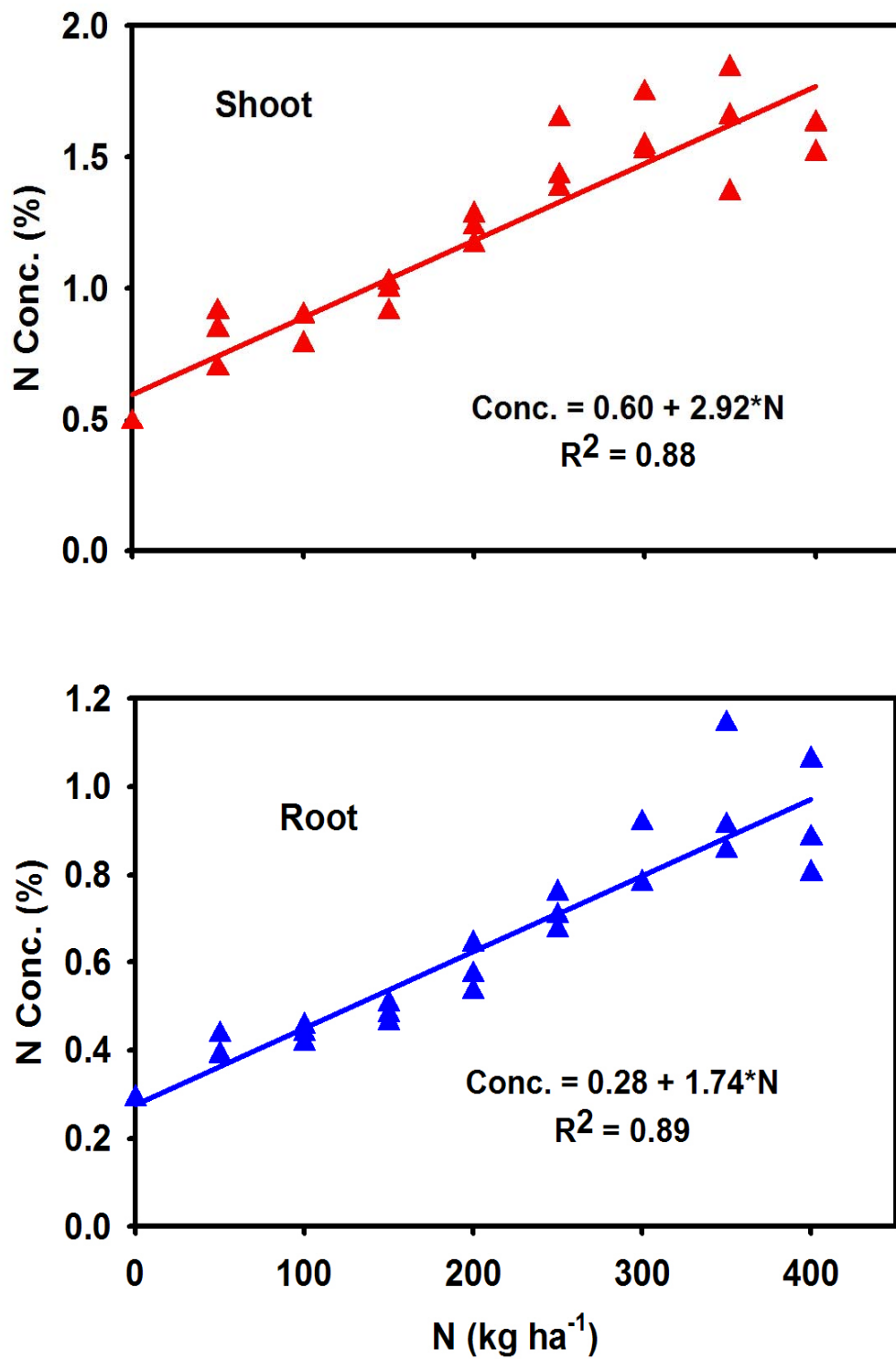


Fig. 6.3. Changes on shoot and root N concentrations of greenhouse-grown switchgrass seedlings provided different N rates (Study A).

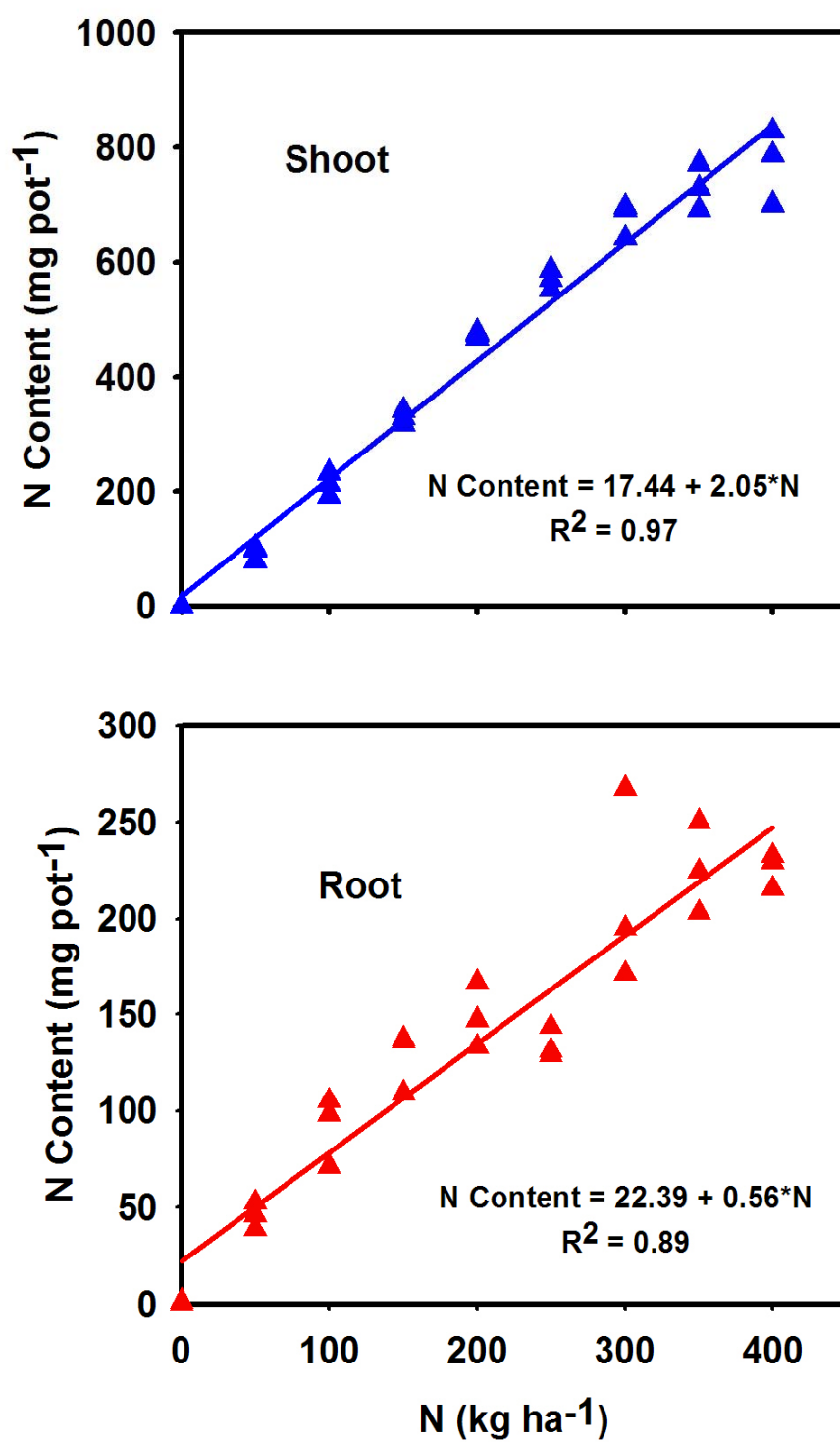


Fig. 6.4. Changes on shoot and root N content of greenhouse-grown switchgrass seedlings provided different N rates (Study A).

