EVALUATION OF SWITCHGRASS, _M. X GIGANTEUS_, AND SORGHUM AS BIOMASS CROPS: EFFECTS OF ENVIRONMENT AND FIELD MANAGEMENT PRACTICES

BY

MATTHEW W. MAUGHAN

DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Crop Sciences in the Graduate College of the University of Illinois at Urbana-Champaign, 2011

Urbana, Illinois

Doctoral Committee:

Professor Germán A. Bollero, Chair
Assistant Professor DoYoungh Lee, Director of Research
Associate Professor Thomas B. Voigt
Professor Donald G. Bullock
Assistant Professor Fernando E. Miguez, Iowa State University
ABSTRACT

Switchgrass (*Panicum virgatum* L.), *Miscanthus x giganteus* (*M. x giganteus*), and sorghum (*Sorghum bicolor* L.) have been proposed as potential bioenergy feedstock crops. This study evaluates how these crops perform in different environments under different crop management practices, particularly nitrogen (N) fertilizer rates. Chapter 1 provides the rationale of this research and a general discussion of the unique characteristics of these three crops. In Chapter 2, an extensive database of switchgrass biomass yields from 106 sites and 45 field studies in eastern two thirds of the USA and southeastern Canada is evaluated using descriptive statistics, and using a random coefficients model. Switchgrass has been researched extensively in North America as a biomass crop and data reported since the 1990’s reveal large variability in dry biomass yields which are related to multiple environment and field management practices. This analysis describes switchgrass biomass N response, and shows that in addition to N fertilizer rate the most important factors affecting switchgrass dry biomass yields are growing region, spring precipitation, growing season, ecotype, and harvest timing. Chapter 3 remarks that studies reporting *M. x giganteus* dry biomass yields to date in the USA are few in number and little information is available to suggest a suitable growing region. This study investigates *M. x giganteus* in four Midwest and Atlantic Coast environments under three N rates. Establishment success, plant growth, morphology, and dry biomass yields were evaluated and results reveal no response to N rate during the establishment years, large biomass yield differences among environments, and decreased yield when the crop experienced a combination of high heat and dry conditions. Chapter 4 introduces two types of sorghum, forage sorghum and biomass sorghum (referred to as energy sorghum) which have been proposed as crops with high biomass production potential although prior to this study no research had evaluated these
sorghum types grown for biomass in IL. This field study evaluated two forage sorghum and two energy sorghum hybrids in four IL environments under different N rates. Measurements of morphology and crop growth were measured throughout the growing season, and dry biomass yields revealed significant differences between the two sorghum types. The energy sorghum hybrids achieved the greatest biomass yields in each environment with the effects of environment and N rate affecting the biomass yields. The results of these studies provide valuable information for stakeholders, producers, and scientists regarding the impact of environment and management practices on biomass yields of switchgrass, *M. x giganteus*, and sorghum. It is necessary that these factors be evaluated prior to making decisions as to which crop species and which cultivar or hybrid to plant in a given location. In most cases, no regional recommendations for species selection and N fertility rates are adequate and most field management practices must be made on a site-by-site basis.
ACKNOWLEDGMENTS

It has been a pleasure and honor being a graduate student in the Dept. of Crop Sciences at the University of Illinois Urbana-Champaign. My time as a graduate student has been a time of growth and learning. The knowledge and experience I have gained are invaluable stepping stones in my life.

First I would like to thank my wife, Julie, for her continued sacrifice and support in my behalf. Her encouragement and confidence in me have been a source of strength and joy to me, and I could not have come this far without her love, companionship, and friendship. She has tirelessly and lovingly cared for our four children Timothy, Porter, Emmett, and Amelia, who have also been a wonderful support to me, helping me to maintain a balance in life.

I express many thanks to my dissertation committee members for their support and guidance. I am grateful for the opportunity I had to meet Dr. Germán Bollero at an Agronomy Society of America meeting several years ago in Salt Lake City when I was applying to graduate school. I was fortunate to have been offered an assistantship and co-advised by him as a Master’s student and then later offered a position by him and Dr. Tom Voigt to stay at Illinois to pursue a Doctoral degree. His guidance as an advisor has been tremendous, and his sincerity and concern for me as a person and as a student have truly shaped me into a better and more qualified person and agronomist. Serving as a teaching assistant for his course, Crop Science 440, Applied Statistical Methods I, truly laid a statistical foundation for me that has been invaluable in my research and evaluation of experiments. I thank Dr. DoKyoung (D.K.) Lee for the opportunity to be involved in multiple research projects that have taught me many things about applied agronomy research and how to set up field experiments so that planting, management, and harvesting of the crops are straightforward. Additionally, his knowledge and passion of
biomass crops has been a tremendous asset when considering each of my experiments. We have had many fruitful conversations about field experiments, challenges, and future opportunities. I express gratitude for the opportunity of working with Dr. Tom Voigt. Through him I was fortunate to be the recipient of a PhD research assistantship funded by the Sun Grant/U.S. Department of Energy Regional Biomass Feedstock Partnership. We have had some enjoyable trips together traveling to field sites in IN, NE, SD, and KY. Our conversations about research and life have been helpful in my work. I also thank him for the many editing versions of manuscripts that he has provided to help improve my writing and flow of the manuscripts. I am thankful to Dr. Fernando Miguez for his invaluable modeling skills, statistical skills, and R software skills. His help with statistical modeling and abilities to use R as a statistical modeling and graphical tool have been invaluable in my research. He provided a great deal of R code and example R code that have given me the opportunity to become experienced with two statistical software’s, R and SAS. His published research has also been a valuable resource in my research and writing. One of the greatest opportunities I have had as a graduate student is being a teaching assistant for Dr. Don Bullock. He gave me the opportunity to be a teaching assistant for two courses, Crop Science 542, Applied Statistical Methods II, and Crop Science 541, Regression Analysis, which was very challenging and a huge learning experience. This gave me the opportunity to be mentored by him, and to work with excellent teaching assistants and students. These experiences not only helped me to learn the statistical material very well, but also helped become more comfortable teaching and presenting to audiences. The statistical skills and resources I gained from these courses have been invaluable in my research, which I have used over and over. Because of Dr. Bullock’s passion for analyzing data in the most appropriate and correct way, I often evaluated my own work to make sure that it would measure up.
Last but not least I thank the many collaborators, field crews, and undergraduate students that have made these experiments possible. Allen Parrish, in particular, was very helpful in setting up experiments and harvesting of biomass.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER 1</th>
<th>Rationale for Research</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAPTER 2</td>
<td>Management and Environmental Factors that Affect Switchgrass Biomass Production</td>
<td>9</td>
</tr>
<tr>
<td>CHAPTER 3</td>
<td><em>Miscanthus x giganteus</em> Productivity: The Effects of Management in Different Environments</td>
<td>52</td>
</tr>
<tr>
<td>CHAPTER 4</td>
<td>Management of Forage and Energy Sorghum for Biomass Production in Illinois</td>
<td>86</td>
</tr>
<tr>
<td>CHAPTER 5</td>
<td>Supplementary Information to Ch. 4</td>
<td>115</td>
</tr>
<tr>
<td>CONCLUDING REMARKS</td>
<td></td>
<td>127</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>Selected SAS and R code for Ch. 2</td>
<td>132</td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>Selected SAS and R code for Ch. 3</td>
<td>143</td>
</tr>
<tr>
<td>APPENDIX C</td>
<td>Selected SAS and R code for Ch. 4</td>
<td>156</td>
</tr>
<tr>
<td>APPENDIX D</td>
<td>Selected SAS code for Ch. 5</td>
<td>170</td>
</tr>
<tr>
<td>CURRICULUM VITAE</td>
<td></td>
<td>183</td>
</tr>
</tbody>
</table>
CHAPTER 1

Rationale for Research

The need to produce high yielding biomass crops has become an increasingly important priority in the USA because of finite energy supplies, increasing energy prices, and volatile foreign oil and gas markets (Perlack et al., 2005; Asif and Muneer, 2007; U.S. Chamber of Commerce, 2010). The USA accounts for 25% of the world’s oil consumption, primarily to fuel the transportation and shipping sectors of its economy (Biomass Research and Development Board, 2008). These reasons have urged the USA to attempt shifting its reliance on oil and gas to more renewable sources of energy and liquid transportation fuel, especially biomass based energy (Heaton et al., 2008a). Continued research efforts and the scaling up of a plant and biomass based energy industry is necessary to meet the USA’s vision of replacing 30% of current petroleum consumption by 2030 with biofuels (Perlack et al., 2005). These efforts will also help to meet the government Renewable Fuels Standard (RFS) mandates of producing 136 billion liters of biofuels by the year 2022 (Energy Independence and Security Act, 2007). Of this 136 billion liters, 79 must be from advanced biofuels (not corn starch) including 60 must come from cellulosic feedstock sources. In response, several herbaceous crops are being researched as potential sources of bioenergy feedstock that can be utilized as energy sources. Three of these crops are switchgrass (*Panicum virgatum* L.), *Miscanthus x giganteus* (*M. x giganteus*) and sorghum (*Sorghum bicolor* L.), and each has been proposed as potential bioenergy crops for the USA. These crops provide an opportunity to grow and utilize a renewable source of energy, and can help to meet the mandate. Biomass yields and biomass yield potential of these crops has been reported but varies greatly between and within them. Since the early 1990’s, switchgrass has been researched extensively in North America as a biomass feedstock crop (Wright and
Turhollow, 2010; Wullschleger et al., 2010), while less research has evaluated *M. x giganteus* and sorghum as biomass feedstock crops in North America. This dissertation research (Ch. 2, Ch. 3, Ch. 4, and Ch. 5) focuses on the growth, management, dry biomass yield, and statistical modeling of these crops. The main objective of this research is to evaluate reported biomass yields of switchgrass in North America, describe the factors that most influence these yields, and implement field studies to evaluate *M. x giganteus* and sorghum in different environments, and evaluate field management practices, in particular N rate, that influence biomass yield in these environments.

No direct field comparisons among these three crops are made in the research contained in Chapters 2, 3, and 4, although this chapter describes some differences between the crops that may favor one over the other in certain situations or environments. Particular emphasis is placed on the Midwest, although the area that is covered by each research project is different. Chapter 2 covers the largest area investigating switchgrass biomass yields across the eastern two thirds of the U.S. and southern Canada. Chapter 3 evaluates *M. x giganteus* in three Midwest environments and one Atlantic Coast environment. Finally, Chapter 4 is confined to evaluating sorghum in four IL environments. Literature review for each of these crops and their specific research objectives are primarily contained in their respective chapters. Commonalities that are focused on in each chapter relate to the biomass yield and N response of the crops. Nitrogen response in these crops has varied significantly from site-to-site as described in Chapter’s 2, 3, and 4, while biomass yield is arguably the most important characteristic to consider when selecting a biomass crop. Additionally, these crops are all C₄ photosynthetic grasses and as such exhibit higher photosynthetic carbon uptake rates than C₃ crops (Hopkins and Hüner, 2004). When considering the reaching effects of a biomass based energy industry it is necessary to take
a skeptical or investigative approach when evaluating these crops. This is necessary to fully understand the impacts that such production could have on current cropping systems, and the difficulty of incorporating such crops into current cropping systems, in particular Midwest cropping systems.

Large scale bioenergy production of *M. x giganteus*, switchgrass, and sorghum in the Midwest, may or may not be adopted by farmers in the future given the dominance of corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) production. Also, if market prices of corn, soybean, and wheat (*Triticum aestivum* L.) remain high as they have during 2010 and 2011, much leverage would be required to convince farmers to grow bioenergy crops that have an uncertain market and future. One of the purposes of this research is to develop useful agronomic information for stakeholders, producers, and researchers that will help them make this decision. Currently, little infrastructure or industry in the Midwest exists for processing and handling dedicated biomass energy crops. On the other hand, the infrastructure will likely not be established until there is a reasonable amount of biomass production already occurring.

Feedstock composition will likely not favor one crop over the other, since research has shown that most biomass feedstocks have similar chemical composition when harvested at physiological maturity (Lee et al., 2007). The decision on which crop to produce will likely depend on a decision of which crop will best fit into a producer’s crop rotation, provide reliable and stable biomass yields, and produce significant positive net returns. Table 1.1 summarizes some of the major advantages and limitations to producing these three crops and provides a framework for helping to select the right crop for the right situation. It must be noted that a similar summary table has been published comparing C₄ rhizomatous grasses, switchgrass, and *M. x giganteus* (Heaton et al., 2004).
One major distinction between these crops is that *M. x giganteus* and switchgrass are perennial crops and sorghum is an annual crop. For Midwest farmers, an annual crop like sorghum may be a front runner candidate, at least in the short term because it will more easily fit into current corn and soybean crop rotations and does not require committing land to production for multiple years like perennial switchgrass and *M. x giganteus*. As energy markets and a stable bioenergy industry infrastructure are developed, perennial switchgrass and *M. x giganteus* may provide long term options, where contracts can support committing farm ground to perennial crop production. One major advantage of these two perennial crops is that they do not require planting every year and may be well suited to soil that is less productive for corn and soybean production and highly erodible for annual row crop production. There are also other advantages and limitations associated with perennial vs. annual bioenergy crop production. One of the limitations of switchgrass and *M. x giganteus* production is the duration period required to reach maturity and become fully productive. Often, establishment year yields are non harvestable, meaning that establishment year yields are minimal and harvesting is not justified. In most cases, *M. x giganteus* takes at least three years to become fully productive (Miguez et al., 2008), while switchgrass may become fully productive in as few as two years (Grassini et al., 2009; Schmer et al., 2010), but it usually requires three years (Parrish and Fike, 2005; Heaton et al., 2004; Schmer et al., 2010). Because establishment year yields of *M. x giganteus* and switchgrass are usually non-harvestable, a compromise between waiting for full productivity and receiving some economic benefit during establishment year is the use of a companion crop. Studies involving corn and sorghum-sudangrass companion cropped with switchgrass have simultaneously resulted in harvestable corn and sorghum-sudangrass crops and successfully established switchgrass stands (Hintz et al., 1998; Cossar and Baldwin, 2002). Sorghum requires
planting every year but energy sorghum hybrids can be planted on the same row spacing as corn (0.76 m) using corn planting equipment. This provides an advantage over switchgrass which generally requires narrower spacing and the need for equipment that can plant small seeds on narrow row spacing, and *M. x giganteus* which requires vegetative propagation (Pyter et al., 2009).

**REFERENCES**


### Table 1.1. Summary† of several major advantages and limitations of growing and using switchgrass, *M. x giganteus*, and sorghum (forage sorghum or energy sorghum) as biomass feedstock crops. Emphasis is placed on growing these crops in the Midwest. A positive sign (+) represents a positive characteristic or advantage, while a negative sign (-) represents a negative characteristic or limitation. A 0 represents a neutral or undecided basis. Superscripts are included where particular advantages and limitations are referenced.

<table>
<thead>
<tr>
<th>Characteristics/attributes</th>
<th>Switchgrass</th>
<th><em>M. x giganteus</em></th>
<th>Sorghum</th>
</tr>
</thead>
<tbody>
<tr>
<td>High yielding biomass potential</td>
<td>+b, j, k, l</td>
<td>+a, b, e</td>
<td>+g, p, q</td>
</tr>
<tr>
<td>Low energy inputs (fertilizer)</td>
<td>0d</td>
<td>0s, t, u</td>
<td>r</td>
</tr>
<tr>
<td>Environmental benefits</td>
<td>+c</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Annual nutrient recycling</td>
<td>+b</td>
<td>+b</td>
<td>-</td>
</tr>
<tr>
<td>Breeding improvement potential</td>
<td>+c, i, m</td>
<td>+e</td>
<td>+g</td>
</tr>
<tr>
<td>Population genetic diversity</td>
<td>+c, n</td>
<td>-a</td>
<td>+g</td>
</tr>
<tr>
<td>Market prices</td>
<td>-f</td>
<td>-f</td>
<td>0</td>
</tr>
<tr>
<td>Ease of establishment</td>
<td>0o</td>
<td>-a</td>
<td>+</td>
</tr>
<tr>
<td>Non Invasiveness</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Perennial</td>
<td>+i</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Annual</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Broad adaptation</td>
<td>+i</td>
<td>-</td>
<td>+h</td>
</tr>
<tr>
<td>C₄ photosynthetic</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

† A similar summary table was published in Heaton et al., 2004, and some similar information is reported here.

a) Lewandowski et al. (2000)  
g) Rooney et al. (2007)  
n) Narasimhamoorthy et al. (2008)  
b) Heaton et al. (2004)  
h) Rooney and Aydin, 1999  
o) Sanderson et al. (1996)  
c) Sanderson et al. (2006)  
j) Gonzalez et al. (2009)  
p) McCollum et al. (2005)  
d) Parrish and Fike, 2005  
k) Sladden et al. (1991)  
r) Sorghum Management Guide, 2010  
e) Heaton et al. (2008b)  
l) Kiniry et al. (1999)  
s) Christian et al. (2008)  
f) Khanna et al. (2008)  
m) Bhandari et al. (2011)  
t) Ercoli et al. (1999)  
g) Rooney et al. (2007)  
p) McCollum et al. (2005)  
h) Gonzalez et al. (2009)  
j) Kiniry et al. (1999)  
k) Sladden et al. (1991)  
l) Heaton et al. (2004)  
m) Bhandari et al. (2011)  
o) Sanderson et al. (1996)  
p) McCollum et al. (2005)  
n) Narasimhamoorthy et al. (2008)  
l) Heaton et al. (2004)  
m) Bhandari et al. (2011)  
o) Sanderson et al. (1996)  
p) McCollum et al. (2005)  
n) Narasimhamoorthy et al. (2008)
CHAPTER 2

Management and Environmental Factors that Affect Switchgrass Biomass Production

ABSTRACT

Switchgrass (*Panicum virgatum* L.) dry biomass yields can be largely impacted by multiple environmental factors and field management practices factors that must be understood so that when switchgrass is grown as a bioenergy crop, proper management practices are implemented. The objective of this study was to compile an extensive database regarding switchgrass biomass production and perform a meta-analysis to evaluate the effects of growing region, spring precipitation, growing season, ecotype, harvest frequency, harvest timing, and nitrogen rate (N) rate on dry biomass yields. Data from 106 sites and 45 studies were gathered from the eastern two thirds of the U.S. and southeastern Canada. A random coefficients model was implemented to describe switchgrass biomass N response and other environmental and management factors were incorporated into the model. The linear N rate (*P* < .0001), quadratic N rate (*P* = 0.0363), region (*P* < .0001), spring precipitation (*P* = 0.0001), growing season (*P* = 0.0466), ecotype (*P* < .0001), harvest timing (*P* = 0.0771), spring precipitation x ecotype (*P* = 0.0092), spring precipitation x growing season (*P* = 0.0007), linear N rate x ecotype (*P* = 0.064), and region x harvest timing (*P* = 0.0817) effects were all significant. Results revealed that N response varies from site-to-site and the critical N fertilizer rate (Max N) required for maximum biomass yield may be quite higher than the economical optimum N rate (EONR). Switchgrass grown in the lower and upper central U.S. regions produced greater biomass yields than switchgrass grown in the north or south, and the lowland ecotype yielded better than the upland ecotype, but this depended on the region.
INTRODUCTION

Volatile energy markets, high prices, and finite supplies are reasons for the USA to shift its reliance on oil and gas to more renewable sources of energy and liquid transportation fuel, especially biomass based energy (Heaton et al., 2008). The USA accounts for 25% of the world’s oil consumption, primarily to fuel the transportation and shipping sectors of its economy (Biomass Research and Development Board, 2008). As part of the U.S. Energy Independence Security Act of 2007 a Renewable Fuels Standard (RFS) mandates the production of 136 billion liters of biofuels by the year 2022 (Energy Independence and Security Act, 2007). Of this 136 billion liters, 79 must be from advanced biofuels (not corn starch) and 60 must come from cellulosic feedstock sources. Advanced biofuels or cellulosic biofuel crops like switchgrass (*Panicum virgatum* L.) provide an opportunity to grow and utilize a renewable source of energy, and can help to meet the mandate.

Switchgrass has received a great deal of attention among researchers and producers because of its use as a forage crop and its potential as an herbaceous bioenergy crop. Switchgrass is a warm-season perennial grass that is native throughout much of North America east of the Rocky Mountains, and is most abundant east of 100°W (Vogel, 2004; Samson and Omelian, 1994). It has been the subject of much research in the USA since the early 1990s when the Department of Energy evaluated a wide variety of herbaceous species across a range of environments and identified it as a ‘model’ bioenergy feedstock (McLaughlin and Kszos, 2005; Wright and Turhollow, 2010). Switchgrass has many desirable characteristics that make it suitable for feedstock production. Among them, the ability to grow on marginal and disturbed sites, provide environmental and ecosystem services, require relatively low moisture and nutrient inputs, and produce relatively high and reliable dry biomass yields across a wide range of
environments (Wright and Turhollow, 2010; Parrish and Fike, 2005; Mitchell et al., 2008; Bransby et al., 1998; Sanderson et al., 1996; Sanderson et al. 2006; Lemus and Parrish, 2009).