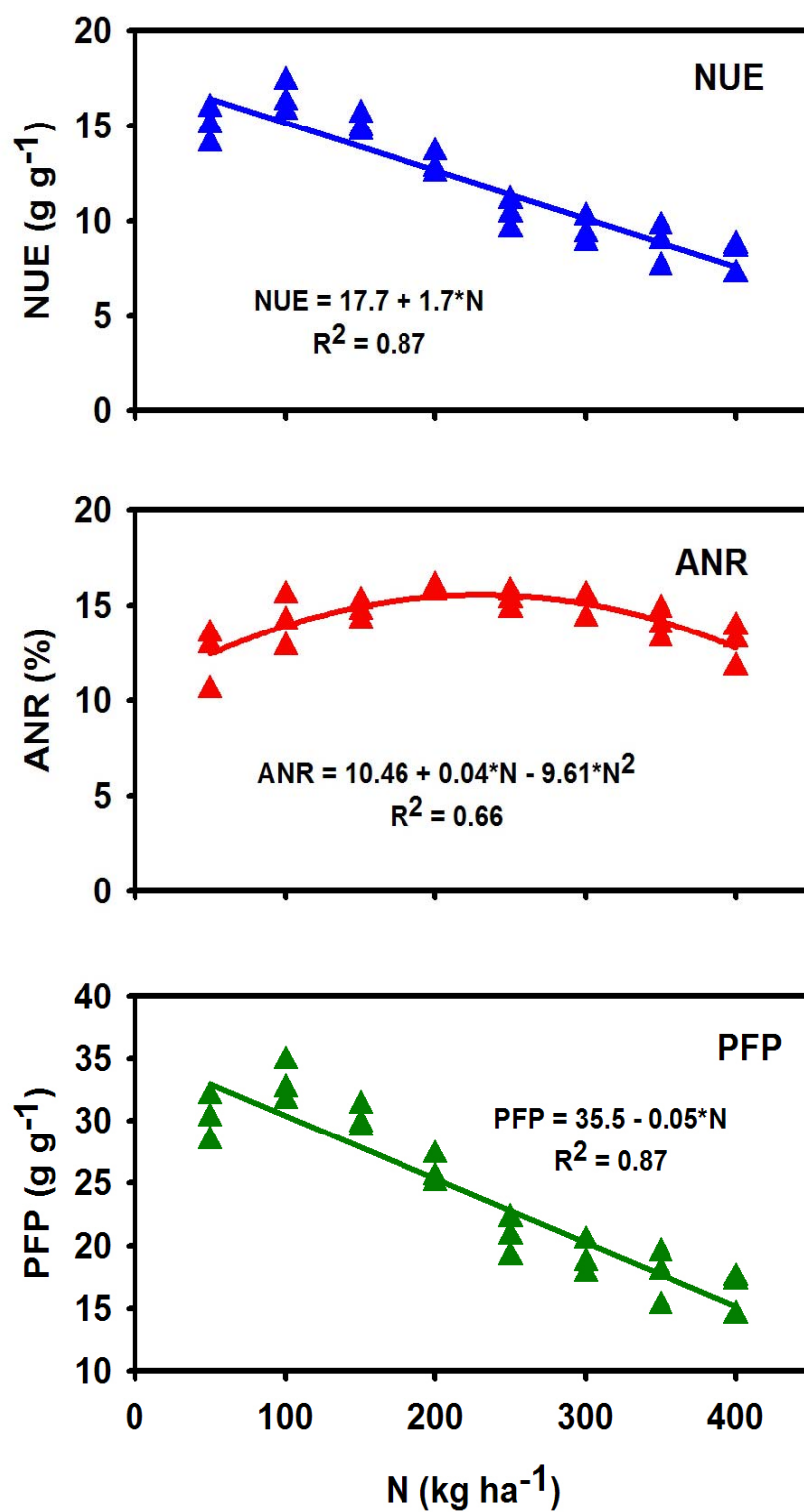


Fig. 6.5. Effect of N rate on N-use efficiency (NUE), apparent N recovery (ANR), and partial factor productivity (PFP) of greenhouse-grown switchgrass seedlings (Study A).

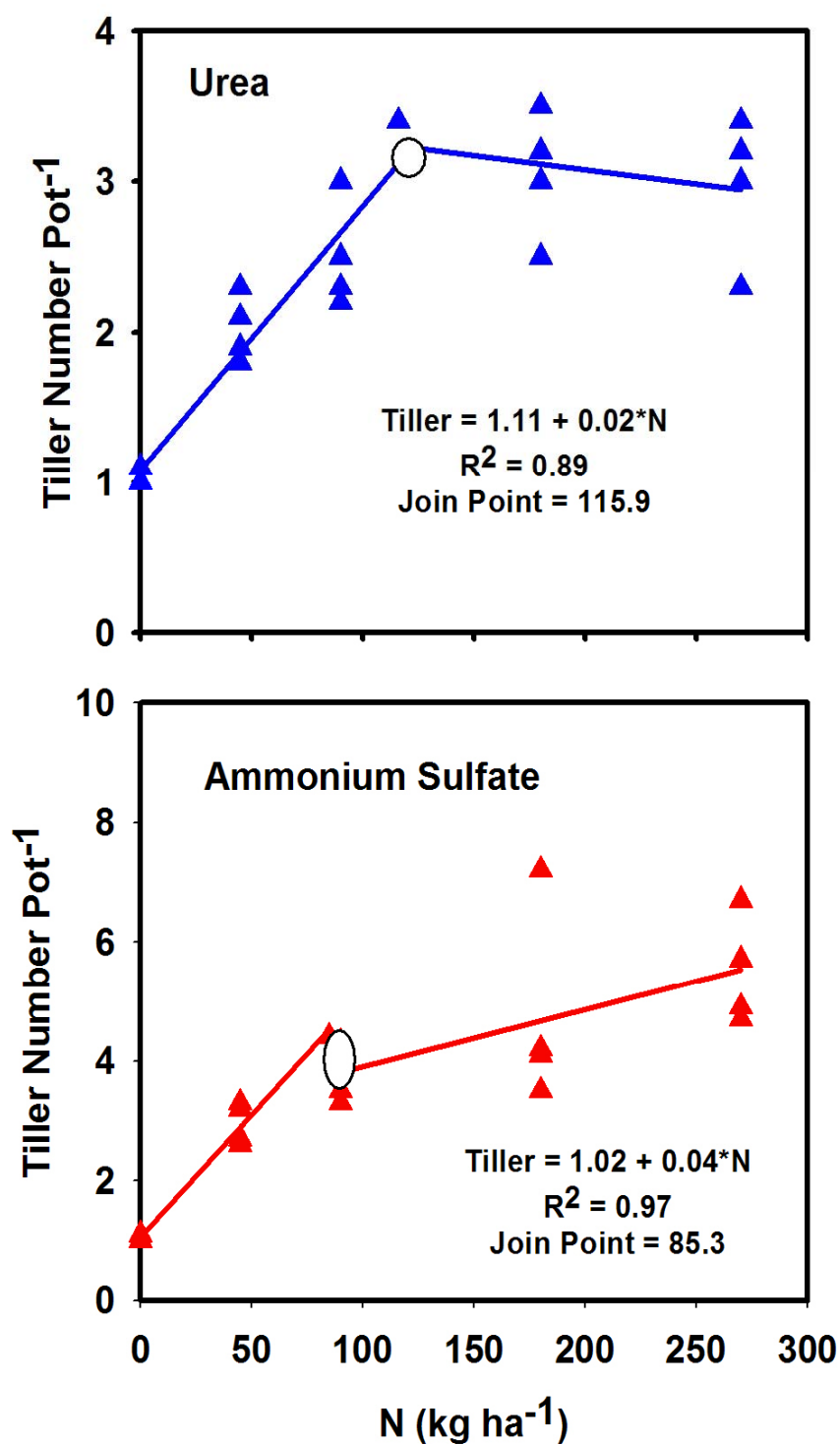


Fig. 6.6. Changes in tiller number with N applied from two sources to greenhouse-grown switchgrass seedlings (Study B).