Moreover, Gonzalez et al. (2009) described several traits that herbaceous bioenergy crop species should posses, including not directly competing with food crops for land and resources, producing reliable yields in a broad range of environments under limited inputs, being perennial, and having the potential for improvement through breeding. Switchgrass possesses each of these characteristics.

Several reviews (Bransby et al., 1998; Parrish and Fike, 2005; Lemus and Parrish, 2009; Mitchell et al., 2008; Sanderson and Adler, 2008; Sanderson et al., 1996; Sanderson et al., 2006a; Wright and Turnhollow, 2010) and meta-analytical (Heaton et al., 2004; Wang et al., 2010; Wullschleger et al., 2010) articles have been published regarding switchgrass production. From a production perspective, dry biomass yields among switchgrass cultivars are highly variable. In a database compilation of 39 studies ranging across much of the eastern two-thirds of the US, Wullschleger et al. (2010) reported yields ranging from 1 Mg ha\(^{-1}\) to 39.1 Mg ha\(^{-1}\). Biomass yields can be influenced by the climate, location and geography of the experiment, management practices, and site-to-site conditions (Johnston et al., 2009; Wang et al., 2010). These factors must be considered to maximize biomass yields and maintain stand longevity. From the early 1990s through the present, much research has focused on cultivar and ecotype adaptation and evaluation, harvest management, and nitrogen and fertilizer response (Table 2.1).

The overall purpose of this study was to perform a meta-analysis of important factors in switchgrass production that influence dry biomass yield and was accomplished by collecting and synthesizing data from the literature of independent studies (Cooper et al., 2009; Gurevitch and Hedges, 1999; Gates, 2002). A random coefficients model was then implemented to account for
the variability among sites (St-Pierre, 2002) and describe the effects of different factors on switchgrass biomass yield. Wullschleger et al. (2010) recently performed a statistical analysis of switchgrass and various factors affecting biomass yields, covering 39 different studies from across the USA. Their study evaluated site location, stand age, plot size, cultivar, crop management, biomass yield, temperature, precipitation, and ecotype, and concluded that the most important predictors of biomass yield were ecotype, temperature, precipitation, and N fertilization. To further add to the understanding of these factors, we compile a more extensive database of 106 sites from 45 studies throughout North America, which includes many of the studies that were part of previous meta-analysis (Heaton et al., 2004; Wang et al., 2010; Wullschleger et al., 2010) as well as additional studies that were either missed or published during the review process of these meta analyses (Table 2.3). A quadratic function is the most common functional form that has been evaluated in switchgrass N response trials (Muir et al., 2001; Heggenstaller et al., 2009; Lemus et al., 2008a; Haque et al., 2009; Vogel et al., 2002) and we suspected that a quadratic function would best describe the relationship between biomass yield and N rate, but that environmental and site differences would result in variation in the strength and magnitude of the N response observed from site-to-site (i.e. intercept and slope would vary from site-to-site). We hypothesized that selection of proper ecotype (and specific cultivars within ecotype) would significantly affect biomass yield potential in different regions of the USA and southern Canada. We also hypothesized that harvest timing and number of annual harvests play an important role in affecting dry biomass yields. The database resulting from our literature search contains information on region of growth, spring precipitation, growing season, ecotype, number of annual harvests, harvest timing, and annual N application rate. Following the compilation of this database, the specific objectives of the analysis were to develop a random
coefficients model that best describes the curvilinear relationship between biomass yield and annual N application rate and then incorporate other selected factors into the model that have a significant influence on dry biomass yield. The approach in our statistical analysis that distinguishes it from previous analysis (Heaton et al., 2004; Wang et al., 2010; Wullschleger et al., 2010) is that it includes a quantification of the curvilinear N fertilization response of switchgrass. The N responses were quantified for specific regions of the USA and southern Canada that were categorized into groups of relatively similar growing season length, temperatures, day length, and winter freezing conditions. Spring (Apr. through Jun) precipitation rather the growing season or annual precipitation was used as a covariate in the model because early season water availability can have an important impact on biomass yield (Cassida et al., 2005) and early season precipitation has been shown to be a good predictor of biomass yield (Fike et al., 2006b; Lee and Boe, 2005).

MATERIALS AND METHODS

Database Compilation and Description

A literature search of primary research was conducted using the ISI Web of Knowledge (ISI, Philadelphia, PA) electronic database, and through location of studies included in the references. Switchgrass is a multi-purpose crop and has been grown for livestock forage, for biomass, as vegetative filter or streamside buffers, and as prairie or restorative plantings (Parrish and Fike, 2005). Switchgrass grown for these different purposes can be managed quite differently and in order make more meaningful comparisons, only data coming from studies that focused on switchgrass grown as a biomass crop or that were managed similar to switchgrass grown for biomass were included. Only literature published since 1990 measuring switchgrass dry biomass yields were included in the database using data gathered from the USA and southern
Canada. Switchgrass literature published before 1990 focused primarily on switchgrass grown as a forage crop, whereas most literature on switchgrass production since 1990 has focused on switchgrass grown as a biomass crop. In addition to the criteria just described studies were excluded from our database if dry biomass yields were averaged across N rates or ecotype, if biomass was harvested more than twice a year or studies were un-replicated. Studies that averaged biomass yields harvested at different times, meaning biomass harvested at peak biomass (before physiological maturity) or at the end of the growing season once the crop reached physiological maturity or following a post killing frost, were also excluded. Studies in which switchgrass plants were transplanted rather than seeded were excluded from the database unless the plants were in the second growing season or beyond, given the crop’s ability to spread out, fill in stand gaps, and achieve similar yields across a wide range of plant spacings (Parrish and Fike, 2005). Also, before the statistical model and predictions were developed, several biomass yield values from Thomason et al., 2004, and Sanderson et al., 2001 receiving annual N application rates ranging from 322 to 896 kg N ha\(^{-1}\) were removed. There were very relatively few observations in this N application range, and the N application rates from all of the other studies were less than 300 kg N ha\(^{-1}\), thus annual N application rates for each site were limited to a range between 0 and 300 kg N ha\(^{-1}\).

In the database, studies and experiments were separated into individual sites in order to disaggregate varying responses to annual N application. In some cases the reported biomass values specified for a particular site were averaged across more than one location within a particular study, where it was not possible to separate the studies by location. Cultivars, varieties, experimental lines, and synthetic lines (each referred to as cultivars) were classified into two categories, upland and lowland ecotype (Table 2.2). The assignment of most upland or
lowland ecotype classifications were obtained from references cited in Table 2.2. The reported harvest time varied from study to study, so we classified the final biomass harvest into two categories: peak standing crop (PSC) or end of season (ES). These classifications were assigned according to harvest and morphology information reported in the individual studies. Peak standing crop refers to harvests at or near peak biomass, which usually occurred at or near anthesis and before physiological maturity. The ES harvest timing is associated with harvests occurring after a killing frost or once the crop had begun to senesce and field dry.

Where possible, spring precipitation (April through June) values were obtained from the studies when reported, or were estimated from the long-term averages when specific seasons of precipitation were not reported. In cases, where no precipitation data was reported, spring precipitation was obtained from the North American Regional Reanalysis (NARR) database (Mesinger et al. 2006). A few observations that utilized irrigation in any specific year were excluded from the database and statistical analysis so that recorded spring precipitation levels were not confounded with applied irrigation in the statistical analysis.

Growing seasons were divided into 3 categories: establishment (growing season 1), maturation (growing season 2), and production (growing seasons >=3). Growing seasons >=3 were grouped together, primarily because the number of growing seasons >=3 ranged from 3 to 26 year old stands, and insufficient data were available to provide reliable estimates for each of these individual growing seasons. It was assumed that by the time the crop reaches three years of growth, the crop is fully productive and potentially achieving its maximum yields (Parrish and Fike, 2005; Heaton et al., 2004; Schmer et al., 2010). In some studies included in the database, biomass yield was reported as an average of growing seasons 2 and 3 (Casler et al., 2004; Vogel et al., 2002, Hopkins et al., 1995) and sometimes as an average of growing seasons 2, 3, and 4.
Rather than disregard these data, we categorized these data into growing seasons \( \geq 3 \). In these cases we assumed that the authors were reporting data from stands that were fully or near fully productive during their second season (Grassini et al., 2009) as it has been shown that switchgrass stands can reach their yield potential in as few as two years (Schmer et al., 2010).

Within the database, the data was divided into 4 regions or areas of growth that were classified as: North Region (NR), Upper-Central Region (UCR), Lower-Central Region (LCR), and South Region (SR) (Fig. 2.1 and Table 2.3). These regions were created based on information from the USDA plant hardiness zone map and latitude. Fig. 2.1 shows the sites categorized by region overlaid on the USDA plant hardiness zone map. The allocation of the studies into the 4 regions was fairly balanced with the NR, UCR, LCR, and SR containing data from 29, 24, 31, and 22 sites and locations, respectively (Table 2.3). In this way we simplified the range of production into groups of data originating from areas with relatively similar growing season lengths, day lengths and photoperiods, and winter freezing conditions (Fig. 2.1). Data from some regional scale experiments (Heaton et al., 2008; Casler et al., 2004; Casler et al., 2007; Adler et al., 2006; Schmer et al., 2010) were split into 2 or more regions depending on the geographical spread of the study sites (Table 2.3). Several data points in the NR, coming from Casler et al., 2004 and Madakadze et al., 1998b, were excluded from the analysis because they were the only studies reporting lowland ecotype yields in this region, producing little information for prediction of lowland ecotype biomass yields in the NR. Most other studies in the NR, did not plant lowland cultivars, most likely because of their susceptibility to winter kill in northern environments.
In total there were 106 sites from 45 studies totaling 1476 observations in the database. Forty-one of these studies came from the eastern two thirds of the U.S. with the remaining four studies coming from southeastern Canada. All studies originated from peer-reviewed journal articles, except Fuentes and Taliaferro (2002) which was published in a conference proceeding. Factors considered in the statistical analysis were: region (NR, UCR, LCR, SR), spring precipitation (April through June), growing seasons (1, 2, >=3), ecotype (lowland or upland), number of annual harvests (1 or 2), harvest timing (PSC or ES), and annual N application rate.

**Preliminary Statistical Analysis**

Cultivar means, standard error of the mean (SEM), minimum, and maximum dry biomass yields were calculated using the MEANS procedure of SAS (SAS Institute, 2007) for growing season 2 and growing seasons >=3 categorized by region (Table 2.4). Data exploration, graphing, and data manipulation was performed using the graphical interface and descriptive statistical packages of R statistical software (R Core, v. 2.12.1, 2010), in particular the ‘graphics’ v.2.12.1 and ‘lattice’ v.0.19-13 packages. Before statistical analysis and development of model, biomass yields were averaged across their respective ecotype within region, site, spring precipitation, growing season, and number of annual harvests. Based upon these averages, mean ecotype values and their respective SEM were then calculated.

**Statistical Analysis and Model Development**

A ‘random coefficient model’ was used to describe the response of mean switchgrass dry biomass yield (averaged across ecotype within region, site, spring precipitation, growing season, and number of annual harvests) to N rate. This allowed unique N response curves to be estimated for each site and was necessary due to site-to-site conditions that created variation in the response of dry biomass to N rate (Aitkin et al., 2009; Littell et al., 2006; St-Pierre, 2002).
The first step was to develop the basic model structure by considering the linear and quadratic components of N rate. Three models were tested each model included fixed linear and quadratic components of N rate ($x_{ij}$). In addition, the first model also had a random intercept. The second model also had a random intercept and random linear and quadratic components of N rate. The third model also had a random intercept and a random linear component of N rate, but no random quadratic component of N rate. Akaike Information Criterion (AIC) was used to compare these three models, and favored the third model, which had lower a lower AIC value (3480) than the first (3491) and second (3486) models. Each of these models resulted in significant fixed linear ($P < .0001$) and fixed quadratic ($P \leq 0.0674$) N rate components. The third model that was selected takes on the following basic form:

$$y_{ij} = (\mu + u_i) + (\alpha + a_i)x_{ij} + \beta x_{ij} + e_{ij},$$

$$u_i \sim N(0, \psi_1), \ a_i \sim N(0, \psi_2), \ e_{ij} \sim N(0, \sigma^2)$$

[eq. 1]

where dry biomass yield ($y_{ij}$) depends on N rate ($x_{ij}$), the $j^{th}$ mean biomass value within the $i^{th}$ site and is a function of the fixed ($\mu$) and random ($u_i$) intercept, fixed ($\alpha$) and random ($a_i$) linear N rate effects, and fixed quadratic N rate effect ($\beta$). The random intercept ($u_i$) depends on site ($i$) and the random linear N rate ($a_i$) effect which enters linearly into the model. The model assumes the random effects have a mean of zero and a general variance-covariance matrix, (i.e. $\psi_1$ for random intercept and $\psi_2$ for the random linear N rate effect), and that the errors ($e_{ij}$) have a mean of zero and common variance. Once the basic form of this model was developed, a backward elimination method was implemented to investigate the fixed main effects of region, spring precipitation, ecotype, growing season, number of annual harvests, and harvest timing, and interaction effects of region x spring precipitation, ecotype x spring precipitation, growing season x spring precipitation, linear N rate x ecotype, quadratic N rate x ecotype and region x
harvest timing. Backward stepwise searches are recommended over forward stepwise searches when the number of potential predictor variables is relatively small as is the case here and allows each potential predictor variable to be considered under the premise that it has been adjusted for all other potential predictor variables (Kutner et al., 2004). In the first step each of the variable and interactions listed above were simultaneously investigated. The following non-significant terms were then removed if their p-values were greater than $\alpha = 0.1$: number of annual harvests ($P = 0.6591$), region x spring precipitation ($P = 0.1951$), and quadratic N rate x ecotype ($P = 0.6411$), and growing season x ecotype ($P = 0.6429$). The next step involved reanalyzing those variables that were significant in step one less the non-significant variables in step one. No further terms were eliminated, and based upon these results a final model was established (Table 2.5) from which model predictions were calculated. Other suspected interactions (e.g. region x ecotype) were not included in the analysis because when investigated, resulted in model singularity, due to the elimination of the lowland ecotype from the NR. Statistical analysis was performed using a linear mixed-effect model in the ‘nlme’ v.3.1-97 package of R statistical software (R Core, v. 2.12.1, 2010). Residuals were examined for normality and the assumption of common variance by inspection of normal quantile and residual plots. Individual site predictions based upon the final model were plotted to show visual agreement between observed yield and model predictions (Fig. 2.3). Several unusually high mean biomass yields were deemed outliers, when visually assessing the residual plots. These values were not removed from the analysis because they did not modify the results of the model (Table 2.5), when the model was rerun without them. Furthermore, they may represent the potential of the switchgrass crop or potential sampling error, and were retained in the model. The critical rate of N fertilizer required to achieve maximum dry biomass yield (Max N) and ex post economic optimum N rates
were calculated only for sites which reported biomass yields across at least four N rates and this included 14 sites. Coefficients were extracted from eq. 1, and do not reflect the fixed main effects or investigated interactions shown in Table 2.5 other than the linear N rate and quadratic N rate effects. The critical rate of N fertilizer (Max N) required to achieve maximum biomass yield was calculated using the following equation:

\[
Max \, N_i = -\frac{a_i}{2\beta}
\]  

[eq. 2]

Where \(Max \, N_i\) depends on the \(i^{th}\) site and \(a_i\) is the random linear N rate coefficient from eq. 1, and \(\beta\) is the fixed quadratic coefficient from eq. 1. Based upon the price of Mar. urea (46% N) from 2006 to 2011 (USDA/ERS, 2011), three prices of urea ($362 ton\(^{-1}\) ($328.3 Mg\(^{-1}\)), $448 ton\(^{-1}\) ($406.3 Mg\(^{-1}\)), and $552 ton\(^{-1}\) ($500.6 Mg\(^{-1}\)) and respective unit prices of a kg of N ($0.87 kg\(^{-1}\) N, $1.07 kg\(^{-1}\) N, and 1.32 kg\(^{-1}\) N), economical optimum N rates (EONR) were calculated by considering three theoretical prices of a Mg of dry biomass: $35 Mg\(^{-1}\), $50 Mg\(^{-1}\), and $65 Mg\(^{-1}\) (Table 2.6). These EONR were calculated ex post (after the fact) using the following equation:

\[
EONR = \frac{(w)}{2 \beta} - a
\]  

[eq. 3]

where \(w\) is the cost of N fertilizer ($ kg\(^{-1}\)), \(p\) is the price of dry biomass ($ Mg\(^{-1}\)), \(a_i\) is the random linear N rate coefficient from eq. 1, and \(\beta\) is the fixed quadratic coefficient from eq. 1.

**RESULTS AND DISCUSSION**

**Preliminary Results**

Mean biomass yields (± SEM) across all regions and both ecotypes were the lowest in growing season 1 (6.6 ± 3 Mg ha\(^{-1}\)), which increased to 9.1 ± 5.5 Mg ha\(^{-1}\) in growing season 2 and 10.9 ± 5.2 Mg ha\(^{-1}\) in growing seasons >=3. This is in agreement with the literature, which reports that the necessary time for switchgrass to achieve full productivity varies, but is generally
three years (Parrish and Fike, 2005; Heaton et al., 2004; Schmer et al., 2010), although switchgrass stands may become fully or near-fully productive during their second season (Grassini et al., 2009; Schmer et al., 2010). Factors that influence establishment, including seed quality, seedbed preparation, planting date, planting rate, and planting depth, can effect the time needed to reach full productivity (Masters et al., 2004). Moreover, low stand densities achieved during growing season 1 tended to result in lower biomass yields in growing season 2 than those having higher stand densities (Schmer et al., 2006).

Overall, the lowland ecotype produced greater yields than the upland ecotype. In growing season 2, ecotype mean biomass yields (± SEM) were greater for the lowland ecotype (11.1 ± 6.1 Mg ha\(^{-1}\)) than for the upland ecotype (6.7± 3.2 Mg ha\(^{-1}\)). Similarly, in growing seasons >=3, ecotype mean biomass yields (± SEM) were greater for the lowland ecotype (12.6 ± 5.4 Mg ha\(^{-1}\)) than for the upland ecotype (9.3 ± 4.3 Mg ha\(^{-1}\)).

Switchgrass yields were the greatest when grown in the two central regions (Fig. 2.2) with mean biomass yields (± SEM) averaged across growing season 2 and growing seasons >=3 the greatest in the LCR (13.4 ± 4.5) and UCR (10.1 ± 4.3) when compared to the SR (9.3 ± 5.7) and NR (7.3 ± 3.1). Mean biomass yield values for the different regions were highly variable with large ranges: NR (1.1 to 14.5 Mg ha\(^{-1}\)), UCR (2.5 to 26 Mg ha\(^{-1}\)), LCR (4.6 to 33.4 Mg ha\(^{-1}\)), and SR (0 to 30.4 Mg ha\(^{-1}\)). Mean biomass yields of zero in the SR came from Cassida et al. (2005) which reported negligible yields at or near zero in LA in which stand densities of the upland ecotype had declined to zero or near zero after two years of production resulting in biomass yields equal to 0 Mg ha\(^{-1}\). In the NR, mean yields were less variable than in the other regions and the greatest mean yields in this region, reaching yields greater than 13 Mg ha\(^{-1}\) were
achieved in SD, WI, and Montreal, QC (Boe, 2007; Casler and Boe, 2003; Madakadze et al., 1998b).

Although mean biomass yields among the four regions were quite variable (Fig. 2.2), the lowland ecotype produced greater yields than the upland ecotype, especially in the LCR, where mean yields greater than 20 Mg ha\(^{-1}\) were achieved by lowland cultivars Alamo and Kanlow in TN, VA, and OK (Fike et al., 2006a; Fike et al., 2006b; Thomason et al., 2004). In the UCR, there were relatively few lowland mean biomass values, although lowland yields reached greater than 14.5 Mg ha\(^{-1}\) (Vogel and Mitchell, 2008) and up to 21 Mg ha\(^{-1}\) (Casler et al., 2004) in Mead, NE.

Mean, SEM, and median calculations of individual cultivars indicate that biomass yields were greatly impacted by the region in which they were grown (Table 2.4). For example, Cave-in-Rock (Table 2.2) is a commonly planted cultivar that has been evaluated in experiments in each of the regions described in this analysis. Cave-in-Rock mean yields, while quite variable, were greatest when grown in the two central regions (UCR and LCR), achieving mean yields (± SEM) of 11.2 ± 5.3 in the UCR and 12.5 ± 3.9 in the LCR for growing seasons >=3 (Table 2.4). However when grown in the NR or SR (both distant from its origin), its mean yields decreased, dropping to 4.4 ± 3 in the SR and 8.5 ± 5 in the NR (Table 2.4).

**Ecotype, Region, and Growing Season**

The effects of region, ecotype, and growing season were each significant (Table 2.5). The significant effect of growing season is related to the time it takes for switchgrass to reach full productivity (maximum biomass yields), while the effect of ecotype appears to be dependent on region and the cultivar or ecotype being produced. Due to this we suspected that an ecotype x season interaction was also significant. However, when the ecotype x season interaction was
included in the model it resulted in model singularity (an indication of the unbalanced nature of the data and potential model over parameterization), so we were unable to estimate its effect.

Overall, the lowland ecotype had significantly greater biomass yields than the upland ecotype ($P < .0001$) (Table 2.5).

The overall higher biomass yields of the lowland ecotype compared to the upland ecotype likely has to do with the morphological differences between the two. Compared to the upland ecotype, the lowland ecotype is adapted to longer growing seasons with reduced photoperiod and lowland cultivars generally produce taller plants with thicker leaves and stems, have fewer tillers with greater tiller diameter, and generally have more of a ‘bunch form’ growth pattern as opposed to a ‘sod formation’ growth pattern (Parrish and Fike, 2005; Cassida et al., 2005).

Although not observed in this study, variation in the morphology of switchgrass and the impact of environment has tended to produce an ecotype x environment interaction in experimental studies (Boe and Casler, 2005; Cassida et al., 2005; Casler and Boe, 2003; Casler, 2005).

Moving cultivars south of their origin hastens reproductive development and the end of vegetative growth, while moving populations north of their origin can prolong vegetative growth (Parrish and Fike, 2005; Vogel, 2004). This potentially increases biomass yields, but Casler et al. (2007) indicated that movement of switchgrass populations north or south of their origin should be limited to no more than one USDA plant hardiness zone due to risk of winter kill.

Two switchgrass cultivars, Cave-in-Rock, originating from ~38° N in Southern IL and OK-NU-2 originating from 35° N latitude in Oklahoma, grown in Mandan, ND (46°48’ N) were severely affected by the northern movement from their origin (Berdahl et al., 2005). In the span of 4 years their survival percentages decreased from near 100\% to 20 or 30\%. Other studies have also evaluated switchgrass cultivars in regions where adaptation is unlikely, resulting in large
yield variation, and often low yields. For example, a TX study evaluated several cultivars, including Alamo (a cultivar adapted to Texas) and Summer (a cultivar originating in the northern Great Plains) (Sanderson et al., 1999b). Summer is not well suited to biomass production in TX producing dry yields as low as 1.75 Mg ha$^{-1}$, while Alamo produced 17.59 Mg ha$^{-1}$ in the same study.

**Spring Precipitation**

The spring precipitation x growing season, spring precipitation x ecotype, and precipitation effects were all significant (Table 2.5). The lowland ecotype generally produced greater yields than the upland ecotype under similar spring precipitation levels (Fig. 2.4). This can be partially explained by the adaptation differences of the different ecotypes. Cultivars within the lowland ecotype are best adapted to more southern latitudes and lower wetter areas, while cultivars within the upland ecotype are better suited to more northern latitudes and mesic environments with moderate soil moisture conditions. Because cultivars within the upland ecotype are generally more adapted to drier environments, they are typically less sensitive to dry conditions than cultivars within the lowland ecotype (Vogel, 2004; Parrish and Fike, 2005; Porter, 1966).

As the crop matures from growing season 1 to growing seasons $\geq 3$, similar precipitation levels result in higher biomass yields. Precipitation has limited switchgrass growth in the Northern Great Plains where annual levels have been as low as 193 mm (Lee and Boe, 2005), and in droughty TX conditions where stand loss has been threatened (Cassida et al., 2005). Total annual precipitation is probably not as important as the timing and number of the precipitation occurrences (Wullschleger et al., 2010). Fike et al. (2006b) showed that biomass yields are
strongly influenced by early season rainfall, while Lee and Boe (2005) reported that early season
(April-May) rainfall is a good predictor of biomass yield.

**Nitrogen Response**

The biomass yield response to applied N was quite variable (Fig. 2.3 and Table 2.5) and consequently the linear N rate x ecotype, linear N rate, and quadratic N rate effects were all significant (Table 2.5). When predictions were made on a regional level (Fig. 2.5), the predicted N response curves for lowland and upland ecotypes were slightly different, with a steeper linear component for the lowland ecotype than the upland ecotypes. This is likely because of the greater number of high mean biomass yields at N rates greater than 100 kg ha\(^{-1}\) for the lowland ecotype in the SR and LCR compared to the upland ecotype, which caused the linear relationship between biomass yield and N rate to be slightly more positive (Fig. 2.5). In Fig.’s 2.5 and 2.6, several mean values stand out in the SR and LCR with particularly high biomass yields (>= 28 Mg ha\(^{-1}\)). These mean values (33.4, 29.5, 28.6, 30.4, and 29.4) come from studies with reported biomass yields reaching up to 36.7, 34.06, and 39.5 Mg ha\(^{-1}\) respectively from Thomason et al. (2004), Sladden et al. (1991), and Kiniry et al. (1999). These data represent N rates ranging from 0 to 224 kg N ha\(^{-1}\), 2 and >=3 growing seasons, 1 or 2 annual harvests, different final harvest timing, and were for lowland cultivars, Kanlow and Alamo. These high yield values data do not appear to be associated with any particular management factor other than being from two high-yielding lowland cultivars, and were not necessarily associated with higher N application rates, although they do represent the high biomass yield potential of switchgrass.

Optimal N rates and associated fertilizer recommendations have varied greatly in the literature and maximum yields have been achieved at a wide range of N rates. Most observed maximum biomass yield have been achieved at rates between 112 and 270 kg N ha\(^{-1}\) (Haque et
al., 2009; Heggenstaller et al., 2009; Vogel et al., 2002; Lemus et al., 2008a; Lemus et al., 2008b; Muir et al., 2001; Mooney et al., 2009; Mulkey et al., 2006), although maximum biomass yields have been achieved at lower rates (67 kg N ha$^{-1}$) (Mooney et al., 2009) and much higher rates (448 kg N ha$^{-1}$ and greater) (Thomason et al., 2004; Sanderson et al., 2001). Recommended or optimum N rates have ranged between 56 and 168 kg N ha$^{-1}$ (Haque et al., 2009; Heggenstaller et al., 2009; Vogel et al., 2002; Lemus et al., 2008b; Muir et al., 2001; Mulkey et al., 2006), while the most-efficient N rates, in terms of N use (calculated as the percentage of N removed from the crop) have ranged between 56 an and 112 kg N ha$^{-1}$ (Lemus et al., 2008a; Lemus et al., 2008b; Muir et al., 2001). As the literature suggests, achieving maximum biomass yields may not be the best way to optimize fertilizer application, and in many cases, biomass yields slightly lower than the maximum can be achieved from much lower N rates. This further implies that the EONR is generally lower than the N rate required to achieve maximum biomass.

Even though general response curves were generated from the results of this analysis for a specific set of management practices and spring precipitation levels (Fig. 2.5), it must be noted that it is difficult to make any general or even regional recommendation regarding an optimal N rate for switchgrass, due the random variation from site-to-site which was high (Fig. 2.3) and a 95% confidence interval for the linear N rate coefficients was 0.019 to 0.055. Nitrogen-application decisions are best made by considering individual site conditions, and individual site predictions may provide some useful information for making these decisions (Fig. 2.3). In most cases the sites exhibited good agreement between observed values and predicted N response (Fig. 2.3). Due to the nature of the quadratic model, it has been shown to predict a decline in crop yield with increasing levels of N fertilizer beyond Max N (Bullock and Bullock, 1994a). These yield decreases are often associated with excessive amounts of N application that cause
problems such as lodging. The N application range for this study was constrained to a range of 0 to 300 kg N ha\(^{-1}\) and at most sites higher N rates did not result in observed or predicted biomass decreases (Fig. 2.3). There were 14 sites in the statistical analysis that reported biomass yields across at least four N rates. These sites were 31a, 32a, 32b, 60a, 64a, 65a 65c, 65f, 65g, 65h, 65i, 65j, 69a, and 73a, and come from several studies (Vogel et al., 2002; Muir et al., 2001; Mooney et al., 2001; Sanderson et al., 2001; Schmer et al., 2010; Haque et al., 2009; Heggenstaller et al., 2009) (Table 2.3 and Fig. 2.3). Specifically, sites 31a (Vogel et al., 2001) and 73a (Heggenstaller et al., 2009), showed a reliable fit to the data (Fig. 2.3) with maximum biomass yields being achieved at 259 kg N ha\(^{-1}\) and 260 kg N ha\(^{-1}\), respectively (Table 2.6). Max N for these sites were calculated by setting the first derivative of the quadratic function equal to zero and solving for N rate. At some of these sites predicted Max N was beyond the highest level of actual N applied in the studies. Due to this the observed maximum yields reported in the studies were sometimes lower than Max N predicted in this analysis. For example, in a two-year study in Boone County, IA (site 73a), maximum observed biomass yields were achieved at the highest N rate applied in the study (220 kg N ha\(^{-1}\)), while Max N calculated in this analysis was at 260 kg N ha\(^{-1}\) (Fig. 2.3 and Table 2.6). It is likely that if higher N rates had been applied in this study, higher observed maximum yields would also have been observed. In 13 out of these 14 sites, the N rate (Max N) required to achieve maximum biomass ranged from 214 kg N ha\(^{-1}\) to 287 kg N ha\(^{-1}\), with the exception of site 32a at 413 kg N ha\(^{-1}\) (Table 2.6). Economical optimum N rates, calculated ex post (after the fact) (Bullock and Bullock, 1994b) for these 14 sites showed a wide range of values, depending on the N rate price and dry biomass price ratio (Table 2.6). As this ratio decreased, or as N rate prices decreased and the price of dry biomass increased, EONR increased.
Harvest Timing

Even though the number of annual harvests was not significant in the modeling process, it should not be concluded that this is of little importance. Harvest frequency can have a major impact on N use and removal, and is likely best considered in combination with harvest timing. Harvest timing and its associated region x harvest timing interaction were both significant (Table 2.5). Results of the region x harvest timing interaction are variable, especially in the LCR and UCR (Fig. 2.6). However, in the SR, PSC harvests tended to result in greater biomass yields than harvests at ES, but this was not the case in the NR. In fact, the opposite occurred in the NR, with ES harvests yielding greater than PSC harvests. In the SR, a longer growing season and mild winter temperatures are likely to create an environment in which PSC harvests will not pose a significant threat to the survival of the crop as long as increased N removal at early harvests are balanced with N fertilization. In the north, PSC harvests are more likely to injure the switchgrass stands likely because harvesting early at PSC removes carbohydrates needed for winter survival that would have been allocated below ground to the rhizome biomass had the crop been harvested later at ES (Mulkey et al., 2006; Smith and Nelson, 1985). This is consistent with recommended harvest practices. Harvesting switchgrass once at ES or after a killing frost is the recommended harvest practice (Parrish and Fike, 2005) unless higher levels of fertilizer, especially N, are applied to compensate for greater nutrient removal, since harvesting twice per year removes greater amounts of N than a single annual harvest (Fike et al., 2006a; Lemus et al., 2009; Lemus et al., 2008b). Harvesting at ES allows the switchgrass plants to prepare for winter by remobilizing carbohydrates and nutrients to the rhizomes, thus preparing the plant to survive the winter, and increasing the N recycling process. This is probably most important in northern environments where inadequate levels of carbohydrates may result in poor winter hardiness.
Harvesting early at PSC or multiple times per year can result in decreased stand longevity and lowered biomass yields (Casler and Boe, 2003; Monti et al., 2008; Sanderson et al., 1999a), unless N recommendations are made to account for N removal rates associated with these practices (Parrish and Fike, 2005).

CONCLUSIONS

As the literature suggests, and this analysis confirms, switchgrass yields are highly variable, being influenced greatly by multiple factors. In this analysis, we found that the region, spring precipitation (April through June), growing season, ecotype, harvest timing, and annual N application rate were factors that significantly affected yields. In addition, we found that biomass yields can also depend on multiple environment and management factors. Switchgrass grown in the LCR and UCR tended to produce greater biomass yields than switchgrass grown in the NR and SR. The lowland ecotype tended to yield better than the upland ecotype, but this depended on the region. Spring precipitation had a positive effect on biomass yield and switchgrass biomass yields had a quadratic response to N application that was similar from site-to-site, but vary in its intercept and linear components. As large-scale production of switchgrass commences, it becomes necessary for stakeholders and producers to have a solid understanding of the effects these factors can have on biomass yields, especially when selecting the most appropriate ecotype or cultivar for a specific region and then basing N application rates on site conditions, local recommendations, and implemented harvest practices.

Acknowledgements

The authors acknowledge Bhupinder Farmaha for his aide in creating Fig. 2.1.
REFERENCES


31


**Table 2.1.** List of publications on switchgrass covering several important and highly studied agronomic topics.

<table>
<thead>
<tr>
<th>Cultivar and ecotype adaptation/evaluation</th>
<th>Harvest management$^\dagger$</th>
<th>Nitrogen and fertilizer response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alexopoulou et al., 2008</td>
<td>Monti et al., 2008</td>
<td>Boehmel et al., 2008</td>
</tr>
<tr>
<td>Berdahl., et al., 2005</td>
<td>Adler et al., 2006</td>
<td>Christian et al., 2002</td>
</tr>
<tr>
<td>Boe and Lee, 2007</td>
<td>Fike et al., 2006a</td>
<td>Haque et al., 2009</td>
</tr>
<tr>
<td>Boe, 2007</td>
<td>Fike et al., 2006b</td>
<td>Heggenstaller et al., 2009</td>
</tr>
<tr>
<td>Casler and Boe, 2003</td>
<td>Haque et al., 2009</td>
<td>Lee et al., 2007</td>
</tr>
<tr>
<td>Casler et al., 2004</td>
<td>Heaton et al., 2008</td>
<td>Lee et al., 2009</td>
</tr>
<tr>
<td>Casler et al., 2007</td>
<td>Hopkins et al., 1995</td>
<td>Lemus et al., 2008a</td>
</tr>
<tr>
<td>Casler, 2005</td>
<td>Lee and Boe, 2005</td>
<td>Lemus et al., 2008b</td>
</tr>
<tr>
<td>Cassida et al., 2005</td>
<td>Lee et al., 2007</td>
<td>Ma et al., 2001</td>
</tr>
<tr>
<td>Christian et al., 2002</td>
<td>Lee et al., 2009</td>
<td>Madakadze et al., 1999a</td>
</tr>
<tr>
<td>Christian, 1994</td>
<td>Lemus et al., 2008b</td>
<td>Mooney et al., 2009</td>
</tr>
<tr>
<td>Fike et al., 2006a</td>
<td>Lemus et al., 2009</td>
<td>Muir et al., 2001</td>
</tr>
<tr>
<td>Fike et al., 2006b</td>
<td>Ma et al., 2001</td>
<td>Piscioneri et al., 2001</td>
</tr>
<tr>
<td>Fuentes and Taliaferro, 2002</td>
<td>Madakadze et al., 1999a</td>
<td>Sanderson and Reed, 2000</td>
</tr>
<tr>
<td>Garten Jr et al., 2010</td>
<td>Madakadze et al., 1999b</td>
<td>Sanderson et al., 2001</td>
</tr>
<tr>
<td>Hopkins et al., 1995</td>
<td>Reynolds et al., 2000</td>
<td>Shinners et al., 2010</td>
</tr>
<tr>
<td>Lee and Boe, 2005</td>
<td>Sanderson et al., 1999a</td>
<td>Staley et al., 1991</td>
</tr>
<tr>
<td>Lemus et al., 2002</td>
<td>Sanderson et al., 2004</td>
<td>Stout, 1992</td>
</tr>
<tr>
<td>Madakadze et al., 1998a</td>
<td>Sladden et al., 1991</td>
<td>Thomason et al., 2004</td>
</tr>
<tr>
<td>Madakadze et al., 1998b</td>
<td>Staley et al., 1991</td>
<td>Vogel and Masters, 1998</td>
</tr>
<tr>
<td>Madakadze et al., 1998c</td>
<td>Stork et al., 2009</td>
<td>Vogel et al., 2002</td>
</tr>
<tr>
<td>Madakadze et al., 1999a</td>
<td>Thomason et al., 2004</td>
<td>Vogel and Masters, 1998</td>
</tr>
<tr>
<td>Madakadze et al., 1999b</td>
<td>Vogel and Masters, 1998</td>
<td></td>
</tr>
<tr>
<td>Piscioneri et al., 2001</td>
<td>Vogel et al., 2002</td>
<td></td>
</tr>
<tr>
<td>Sanderson et al., 1999b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sharma et al., 2003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sladden et al., 1991</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stork et al., 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vogel and Masters, 1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vogel and Mitchell, 2008</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^\dagger$ This is an incomplete list of publications on these topics.