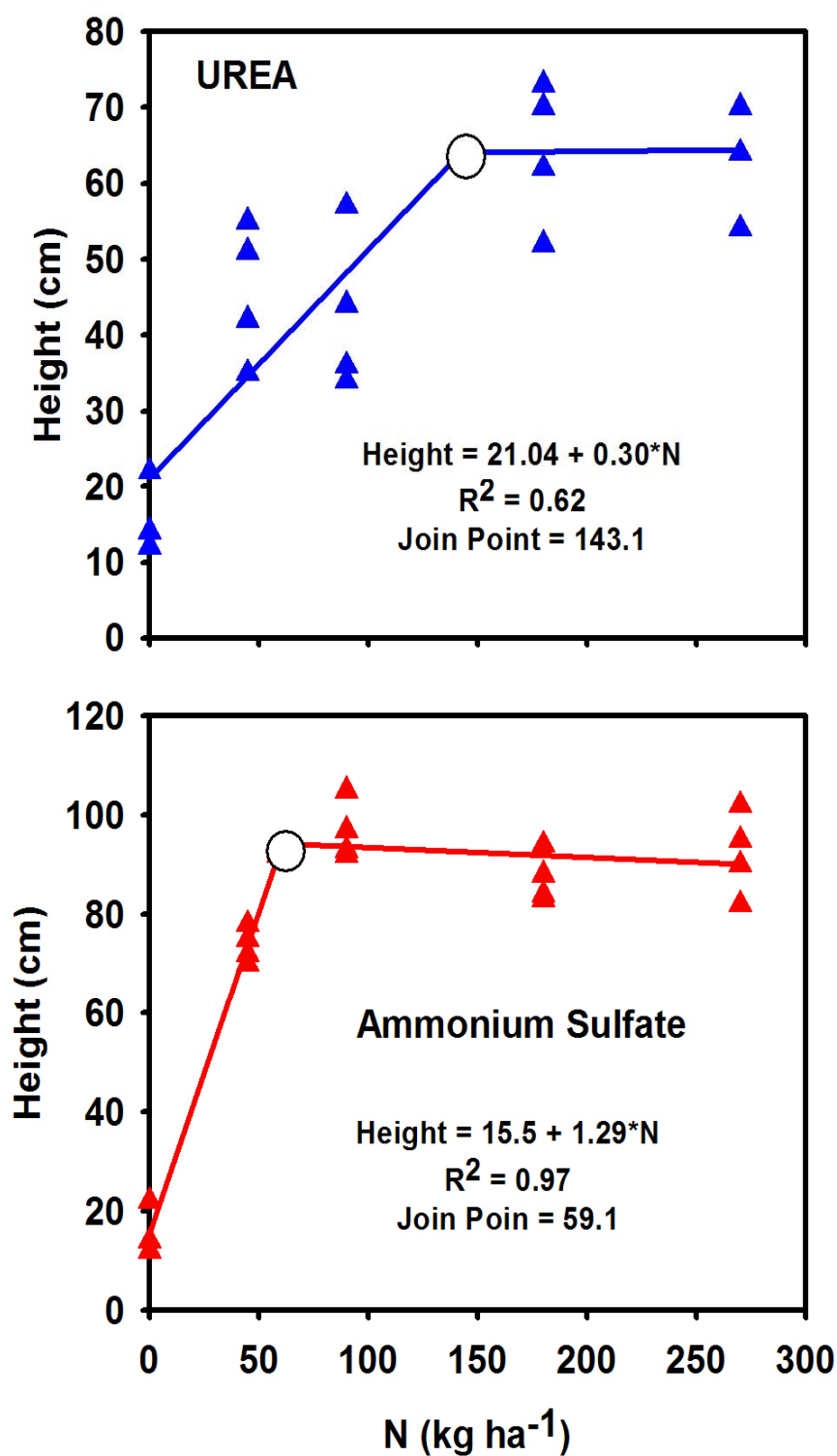


Fig. 6.7. Changes in height with N applied from two sources to greenhouse-grown switchgrass seedlings (Study B).

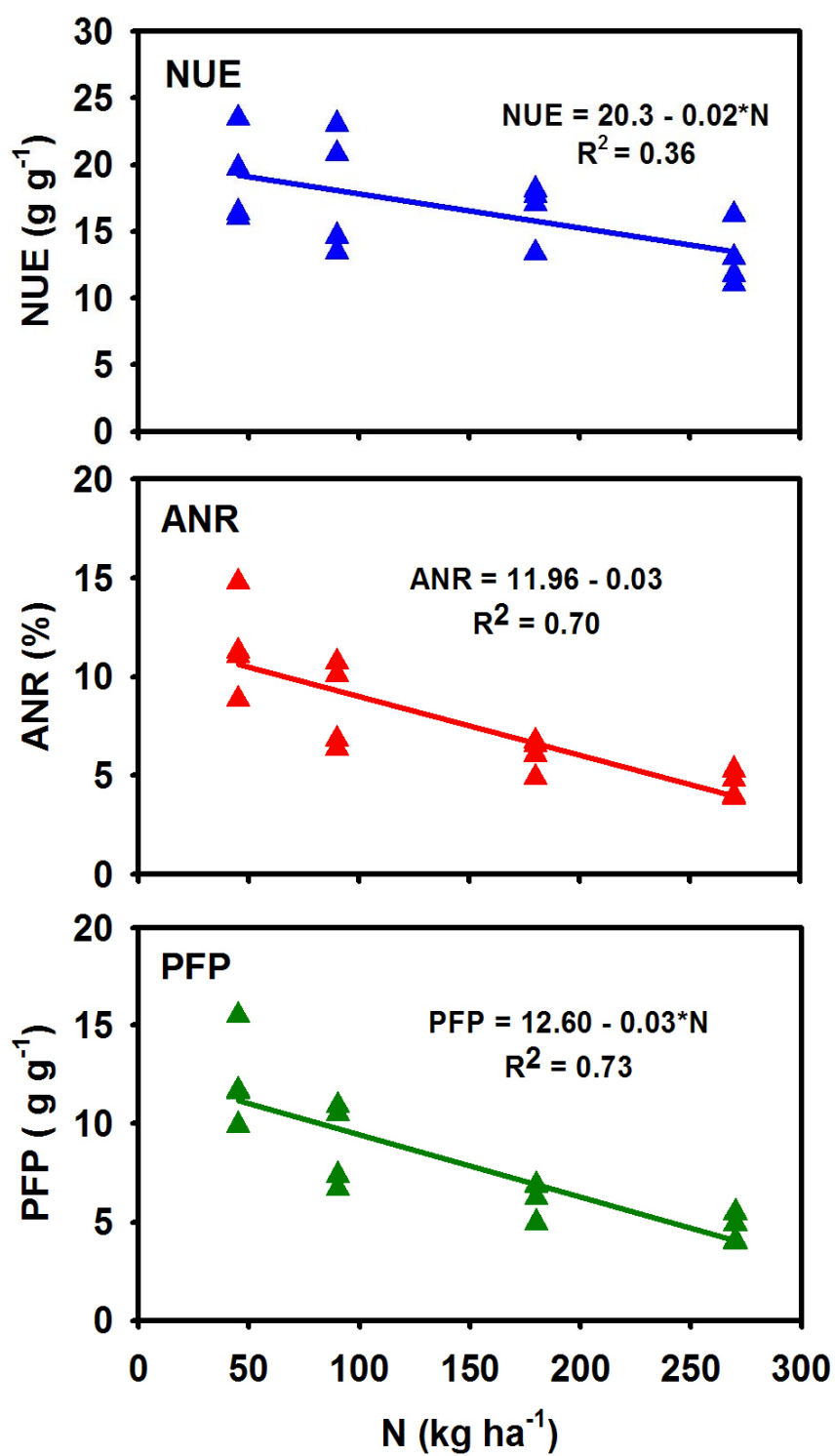


Fig. 6.8. Effect of N rate on N-use efficiency (NUE), apparent N recovery (ANR), and partial factor productivity (PFP) of greenhouse-grown switchgrass seedlings (Study B).

CHAPTER 7

SUMMATION/CONCLUSIONS

Biofuels crops, such as switchgrass might prove to be, can provide alternative energy sources for a future when fossil fuels are less available. Research on switchgrass has indicated that proper management can increase yields significantly. Important management considerations include N fertilization, cultivar choice, and harvest management. In this work, four cultivars were evaluated across diverse environments in the upper Southeast and one of them was looked at more closely for its N relations. In another study, done at two sites in VA, one cultivar was used to look at N management strategies and the agroecosystem's N dynamics. Finally I examined in detail switchgrass' response to N and P in a more defined, soilless substrate.

Differences in yield among cultivars in the large field study were site and year specific and related to harvest management as well as ecotype. All cultivars maintained good biomass production into their tenth year after establishment. This long-term study (of which the final 2 yr are reported here) conducted at eight locations showed that lowland cultivars harvested once at the end of the season produce high, sustainable yields. When cut twice per season, upland and lowland cultivars had similar yields. Upland – but not lowland – cultivars generally yielded slightly more if harvested twice. The latitude of origin of each cultivar suggests why the lowland cultivars used in this study might be better adapted to the upper Southeast. Plots under one-cut management had lower stand densities (fewer tillers per area) at most locations, indicating that the two-cut management promoted tiller development. Stands were highly productive 10 yr after establishment, indicating a truly perennial yield potential.