$^\ddagger$ Harvest management encompasses harvest timing (i.e. peak biomass, after killing frost, etc…) and multiple harvests per year.
Table 2.2. Names of 41 different switchgrass cultivars, varieties, experimental lines, and synthetic lines (each referred to as cultivars) used in analysis, their ecotype, upland (U) or lowland (L), and their latitude or location of origin.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Ecotype</th>
<th>Latitude/Location of origin</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamo</td>
<td>L</td>
<td>near George West, TX (Southern Texas)</td>
<td>Cassida et al., 2005; Alderson and Sharp, 1995; Sanderson et al., 1999b</td>
</tr>
<tr>
<td>Blackwell</td>
<td>U</td>
<td>36°N, Northern Oklahoma; Blackwell, OK</td>
<td>Hopkins et al., 1995; Casler et al., 2004; Alderson and Sharp, 1995; Sanderson et al., 1999b</td>
</tr>
<tr>
<td>Caddo</td>
<td>U</td>
<td>Stillwater, OK</td>
<td>Cassida et al., 2005; Sanderson et al., 1999b</td>
</tr>
<tr>
<td>Cave-in-Rock</td>
<td>U</td>
<td>38°28'N, Near Cave-In-Rock, IL (Southern Illinois)</td>
<td>Berdahl et al., 2005; Casler et al., 2004; Alderson and Sharp, 1995</td>
</tr>
<tr>
<td>Cave-in-Rock high yield-DMD C1 (CIR HY DDM C1)</td>
<td>U</td>
<td></td>
<td>Hopkines et al., 1995</td>
</tr>
<tr>
<td>Dacotah</td>
<td>U</td>
<td>46°30'N, Near Breien, North Dakota</td>
<td>Boe and Casler, 2005; Alderson and Sharp, 1995; Berdahl et al., 2005</td>
</tr>
<tr>
<td>Dakota</td>
<td>U</td>
<td>47°N, North Dakota</td>
<td>Madakadze et al., 1998b</td>
</tr>
<tr>
<td>EY x FF LDMDC1</td>
<td>U</td>
<td>same base population as Trailblazer</td>
<td>Redfearn et al., 1997</td>
</tr>
<tr>
<td>EY x FF LDMDC3</td>
<td>U</td>
<td>same base population as Trailblazer</td>
<td>Redfearn et al., 1997</td>
</tr>
<tr>
<td>Ey x FF high yield C3</td>
<td>U</td>
<td></td>
<td>Hopkines et al., 1995</td>
</tr>
<tr>
<td>Ey x FF low IVDMD C1</td>
<td>U</td>
<td></td>
<td>Hopkines et al., 1995</td>
</tr>
<tr>
<td>Forestburg</td>
<td>U</td>
<td>44°N, Forestburg, South Dakota</td>
<td>Madakadze et al., 1998b; Casler et al., 2004; Alderson and Sharp, 1995; Christian et al., 2002</td>
</tr>
<tr>
<td>GA992 and GA993</td>
<td>L</td>
<td>Derived from Kanlow and Alamo, respectively</td>
<td>Garten Jr. et al., 2010</td>
</tr>
<tr>
<td>Kanlow</td>
<td>L</td>
<td>35°N, Central Oklahoma (Wetumka, OK)</td>
<td>Hopkines et al., 1995; Casler et al., 2004; Alderson and Sharp, 1995; Sanderson et al., 1999b</td>
</tr>
<tr>
<td>Kanlow N1</td>
<td>L</td>
<td></td>
<td>Vogel and Mitchell, 2008</td>
</tr>
<tr>
<td>Kansas Native</td>
<td>U</td>
<td></td>
<td>Sladden, 1991</td>
</tr>
<tr>
<td>KYPV 9504</td>
<td>U</td>
<td>West Virginia</td>
<td>Stork et al., 2009</td>
</tr>
<tr>
<td>KYPV 9505</td>
<td>U</td>
<td>West Virginia</td>
<td>Stork et al., 2009</td>
</tr>
<tr>
<td>KYPV 9506</td>
<td>U</td>
<td>West Virginia</td>
<td>Stork et al., 2009</td>
</tr>
<tr>
<td>late synthetic</td>
<td>U</td>
<td>Experimental breeding line from Nebraska</td>
<td>Sanderson et al., 1999b</td>
</tr>
<tr>
<td>Late synthetic high yield (Late syn HY)</td>
<td>U</td>
<td></td>
<td>Fuentes and Taliaferro, 2002</td>
</tr>
<tr>
<td>Late syn high yield C3 (Late syn HY C3)</td>
<td>U</td>
<td></td>
<td>Hopkines et al., 1995</td>
</tr>
<tr>
<td>Late syn high yield-DMD C2 (Late syn HY DMD C2)</td>
<td>U</td>
<td></td>
<td>Hopkines et al., 1995</td>
</tr>
<tr>
<td>Cultivar</td>
<td>Ecotype</td>
<td>Latitude/Location of origin</td>
<td>Reference(s)</td>
</tr>
<tr>
<td>----------------</td>
<td>---------</td>
<td>-----------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>NCSU-1</td>
<td>L</td>
<td></td>
<td>Sanderson et al., 1999b</td>
</tr>
<tr>
<td>NCSU-2</td>
<td>L</td>
<td></td>
<td>Sanderson et al., 1999b</td>
</tr>
<tr>
<td>ND3743</td>
<td>U</td>
<td>49°N, Near Upham, ND</td>
<td>Berdahl et al., 2005; Madakadze et al., 1998b</td>
</tr>
<tr>
<td>Nebraska 28</td>
<td>U</td>
<td>42°N, Holt Co, NE</td>
<td>Alderson and Sharp, 1995</td>
</tr>
<tr>
<td>NJ50/Carthage</td>
<td>L</td>
<td>North Carolina</td>
<td>Madakadze et al., 1998b</td>
</tr>
<tr>
<td>NL 94-2, NL 93-1</td>
<td>L</td>
<td>Synthetic lines from OK and southern KS</td>
<td>Cassida et al., 2005</td>
</tr>
<tr>
<td>NU 94-2</td>
<td>U</td>
<td>Synthetic line from OK and southern KS</td>
<td>Cassida et al., 2005</td>
</tr>
<tr>
<td>OK NU-2</td>
<td>U</td>
<td>35°N, Oklahoma Agric. Exp. Stn.</td>
<td>Berdahl et al., 2005</td>
</tr>
<tr>
<td>Pathfinder</td>
<td>U</td>
<td>Nebraska and Kansas</td>
<td>Hopkins et al., 1995; Alderson and Sharp, 1995; Madakadze et al., 1998b</td>
</tr>
<tr>
<td>Pathfinder HYDMDC2</td>
<td>U</td>
<td>experimental line from Pathfinder</td>
<td>Redfearn et al., 1997</td>
</tr>
<tr>
<td>PMT-279</td>
<td>L</td>
<td>Collected in south Texas</td>
<td>Sanderson et al., 1999b</td>
</tr>
<tr>
<td>PMT-785</td>
<td>L</td>
<td>Collected in south Texas</td>
<td>Sanderson et al., 1999b</td>
</tr>
<tr>
<td>Shawnee</td>
<td>U</td>
<td>Southeastern Illinois, selected from Cave in Rock</td>
<td>Boe and Casler, 2005; Berdahl et al., 2005</td>
</tr>
<tr>
<td>Shelter</td>
<td>U</td>
<td>39°N, Near St. Mary’s, West Virginia</td>
<td>Madakadze et al., 1998b; Casler et al., 2004; Alderson and Sharp, 1995;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sanderson et al., 1999b</td>
</tr>
<tr>
<td>SL 93-1, SL 93-2, SL 93-1</td>
<td>L</td>
<td>Synthetic lines from central and southern TX</td>
<td>Cassida et al., 2005</td>
</tr>
<tr>
<td>SU 94-2</td>
<td>U</td>
<td>Synthetic line from central and southern TX</td>
<td>Cassida et al., 2005</td>
</tr>
<tr>
<td>Summer</td>
<td>U</td>
<td>40°40’N, south of Nebraska City, NE</td>
<td>Gunter et al., 1996; Casler et al., 2004; Alderson and Sharp, 1995; Berdahl</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>et al., 2005</td>
</tr>
<tr>
<td>Sunburst</td>
<td>U</td>
<td>43°N to 42°.40’N, Union County, South Dakota</td>
<td>Berdahl et al., 2005; Madakadze et al., 1998b; Casler et al., 2004</td>
</tr>
<tr>
<td>Trailblazer</td>
<td>U</td>
<td>43°N to 37°N, Nebraska and Kansas collections</td>
<td>Berdahl et al., 2005; Vogel et al., 1991; Casler et al., 2004; Alderson and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sharp, 1995</td>
</tr>
<tr>
<td>WS-SB</td>
<td>U</td>
<td>Sterling Barrens State National Area, WI</td>
<td>Casler et al., 2007</td>
</tr>
<tr>
<td>WS-IP</td>
<td>U</td>
<td>Ipswitch Prairie State Natural Area, WI</td>
<td>Casler et al., 2007</td>
</tr>
</tbody>
</table>
Table 2.3. Publications from the database included in the analysis, their Country, Experiment number, site number(s) and location(s), and their Region of classification (North, Upper Central, Lower Central, and South). For each region, information is sorted by site.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Country</th>
<th>Experiment</th>
<th>Site number(s) and locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>For each region, information is sorted by site.</td>
<td>North</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boe, 2007</td>
<td>USA</td>
<td>07</td>
<td>07a – South Shore, SD</td>
</tr>
<tr>
<td>Boe and Lee, 2007</td>
<td>USA</td>
<td>08</td>
<td>08a – Aurora, SD</td>
</tr>
<tr>
<td>Berdahl et al., 2005</td>
<td>USA</td>
<td>09</td>
<td>09a – Mandan 1, ND, 09b – Mandan 2, ND, 09c – Dickinson, ND</td>
</tr>
<tr>
<td>Lee and Boe, 2005</td>
<td>USA</td>
<td>15</td>
<td>15a – Dakota Lakes 1, 15b – Dakota Lakes 2, SD</td>
</tr>
<tr>
<td>Boe and Casler, 2005</td>
<td>USA</td>
<td>19, 20</td>
<td>19a – Bristol, SD, 19b – South Shore, SD, 20a – Pierre, SD</td>
</tr>
<tr>
<td>Casler et al., 2004</td>
<td>USA</td>
<td>23</td>
<td>23a – Spooner, WI, 23b – Arlington, WI</td>
</tr>
<tr>
<td>Casler and Boe, 2003</td>
<td>USA</td>
<td>25</td>
<td>25a – Brookings, SD, 25b – Arlington, WI</td>
</tr>
<tr>
<td>Madakadze et al., 1998c</td>
<td>Canada</td>
<td>37</td>
<td>37a – Montreal, QC</td>
</tr>
<tr>
<td>Madakadze et al., 1999a</td>
<td>Canada</td>
<td>43</td>
<td>43a – Montreal, QC</td>
</tr>
<tr>
<td>Madakadze et al., 1998b</td>
<td>Canada</td>
<td>45</td>
<td>45a – Montreal, QC</td>
</tr>
<tr>
<td>Madakadze et al., 1999b</td>
<td>Canada</td>
<td>49</td>
<td>49a – Montreal, QC</td>
</tr>
<tr>
<td>Schmer et al., 2010</td>
<td>USA</td>
<td>65</td>
<td>65a – Munich, ND, 65b – Streeter, ND, 65c – Bristol, SD, 65d – Highmore, SD, 65e – Huron, SD, 65f – Ethan, SD, 65g – Crofton, NE, 65h – Atkinson, NE, 65i – Custer, SD, 65j – Wayne County, IA</td>
</tr>
<tr>
<td>Casler et al., 2007</td>
<td>USA</td>
<td>68</td>
<td>68a – Spooner, WI, 68b – Mandan, ND, Rosemont, MN, Marshfield, Lancaster, &amp; Arlington, WI</td>
</tr>
<tr>
<td>Shinneres et al., 2010</td>
<td>USA</td>
<td>74</td>
<td>74a – Arlington, WI</td>
</tr>
<tr>
<td>Adler et al., 2006</td>
<td>USA</td>
<td>11</td>
<td>11b – Logan, PA</td>
</tr>
<tr>
<td>Casler et al., 2004</td>
<td>USA</td>
<td>23</td>
<td>23c – Mead, NE, 23d – Manhattan, KS</td>
</tr>
<tr>
<td>Vogel et al., 2002</td>
<td>USA</td>
<td>31</td>
<td>31a – Ames, IA</td>
</tr>
<tr>
<td>Heaton et al., 2008</td>
<td>USA</td>
<td>44</td>
<td>44a – Shubbona, IL, 44b – Urbana, IL</td>
</tr>
<tr>
<td>Hopkins et al., 1995</td>
<td>USA</td>
<td>46</td>
<td>46a – Mead, NE, 46b – Ames, IA, 46c – West Lafayette, IN</td>
</tr>
<tr>
<td>Vogel and Mitchell, 2008</td>
<td>USA</td>
<td>48</td>
<td>48a – Mead, NE</td>
</tr>
<tr>
<td>Staley et al., 1991</td>
<td>USA</td>
<td>58</td>
<td>58a – northern Appalachian ridge and valley province 1, PA, 58b – northern Appalachian ridge and valley province 2, PA, 58c – northern Appalachian ridge and valley province 3, PA</td>
</tr>
<tr>
<td>Cuomo et al., 1996</td>
<td>USA</td>
<td>59</td>
<td>59a – Mead, NE</td>
</tr>
<tr>
<td>Redfearn et al., 1997</td>
<td>USA</td>
<td>61</td>
<td>61a – Ames, IA, 61b – Mead, NE</td>
</tr>
<tr>
<td>Lemus et al., 2008a</td>
<td>USA</td>
<td>63</td>
<td>63a – Lucas County, IA, 63b – Wayne County, IA</td>
</tr>
<tr>
<td>Schmer et al., 2010</td>
<td>USA</td>
<td>65</td>
<td>65i – Douglas, NE, 65j – Lawrence, NE</td>
</tr>
<tr>
<td>Casler et al., 2007</td>
<td>USA</td>
<td>68</td>
<td>68c – Mead, NE, Ames, IA, Columbia, MO, Dekalb, IL</td>
</tr>
<tr>
<td>Propheter and Staggenborg, 2010</td>
<td>USA</td>
<td>71</td>
<td>71a – Troy, KS, 71b – Manhattan, KS</td>
</tr>
<tr>
<td>Heggenstaller et al., 2010</td>
<td>USA</td>
<td>73</td>
<td>73a – Boone County, IA</td>
</tr>
<tr>
<td>For each region, information is sorted by site.</td>
<td>Lower Central</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adler et al., 2006</td>
<td>USA</td>
<td>11</td>
<td>11a – Rock springs, PA</td>
</tr>
<tr>
<td>Fike et al., 2006b</td>
<td>USA</td>
<td>13</td>
<td>13a – Princeton, KY, 13b – Raleigh, NC, 13c – Jackson, TN, 13d – Knoxville, TN, 13e – Blacksburg A, VA, 13f – Blacksburg B, VA, 13g – Orange, VA, 13h – Morgantown, WV</td>
</tr>
<tr>
<td>Fike et al., 2006a</td>
<td>USA</td>
<td>14</td>
<td>14a – Princeton, KY, 14b – Raleigh, NC, 14c – Jackson, TN, 14d – Knoxville, TN, 14e – Blacksburg A, VA, 14f – Blacksburg B, VA, 14g – Orange, VA, 14h – Morgantown, WV</td>
</tr>
<tr>
<td>Evanyslo et al., 2005</td>
<td>USA</td>
<td>21</td>
<td>21a – Wise County, VA</td>
</tr>
<tr>
<td>Casler et al., 2004</td>
<td>USA</td>
<td>23</td>
<td>23e – Stillwater, OK</td>
</tr>
<tr>
<td>Thomason et al., 2004</td>
<td>USA</td>
<td>24</td>
<td>24a – Chickasha, OK, 24b – Perkins, OK</td>
</tr>
<tr>
<td>Fuentes and Taliaferro, 2002</td>
<td>USA</td>
<td>41</td>
<td>41a – Chickasha, OK, 41b – Haskell, OK</td>
</tr>
<tr>
<td>Heaton et al., 2008</td>
<td>USA</td>
<td>44</td>
<td>44c – Simpson, IL</td>
</tr>
<tr>
<td>Mooney et al., 2009</td>
<td>USA</td>
<td>60</td>
<td>60a – Milan, TN</td>
</tr>
<tr>
<td>Lemus et al., 2008b</td>
<td>USA</td>
<td>62</td>
<td>62a – Blacksburg &amp; Orange, VA</td>
</tr>
<tr>
<td>Sanderson et al., 2004</td>
<td>USA</td>
<td>66</td>
<td>66a – Rock Springs, PA</td>
</tr>
<tr>
<td>Casler et al., 2007</td>
<td>USA</td>
<td>68</td>
<td>68d – Stillwater, OK &amp; Fayetteville, AR</td>
</tr>
<tr>
<td>Haque et al., 2009</td>
<td>USA</td>
<td>69</td>
<td>69a – Stillwater, OK</td>
</tr>
<tr>
<td>Garten Jr. et al., 2010</td>
<td>USA</td>
<td>70</td>
<td>70a – Milan, TN</td>
</tr>
<tr>
<td>Stork et al., 2009</td>
<td>USA</td>
<td>72</td>
<td>72a – Lexington, KY</td>
</tr>
<tr>
<td>For each region, information is sorted by site.</td>
<td>South</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bow et al., 2008</td>
<td>USA</td>
<td>04</td>
<td>04a – Stephenville, TX</td>
</tr>
<tr>
<td>Cassida et al., 2005</td>
<td>USA</td>
<td>10</td>
<td>10a – College Station, TX, 10b – Dallas, TX, 10c – Stephenville, TX, 10d – Hope, AK, 10e – Clinton, LA</td>
</tr>
<tr>
<td>Ma, 2001</td>
<td>USA</td>
<td>30</td>
<td>30a – Shorter, AL, 30b – Piedmont substation, AL</td>
</tr>
<tr>
<td>Muir et al., 2001</td>
<td>USA</td>
<td>32</td>
<td>32a – Stephenville, TX, 32b – Beeville, TX</td>
</tr>
<tr>
<td>Sanderson et al., 1999b</td>
<td>USA</td>
<td>35, 36</td>
<td>35a – Beeville, TX, 35b – College Station, TX, 5c – Dallas, TX, 35d – Stephenville, TX, 35e – Temple, TX, 36a – Stephenville, TX, 36b – College Station, TX</td>
</tr>
<tr>
<td>Sladden et al., 1991</td>
<td>USA</td>
<td>40</td>
<td>40a – East Central, AL</td>
</tr>
<tr>
<td>Sanderson et al., 1999a</td>
<td>USA</td>
<td>42</td>
<td>42a – Dallas, TX, 42b – Stephenville, TX</td>
</tr>
<tr>
<td>Sanderson et al., 2001</td>
<td>USA</td>
<td>64</td>
<td>64a – Stephenville, TX</td>
</tr>
<tr>
<td>Kiniry et al., 1999</td>
<td>USA</td>
<td>67</td>
<td>67a – Temple, TX</td>
</tr>
</tbody>
</table>
Table 2.4. Frequency/sample size (n), mean, standard error of mean (SEM), minimum (min), and maximum (max) biomass yields of switchgrass cultivars in growing seasons >=3 categorized by region. Values are sorted by mean from largest to smallest.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>n/freq</th>
<th>Mean</th>
<th>SEM</th>
<th>Min</th>
<th>Max</th>
<th>Cultivar</th>
<th>n/freq</th>
<th>Mean</th>
<th>SEM</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>NJ50/Carthage</td>
<td>2</td>
<td>13.9</td>
<td>0.9</td>
<td>13.2</td>
<td>14.5</td>
<td>Pathfinder HYDMDC2</td>
<td>3</td>
<td>16.7</td>
<td>6.4</td>
<td>12.8</td>
<td>24.1</td>
</tr>
<tr>
<td>Shelter</td>
<td>2</td>
<td>11.5</td>
<td>0.3</td>
<td>11.3</td>
<td>11.8</td>
<td>NL</td>
<td>2</td>
<td>15.6</td>
<td>7.5</td>
<td>10.3</td>
<td>20.9</td>
</tr>
<tr>
<td>Shawnee</td>
<td>26</td>
<td>10</td>
<td>4.6</td>
<td>2.9</td>
<td>18.9</td>
<td>CIR HY-DMD C1</td>
<td>2</td>
<td>14.2</td>
<td>1</td>
<td>13.5</td>
<td>14.9</td>
</tr>
<tr>
<td>WS-SB</td>
<td>2</td>
<td>10</td>
<td>1.2</td>
<td>9.2</td>
<td>10.8</td>
<td>SL</td>
<td>2</td>
<td>13.4</td>
<td>5.8</td>
<td>9.3</td>
<td>17.5</td>
</tr>
<tr>
<td>Pathfinder</td>
<td>13</td>
<td>9.8</td>
<td>3</td>
<td>4</td>
<td>14.4</td>
<td>late syn HY C3</td>
<td>2</td>
<td>12.8</td>
<td>2.2</td>
<td>11.2</td>
<td>14.4</td>
</tr>
<tr>
<td>Blackwell</td>
<td>5</td>
<td>9.7</td>
<td>3.3</td>
<td>4</td>
<td>13.3</td>
<td>EY x FF LDMD C1</td>
<td>2</td>
<td>12.7</td>
<td>0.3</td>
<td>12.2</td>
<td>13.3</td>
</tr>
<tr>
<td>SU†</td>
<td>2</td>
<td>9.4</td>
<td>2.9</td>
<td>7.4</td>
<td>11.4</td>
<td>EY x FF LDMD C3</td>
<td>2</td>
<td>11.7</td>
<td>0.3</td>
<td>8.7</td>
<td>14.8</td>
</tr>
<tr>
<td>NU‡</td>
<td>2</td>
<td>8.8</td>
<td>2.1</td>
<td>7.3</td>
<td>10.3</td>
<td>SU</td>
<td>2</td>
<td>11.5</td>
<td>5</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>WS-IP</td>
<td>2</td>
<td>8.7</td>
<td>1.3</td>
<td>7.7</td>
<td>9.6</td>
<td>Cave-in-Rock</td>
<td>3</td>
<td>11.2</td>
<td>3.7</td>
<td>7.1</td>
<td>14.2</td>
</tr>
<tr>
<td>Sunburst</td>
<td>34</td>
<td>8.6</td>
<td>3.7</td>
<td>2.6</td>
<td>17.1</td>
<td>Pathfinder</td>
<td>3</td>
<td>10.4</td>
<td>3.2</td>
<td>6.9</td>
<td>13.3</td>
</tr>
<tr>
<td>Cave-in-Rock</td>
<td>47</td>
<td>8.5</td>
<td>5</td>
<td>1.4</td>
<td>20.6</td>
<td>Sunburst</td>
<td>3</td>
<td>10.4</td>
<td>3.2</td>
<td>6.9</td>
<td>13.3</td>
</tr>
<tr>
<td>Trailblazer</td>
<td>19</td>
<td>8.2</td>
<td>3.7</td>
<td>2.9</td>
<td>14.1</td>
<td>NU</td>
<td>2</td>
<td>9.9</td>
<td>4</td>
<td>7.1</td>
<td>12.7</td>
</tr>
<tr>
<td>NL§</td>
<td>2</td>
<td>7.6</td>
<td>4.2</td>
<td>4.6</td>
<td>10.6</td>
<td>Blackwell</td>
<td>2</td>
<td>9.9</td>
<td>1.8</td>
<td>8.6</td>
<td>11.2</td>
</tr>
<tr>
<td>Forestburg</td>
<td>21</td>
<td>7.1</td>
<td>3.2</td>
<td>2.3</td>
<td>13.5</td>
<td>NJ50/Carthage</td>
<td>16</td>
<td>9.6</td>
<td>3.0</td>
<td>4.4</td>
<td>14.1</td>
</tr>
<tr>
<td>ND 3743</td>
<td>2</td>
<td>6.6</td>
<td>0.6</td>
<td>6.1</td>
<td>7</td>
<td>Trailblazer</td>
<td>7</td>
<td>8.4</td>
<td>3.9</td>
<td>3.3</td>
<td>13.4</td>
</tr>
<tr>
<td>Summer</td>
<td>4</td>
<td>5.6</td>
<td>0.6</td>
<td>4.8</td>
<td>6.1</td>
<td>Shelter</td>
<td>4</td>
<td>3.2</td>
<td>1.3</td>
<td>2.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Dakota§</td>
<td>2</td>
<td>5.4</td>
<td>0.2</td>
<td>5.3</td>
<td>5.6</td>
<td>Pathfinder HYDMDC2</td>
<td>3</td>
<td>16.7</td>
<td>6.4</td>
<td>12.8</td>
<td>24.1</td>
</tr>
<tr>
<td>Dacotah</td>
<td>36</td>
<td>5.2</td>
<td>2.6</td>
<td>1.5</td>
<td>10.3</td>
<td>NL</td>
<td>2</td>
<td>15.6</td>
<td>7.5</td>
<td>10.3</td>
<td>20.9</td>
</tr>
<tr>
<td>SL§</td>
<td>2</td>
<td>5.1</td>
<td>1.9</td>
<td>3.8</td>
<td>6.5</td>
<td>CIR HY-DMD C1</td>
<td>2</td>
<td>14.2</td>
<td>1</td>
<td>13.5</td>
<td>14.9</td>
</tr>
</tbody>
</table>

+ only cultivars with frequencies or sample size (n) >=2 were included.
+ Mean, min, and max were calculated within region across nitrogen rates (0 to 300 kg N ha⁻¹).
+ SEM of cultivars within region and sample size, n.
+ NU, NL, SU, and SL represent northern upland, northern lowland, southern upland, and southern lowland values, which are reported in the literature in most cases as mean values of similar cultivars.
+ Dakota was likely spelled incorrectly in the literature, and the correct spelling of cultivar name should be Dacotah. Rather than make the assumption that the name was misspelled, two names, and consequently two cultivars are distinguished.
Table 2.5. ANOVA table of significant management and environmental effects influencing dry biomass yields of switchgrass obtained from the literature from across the eastern two thirds of the U.S. and southeastern Canada.

<table>
<thead>
<tr>
<th>Effect/Factor</th>
<th>Num. df</th>
<th>Den. df</th>
<th>F-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1</td>
<td>494</td>
<td>900</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Linear N rate</td>
<td>1</td>
<td>494</td>
<td>35</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Quadratic N rate</td>
<td>1</td>
<td>494</td>
<td>4</td>
<td>0.0363</td>
</tr>
<tr>
<td>Region</td>
<td>3</td>
<td>93</td>
<td>16</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Spring precipitation</td>
<td>1</td>
<td>494</td>
<td>15</td>
<td>0.0001</td>
</tr>
<tr>
<td>Growing season</td>
<td>2</td>
<td>494</td>
<td>3</td>
<td>0.0466</td>
</tr>
<tr>
<td>Ecotype</td>
<td>1</td>
<td>494</td>
<td>105</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Harvest timing</td>
<td>1</td>
<td>494</td>
<td>3</td>
<td>0.0771</td>
</tr>
<tr>
<td>Spring precipitation x Ecotype</td>
<td>1</td>
<td>494</td>
<td>7</td>
<td>0.0092</td>
</tr>
<tr>
<td>Spring precipitation x Growing season</td>
<td>2</td>
<td>494</td>
<td>7</td>
<td>0.0007</td>
</tr>
<tr>
<td>Linear N rate x Ecotype</td>
<td>1</td>
<td>494</td>
<td>3</td>
<td>0.064</td>
</tr>
<tr>
<td>Region x Harvest timing</td>
<td>3</td>
<td>494</td>
<td>2</td>
<td>0.0817</td>
</tr>
</tbody>
</table>
Table 2.6. Site random intercept, random linear N rate, and fixed quadratic N rate coefficients for sites that reported switchgrass biomass yields across at least four N rates. N rate required to achieve maximum biomass (Max N), and ex post economic optimum N rates based upon three prices of a unit of N ($0.87 kg⁻¹ N, $1.07 kg⁻¹ N, and $1.32 kg⁻¹ N) and three prices for a Mg of dry biomass ($35 Mg⁻¹, $50 Mg⁻¹, and $65 Mg⁻¹). These calculations do not take into account the significant effects in Table 2.5 other than the intercept, linear N rate, and quadratic N rate effects. The coefficients were extracted from the basic model described in materials and methods before other effects were incorporated.

<table>
<thead>
<tr>
<th>Sites</th>
<th>Intercept</th>
<th>Linear N rate coefficient</th>
<th>Quadratic N rate coefficient</th>
<th>Max N</th>
<th>0.87/35 =0.025</th>
<th>0.87/50 =0.017</th>
<th>0.87/65 =0.013</th>
<th>1.07/35 =0.031</th>
<th>1.07/50 =0.021</th>
<th>1.07/65 =0.016</th>
<th>1.32/35 =0.038</th>
<th>1.32/50 =0.026</th>
<th>1.32/65 =0.020</th>
</tr>
</thead>
<tbody>
<tr>
<td>31a</td>
<td>8.28677</td>
<td>0.0394</td>
<td>-0.0000761</td>
<td>259</td>
<td>96</td>
<td>145</td>
<td>171</td>
<td>58</td>
<td>118</td>
<td>151</td>
<td>11</td>
<td>85</td>
<td>125</td>
</tr>
<tr>
<td>32a</td>
<td>5.81987</td>
<td>0.062863</td>
<td>-0.0000761</td>
<td>413</td>
<td>250</td>
<td>299</td>
<td>325</td>
<td>212</td>
<td>273</td>
<td>305</td>
<td>165</td>
<td>240</td>
<td>280</td>
</tr>
<tr>
<td>32b</td>
<td>5.371916</td>
<td>0.036925</td>
<td>-0.0000761</td>
<td>243</td>
<td>79</td>
<td>128</td>
<td>155</td>
<td>42</td>
<td>102</td>
<td>135</td>
<td>0†</td>
<td>69</td>
<td>109</td>
</tr>
<tr>
<td>60a</td>
<td>10.37737</td>
<td>0.036313</td>
<td>-0.0000761</td>
<td>239</td>
<td>75</td>
<td>124</td>
<td>151</td>
<td>38</td>
<td>98</td>
<td>130</td>
<td>0†</td>
<td>65</td>
<td>105</td>
</tr>
<tr>
<td>64a</td>
<td>3.066783</td>
<td>0.042905</td>
<td>-0.0000761</td>
<td>282</td>
<td>119</td>
<td>168</td>
<td>194</td>
<td>81</td>
<td>141</td>
<td>174</td>
<td>34</td>
<td>108</td>
<td>149</td>
</tr>
<tr>
<td>65a</td>
<td>3.837839</td>
<td>0.043695</td>
<td>-0.0000761</td>
<td>287</td>
<td>124</td>
<td>173</td>
<td>199</td>
<td>86</td>
<td>147</td>
<td>179</td>
<td>39</td>
<td>114</td>
<td>154</td>
</tr>
<tr>
<td>65c</td>
<td>7.430547</td>
<td>0.032598</td>
<td>-0.0000761</td>
<td>214</td>
<td>51</td>
<td>100</td>
<td>126</td>
<td>13</td>
<td>74</td>
<td>106</td>
<td>0†</td>
<td>41</td>
<td>81</td>
</tr>
<tr>
<td>65f</td>
<td>3.32399</td>
<td>0.039886</td>
<td>-0.0000761</td>
<td>262</td>
<td>99</td>
<td>148</td>
<td>174</td>
<td>61</td>
<td>122</td>
<td>154</td>
<td>14</td>
<td>89</td>
<td>129</td>
</tr>
<tr>
<td>65g</td>
<td>4.196071</td>
<td>0.041798</td>
<td>-0.0000761</td>
<td>275</td>
<td>111</td>
<td>160</td>
<td>187</td>
<td>74</td>
<td>134</td>
<td>167</td>
<td>27</td>
<td>101</td>
<td>141</td>
</tr>
<tr>
<td>65h</td>
<td>3.621642</td>
<td>0.043413</td>
<td>-0.0000761</td>
<td>285</td>
<td>122</td>
<td>171</td>
<td>197</td>
<td>84</td>
<td>145</td>
<td>177</td>
<td>37</td>
<td>112</td>
<td>152</td>
</tr>
<tr>
<td>65i</td>
<td>5.160255</td>
<td>0.040322</td>
<td>-0.0000761</td>
<td>265</td>
<td>102</td>
<td>151</td>
<td>177</td>
<td>64</td>
<td>124</td>
<td>157</td>
<td>17</td>
<td>92</td>
<td>132</td>
</tr>
<tr>
<td>65j</td>
<td>3.420913</td>
<td>0.04271</td>
<td>-0.0000761</td>
<td>281</td>
<td>117</td>
<td>166</td>
<td>193</td>
<td>80</td>
<td>140</td>
<td>173</td>
<td>33</td>
<td>107</td>
<td>147</td>
</tr>
<tr>
<td>69a</td>
<td>7.878856</td>
<td>0.039197</td>
<td>-0.0000761</td>
<td>258</td>
<td>94</td>
<td>143</td>
<td>170</td>
<td>57</td>
<td>117</td>
<td>149</td>
<td>10</td>
<td>84</td>
<td>124</td>
</tr>
<tr>
<td>73a</td>
<td>8.540619</td>
<td>0.039492</td>
<td>-0.0000761</td>
<td>260</td>
<td>96</td>
<td>145</td>
<td>172</td>
<td>59</td>
<td>119</td>
<td>151</td>
<td>12</td>
<td>86</td>
<td>126</td>
</tr>
</tbody>
</table>

† Economic optimum N rates calculated were less than zero.
FIGURES

Figure 2.1. Sites and locations included in the statistical analysis of switchgrass biomass yields grouped by region and overlaid on the USDA plant hardiness zones for the USA (excluding AK and HI), and two Canadian provinces (Ontario & Quebec). Description of the USDA plant hardiness zones (labeled 1 to 11 on map) follows that explained by Vogel et al., 2005 and the average annual minimum temperature ranges (°C) are as follows: zone 1, less than -45.6, zone 2, -45.5 to -40.0; zone 3, -39.9 to -34.5; zone 4, -34.5 to -28.9; zone 5, -28.8 to -23.4; zone 6, -23.3 to -17.8; zone 7, -17.7 to -12.3; zone 8, -12.2 to -6.7; zone 9, -6.6 to -1.2; zone 10, -1.1 to 4.4; zone 11, greater than 4.5. Sites from Stout et al., 1992, Staley et al., 1991, and Lemus et al., 2008a were not included on map, because no detailed information regarding latitude and longitude of sites were provided in the papers.
Figure 2.2. Boxplots of mean dry biomass switchgrass yield (Mg ha$^{-1}$) for each growing season, region, and ecotype. From left to right the plots represent growing seasons 1, 2, and >=3. The L and U in the upper part of each panel represent lowland and upland ecotypes, respectively, with upland and lowland ecotypes respectively in the upper and lower panels. The black dot in each boxplot represents the median, while open circles represent outlying values.
Figure 2.3. Individual model predictions for each site included in the statistical analysis. Open circles represent mean switchgrass dry biomass values plotted against N rate. Solid lines represent fixed effects for individual site predictions, and dashed lines represent the random effect of individual sites (experimental units). The number in each panel corresponds to the site number in Table 2.3.
Figure 2.4. Switchgrass dry biomass yield (Mg ha$^{-1}$) plotted against spring precipitation (April through June) fitted with simple linear regression lines. Key showing L and U, represent lowland and upland ecotypes, respectively.
Figure 2.5. Observed lowland and upland ecotype mean switchgrass dry biomass yield values (Mg ha\(^{-1}\)) plotted against nitrogen rate (kg N ha\(^{-1}\)) for each region. Observed mean values are only for growing seasons >=3 are subsetted for PSC harvest (upper figure) and ES harvest (lower figure). Dry biomass yield predictions are based on the model in Table 2.5 for growing seasons >=3, harvested at PSC (upper figure) or ES (lower figure), with a spring precipitation (April – June) level of 300 mm. Open circles represent the lowland ecotype while solid triangles represent the upland ecotype. The darker dashed prediction line represents the lowland ecotype while the lighter solid prediction line represents the upland ecotype.
Figure 2.6. Mean switchgrass dry biomass yield values (Mg ha\(^{-1}\)) plotted against nitrogen rate (kg N ha\(^{-1}\)) for each region, and 80% confidence ellipses grouped by harvest timing: peak standing crop (PSC) and end of season (ES). Solid squares and solid lines represent PSC, and open triangles and dashed lines represent ES.
CHAPTER 3

*Miscanthus x giganteus* Productivity: The Effects of Management in Different Environments

ABSTRACT

Little research has been published in the USA investigating *Miscanthus x giganteus* (*M. x giganteus*), a C₄ perennial grass showing great potential as a high yielding biomass crop. Understanding the growth and biomass yield potential of *M. x giganteus* in different environments in the USA is critical to identifying a suitable growing region. This study investigated the establishment success, plant growth, and dry biomass yield of *M. x giganteus* during its first three seasons at four locations (Urbana, Illinois; Lexington, Kentucky; Mead, Nebraska; Adelphia, NJ, referred to as IL, KY, NE, and NJ) in the USA. Three nitrogen rates (0, 60, and 120 kg ha⁻¹) were applied at each location each year. Good survival of *M. x giganteus* during its first winter was observed at KY, NE, and NJ (79-100%), and poor survival at IL (17%), due to late planting and cold winter temperatures that dropped to -27°C. Site soil conditions, and growing season precipitation and temperature had the greatest impact on dry biomass yield between season two (2009) and season three (2010). This was especially true at NE, where ideal weather conditions, resulted in significant yield increases (p<.0001), 15.63 Mg ha⁻¹ to 27.32 Mg ha⁻¹. Biomass yield decreases of 17.02 to 13.21 Mg ha⁻¹ in KY and 13.46 to 11.37 Mg ha⁻¹ in NJ were observed between season two and three. These decreases were primarily related to excessive spring rain and hot dry conditions later in the growing season at KY, and hot dry weather, and poor soil conditions in NJ. Season three yields were positively correlated with end-of-season plant height (\( \hat{\rho} = 0.91 \)) and tiller density (\( \hat{\rho} = 0.76 \)). N fertilization had no significant effect on plant height, tiller density, or dry biomass yield at any of the sites during seasons two or three.
INTRODUCTION

Current worldwide energy instability has resulted in the investigation of alternative energy sources. In response, several herbaceous crops are being researched as potential sources of biomass feedstock that can be utilized as energy sources. One of these crops, *Miscanthus x giganteus*, is a sterile and rhizomatous perennial C$_4$ photosynthetic plant (Lewandowski et al., 2000) that has potential for producing high dry biomass yields (Heaton et al., 2004), exhibits efficient conversion of solar radiation to biomass, efficient use of nitrogen and water, and possesses good pest and disease management (Beale and Long, 1995; Beale et al., 1999). This long-lived perennial grass is a cross between *M. sinensis* and *M. sacchariflorus* (Hodkinson and Renoize, 2001) as confirmed by Hodkinson et al. (2002) and Swaminathan et al. (2010). *M. x giganteus* was first collected in Japan in 1935 (Hodkinson et al., 2002) and was initially planted as a landscape ornamental, and later a bioenergy feedstock in Europe. From the time a new crop of *M. x giganteus* is planted, 3-5 seasons are necessary for the crop to become fully established and be considered a mature crop that can achieve ceiling biomass yields (Miguez et al., 2008). A high-yielding feedstock, mature stands of *M. x giganteus* have been close to 40 Mg ha$^{-1}$ peak biomass yields in some European locations (Miguez et al., 2008). A quantitative review of mature *M. x giganteus* stands across Europe reported a mean peak biomass yield of 22 Mg ha$^{-1}$, averaged across nitrogen rates and precipitation levels (Heaton et al., 2004), while harvestable yields up to 25 Mg ha$^{-1}$ from mature stands of *M. x giganteus* have been reported in areas between central Germany and southern Italy (Lewandowski et al., 2000). *M. x giganteus* is typically harvested during the winter or early spring once significant drying of stems and leaves, and translocation of nutrients from above ground plant tissue to rhizomes, has occurred. There is a tradeoff between harvesting early, at the end of the growing season, or late, during the winter
or in the early spring. End of season or ‘peak biomass’ harvests have higher yields, but higher moisture levels and higher content of undesirable minerals, particularly nitrogen. Waiting to harvest until winter or early spring reduces yields, but the need for fertilization is reduced and feedstock quality is improved (Heaton et al., 2009; Lewandowski et al., 2000; Beale and Long, 1997; Clifton-Brown and Lewandowski, 2002). Waiting to harvest until winter or early spring is the recommended practice and results in approximately a 33% reduction from peak biomass yields (Lewandowski et al., 2003), lost primarily from drying tissue and senesced leaves that have dropped from the stems.

More extensive study of *M. x giganteus* as a bioenergy feedstock in the USA has taken place over the past decade, and relatively little information regarding plant growth, biomass yield and its response to agronomic treatments such as nitrogen, are available. At present, *M. x giganteus* biomass yields in the USA have been reported in only four publications from Illinois and Kansas (Heaton et al., 2008; Dohleman and Long, 2009; Propheter et al., 2010; Propheter and Staggenborg, 2010). Propheter et al. (2010) reported mean harvestable biomass yield increases of 2.7 to 11.8 Mg ha<sup>-1</sup> and 4.0 to 13.7 Mg ha<sup>-1</sup> from season 1 to season 2 for Manhattan, Kansas and Troy, Kansas, respectively. Heaton et al. (2008) and Dohleman and Long (2009) reported mean *M. x giganteus*, biomass yields ranging from 17.9 to 34.6 Mg ha<sup>-1</sup> in Illinois from mature stands.

Several current studies are in progress that will significantly expand the number of *M. x giganteus* evaluation sites throughout the USA and include much of the Midwest, areas of the Great Plains, and Atlantic coast regions. Data from these studies will provide valuable information that can be used to identify the optimal growing region for *M. x giganteus*. Such data will also provide valuable information about establishment success, responses to new and
varying environments, growth patterns from season to season, and response to N fertilizer. Because there are limited USA sites growing *M. x giganteus*, scant information is available to suggest a suitable growing region for the grass.

It is believed that *M. x giganteus* should be grown in temperate climates, as a frost period is needed in order to mark the end of the growing season and the beginning of dormancy, which in turn promotes plant senescence (Pyter et al., 2009). *M. x giganteus* possesses winter hardiness traits obtained from *M. sinensis* (Clifton-Brown and Lewandowski, 2000), however there are still concerns about the ability of this crop to withstand harsh winter environments (low and fluctuating winter temperatures) (Clifton-Brown and Lewandowski, 2000). In northern Europe, testing has shown that *M. x giganteus* rhizomes are severely affected by temperatures < -3.4°C (Clifton-Brown and Lewandowski, 2000). Additionally, late-spring frosts have proven to negatively affect emerging and young *M. x giganteus* tillers (Farrell et al., 2006). The risk of growing this crop in some colder environments may be confined primarily to the establishment years, because mature stands of *M. x giganteus* have survived winters in IL with air temperatures lower than -26°C (-15°F) (personal observations).

Beyond the need to identify the optimal *M. x giganteus* growing regions in the USA, additional research is needed regarding its response to applied N. The literature shows varied response to applied N (Miguez et al., 2008; Lewandowski et al., 2000; Heaton et al., 2004). For example in Italy over 4 years *M. x giganteus* responded favorably to applied N up to 200 kg N ha⁻¹ (179 lb N acre⁻¹) (Ercoli et al., 1999). At Rothamsted, England, *M. x giganteus* grown for 14 years on a silty clay loam did not respond to cumulative applications of 60 and 120 kg N ha⁻¹ (Christian et al., 2008). Across 14 years there was only a 5% difference in biomass yield between N treatments. In their study Christian et al. (2008) suggested that annual applications of
7 kg P ha\(^{-1}\) and 100 kg K ha\(^{-1}\) were important for soil maintenance. One major difference between these two studies, aside from site differences, is that the Italian study was harvested at peak biomass, while the English study was harvested in winter, the recommended harvest timing. In general it appears that yield response to applied N will occur on a site-by-site basis. It has also been suspected that some N may be made available from biological N-fixation (Davis et al., 2010). Other factors that may impact N response include: soil type and quality (i.e. texture, bulk density, rooting depth), % soil organic matter which influences the amount of annual N mineralization, harvest timing, status of other soil nutrients, and the length of time since planting.

As part of the Sun Grant/U.S. Department of Energy Regional Biomass Feedstock Partnership, \(M. x\) giganteus was planted in replicated trials in four locations through the central region of the eastern half of the US. The locations ranging from west to east were Mead, NE; Urbana, IL; Lexington, KY; and Adelphia, NJ (referred to as NE, IL, KY, and NJ). This experiment began in 2008 and will be ongoing for five or more years, allowing sufficient time for the crop to reach maturity at each of the sites. This experiment involves various investigators from multiple institutions, and multiple aspects of production and sustainability are being evaluated. The overall objective for this experiment is to develop and analyze data regarding sustainability, soil C sequestration, growth, morphology, and biomass yield under different N rates for assessing the potential expansion of \(M. x\) giganteus as a bioenergy feedstock resource.