Nutrient balances for Alamo switchgrass were investigated closely in a multi-state study. More N was removed as biomass than was applied as fertilizer

under the two-cut management; but, in the one-cut management, less N was removed than applied. Also, P, K, and Ca removal was generally greater than the amount applied. Differences in N removal between harvest systems reflected the lower N concentrations in biomass of the late-fall harvests in the one-cut system and higher N concentrations of the biomass in the midsummer harvests of the two-cut system. Studies with Alamo showed a clear decline in tissue N levels during the last half of the season. This seems to reflect mobilization and translocation of N to roots during senescence of the shoots and perhaps N loss via leaching of senesced/dead leaves.

If low nutrient concentrations are desired for the combustion of biomass and economic production, a one-cut system with one late-fall harvest is preferable. Delaying harvest to enable nutrient remobilization to be completed can reduce nutrient concentrations, allow nutrient recycling, and reduce N input requirements.

Under field conditions in VA, switchgrass showed no response to N fertilizer during the year of application. Slightly greater production due to residual N was achieved during the following 2 yr, and N supply within the plant and soil systems was reduced, apparently due to N removal in the biomass. Nitrogen removal during the midsummer harvest apparently “short circuits” the plant’s potential for internal conservation.

Even with no N applied, yields were quite good and N removal was surprisingly large. Obviously, endogenous N (or unidentified inputs) provided for such yields. A correlation between biomass yield and N mineralization suggests that significant amounts of N in labile organic matter were made available. Mycorrhizae and N-containing precipitation might also be involved in maintaining yield and N uptake, but these sources need to be evaluated under VA field conditions.

Nitrogen contained in organic matter can become available at varying rates via mineralization throughout the growing season. The rate of mineralization depends on soil properties and organic matter quantity and quality, as well as climatic conditions such as soil temperature and soil moisture. One

way to estimate potential N mineralization is through anaerobic incubations. Highest rates of mineralization demonstrated in soil supporting switchgrass growth were seen in samples taken from July to September. The mineralization rate of crop residues still needs to be established but likely depends on site-specific climatic conditions. The relationship between soil organic N and potential mineralization warrants further investigation. Regular assessments using mineralization potential measurements could provide an important assessment of potential changes in soil N supply.

Estimations of switchgrass NUE, ANR, and PFP were greatest at N levels of 45 to 100 kg N ha⁻¹. Lower applied-N recoveries were generally associated with high N application rates. Nitrogen recoveries of only 10 to 15% are not desirable. Perhaps ANR provides a better indication of the potential return from applied N, since it estimates plant N acquired from the applied N as well increases in N uptake from endogenous N sources. A better understanding of N-use efficiency estimators is needed. More accurate methods of predicting N use – especially those that might better take into account pre-existing soil N pools – will lead to development of more efficient management practices.

Responses of switchgrass clearly showed that N availability and N use efficiency are not solely a function of the amount of N applied. The source of N may impact as well. Results of the N-budget field study agree with the greenhouse work showing that NUE is low under urea applications. In the greenhouse, where we had a much clearer control of N status, plant response to increased N was evident up to at least 210 kg N ha⁻¹. Yield increases reflected greater tiller density, with mass tiller⁻¹ showing a much smaller response. All this suggests that switchgrass' non-responses to N in the field in Virginia must be a function not of switchgrass' inherent capacity to use N, but of the soil N supplying capacity to supply it.

These studies indicate that switchgrass, indigenous to VA, is sufficiently efficient at extracting soil N in some soils to meet its needs for significant levels of biomass production; but long-term management strategies to avoid N deficits in the plant/soil system will be required. Recommended N fertilizer for

switchgrass production should be adjusted based on contributions of soil N (primarily mineralization) and other inputs/contributions as well as losses. Traditional methods used to examine switchgrass response to N in the field are quite inadequate for assessing and interpreting these relationships. A more analytical procedure that includes partitioning differences in yield into N components associated with soil and plant processes is needed. Sound fertilizer recommendations should be based in part on good stewardship of the soil, the environment, and on economics. Perhaps analytical models can be developed that will aid in evaluating switchgrass production with respect to all processes influencing N use.

APPENDIX

AMMONIA VOLATILIZATION FROM UREA APPLIED TO SOIL UNDER SWITCHGRASS MANAGEMENT

INTRODUCTION

Soil N has a variety of pathways for efflux from agroecosystems and can have important negative impacts on yields and the environment when it is lost (Gil and Fick, 2001). Investigations into N utilization by plants have indicated that a substantial portion of the N applied is apparently lost and that crop recovery is often less than 50% (Torello et al., 1983). Gases (NO_x and NH_3) can represent major forms of efflux. One of the obstacles that limit N balance studies in the field is quantification of losses of nitrogenous gases.

Urea [$\text{CO}(\text{NH}_2)_2$] is a popular N source for switchgrass producers because of its high N content, easy handling, and relatively low cost (Vlek and Byrnes, 1986). Urea makes an excellent N source, but significant losses have been observed due to ammonia (NH_3) volatilization. Broadcasting urea makes NH_3 volatilization a major pathway for N loss, with losses reaching up to 50% (Roelcke et al., 1996) or even 80% (Gould et al., 1986; Ramos, 1996) of the applied urea. Roelcke et al. (1996) reported that NH_3 volatilization is the major pathway for mineral N loss in calcareous soils, with maximum losses reaching 50% of the fertilizer-N applied, while up to 29% of the N in surface-applied urea can volatilized from acidic soils (Watson, 1990). An effective way to reduce NH_3 emissions after urea application is by injecting it into the soil (Ramos, 1996), but injection could be hard to justify (or simply difficult) for biofuels crops, especially a perennial crop such as switchgrass.

The potential for NH_3 volatilization from urea fertilizer following surface application has been recognized for many years (McInnes, 1986; Black et al.,

1987). Ammonia volatilization rates are affected by many different processes, with significant interactions occurring between variables (Kirk and Nye, 1991). Some of the properties, processes, and factors that influence NH_3 volatilization are soil type (cation exchange capacity, hydrogen-ion buffering capacity, pH, CaCO_3 content, urease activity, urea leaching, immobilization, nitrification, soil temperature, surface cover, and soil texture), environmental conditions (temperature, atmospheric NH_3 concentration, soil water content, rainfall pattern, wind speed, and relative humidity), and fertilizer management (fertilizer type, timing, placement, and rate of application) (Lightner et al., 1990). Predicting optimal agricultural practices is very difficult, because of the complex interactions of the processes involved in this phase of the N cycle in soil (Ramos, 1996).

Microenvironmental effects on urea volatilization make it difficult to estimate the application rate required to supply the desired amount of plant-available N to switchgrass. Consequently, the ability to estimate how urea behaves will help to determine plant-available N and prevent over applications as well as losses and immobilization. The purpose of this study was to assess loss of NH_3 under controlled conditions following surface application of urea to soil under switchgrass management.

MATERIAL AND METHODS

Two short-term (7-d) greenhouse trials were conducted on June 16 to 23 and September 8 to 15, 2003 to evaluate the potential for NH_3 volatilization on soils that have been under long-term (>12 yr) switchgrass production. The study used the top 15 cm of soil obtained from Cave-in-Rock switchgrass plots in Blacksburg, VA. The soil type was Chatter (Clayey, kaolinitic, mesic, Typic Paleudult) with 2 to 5% slope. Sixteen, 4.5-L plastic pots (20 cm outer diameter X 14 cm height) were filled with 10 cm of soil, leaving 4 cm of head space. Potted soils were watered to field capacity and allowed to draining for 48 hr before NH_3 experiments were carried out. Urea (46-0-0) was broadcast on the soil surface at rates of 0, 90, 180, and 270 kg N ha⁻¹.

The NH_3 collection system was similar to one by Kissel et al. (1977), with some modifications as described by Lightner et al. (1990) (Fig. A.1). Collection chambers were constructed from polyvinyl chloride (PVC) cylinders, 20 cm inner diameter and 5 cm high, with a plexiglass top. The chambers fit down over each pot to provide a seal with minimal air passage when under no pressure differential. Mason jars (0.95 L) with a boric acid solution were used as NH_3 traps. The connections between each chamber, the trap, and the vacuum system were made with tygon tubing (6.4 mm i.d.). Polyethylene tubing (6.4 mm i.d) was fitted through an orifice in the side of each pot to allow air flow when the system was placed under negative pressure. The dome lid on the trap was modified with two fittings (inlet and outlet) and completely sealed. The inlet of the jar had a polyethylene tube immersed into 250 ml of 0.5 M boric acid solution (Quemada et al., 1998; Siva et al., 2000). The polyethylene tube was fitted with a tip strainer to disperse small bubbles into the solution (Black et al., 1987). The outlet of the trap was connected to a vacuum manifold built from PVC pipe (3.8 cm i.d).



Fig. A.1. Ammonia volatilization chambers, traps, and manifolds.