This specific study focuses predominately on aboveground plant material. The first three years of production as establishment years for the crop were considered. The specific objectives of this study were to: 1) establish \(M. x\) giganteus at these four locations and assess their overwintering capability, and 2) collect morphological, plant growth, and biomass yield data that
can be used to assess the impact of temperature and precipitation, season of growth, and N rate on the productivity of *M. x giganteus* at each of these locations.

**MATERIALS AND METHODS**

**Site Descriptions**

This field study was conducted at four university field sites: University of Illinois Urbana-Champaign, Urbana, IL (40°06’20” N, 88°19’18” W); University of Kentucky, Lexington, KY (38°07’45” N, 84°30’08” W); University of Nebraska-Lincoln, Mead, NE (41°10’07” N, 96°28’10” W); and Rutgers, The State University of New Jersey, Adelphia, NJ (40°13’31” N, 74°14’54” W). At IL, the soil is classified as a very deep, well-drained Wyanet silt loam (loamy, mixed, active, mesic Typic Argiudolls). The upper 30 cm of soil at this site is dominated by a sandy loam soil texture that transitions into a silty clay loam soil texture at the 50 to 100 cm depth (Table 3.1). The water table at this site ranges between 61 and 107 cm in depth. Organic matter levels are relatively low ranging from 1.9% at the 0-10 cm depth down to 1.2% at the 50-100 cm depth (Table 3.1). This is a non-typical site for the east-central IL area; typical soils for this area are usually Drummer (very deep, poorly drained, silty clay loam soils) or Flanagan (very deep, somewhat poorly drained, silt loam soils) series. At KY, the soil is classified as very deep, well drained Maury silt loam (Fine, mixed, active, mesic Typic Paleudalfs) with a water table deeper than 200 cm. Percent organic matter levels at this site range from 4.7% at the 0-10 cm depth to 1.8% at the 50-100 cm depth. At NE, the soil is classified as a very deep well drained Tomek silt loam (Fine, smectitic, mesic Pachic Argiudolls), however this specific site is dominated by a silty clay loam soil texture (Table 3.1). The water table at this site is greater than 200 cm in depth and percent organic matter levels range from 5.1% at the 0-10 cm depth down to 1.4% at the 50-100 cm depth. At NJ, the soil is a
Holmdel sandy loam (Fine-loamy, mixed, active, mesic Aquic Hapludults) with a relatively high water table ranging between 15 and 91 cm in depth. Percent organic matter levels at this site range from 2.1% at the 0-10 cm depth down to 0.8% at the 50-100 cm depth. At this site there is a restrictive soil layer or rather a bedrock layer between 50 cm and 80 cm depth, depending on the plot.

**Crop Establishment**

In fall 2007, rhizomes were harvested from a demonstration planting of *M. x giganteus* at the University of Illinois Landscape Horticulture Research Center, Urbana, IL. This demonstration was planted in 1988 using rhizomes obtained from the Chicago Botanic Garden (Glencoe, IL, USA). Propagation took place in University of Illinois greenhouses where rhizomes of approximately 25 g were planted into 9-cm square pots during winter and spring 2008, in artificial soil mixes and grown in the greenhouse. In early-to-mid summer 2008, 1200 potted plants were shipped to each location for hardening and transplanting. At each location, twelve 10 m x 10 m plots comprised of 100 *M. x giganteus* plants per plot were transplanted at a density of 1 plant m\(^{-2}\), with 5 m alleys between the plots. Throughout this study, the stand density of 1 plant m\(^{-2}\) was maintained, since *M. x giganteus* produces sterile seed and the plants during the duration of this study are slowly filling in the gaps between plants. Transplanting dates were 24 July, 20 June, 18 June, and 19 June, respectively in IL, KY, NE, and NJ. Late planting at the IL site occurred due to the time necessary to propagate additional *M. x giganteus* plants. The plots at each location were arranged in a randomized complete block design with four replicates. Three N treatments (0, 60, and 120 kg ha\(^{-1}\)) were applied at each location in each replicate each year beginning with establishment year (2008). During the planting year, irrigation and mechanical weed control were provided where necessary at each location to
promote establishment of *M. x giganteus*. In spring 2009, the number of surviving plants from those transplanted in 2008 at each location was counted to determine % winter survival. Percent survival across all N rates at each location was 17, 99, 79, and 100% respectively at IL, KY, NE, and NJ. Poor survival at Urbana, IL during the first winter required replanting in 2009 to bring the plots to a fully-planted status. Percent winter survival was measured again in each plot at each location in spring 2010.

**Soil Sampling and Weather**

Three 1-m deep soil cores from each plot at each location were sampled in 2008 on 17 July in IL, 5 Aug. in KY, 14 Aug. in NE, and 3 Sept. in NJ. Each core sample was split into 5 segments: 0-10, 10-20, 20-30, 30-50, and 50-100 cm depths. Table 3.1 summarizes selected variables from these soil data at each location averaged across plot and treatment. Weather data from stations nearby Urbana, IL; Lexington, KY; Mead, NE; and Adelphia, NJ were obtained from the Midwestern Regional Climate Center, a cooperative program of the Illinois State Water Survey and the National Climatic Data Center, or directly from the National Climatic Data Center. Data from each location were collected from stations nearby Urbana, IL; Lexington, KY; Mead, NE; and Adelphia, NJ, respectively with station name and cooperative identification number Urbana, IL (118740), Lexington Bluegrass AP, KY (154746), Mead 6S, NE (255362), Hightstown 2W, NJ (283951). Monthly weather data for 2008, 2009, and 2010 are summarized in Tables 3.2 and 3.3. Accumulated thermal time (aka growing-degree days) was calculated with a base temperature of 0°C as has been done in other studies (Miguez et al., 2008; Miguez et al., 2009; Hastings et al., 2009).
Plant Measurements

Throughout the second (2009) and third (2010) growing seasons, plant growth and morphological measurements were collected at KY, NE, and NJ. These data were not collected in IL until 2010 due to 2009 replanting. Average emergence date was determined in the spring when approximately the first 10 plants in each plot had emerged. Date of full-headed flowering (R3) (Moore et al., 1991) was determined when approximately 50% of the plants in each plot were fully flowered. In 2009 at KY, N, and NJ, average plant height and leaf number per tiller were measured throughout the season. Average plant height was determined by measuring the height of the upper most fully expanded leaf of the tallest tiller on five randomly selected plants in each plot each month in 2009 and 2010. In 2009 and 2010, average tiller density (tillers m\(^{-2}\)) was determined by counting the number of tillers per plant on at least five random plants in each plot after the end of the growing season. These sampling dates are shown in Table 3.4. In 2010 when the tiller density measurements were collected the average number of phytomers tiller\(^{-1}\), and average tiller diameter were also determined. This was done by randomly selecting a total of 10 representative tillers from each of five plants. Tiller diameter was determined by measuring each tiller at the center of the first full internode above the ground level of the tiller. Phytomer number was determined by recording the number of nodes on each tiller. Average tiller diameter and phytomer number were determined by first calculating the average within plants and then across all plants within a plot.

In 2009 and 2010 dry biomass yield estimates were obtained at each location after the end of the growing season. Harvest dates for the 2009 are shown in Table 3.4. Harvesting at all locations in 2009 and 2010, with exception of NE, employed the following protocol. A representative plant in each plot was selected, avoiding plants on the border rows of the plot. A
1 m² quadrat was centered on the middle of the plant and all standing tillers within the meter-squared area were cut at ~10 cm above the ground. No ground litter was included in the sample. After harvesting the first plant, the 1 m² quadrat was flipped directly to the north and the adjacent meter-square area (i.e. single plant) was harvested. If the adjacent sampling area happened to fall on edge of the plot, the quadrat was flipped to the south and that adjacent meter-square area was harvested. This process was repeated a second time by selecting a second representative M. x giganteus plant in each plot. This resulted in a total of 4 harvested plants, each representing a 1 m² area from each M. x giganteus plot. Fresh weight was determined by weighing a subsample, and dry biomass (Mg ha⁻¹) was determined by calculating the percent moisture of a subsample dried in the oven at 60° C for at least 48 hours. The NE plots were harvested using a mechanical forage plot harvester (Carter MFG Co., Inc. Brookston, IN) by harvesting one row of plants (10 plants) for a total area of 10 m² in each plot. A subsample from each plot was collected, weighed, and dried to calculate % moisture and determine dry biomass yield.

**Statistical Modeling and Analysis**

Data from IL were not statistically analyzed with the other locations for any of the analyzed variables, because this location (as of 2010) possessed a mixture of two and three year old plants, and the stand was non-uniform. When applicable, mean values from IL were reported in the results to provide some information regarding this location, and these mean values were calculated using the MEANS procedure of SAS (SAS Institute, 2007).

Dry biomass yield was analyzed in the MIXED procedure of SAS (SAS Institute, 2007) while tiller density, which follow a Poisson distribution (aka count data), was analyzed in the GLIMMIX procedure of SAS (SAS Institute, 2007). Locations (KY, NE, and NJ) and years
(2009 and 2010) were combined to create six environments: KY-2009, KY-2010, NE-2009, NE-2010, NJ-2009, and NJ-2010. Environments, blocks, and subsamples were considered random effects while nitrogen rate was declared a fixed effect. The mixed model was described as follows

\[ y_{ijkl} = \mu + e_i + b_{j(i)} + \alpha_k + e\alpha_{lk} + error_{j(i)k} + s_{ijkl} \]

where dry biomass yield or tiller density \((y_{ijkl})\) depends on the \(l^{th}\) random subsample of the \(k^{th}\) nitrogen rate in the \(j^{th}\) block nested in the \(l^{th}\) environment, having an intercept \((\mu)\), and being influenced by the random environment \((e_i)\), random block \((b_{j(i)})\), random interaction between environment and nitrogen rate \((e\alpha_{lk})\), and fixed nitrogen rate\((\alpha_k)\) effects. The model assumes that \(e_i, b_{j(i)},\) and \(e\alpha_{lk}\) are independent normal random variables with expectations zero and respective variances \(\sigma_e^2, \sigma_{b(e)}^2, \sigma_{e\alpha}^2\), and that the errors \((error_{j(i)k})\) and subsamples \((s_{ijkl})\) have means of zero and common variances. Environments were considered random to account for different weather and other environmental conditions at each site which could not be controlled. Significance of random effects were calculated using the COVTEST option in the MIXED and GLIMMIX procedures of SAS (SAS Institute, 2007). Best linear unbiased predictions of random effects (aka means of random effects) and their interactions were calculated using estimate statements with appropriate degrees of freedom and standard errors. Residuals were examined for normality and the assumption of common variances by inspection of residual plots.

The non-linear function used to model the increase in \(M. \times giganteus\) plant height throughout the growing season was the logistic growth function,

\[ f(x) = \frac{asym}{1 + exp^{-\left(\frac{x-xmid}{scal}\right)}} \]  

[eq. 1]
Here, \(f(x)\) is *M. x giganteus* plant height (meter units) measured throughout the growing season and \(x\) is the day of year (DOY). Three parameters describe the shape and spread of the function: 1) asymptote (\(asym\)) or maximum height achieved by the crop, 2) scale (\(scal\)) or the elapsed time between the crop achieving half and three quarters of its maximum height, and 3) inflection point (\(xmid\)) or DOY at which the crop achieves half of its maximum height. A nonlinear mixed model was used to implement the logistic growth function and investigate the effects of environment, N rate, and their interaction. This was accomplished by considering \(asym, scal,\) and \(xmid\) for each environment and each N rate as fixed components, and individual plots (experimental units) as random. The modeling process followed principles in Pinheiro and Bates (2000) and was implemented with ‘nlme’ package (Pinheiro et al., 2009) of R statistical software (R Core, v. 2.12.1, 2010). Residuals were checked for patterns by plotting standardized residuals against their fitted values. Parameter estimates and their 95% confidence intervals were obtained using the ‘summary’ and ‘interval’ functions of R (R Core, v. 2.12.1, 2010). Prediction plots and all other graphics were obtained using the ‘graphics’ and ‘lattice’ packages of R (R Core, v. 2.12.1, 2010).

Pearson correlation coefficients and their respective \(P\)-values were calculated using the CORR procedure of SAS (SAS Institute, 2007) to evaluate the linear association of dry biomass yield, end of season plant height, tiller density, phytomers tiller\(^{-1}\), and tiller diameter among environments during the 2010 growing season. End of season plant height measurements were determined by selecting the last set of plant height (between Sept. and Nov.) measurements collected in each environment. For each variable the mean value for each plot was determined using the MEANS procedure of SAS (SAS Institute, 2007), resulting in 12 observations, \(n=12\) (4 blocks \(\times\) 3 N rates) for assessing the effect of environment on these variables. Matrix scatter
plots were obtained using the SGSCATTER procedure of SAS (SAS Institute, 2007) to visually assess correlations among environments within a growing season.

**RESULTS**

**Winter Survival**

The percent of *M. x giganteus* plants that survived the first winter was very dependent upon the site. Only 17% of the *M. x giganteus* plants survived the first winter at IL which required replanting to bring the plots to a fully-planted status during the 2009 season. The other three sites had adequate to excellent winter survival. KY, NE, and NJ had 99%, 79%, and 100%, respectively. Poor winter survival at IL was related to late transplanting in summer 2008 which did not occur until 24 July. In addition to being planted late, winter temperatures at IL dropped to -27°C in the middle of Jan. 2009. Percent winter survival at the beginning of the 2010 season was near 100% at each site.

**Plant Height**

The N rate x environment interaction was investigated and found non-significant for the `asym (P = 0.1249), xmid (P = 0.5954)` and `scal (P = 0.9369)` parameters. The N rate main effect was also non-significant for the `asym (P = 0.4392), xmid (P = 0.8832)` and `scal (P = 0.5247)` parameters, while environment was significant for each parameter (`P < .0001`). Plant height increases throughout the growing season showed very similar patterns among different environments and N rates (Fig. 3.1). The estimated `asym` attained in the different environments ranged between 3 and 3.79 m, and there were significant increases in the `asym` in the KY and NE environments from 2009 to 2010 (Table 3.6). The parameters `xmid` and `scal` were quite different from environment to environment ranging from 143.5 to 171.5 for `xmid` and 15.38 to 24.23 for
These differences were environment dependent and appear to be related to the length of the growing season and weather conditions in each environment.

**Biomass Yield**

The environment x N rate interaction did not contribute a significant amount of variation and was not significant ($P = 0.2066$). The main effect of N rate was not significant ($P = 0.7223$), but the environment main effect was significant ($P = 0.0628$). There were significant decreases in biomass yield at KY ($P = 0.0200$) and NJ ($P < .0001$) from 2009 to 2010 (Table 3.7). These yield decreases represent 22% and 16% decreases, respectively for KY and NJ. Conversely, biomass yields at NE increased 75% from 2009 to 2010 ($P < .0001$) (Table 3.7). Mean biomass yields at IL in 2009 were 1.1, 3.8, and 4 Mg ha$^{-1}$ for 0, 60, and 120 kg N ha$^{-1}$, respectively, while 2010 mean biomass yields at IL were 14.8, 16.1, and 16 Mg ha$^{-1}$ for 0, 60, and 120 kg N ha$^{-1}$, respectively.

**Tiller Density**

There was no significant tiller-density response to applied N in any of the environments and the only significant effects was the environment main effect ($P = 0.0624$). There were significant increases in tiller densities in the KY ($P < .0001$) and NE ($P < .0001$) environments from 2009 to 2010 (Table 3.7). To put this in perspective, tiller densities in 2010 were approximately 52% and 56% greater than in the 2009 seasons for KY, and NE, respectively (Table 3.7). Tiller densities were relatively constant ($P = 0.7820$) between the NJ-2009 and NJ-2010 environments. Mean tiller densities at IL in 2010 were 37.3, 32.3, and 37.6 tillers m$^{-2}$ respectively for 0, 60, and 120 kg N ha$^{-1}$. 

65
Correlations Among Variables

In 2010 there was a strong positive correlation between end of season plant height and dry biomass yield \( (\hat{\rho} = 0.91) (P < .0001) \). There were also strong positive correlations between dry biomass and tiller density \( (\hat{\rho} = 0.76) (P < .0001) \), and between plant height and tiller density \( (\hat{\rho} = 0.88) (P < .0001) \). There were moderate positive correlations between plant height and tiller diameter \( (\hat{\rho} = 0.59) (P = 0.0002) \), and between tiller density and tiller diameter \( (\hat{\rho} = 0.63) (P < .0001) \). These relationships are summarized with matrix scatter plots in Fig. 3.2 and suggest that higher biomass yields were primarily related to higher tiller densities and taller plant heights.

NE stands out in the consistency of the relationships among these variables, having the highest biomass yields, highest tiller densities, and tallest plant heights in 2010. NJ tended to have the lowest amount of each of these three variables, with KY lying in between NE and NJ. Tiller diameter and phytomers tiller\(^{-1}\) did not produce any noteworthy relationships to biomass yield.

DISCUSSION

The percent of *M. x giganteus* plants that survived the first winter was very dependent upon the site, and was primarily related to late planting and cold winter temperatures. The European literature reports that rhizomes from newly planted *M. x giganteus* are severely affected by soil temperatures less than -3.4°C (26°F), providing a lethal dose (50% kill) to the rhizomes exposed to these temperatures (Clifton-Brown and Lewandowski, 2000). Generally, winterkill is primarily an issue during the establishment year. This is considering that mature stands of *M. x giganteus* have survived winters in IL with temperatures lower than -26°C (-15°F) (personal observations). Clifton-Brown and Lewandowski (2000) suggests that larger plants having rhizomes with low moisture content that initiate dormancy on their own before the first fall frost will tend to overwinter better than *M. x giganteus* plants that are shorter, have high
rhizome moisture content and that do not begin dormancy until the first fall frost occurs. To promote overwintering capability, *M. x giganteus* should be planted in mid-to-late spring, providing ample time for the crop to develop and prepare for winter by developing larger rhizome biomass.

*M. x giganteus* is impressive in its ability to begin growth early in the growing season and it is interesting to note, that approximately half of the crops plant height is achieved by late May in KY and by mid June in NE (Table 3.6). This implies that this crop may reach 1.5 to 2 m by early June. This early growth habit, allows the crop to close its canopy relatively early in the growing season, allowing it to intercept more photosynthetic active radiation. *M. x giganteus* has been shown to intercept about 95% of photosynthetic active radiation between June and the later end of the growing season, when senescence begins (Heaton et al., 2008). *M. x giganteus* achieves greater amounts of seasonal canopy-level photosynthesis than some other C₄ photosynthetic grasses such as perennial switchgrass (*Panicum virgatum* L.) (Dohleman et al., 2009) and maize (*Zea mays*) (Dohleman and Long, 2009). In addition to being able to develop a leaf canopy early in the season it also has the ability to remain vegetative late into the season, when grown in northern environments, resulting in a long canopy duration (Dohleman and Long, 2009). The sites selected for this study, generally allowed the crop to remain green and vegetative until at least early September (Table 3.5). The ability of this crop to remain vegetative late in the season provides time for the crop to intercept more light and potentially produce more biomass. This generally should be true as long the crop is not grown too far north where longer day lengths in late summer and early fall could potentially keep the crop from flowering and properly entering dormancy. In environments where winter kill is a concern, there
should be ample time between flowering and the first killing frost, allowing carbohydrates to translocate to storage organs and build up of these carbohydrates for winter survival.

The dry biomass yields at each location in 2009 were slightly higher than other second season biomass yields that have been achieved in the USA. Second season biomass yields in this study were 17, 15.6, and 13.5 Mg ha\(^{-1}\) in KY, NE, and NJ, respectively. These values are higher than second season mean biomass yields in a study in Kansas, USA that ranged from 11.8 Mg ha\(^{-1}\) to 13.7 Mg ha\(^{-1}\) depending on the site (Propheter and Staggenborg, 2010). The growing conditions were adequate for growth in each environment in 2009. This was especially true in KY which had more growing-season precipitation (April through September) (863 mm) than either NE (527 mm) or NJ (829 mm) in 2009 (Table 3.2). These precipitation levels are reflected in the yields that were attained in 2009, except for NJ where the yields were lowest; this is most likely due to the shallow, sandy soils at that site (Table 3.1). Tiller densities at each site in 2009 were similar at 38 tillers m\(^{-2}\) in KY, 44.5 tillers m\(^{-2}\) in NE, and 43.8 tillers m\(^{-2}\) in NJ. It was expected that tiller densities and biomass yields would have increased from 2009 to 2010 at each site (Miguez et al., 2008), but this was not the case.