In the completely assembled system, volatilized NH_3 was evacuated from the chamber in the moving air stream and trapped in the boric acid solution. The

air flow through the chamber head space was established by connecting to a 1 Hp vacuum (Cabrera et al., 2001). A flow meter (King Instrument Co., Garden Grove, CA) was used to measure and adjust airflow through the individual chambers. Air was pulled through each chamber at a flow rate of 17 L min⁻¹. The exchange air rate was sufficiently high that removal of volatilized NH₃ was not limited by the air flow (Kissel et al., 1977; Burch and Fox, 1989). Ruess and McNaughton (1988) have shown this method is 97.1% efficient at capturing NH₃ volatilized. Chambers were covered with aluminum foil to reduce heating through the plexiglass, which could affect the N volatilization process. Temperature was measured inside the chamber and in the greenhouse at each collection time. Soil moisture content was measured at the beginning and the completion of the experiment using a time domain reflectrometry (TDR) device (ESI, Vancouver, B.C).

Chambers were left in place continuously. Samples were collected discontinuously for 20 min at 6, 12, 24, 36, 48, 60, 72, 84, 96, and 168 h after fertilizer applications in the first trial. The 6, 60, and 84 h collection intervals were deleted from the second trial. The vacuum was turned off except during the collection, so each 20-min collection period presumably captured all the NH₃ produced and accumulated since the previous sampling period. Samples from the boric acid trap were frozen until ready for analysis. Traps were acid washed, rinsed with DI water and refilled with fresh boric acid solution after each collection time. The amount of NH₃ trapped in the boric acid solution was determined colorimetrically on a Lachat Instruments Automated Analyzer using QuickChem Methods 10-07-06-2A and 10-107-04-1-A (Lachat Instruments, Milwaukee, WI).

The background quantities of NH₃-N from the control (0 N) chambers were subtracted from the amounts measured in the treatment chambers to determine NH₃-N volatilization loss estimates (Fox et al., 1996). The NH₃ loss from the applied urea was calculated as: $\text{NH}_3 \text{ loss (\%)} = [(A - B)/C] \times 100$; where: A is the amount of NH₃-N volatilized from urea applications, B is the amount of NH₃ volatilized from the control, and C is the amount of applied urea-N (Gezgin and Bayraklı, 1995).

The experimental design was a randomized complete block with four N treatments replicated four times. Analysis of variance (ANOVA) was conducted using the GLM procedure of SAS (SAS Inst., 2003) at $P_{0.05}$ to test the effects for N rate and sampling time. The two trials of this experiment were analyzed separately because of differences in soil moisture levels, temperatures, and sampling times. Means were separated by the least significant difference (LSD) at $P_{0.05}$ probability level

RESULTS AND DISCUSSION

This study provides estimates of NH_3 volatilization following urea application to soils that have been under switchgrass management. Understanding these losses might be important in managing urea applications and improving fertilizer efficiency. The intent in the study was not to look in detail at the effects that differing variables such as soil water content, temperature, pH, and other factors might have on urea volatilization, but to get an indication of the magnitude of N losses.

Results were obtained from two separate trials. Ammonia losses with time from urea applied at four rates in two separate trials (A and B) are shown in Fig. A.2. Analyses of results from NH_3 volatilized over a 7-d period indicated that N losses were very small under the experimental conditions. Following fertilizer application, there was a 24-h delay before appreciable NH_3 volatilization occurred. This delay could be due to a relatively slow increase in soil pH and low concentrations of the urease enzyme (Clay et al., 1990). After the delay, most volatilization losses occurred between 36 and 72 h after application, reaching peak around 48 h.

Cumulative NH_3 -N volatilization losses from N applications are given in Fig. A.3. Trial B had higher NH_3 losses at each N rate, perhaps related to its slightly higher soil moisture content. Lower soil moisture in trial A may have restricted urea dissolution and urea hydrolysis and thus decreased NH_3 losses (Vlek and Carter, 1983). Volatilization losses were substantially lower than

expected (Fig. A.4), since reports of NH_3 losses commonly range from 20 to 60% of the applied N (Hargrove, 1988). The possibility exists that NH_3 built up within the chambers between evacuations and that may have caused feedback inhibition of urease. Similar discontinuous evacuation studies have been used in the literature and show higher N losses. There is the possibility that the soil used in these studies was inherently less prone to urease activity.

Temperature seemed to have no effect in NH_3 volatilization (Fig. A.5). No significant correlations were found between amount of N volatilized and temperature.

The method selected for NH_3 measurements in our work was simple and relatively inexpensive, and it allows NH_3 loss measurements in replicated small experiments. The amount of NH_3 lost increased after 24 h, with higher losses at higher application rates. Cumulative NH_3 losses were small compared to reports from the literature. Although environmental conditions varied somewhat between trials, our results indicate that NH_3 volatilization may not be very important in reducing the fertilizer efficiency of urea applied to switchgrass. Other soil reactions which may affect efficiency of applied urea deserve further study under field conditions, and results obtained with this method must be regarded as estimates of NH_3 loss under the experimental conditions.

LITERATURE CITED

- Black, A. S., R. R. Sherlock, and N. P. Smith. 1987. Effect of timing of simulated rainfall on ammonia volatilization from urea, applied to soil of varying moisture content. *J. Soil Sci.* 38: 679-687.
- Burch, J. A., and R. H. Fox. 1989. The effect of temperature and initial soil moisture content on the volatilization of ammonia from surface applied urea. *Soil Sci.* 147 (5): 311-318.
- Cabrera, M. L., D. E. Kissel, R. C. Davis, N. P. Qafoku, and W. I. Segars. 2001. Design and ammonia-recovery evaluation of a wind speed-sensitive chamber system. *Soil Sci. Soc. Am. J.* 65: 1302-1306.

- Clay, D. E., G. L. Malzer, and J. L. Anderson. 1990. Ammonia volatilization from urea as influenced by soil temperature, soil water content, and nitrification and hydrolysis inhibitors. *Soil Sci. Am. J.* 54: 263-266.
- Gil, J. L., and W. H. Fick. 2001. Soil nitrogen mineralization in mixtures of eastern gammagrass with alfalfa and red clover. *Agron. J.* 93: 902-910.
- Gould, W. D., C. Hagedorn, and R. G. L. McCready. 1986. Urea transformations and fertilizer efficiency in soil. *Adv. Agron.* 40: 209-238.
- Kirk, G. J., and P. H. Nye. 1991. A model of ammonia volatilization from applied urea. V. The effects of steady-state drainage and evaporation. VI. The effects of transient-state water evaporation. *J. Soil Sci.* 42: 103-125.
- Kissel, D. E., H. L. Brewer, and G. F. Arkin. 1977. Design of a test of a field sampler for ammonia volatilization. *Soil Sci. Soc. Am. J.* 41: 1133-1138.
- Lightner, J. W., D. B. Mengel, and C. L. Rhykerd. 1990. Ammonia volatilization from nitrogen fertilizer surface applied to orchardgrass sod. *Soil Sci. Soc. Am. J.* 54: 1478-1482.
- McInnes, K. J., R. B. Ferguson, D. E. Kissel, and E. T. Kanemasu. 1986. Field measurements of ammonia loss from surface applications of urea solution to bare soil. *Agron. J.* 78: 192-196.
- Quemada, M., B. Lasa, C. Lamsfus, and P. M. Aparicio-Tejo. 1998. Ammonia volatilization from surface or incorporated biosolids by the addition of dicyandiamide. *J. Environ. Qual.* 27: 980-983.
- Ramos, C. 1996. Effect of agricultural practices on the nitrogen losses to the environment. *Fert. Res.* 43: 183-189.
- Roelcke, M., Y. Han, S. X. Li, and J. Ritcher. 1996. Laboratory measurements and simulations of ammonia volatilization from urea applied to calcareous Chinese loess soils. *Plant and Soil* 181: 123-129.
- Ruess, R. W., and S. J. McNaughton. 1988. Ammonia volatilization and the effects of large grazing mammals on nutrient loss from East African grasslands. *Oecologia* 77: 382-386.
- SAS Institute. 2003. *SAS User's Guide: Statistics. Version 8.2.* SAS Inst., Cary, NC.
- Silva, K. B., H. Aminuddin, and M. H. A. Husni. 2000. Ammonia volatilization from urea as affected by humic substances derived from palm oil mill effluent (POME) and tropical peat. *J. Trop. Agric.* 77: 13-20.

- Torello, W. A., D. J. Wehner, and A. J. Turgeon. 1983. Ammonia volatilization from fertilized turfgrass stands. *Agron. J.* 75: 454-456.
- Vlek, P. L. G., and B. H. Byrnes. 1986. The efficacy and losses of fertilizer N in low land rice. *Fert. Res.* 9: 131-147.
- Watson, C. J. 1990. The influence of soil properties on the effectiveness of phenylphosphorodiamidate (PPD) in reducing ammonia volatilization from surface applied urea. *Fert. Res.* 24: 1-10.

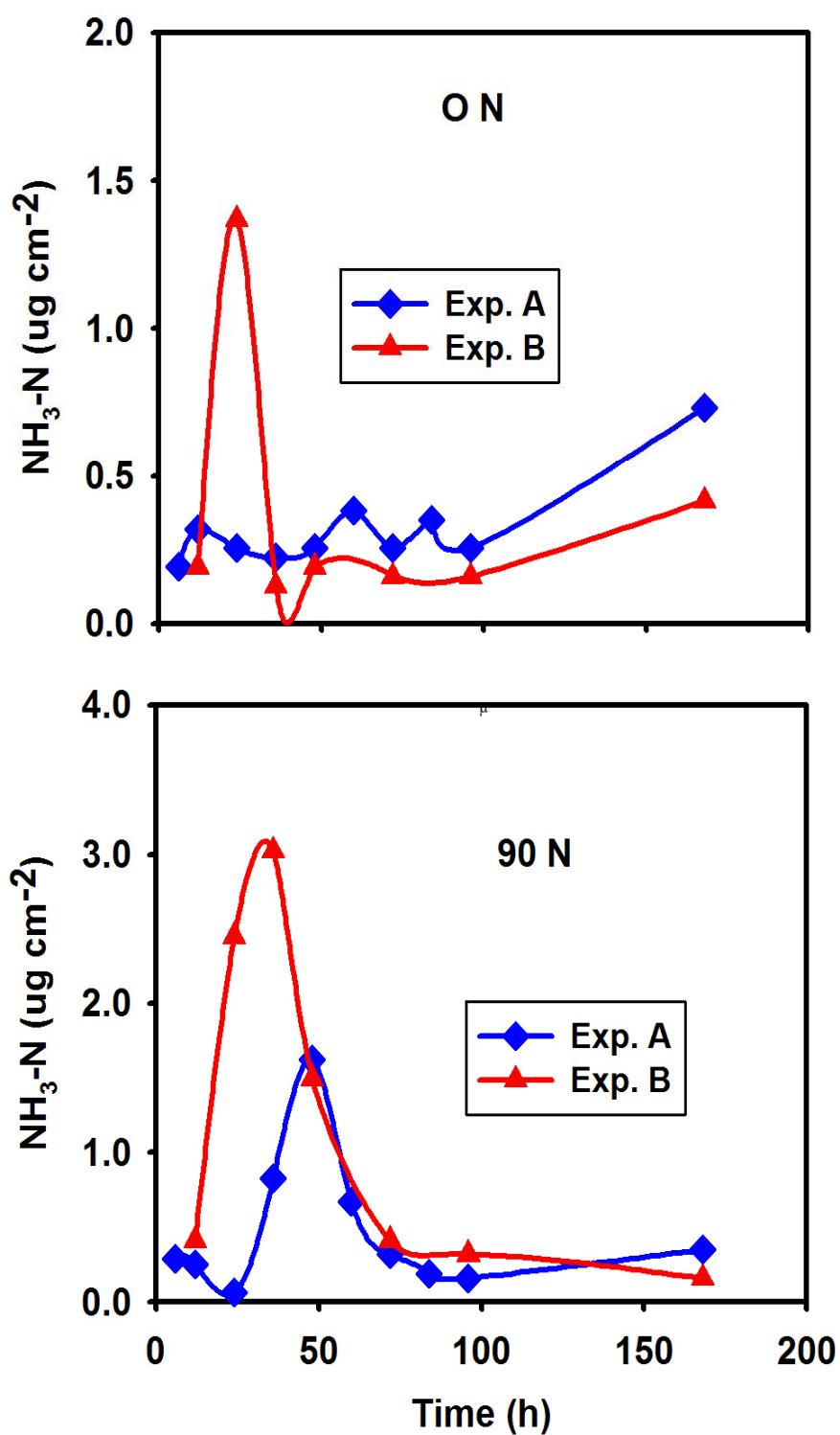


Fig. A.2. Ammonia volatilization time course of two trials carried out in the Greenhouse at different four N rates.

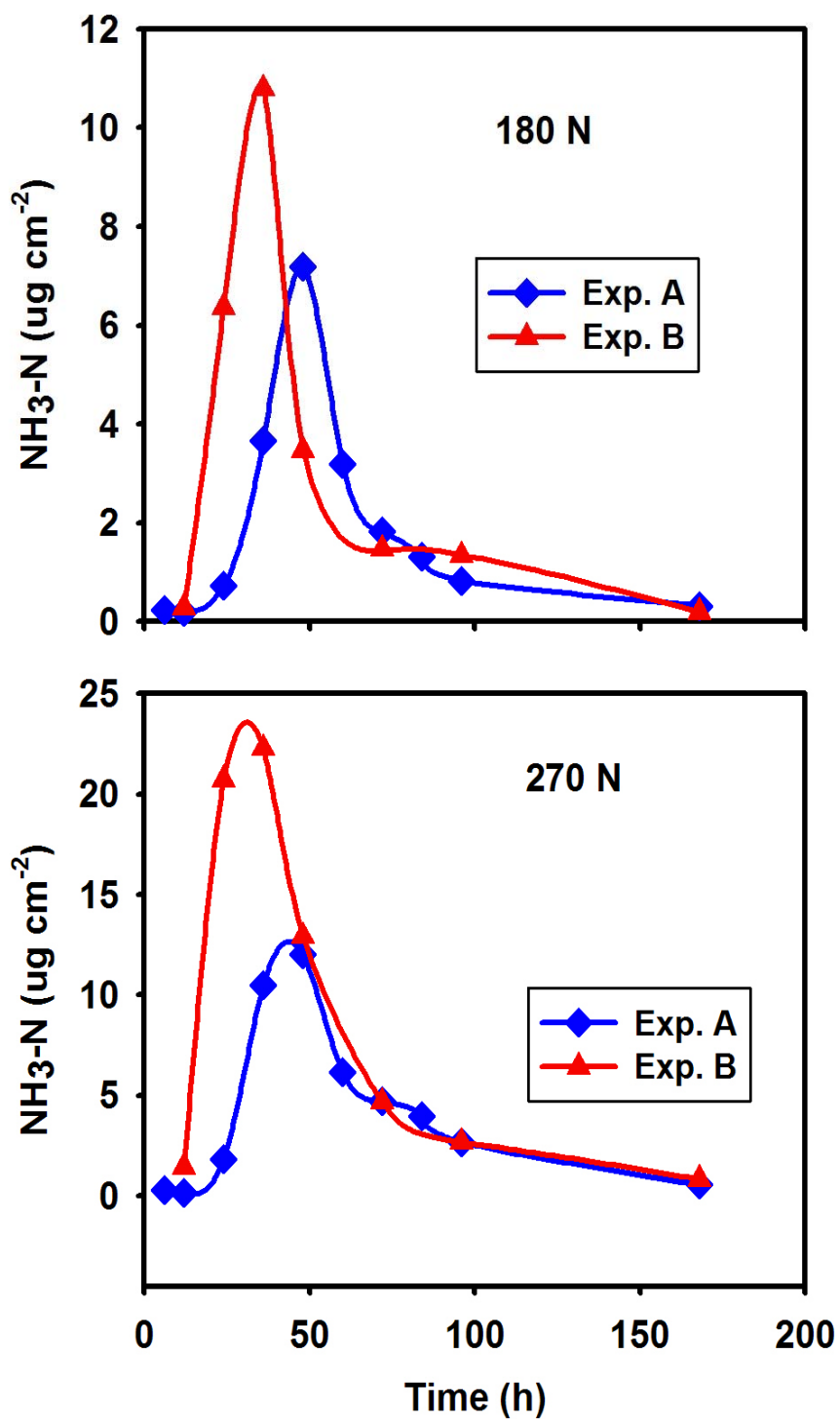


Fig. A.2 (Cont.). Ammonia volatilization time course of two trials carried out in the Greenhouse at different four N rates.