Dry biomass yield were surprisingly low at KY in 2010 and this was due to abnormal weather conditions that resulted in a highly stressed crop. The crop emerged on 2 April (Table 3.5), and a late frost on 19 April resulted in some frost damage. The effects of this frost damage were not quantified, but it is likely that some of the actively growing tillers were either killed or stunted. Farrell et al. (2006) showed that newly emerging shoots exposed to freezing temperatures can have a negative impact on \(M. \times \text{giganteus}\) biomass yields. Early season precipitation was much higher than normal, with 253 mm precipitation in May, 132 mm more than the long term average. The latter end of the growing season was very dry, with
precipitation levels of 15 mm in both Aug. and Sept. The normal precipitation levels for these months are 96 mm and 79 mm, respectively. Limited precipitation in Aug. and Sept. was coupled with hot summer temperatures resulting in 44 days with the temperature greater than or equal to 32.2°C between May and Sept. Generally, high summer temperatures should not have a large negative impact on this C₄ crop, but when combined with low precipitation, it appears to generate highly stressful growing conditions. The combination of conditions present at KY in 2010 caused the *M. x giganteus* plants to go dormant earlier than normal while the crop was still in a vegetative growth stage. This resulted in the *M. x giganteus* crop not flowering in 2010 (Table 3.5).

Similar weather patterns were observed in NJ in 2010. New Jersey weather was very warm in 2010 accumulating 4601 thermal heating units compared to 3459 heating units in 2009. In 2010, there were 49 days between May and Sept. when the temperature was greater than or equal to 32.2°C (90°F). High temperatures were combined with less than normal precipitation (399 mm) between April and September compared to the average for this period (670 mm). Growing-season precipitation has been shown to be extremely important for *M. x giganteus* to achieve its biomass yield potential (Heaton et al., 2004). At one mature *M. x giganteus* site in England, variables relating available water capacity and soil moisture to biomass yield during the growing season accounted for 70% of annual biomass yield variation (Richter et al., 2008). Areas of low precipitation or prolonged periods of drought are not suitable for growing *M. x giganteus*, as it lacks drought tolerance or the capacity to survive under low precipitation environments, and will begin to senesce under water stressed conditions (Clifton-Brown et al., 2002). In NJ in 2010, not all of the plots reached full maturity with only half of the plots flowering. Those that flowered were the plots fertilized with 0 kg N ha⁻¹ or 60 kg N ha⁻¹. There
was limited flowering in the 60 kg ha\(^{-1}\) plots and none of the 120 kg N ha\(^{-1}\) plots flowered. The NJ plots that did flower did so on 30 Oct., and the season’s first fall frost on 1 Nov., limited flowering of any remaining plants. Similar results have reported that nitrogen-fertilized plots of \textit{M. x giganteus} retain their leaves and potentially remain vegetative longer than unfertilized plots (Himken et al., 1997); however, a difference in the yields of these plots was not observed once leaf senescence was complete and the plots were harvested in the winter. Lower yields at NJ in 2010 were due to several reasons including weather conditions that were both warmer and drier than normal. Also, the standing residue left behind following the winter harvest from the 2009 season was not mowed until early April 2010, around the time the crop was beginning to green up. This may have damaged some emerging shoots and consequently affected the 2010 biomass yields. The shallow and sandy soils at that site may have also contributed to the low yields. In particular, the bedrock layer that is present between 50 and 80 cm is possibly impeding \textit{M. x giganteus} root development and restricting the plant’s ability to obtain water at deep soil depths. In a mature stand of \textit{M. x giganteus} in Germany, roots have been shown to reach down to 250 cm in the soil, with almost half of the roots deeper than 90 cm (Neukirchen et al., 1999).

In 2010, NE growing conditions were favorable for crop growth, and this is reflected in the high biomass yields which were highly correlated with end of season plant height (Table 3.7, Fig. 3.2). Similar results relating biomass to plant height have been reported in production in central Italy (Angelini et al., 2009). Between Apr. and Sept. there was 814 mm of precipitation, 295 mm greater than the normal rainfall for this period at the NE site in 2010. This amount of rainfall was greater than any of the other sites in 2010, which received 570, 613, and 399 mm respectively in IL, KY, and NJ. Additionally, there were 25 days during the growing season at
NE when the temperature was greater than or equal to 32.2°C (90°F). This combination of warm temperatures and adequate precipitation levels spread throughout the growing season promoted an ideal set of growing conditions. Optimal growing temperatures for *M. x giganteus* are between 30 and 35°C (Naidu et al., 2003).

Even though there was no significant effect of applied N on any of the measured variables in any of the environments, it does not suggest, however that *M. x giganteus* does not require N fertilizer. As the literature suggests, N response varies from site-to-site. To fully understand the N needs of *M. x giganteus*, various aspects of the crop and the site where it is being grown require consideration. Since *M. x giganteus* has the ability to recycle its nutrients from year to year, much of the crop’s nutrient needs are likely met on an annual basis without annual applications of N fertilizer provided, harvesting takes place in the winter after nutrients from above-ground plant parts have been recycled via translocation from shoots to rhizomes, fallen leaves, and leaching from stems (Cadoux et al., 2011). In a review, Cadoux et al. (2011) reported that three year old stands of *M. x giganteus* harvested during the winter remove approximately 4.9 g N kg⁻¹ dry matter, and maximum N fertilization rates should be 49, 73.5, and 98 kg N ha⁻¹, respectively, for harvestable dry biomass yields of 10, 15, and 20 Mg ha⁻¹. This study also recommended that fertilizer should not be applied during the first two years after *M. x giganteus* is planted, unless it is planted in poor soils. This recommendation is supported by a recent meta-analysis reporting that there was little response to N fertilizer during the establishment years (years 1-3) of *M. x giganteus* but once the crop reached maturity, a response to N fertilizer was detected (Miguez et al., 2008). A lack of N fertilizer response is doubly supported when *M. x giganteus* is planted in locations where soil N is abundant, or where high levels of soil organic matter can meet the N needs of the crop through N mineralization from soil.
organic matter. At this reporting, our study is still in its ‘yield building’ or establishment years (Clifton-Brown et al., 2007), however, a response to N may occur in future years of production at some locations as the biomass yields more or less stabilize. It can be anticipated that if any site shows a response to N in the future, it will occur at the IL or NJ sites where soil texture is coarse and there are relatively low amounts of soil organic matter. With rooting depths reaching down to 250 cm in mature stands, roots can explore large areas of soil for nutrients (Neukirchen et al., 1999). An extensive root system tends to limit the amount of N that is leached from the soil profile. It is also important to consider how much N is being removed from the system at harvest and how much is being recycled back into the system. Christian et al. (1997), reported that of the 117 kg N ha\(^{-1}\) that the crop acquired from the soil during the growing season, about 20% came from the labeled N source when 60 kg N ha\(^{-1}\) of labeled N was applied to \(M. \times \text{giganteus}\) during the second season of growth. The authors suspected that the majority of the actual N taken up by the crop came from mineralized soil organic matter.

**CONCLUSIONS**

This study increases our understanding of how different environments impact \(M. \times \text{giganteus}\) morphology, growth, and biomass yield. Not surprisingly, increases in biomass yield from season two to season three rely on good growing conditions. Significant biomass yield decreases from 2009 (season 2) to 2010 (season 3) were related to a late spring frost and excessively wet spring, followed by a hot and excessively dry late summer in KY, and hot, dry weather, and poor soil conditions in NJ. Significant increases in dry biomass yields between season two and season three are highly correlated with taller plants and greater tiller densities, which are a function of adequate precipitation and warm summer temperatures, as was the case for NE in 2010. Also of importance, nitrogen fertilization had no significant effects on \(M. \times \text{giganteus}\).
giganteus biomass in season two or three at any site. As the crop matures and becomes fully productive, this experiment will shed important light on the capacity of M. x giganteus to provide stable and reliable biomass yields at these locations.

Acknowledgements

The authors acknowledge the Sun Grant/U.S. Department of Energy Regional Biomass Feedstock Partnership for funding this study, as well as the Energy Biosciences Institute Energy Farm at the University of Illinois Urbana-Champaign for providing land and labor support for this study.

REFERENCES


### TABLES

**Table 3.1.** Selected soil variables from each site sampled during summer 2008 at five soil depths (0-10, 10-20, 23-30, 30-50, and 50-100 cm).

<table>
<thead>
<tr>
<th>Location</th>
<th>depth, cm</th>
<th>% sand</th>
<th>% silt</th>
<th>% clay</th>
<th>pH</th>
<th>CEC, cmol(_e) kg(^{-1})</th>
<th>% SOM</th>
<th>Total (%)</th>
<th>----</th>
<th>----</th>
<th>----</th>
<th>----</th>
<th>----</th>
<th>----</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-10</td>
<td>55</td>
<td>30</td>
<td>16</td>
<td>5.7</td>
<td>10.6</td>
<td>1.9</td>
<td>1.14 0.11</td>
<td>39.1</td>
<td>110</td>
<td>1390</td>
<td>154</td>
<td>15.8</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>54</td>
<td>30</td>
<td>15</td>
<td>5.9</td>
<td>10.7</td>
<td>1.9</td>
<td>1.11 0.11</td>
<td>47.1</td>
<td>144</td>
<td>1613</td>
<td>154</td>
<td>17.1</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>52</td>
<td>32</td>
<td>16</td>
<td>6.0</td>
<td>10.9</td>
<td>1.9</td>
<td>1.08 0.11</td>
<td>39.5</td>
<td>130</td>
<td>1686</td>
<td>177</td>
<td>17.4</td>
<td>1.66</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>36</td>
<td>43</td>
<td>21</td>
<td>6.0</td>
<td>12.0</td>
<td>1.6</td>
<td>0.75 0.08</td>
<td>11.3</td>
<td>75</td>
<td>1722</td>
<td>325</td>
<td>13.4</td>
<td>1.59</td>
</tr>
<tr>
<td>Mead, NE</td>
<td>50-100</td>
<td>11</td>
<td>53</td>
<td>35</td>
<td>6.5</td>
<td>20.9</td>
<td>1.2</td>
<td>0.41 0.05</td>
<td>1.4</td>
<td>126</td>
<td>2659</td>
<td>840</td>
<td>11.4</td>
<td>1.64</td>
</tr>
<tr>
<td>Lexington, KY</td>
<td>0-10</td>
<td>9</td>
<td>64</td>
<td>27</td>
<td>5.1</td>
<td>18.6</td>
<td>4.7</td>
<td>2.49 0.31</td>
<td>322.2</td>
<td>229</td>
<td>1860</td>
<td>214</td>
<td>45.5</td>
<td>1.38</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>9</td>
<td>63</td>
<td>28</td>
<td>5.8</td>
<td>16.2</td>
<td>3.2</td>
<td>1.64 0.21</td>
<td>302.8</td>
<td>117</td>
<td>2122</td>
<td>174</td>
<td>25.2</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>8</td>
<td>60</td>
<td>32</td>
<td>5.9</td>
<td>16.0</td>
<td>2.4</td>
<td>1.08 0.15</td>
<td>321.7</td>
<td>91</td>
<td>2145</td>
<td>144</td>
<td>16.3</td>
<td>1.57</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>10</td>
<td>52</td>
<td>38</td>
<td>6.0</td>
<td>17.8</td>
<td>1.8</td>
<td>0.66 0.10</td>
<td>383.4</td>
<td>92</td>
<td>2405</td>
<td>133</td>
<td>12.5</td>
<td>1.71</td>
</tr>
<tr>
<td></td>
<td>50-100</td>
<td>14</td>
<td>38</td>
<td>48</td>
<td>5.9</td>
<td>25.6</td>
<td>1.8</td>
<td>0.46 0.09</td>
<td>391.8</td>
<td>106</td>
<td>3453</td>
<td>146</td>
<td>17.3</td>
<td>1.83</td>
</tr>
<tr>
<td>Adelphia, NJ</td>
<td>0-10</td>
<td>4</td>
<td>59</td>
<td>36</td>
<td>6.1</td>
<td>22.4</td>
<td>5.1</td>
<td>2.99 0.33</td>
<td>108.3</td>
<td>667</td>
<td>3053</td>
<td>610</td>
<td>19.6</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>4</td>
<td>58</td>
<td>39</td>
<td>6.7</td>
<td>22.6</td>
<td>3.6</td>
<td>1.98 0.24</td>
<td>74.7</td>
<td>672</td>
<td>3082</td>
<td>634</td>
<td>16.2</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>4</td>
<td>55</td>
<td>42</td>
<td>6.7</td>
<td>23.3</td>
<td>3.2</td>
<td>1.70 0.20</td>
<td>60.3</td>
<td>614</td>
<td>3098</td>
<td>715</td>
<td>14.9</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>3</td>
<td>54</td>
<td>43</td>
<td>6.9</td>
<td>23.8</td>
<td>2.5</td>
<td>1.18 0.14</td>
<td>28.4</td>
<td>575</td>
<td>3006</td>
<td>834</td>
<td>13.7</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>50-100</td>
<td>4</td>
<td>56</td>
<td>40</td>
<td>7.0</td>
<td>23.2</td>
<td>1.4</td>
<td>0.53 0.07</td>
<td>24.9</td>
<td>414</td>
<td>2861</td>
<td>879</td>
<td>11.6</td>
<td>1.53</td>
</tr>
</tbody>
</table>

Abbreviations are as follows: cation exchange capacity (CEC), soil organic matter (SOM), and bulk density (BD).

* a restrictive soil feature ranging between 50 and 80 cm precluded the calculation of bulk density at this NJ site.
Table 3.2. Total monthly precipitation (mm) at each location during 2008, 2009, and 2010, and their 30-yr normal averages.