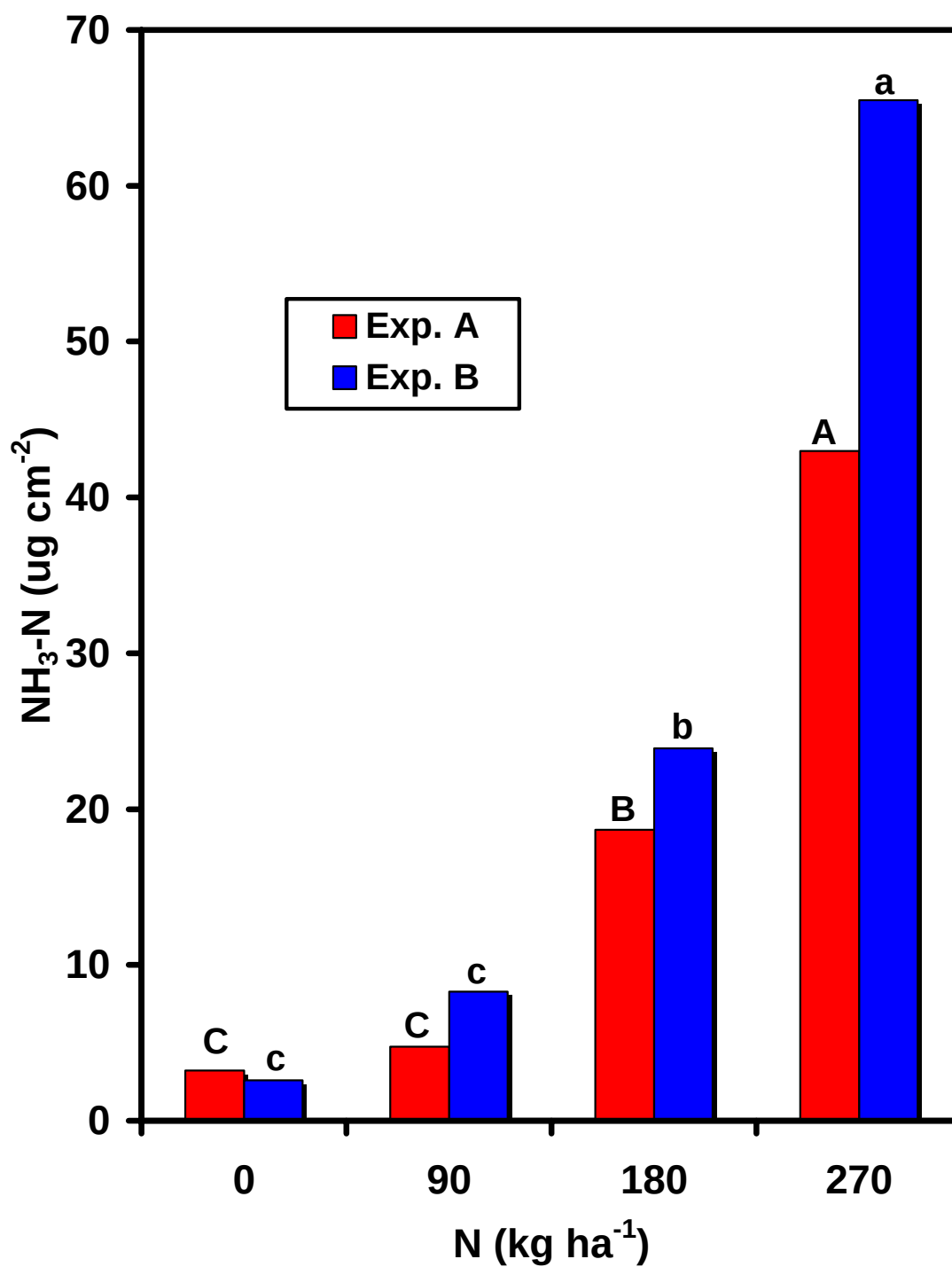


Fig. A.3. Cumulative NH₃ losses at different rates of N application. Uppercase letters are for comparison of N rates within experiment A and lowercase letters are from comparison of N rates within experiment B.

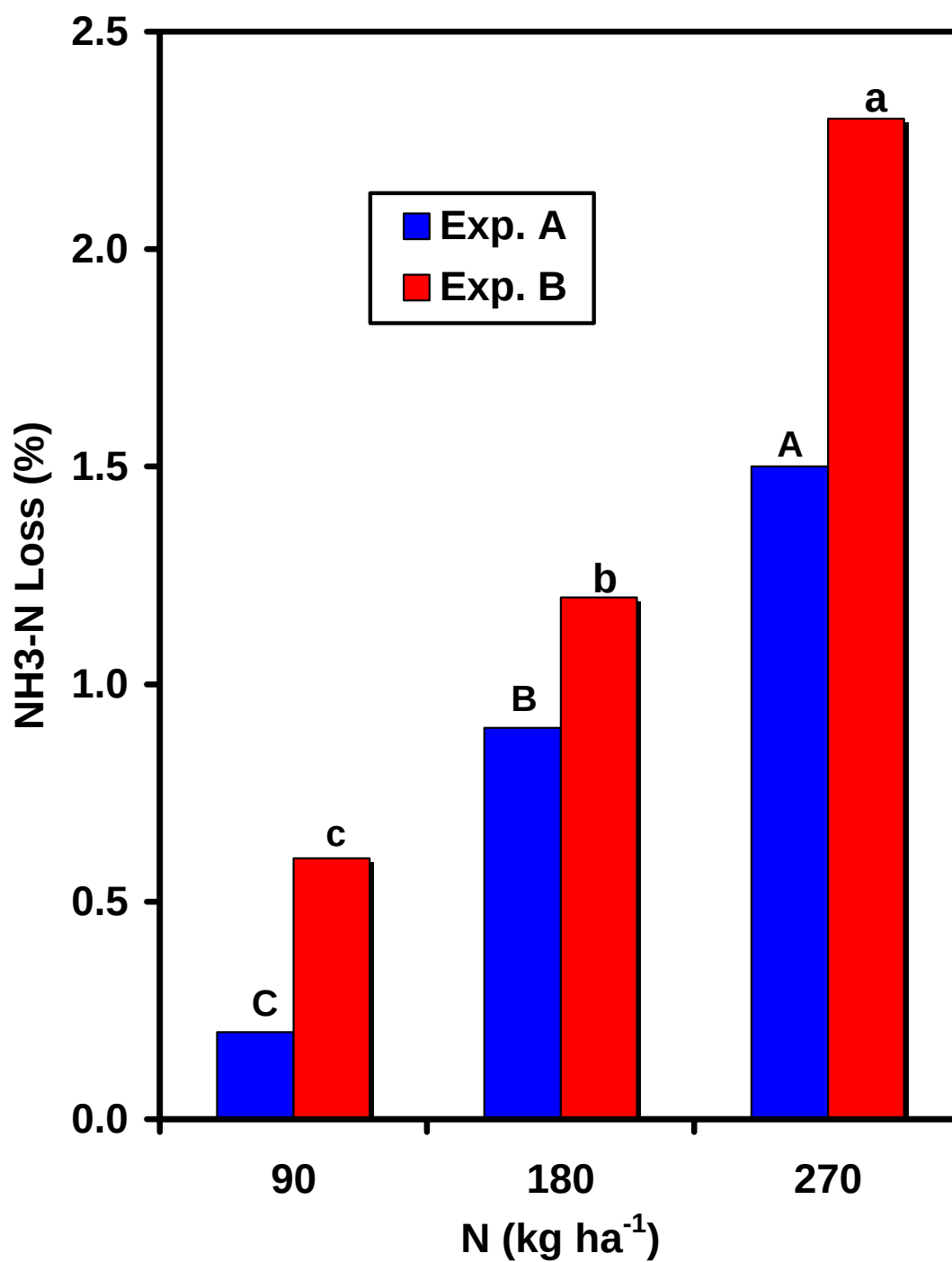


Fig. A.4. Percent NH₃ losses at different rates of N application. Uppercase letters are for comparison of N rates within experiment A and lowercase letters are from comparison of N rates within experiment B.

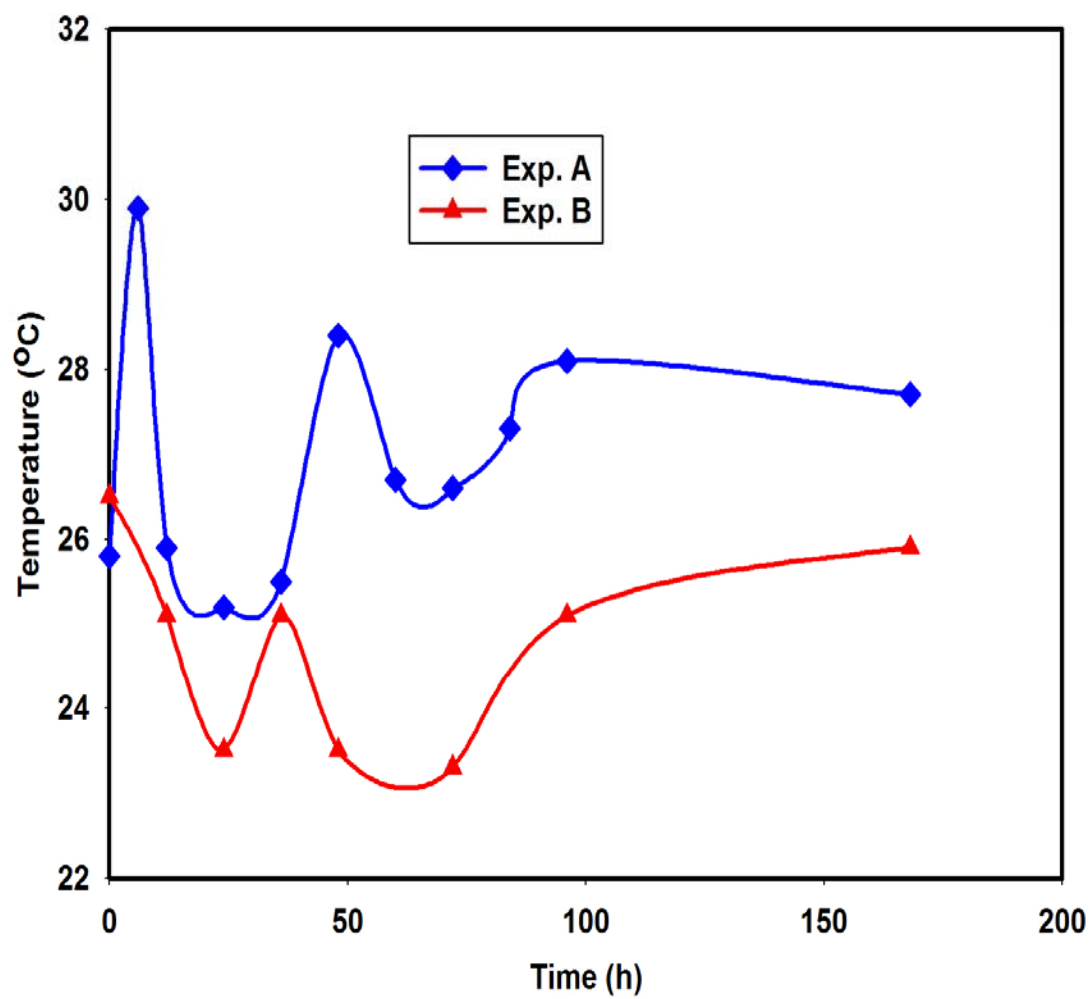


Fig. A.5. Temperatures inside volatilization chambers at the time of collection where trials were carried out in the greenhouse.

VITA

Roque W. Lemus

Education

Virginia Polytechnic Institute and State University

Ph.D., Crop and Soil Environmental Sciences (CSES), January 2004

Dissertation: Switchgrass as a Bioenergy Crop: Fertilization, Cultivar Choice, and Management.

Iowa State University, Ames, Iowa

M.S., Agronomy - Crop Production and Physiology, May 2000

Thesis: Cultivar and Fertility Effects on Switchgrass Biofuel Production in Southern Iowa.

Iowa State University, Ames, Iowa

B.S., Biology, Minor: Agronomy - Crop Science, August 1996.

Publications

Abstracts

Lemus, R., D. Parrish, C. Anderson-Cook, B. Pepper, M. Alley, O. Abaye, and A. Niemiera. 2003a. Efficient Fertilization Strategies for Switchgrass Production. In Annual Meetings Abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Lemus, R., D. Parrish, D. Wolf, and C. Anderson-Cook. 2003b. Effects of Cutting Frequency, Cultivar, and Ecotype on Switchgrass Production. In Annual Meetings Abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Parrish, D., **R. Lemus**, M. Alley, C. Anderson-Cook, and A. Niemiera. 2003. N and P Use in Greenhouse-Grown Switchgrass. In Annual Meetings Abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Abaye, O., V. Mulkey, J. Guay, **R. Lemus**, and T. Shanklin. 2003. Evaluation of Matua Prairie Grass and Matua Prairie Grass Alfalfa Mixtures for Animal Performance. In Annual Meetings Abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Lemus, R., D. Parrish, D. Wolf, M. Alley, C. Anderson-Cook, and O. Abaye. 2002. Estimating nitrogen use efficiency under field conditions to improve switchgrass production in Virginia. In Annual Meetings Abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Abaye, O. A., **R. Lemus**, G. Evanylo, C. Zipper, and S. Hutton. 2002. Forage species' persistence on a reclaimed mine soil treated with biosolids. In Annual Meetings Abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Parrish, D. J., D. D. Wolf, and **R. Lemus**. 2002. Managing switchgrass as a biofuels crop. In Annual Meetings Abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Lemus, R., O. Abaye, C. Zipper, and G. Evanylo. 2001. Establishment and potential productivity of forages in partially reclaimed soils. In Annual Meetings Abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Parrish, D. J., D. D. Wolf, and **R. Lemus**. 2001. Ten years of study of switchgrass as a biofuel crop. Agron. In Annual Meetings Abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Lemus, R., N. E. Molstad, E. C. Brummer, L. Burras, and K. J. Moore. 1999. Switchgrass Management for Yield Potential and Biomass Quality in the Chariton Valley, Iowa. Agron. Abs.

Molstad, N. E., **R. Lemus**, L. Burras, E. C. Brummer, and K. J. Moore. 1999. Switchgrass Production for Biofuel in Southern Iowa: Soil Morphology and Selected Soil Properties Related to Yield. Agron. Abs.

Lemus, R., N. E. Molstad, E. C. Brummer, L. Burras, and K. J. Moore. 1998. Switchgrass Management and Productivity in the Chariton River Valley, Iowa. Agron. Abs.

Journal Articles

Lemus, R., E. C. Brummer, C. L. Burras, K. J. Moore, M. F. Barker, and N. E. Molstad. 2003. Effects of Nitrogen Fertilization on Biomass Yield and Quality in Large Fields of Established Switchgrass in Southern Iowa. Biomass and Bioenergy (in press).

Lemus R., E. C Brummer, K. J. Moore, N. E. Molstad, C. L. Burras, and M. F. Barker 2002. Biomass yield and quality of 20 switchgrass populations in southern Iowa, USA. Biomass and Bioenergy 22: 433-442.

Molstad, N.E., C. L. Burras, E.C. Brummer, **R. Lemus**, M. Braster, J. Sellers, and T. Jacobson. 2003. Hillslope pedology and its implications in the Lake Rathbun Watershed, Iowa. J. Soil Sci. (in review).

Proceedings and Reports

Lemus, R., D. Parrish, and D. Wolf. 2002a. Estimating N dynamics under field conditions to improve switchgrass production in Virginia. Proceedings of the Third Eastern native Grass Symposium. Chapel Hill, NC: October 1-3, 2002.

Lemus, R., A. O. Abaye, G. K. Evanylo, C. E. Zipper, and S. J. Hutton. 2002b. Long-term success of forage species planted for reclamation at Powell River project. Proceedings of the Third Eastern native Grass Symposium. Chapel Hill, NC: October 1-3, 2002.

Brummer, E. C., C. L. Burras, M. D. Duffy, K. J. Moore, **R. Lemus**, N. Molstad, V. Nanhon, and W. Waver. 2000. Switchgrass production in Iowa: Economic analysis, soil suitability, and varietal performance. Final Report. Dept. of Energy, Oak Ridge National Laboratory.

Brummer, E. C., C. L. Burras, M. D. Duffy, K. J. Moore, **R. Lemus**, N. Molstad, V. Nanhon, and W. Waver. 1998. Switchgrass production in Iowa: Economic analysis, soil suitability, and varietal performance. Annual Report. Dept. of Energy, Oak Ridge National Laboratory.

Extension Publications

Abaye, O. A., G. K. Evanylo, C. Dundas, C. Zipper, **R. Lemus**, and J. Rocket. 2003a. Survivability and Performance of Selected Forage Crops in Mine Land. Part I. Species diversity, dry matter yield, and bioefficiency. Virginia Agric. Exp. Stn. (in review).

Abaye, O. A., G. K. Evanylo, C. Dundas, C. Zipper, **R. Lemus**, and J. Rocket. 2003b. Survivability and Performance of Selected Forage Crops in Mine Land. Part II. Visual assessment of species diversity and ground cover. Virginia Agric. Exp. Stn. (in review).