<table>
<thead>
<tr>
<th>Month</th>
<th>IL 2008</th>
<th>IL 2009</th>
<th>IL 2010</th>
<th>IL 30-year normal</th>
<th>KY 2008</th>
<th>KY 2009</th>
<th>KY 2010</th>
<th>KY 30-year normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>59</td>
<td>17</td>
<td>31</td>
<td>48</td>
<td>112</td>
<td>110</td>
<td>76</td>
<td>85</td>
</tr>
<tr>
<td>Feb</td>
<td>151</td>
<td>43</td>
<td>41</td>
<td>51</td>
<td>146</td>
<td>65</td>
<td>41</td>
<td>83</td>
</tr>
<tr>
<td>Mar</td>
<td>72</td>
<td>67</td>
<td>74</td>
<td>82</td>
<td>160</td>
<td>61</td>
<td>29</td>
<td>112</td>
</tr>
<tr>
<td>Apr</td>
<td>76</td>
<td>176</td>
<td>53</td>
<td>93</td>
<td>150</td>
<td>121</td>
<td>59</td>
<td>93</td>
</tr>
<tr>
<td>May</td>
<td>154</td>
<td>145</td>
<td>87</td>
<td>122</td>
<td>112</td>
<td>153</td>
<td>253</td>
<td>121</td>
</tr>
<tr>
<td>Jun</td>
<td>163</td>
<td>112</td>
<td>212</td>
<td>107</td>
<td>91</td>
<td>132</td>
<td>117</td>
<td>116</td>
</tr>
<tr>
<td>Jul</td>
<td>200</td>
<td>160</td>
<td>95</td>
<td>119</td>
<td>87</td>
<td>192</td>
<td>154</td>
<td>122</td>
</tr>
<tr>
<td>Aug</td>
<td>20</td>
<td>143</td>
<td>42</td>
<td>111</td>
<td>55</td>
<td>115</td>
<td>15</td>
<td>96</td>
</tr>
<tr>
<td>Sep</td>
<td>207</td>
<td>20</td>
<td>81</td>
<td>82</td>
<td>36</td>
<td>150</td>
<td>15</td>
<td>79</td>
</tr>
<tr>
<td>Oct</td>
<td>75</td>
<td>223</td>
<td>28</td>
<td>71</td>
<td>39</td>
<td>147</td>
<td>31</td>
<td>69</td>
</tr>
<tr>
<td>Nov</td>
<td>33</td>
<td>100</td>
<td>98</td>
<td>88</td>
<td>64</td>
<td>24</td>
<td>113</td>
<td>87</td>
</tr>
<tr>
<td>Dec</td>
<td>124</td>
<td>96</td>
<td>65</td>
<td>70</td>
<td>153</td>
<td>102</td>
<td>63</td>
<td>102</td>
</tr>
<tr>
<td>Annual</td>
<td>1336</td>
<td>1302</td>
<td>906</td>
<td>1043</td>
<td>1205</td>
<td>1372</td>
<td>966</td>
<td>1166</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>6</td>
<td>7</td>
<td>23</td>
<td>12</td>
<td>69</td>
<td>71</td>
<td>67</td>
<td>95</td>
</tr>
<tr>
<td>Feb</td>
<td>10</td>
<td>12</td>
<td>17</td>
<td>13</td>
<td>110</td>
<td>15</td>
<td>110</td>
<td>70</td>
</tr>
<tr>
<td>Mar</td>
<td>17</td>
<td>8</td>
<td>41</td>
<td>47</td>
<td>83</td>
<td>47</td>
<td>229</td>
<td>100</td>
</tr>
<tr>
<td>Apr</td>
<td>118</td>
<td>41</td>
<td>102</td>
<td>70</td>
<td>62</td>
<td>99</td>
<td>67</td>
<td>100</td>
</tr>
<tr>
<td>May</td>
<td>151</td>
<td>30</td>
<td>68</td>
<td>106</td>
<td>116</td>
<td>112</td>
<td>82</td>
<td>112</td>
</tr>
<tr>
<td>Jun</td>
<td>251</td>
<td>165</td>
<td>249</td>
<td>101</td>
<td>107</td>
<td>187</td>
<td>78</td>
<td>100</td>
</tr>
<tr>
<td>Jul</td>
<td>95</td>
<td>67</td>
<td>183</td>
<td>84</td>
<td>89</td>
<td>159</td>
<td>75</td>
<td>126</td>
</tr>
<tr>
<td>Aug</td>
<td>26</td>
<td>185</td>
<td>64</td>
<td>85</td>
<td>39</td>
<td>172</td>
<td>20</td>
<td>123</td>
</tr>
<tr>
<td>Sep</td>
<td>110</td>
<td>39</td>
<td>148</td>
<td>73</td>
<td>178</td>
<td>100</td>
<td>77</td>
<td>109</td>
</tr>
<tr>
<td>Oct</td>
<td>129</td>
<td>110</td>
<td>6</td>
<td>55</td>
<td>90</td>
<td>119</td>
<td>82</td>
<td>87</td>
</tr>
<tr>
<td>Nov</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>40</td>
<td>84</td>
<td>64</td>
<td>50</td>
<td>93</td>
</tr>
<tr>
<td>Dec</td>
<td>30</td>
<td>67</td>
<td>0</td>
<td>18</td>
<td>151</td>
<td>166</td>
<td>74</td>
<td>95</td>
</tr>
<tr>
<td>Annual</td>
<td>987</td>
<td>732</td>
<td>902</td>
<td>704</td>
<td>1177</td>
<td>1311</td>
<td>1012</td>
<td>1211</td>
</tr>
</tbody>
</table>
Table 3.3. Average minimum and maximum air temperature (°C) at each location (IL, KY, NE, and NJ) during 2008, 2009, and 2010, and their 30-y normal averages.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>-8.6</td>
<td>-12.3</td>
<td>-10.1</td>
<td>-8.8</td>
<td>1.8</td>
<td>-2.4</td>
<td>-3.4</td>
<td>0.0</td>
<td>-4.4</td>
<td>-6.5</td>
<td>-5.8</td>
<td>-4.4</td>
<td>4.7</td>
<td>2.6</td>
<td>1.7</td>
<td>4.4</td>
</tr>
<tr>
<td>Feb</td>
<td>-7.9</td>
<td>-5.7</td>
<td>-8.0</td>
<td>-6.1</td>
<td>0.7</td>
<td>-4.7</td>
<td>-3.1</td>
<td>-2.3</td>
<td>-2.1</td>
<td>-5.6</td>
<td>-2.4</td>
<td>6.2</td>
<td>8.5</td>
<td>2.1</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>Mar</td>
<td>-1.1</td>
<td>0.1</td>
<td>1.1</td>
<td>-0.9</td>
<td>8.5</td>
<td>12.6</td>
<td>11.9</td>
<td>9.7</td>
<td>1.2</td>
<td>3.4</td>
<td>2.9</td>
<td>2.2</td>
<td>12.3</td>
<td>14.3</td>
<td>13.4</td>
<td>12.9</td>
</tr>
<tr>
<td>Apr</td>
<td>4.7</td>
<td>5.0</td>
<td>7.6</td>
<td>4.4</td>
<td>16.6</td>
<td>16.3</td>
<td>21.3</td>
<td>16.8</td>
<td>6.8</td>
<td>7.4</td>
<td>8.5</td>
<td>6.7</td>
<td>18.2</td>
<td>18.7</td>
<td>22.0</td>
<td>18.4</td>
</tr>
<tr>
<td>May</td>
<td>8.9</td>
<td>11.4</td>
<td>12.5</td>
<td>10.6</td>
<td>20.4</td>
<td>23.3</td>
<td>23.7</td>
<td>23.1</td>
<td>10.5</td>
<td>13.1</td>
<td>14.4</td>
<td>12.0</td>
<td>22.0</td>
<td>23.1</td>
<td>24.3</td>
<td>23.3</td>
</tr>
<tr>
<td>Jun</td>
<td>17.2</td>
<td>18.1</td>
<td>18.6</td>
<td>15.8</td>
<td>28.6</td>
<td>29.2</td>
<td>29.0</td>
<td>28.1</td>
<td>17.4</td>
<td>17.9</td>
<td>19.5</td>
<td>16.8</td>
<td>29.0</td>
<td>28.3</td>
<td>30.1</td>
<td>27.9</td>
</tr>
<tr>
<td>Jul</td>
<td>17.6</td>
<td>16.0</td>
<td>19.4</td>
<td>18.0</td>
<td>28.8</td>
<td>26.2</td>
<td>30.5</td>
<td>29.6</td>
<td>18.2</td>
<td>17.6</td>
<td>20.3</td>
<td>19.1</td>
<td>30.2</td>
<td>26.8</td>
<td>30.8</td>
<td>29.9</td>
</tr>
<tr>
<td>Aug</td>
<td>16.5</td>
<td>15.8</td>
<td>18.8</td>
<td>16.9</td>
<td>28.0</td>
<td>26.9</td>
<td>31.3</td>
<td>28.4</td>
<td>17.3</td>
<td>17.9</td>
<td>19.4</td>
<td>18.3</td>
<td>30.0</td>
<td>27.9</td>
<td>31.8</td>
<td>29.2</td>
</tr>
<tr>
<td>Sep</td>
<td>14.1</td>
<td>13.9</td>
<td>12.9</td>
<td>12.4</td>
<td>25.3</td>
<td>24.7</td>
<td>26.3</td>
<td>25.3</td>
<td>15.5</td>
<td>15.6</td>
<td>14.2</td>
<td>14.4</td>
<td>28.4</td>
<td>24.9</td>
<td>28.8</td>
<td>25.6</td>
</tr>
<tr>
<td>Oct</td>
<td>6.1</td>
<td>5.3</td>
<td>6.2</td>
<td>6.1</td>
<td>19.2</td>
<td>14.4</td>
<td>20.8</td>
<td>18.4</td>
<td>7.4</td>
<td>6.9</td>
<td>7.4</td>
<td>8.0</td>
<td>20.6</td>
<td>16.6</td>
<td>22.2</td>
<td>19.4</td>
</tr>
<tr>
<td>Nov</td>
<td>-0.6</td>
<td>2.7</td>
<td>-0.7</td>
<td>0.3</td>
<td>8.9</td>
<td>13.1</td>
<td>12.1</td>
<td>9.7</td>
<td>0.9</td>
<td>3.7</td>
<td>2.1</td>
<td>2.9</td>
<td>11.2</td>
<td>14.1</td>
<td>14.4</td>
<td>12.5</td>
</tr>
<tr>
<td>Dec</td>
<td>-7.8</td>
<td>-6.1</td>
<td>-8.8</td>
<td>-5.6</td>
<td>1.3</td>
<td>1.9</td>
<td>-1.4</td>
<td>2.7</td>
<td>-3.3</td>
<td>-2.4</td>
<td>-5.8</td>
<td>-2.0</td>
<td>7.6</td>
<td>5.8</td>
<td>0.8</td>
<td>6.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>12.9</td>
<td>-12.4</td>
<td>-13.4</td>
<td>-12.4</td>
<td>-1.6</td>
<td>0.4</td>
<td>-5.6</td>
<td>-0.7</td>
<td>-3.9</td>
<td>-7.6</td>
<td>-4.9</td>
<td>-5.8</td>
<td>6.4</td>
<td>1.3</td>
<td>4.1</td>
<td>3.7</td>
</tr>
<tr>
<td>Feb</td>
<td>-11.6</td>
<td>-8.4</td>
<td>-11.7</td>
<td>-9.1</td>
<td>-0.4</td>
<td>6.5</td>
<td>-2.7</td>
<td>-2.8</td>
<td>-3.4</td>
<td>-4.8</td>
<td>-5.0</td>
<td>-5.0</td>
<td>6.7</td>
<td>7.4</td>
<td>7.2</td>
<td>5.1</td>
</tr>
<tr>
<td>Mar</td>
<td>-5.0</td>
<td>-4.2</td>
<td>-1.8</td>
<td>-3.0</td>
<td>9.6</td>
<td>10.2</td>
<td>8.8</td>
<td>9.4</td>
<td>0.2</td>
<td>-1.1</td>
<td>2.4</td>
<td>-0.4</td>
<td>11.2</td>
<td>10.4</td>
<td>13.4</td>
<td>10.1</td>
</tr>
<tr>
<td>Apr</td>
<td>0.7</td>
<td>1.1</td>
<td>5.2</td>
<td>3.4</td>
<td>13.4</td>
<td>16.1</td>
<td>20.3</td>
<td>16.7</td>
<td>5.7</td>
<td>5.4</td>
<td>6.3</td>
<td>4.1</td>
<td>18.1</td>
<td>17.4</td>
<td>20.1</td>
<td>16.1</td>
</tr>
<tr>
<td>May</td>
<td>7.9</td>
<td>9.1</td>
<td>8.9</td>
<td>9.8</td>
<td>21.5</td>
<td>23.7</td>
<td>21.4</td>
<td>22.8</td>
<td>8.6</td>
<td>10.6</td>
<td>10.8</td>
<td>9.4</td>
<td>20.8</td>
<td>22.1</td>
<td>24.9</td>
<td>22.0</td>
</tr>
<tr>
<td>Jun</td>
<td>14.9</td>
<td>15.0</td>
<td>15.9</td>
<td>15.3</td>
<td>27.8</td>
<td>27.3</td>
<td>28.4</td>
<td>28.6</td>
<td>16.1</td>
<td>14.7</td>
<td>17.1</td>
<td>14.4</td>
<td>29.4</td>
<td>24.9</td>
<td>30.0</td>
<td>26.8</td>
</tr>
<tr>
<td>Jul</td>
<td>17.3</td>
<td>14.8</td>
<td>18.4</td>
<td>17.9</td>
<td>29.9</td>
<td>27.2</td>
<td>29.6</td>
<td>30.8</td>
<td>18.4</td>
<td>15.7</td>
<td>19.8</td>
<td>17.3</td>
<td>31.0</td>
<td>28.8</td>
<td>32.3</td>
<td>29.4</td>
</tr>
<tr>
<td>Aug</td>
<td>15.2</td>
<td>14.3</td>
<td>17.4</td>
<td>16.4</td>
<td>29.4</td>
<td>27.5</td>
<td>31.1</td>
<td>29.3</td>
<td>14.4</td>
<td>17.6</td>
<td>18.4</td>
<td>16.4</td>
<td>28.9</td>
<td>29.5</td>
<td>29.9</td>
<td>28.4</td>
</tr>
<tr>
<td>Sep</td>
<td>10.4</td>
<td>10.3</td>
<td>11.8</td>
<td>11.1</td>
<td>24.6</td>
<td>24.1</td>
<td>25.5</td>
<td>25.3</td>
<td>13.4</td>
<td>11.7</td>
<td>14.1</td>
<td>12.2</td>
<td>25.6</td>
<td>23.7</td>
<td>27.8</td>
<td>24.6</td>
</tr>
<tr>
<td>Oct</td>
<td>4.2</td>
<td>1.8</td>
<td>3.8</td>
<td>4.1</td>
<td>18.2</td>
<td>12.4</td>
<td>21.7</td>
<td>18.5</td>
<td>3.7</td>
<td>5.4</td>
<td>7.4</td>
<td>5.7</td>
<td>18.6</td>
<td>17.0</td>
<td>19.5</td>
<td>18.4</td>
</tr>
<tr>
<td>Nov</td>
<td>-2.2</td>
<td>-0.7</td>
<td>-2.9</td>
<td>10.1</td>
<td>13.3</td>
<td>.</td>
<td>8.6</td>
<td>1.3</td>
<td>1.3</td>
<td>4.8</td>
<td>0.9</td>
<td>1.4</td>
<td>10.9</td>
<td>14.4</td>
<td>13.3</td>
<td>12.3</td>
</tr>
<tr>
<td>Dec</td>
<td>-12.3</td>
<td>-12.5</td>
<td>-9.3</td>
<td>-0.3</td>
<td>-1.9</td>
<td>.</td>
<td>1.3</td>
<td>-3.0</td>
<td>-3.1</td>
<td>-5.4</td>
<td>-2.9</td>
<td>7.8</td>
<td>6.3</td>
<td>4.1</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>2009 Growing Season</td>
<td>2010 Growing Season</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>---------------------</td>
<td>---------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plant Height</td>
<td>Tiller Density</td>
<td>Biomass Yield</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Measurements</td>
<td>Measurements</td>
<td>Harvest</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL</td>
<td>Jan. 2010</td>
<td>16 Mar. 2010†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KY</td>
<td>24 Apr., 18 May, 19 June, 27 July, 4 Sept.</td>
<td>4 Sept.</td>
<td>1 April 2010†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NE</td>
<td>10 May, 10 June, 15 July, 17 Aug., 15 Sept.</td>
<td>15 Sept.</td>
<td>1 April 2010†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL</td>
<td>29 Nov. 2010</td>
<td>29 Nov. 2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

†Harvesting for the 2009 growing season in IL, KY, and NJ actually occurred early in 2010 before the start of the 2010 growing season.
Table 3.5. Season length, accumulated thermal time, average emergence date, and flowering date(s) for each growing season and location (KY, NE, and NJ).

<table>
<thead>
<tr>
<th>Location</th>
<th>Season length</th>
<th>Accumulated thermal time</th>
<th>Emergence date</th>
<th>Flowering date(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009 growing season</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KY</td>
<td>193 days (8 Apr. – 18 Oct.)</td>
<td>3783</td>
<td>31 Mar.</td>
<td>18 Sept.</td>
</tr>
<tr>
<td>NE</td>
<td>172 days (15 Apr. – 4 Oct.)</td>
<td>3196</td>
<td>26 Apr. – 1 May</td>
<td>23 Sept.</td>
</tr>
<tr>
<td>NJ</td>
<td>185 days (17 Apr. – 19 Oct.)</td>
<td>3459</td>
<td>27 Apr.</td>
<td>~25-30 Sept.</td>
</tr>
<tr>
<td></td>
<td>2010 growing season</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL</td>
<td>196 days (10 Apr. – 23 Oct.)</td>
<td>3911</td>
<td>10 Apr.</td>
<td>1 Oct.</td>
</tr>
<tr>
<td>KY</td>
<td>217 days (27 Mar. – 30 Oct.)</td>
<td>4531</td>
<td>2 Apr.</td>
<td>did not flower</td>
</tr>
<tr>
<td>NE</td>
<td>167 days (19 Apr. – 3 Oct.)</td>
<td>3402</td>
<td>2 week Apr.</td>
<td>27 Sept.</td>
</tr>
<tr>
<td>NJ</td>
<td>218 days (28 Mar. – 1 Nov.)</td>
<td>4601</td>
<td>11 Apr.</td>
<td>30 Oct. #</td>
</tr>
</tbody>
</table>

† Season lengths were calculated as the number of days between the last frost in the spring to the first frost in the fall. One exception is in KY in 2010, where a late frost on 19 Apr. was not used as the beginning of the growing season since there had already been two-to-three weeks of above-freezing weather since the previous frost on 27 March. In this case, 27 Mar. was marked as the last frost in the spring.
‡ Accumulated thermal time was calculated with a base temperature of 0°C, by determining the average of the minimum (when greater than 0°C) and maximum daily (no limit) temperatures, and summing these values across time. In calculating accumulated thermal time for individual days, if the average temperature for that day did not exceed 0°C, no TT was accumulated.
§ Emergence date was determined in the spring when approximately the first 10 plants in each plot had emerged.
¶ Date of full-headed flowering was determined when approximately 50% of the plants in each plot were fully flowered.
# Only plots that flowered at Adelphia, NJ in 2010 were those plots applied with 0 kg N ha⁻¹ and some that were applied with 60 kg N ha⁻¹. Those that did not flower, flowered on 30 Oct. First fall frost was 1 Nov.
Table 3.6. 95% confidence intervals (upper and lower) of the parameters estimates of the logistic growth function for each environment (KY-2009, KY-2010, NE-2009, NE-2010, NJ-2009, and NJ-2010) fit for *M. x giganteus* plant height.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>environment</th>
<th>lower</th>
<th>estimate</th>
<th>upper</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>asym</strong></td>
<td>KY-2009</td>
<td>2.99</td>
<td>3.08</td>
<td>3.17</td>
</tr>
<tr>
<td></td>
<td>KY-2010</td>
<td>3.19</td>
<td>3.39</td>
<td>3.59</td>
</tr>
<tr>
<td></td>
<td>NE-2009</td>
<td>2.62</td>
<td>2.85</td>
<td>3.07</td>
</tr>
<tr>
<td></td>
<td>NE-2010</td>
<td>3.59</td>
<td>3.79</td>
<td>3.99</td>
</tr>
<tr>
<td></td>
<td>NJ-2009</td>
<td>3.17</td>
<td>3.37</td>
<td>3.57</td>
</tr>
<tr>
<td></td>
<td>NJ-2010</td>
<td>2.80</td>
<td>3.00</td>
<td>3.20</td>
</tr>
<tr>
<td><strong>xmid</strong></td>
<td>KY-2009</td>
<td>149.1</td>
<td>151.5</td>
<td>153.8</td>
</tr>
<tr>
<td></td>
<td>KY-2010</td>
<td>138.3</td>
<td>143.5</td>
<td>148.7</td>
</tr>
<tr>
<td></td>
<td>NE-2009</td>
<td>165.4</td>
<td>171.5</td>
<td>177.6</td>
</tr>
<tr>
<td></td>
<td>NE-2010</td>
<td>156.7</td>
<td>161.7</td>
<td>166.8</td>
</tr>
<tr>
<td></td>
<td>NJ-2009</td>
<td>155.1</td>
<td>160.2</td>
<td>165.4</td>
</tr>
<tr>
<td></td>
<td>NJ-2010</td>
<td>141.8</td>
<td>146.8</td>
<td>151.9</td>
</tr>
<tr>
<td><strong>scal</strong></td>
<td>KY-2009</td>
<td>19.71</td>
<td>21.75</td>
<td>23.79</td>
</tr>
<tr>
<td></td>
<td>KY-2010</td>
<td>16.42</td>
<td>20.86</td>
<td>25.30</td>
</tr>
<tr>
<td></td>
<td>NE-2009</td>
<td>19.08</td>
<td>24.23</td>
<td>29.37</td>
</tr>
<tr>
<td></td>
<td>NE-2010</td>
<td>17.53</td>
<td>21.84</td>
<td>26.15</td>
</tr>
<tr>
<td></td>
<td>NJ-2009</td>
<td>15.31</td>
<td>19.82</td>
<td>24.33</td>
</tr>
<tr>
<td></td>
<td>NJ-2010</td>
<td>10.96</td>
<td>15.38</td>
<td>19.81</td>
</tr>
</tbody>
</table>

*asym = maximum height (m), xmid = day of year at which crop achieves half of its maximum height, scal = time (in terms of days) between half and three quarters maximum height.*
Table 3.7. *M. x giganteus* dry biomass yield (Mg ha\(^{-1}\)) and tiller density (number tillers m\(^{-2}\)) estimated for each environment at each of three N rates (kg N ha\(^{-1}\)) and their means averaged across N rates.

<table>
<thead>
<tr>
<th>Environment</th>
<th>N rate, kg N ha(^{-1})</th>
<th>mean(^†)</th>
<th>p-value(^‡)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>------------</td>
<td>------------------------</td>
<td>--------</td>
<td>---------</td>
</tr>
<tr>
<td>KY-2009</td>
<td>16.7§</td>
<td>17.5</td>
<td>16.9</td>
</tr>
<tr>
<td>KY-2010</td>
<td>12.8</td>
<td>13.2</td>
<td>13.6</td>
</tr>
<tr>
<td>NE-2009</td>
<td>15.7</td>
<td>15.9</td>
<td>15.2</td>
</tr>
<tr>
<td>NE-2010</td>
<td>27</td>
<td>27.8</td>
<td>27.4</td>
</tr>
<tr>
<td>NJ-2009</td>
<td>12.2</td>
<td>14.3</td>
<td>13.8</td>
</tr>
<tr>
<td>NJ-2010</td>
<td>11.6</td>
<td>11.7</td>
<td>10.7</td>
</tr>
</tbody>
</table>

\(^†\) mean values are averaged across N rate.

\(^‡\) P values for contrast statements comparing mean environment values within a location (KY-2009 vs. KY-2010, NE-2009 vs. NE-2010, and NJ-2009 vs. NJ-2010).

\(^§\) no contrasts among N rates were made because the environment x N rate and N rate effects were non-significant for both dry biomass and tiller density.
**FIGURES**

*Figure 3.1.* *M. x giganteus* plant height (m) plotted against day of year (DOY) and fit with logistic growth functions for each N rate (0, 60, 120 kg N ha\(^{-1}\)) in each of six environments (KY-2009, KY-2010, NE-2009, NE-2009, NE-2010, NJ-2009, and NJ-2010).
Figure 3.2. Matrix scatter plots showing relationships between *M. x giganteus* dry biomass yield (Mg ha$^{-1}$) end of season plant height (m), tiller density (number tillers m$^{-2}$), average number of phytomers tiller$^{-1}$, and average tiller diameter (cm) grouped by different 2010 environments: KY-2010, NE-2010, and NJ-2010.
CHAPTER 4

Management of Forage and Energy Sorghum for Biomass Production in Illinois

ABSTRACT

No research has been published in IL evaluating forage and energy sorghum as biomass feedstock crops. This study was conducted to evaluate the growth and biomass potential of these sorghum types in different IL environment under different nitrogen (N) rates. Two forage sorghum and two energy sorghum hybrids each were evaluated in 2009 in one environment (Urbana 2009) under four N rates (0, 50, 100, and 150 kg N ha\(^{-1}\)), and in 2010 in three environments (Urbana 2010, Dixon Springs 2010, and Perry 2010) under five N rates (0, 56, 112, 168, and 224 kg N ha\(^{-1}\)). Measurements of biomass yield, plant height, leaf development, and leaf area index (LAI) were collected to evaluate the effects of environment, N rate, sorghum type, and sorghum hybrid. Environment had a major impact on plant growth and total biomass yields. Forage sorghum harvested twice annually (summer and fall) yielded less than energy sorghum harvested once in the fall in both 2009 (\(P < 0.0114\)) and 2010 (\(P < 0.0734\)). Total energy and forage sorghum biomass yields averaged across all 2010 environments were 30.1 Mg DM ha\(^{-1}\) and 19.2 Mg DM ha\(^{-1}\), respectively. Biomass yield, LAI, and plant height response to N rate were observed up to 150 kg N ha\(^{-1}\) in 2009 and up to at least 168 kg N ha\(^{-1}\) in 2010. Energy sorghum reached plant heights of 3.7 m, 4.1 m, and 3.8 m in the Dixon Springs 2010, Perry 2010, and Urbana 2010 environments, respectively. Leaf development was linearly related to GDD and in the warmest environments the average number of fully expanded leaves reached 28 on the energy sorghum hybrids. Photoperiod-sensitive energy and forage sorghum hybrids possess great potential in IL as biomass crops because of their ability to remain vegetative until late Sept., and therefore produce large amounts of biomass.
INTRODUCTION

The need to produce large quantity of bioenergy feedstock has become an increasingly important priority in the US as energy prices continue to increase and foreign oil and gas become more volatile (Perlack et al., 2005; Asif and Muneer, 2007; U.S. Chamber of Commerce, 2010). Continued research efforts and the scaling up of a plant and biomass based energy industry is necessary to meet the US’s vision of replacing 30% of current petroleum consumption by 2030 with biofuels (Perlack et al., 2005). These efforts will also help to meet the government mandate of producing 136 billion liters of renewable fuels by 2022, of which 60 billion liters must come from cellulosic sources (Energy Independence and Security Act of 2007). Forage (Sorghum bicolor L.) and biomass (referred to as energy sorghum) sorghums are sorghum types that can help meet this need because these grasses produce large amounts of structural carbohydrates (cellulosic feedstock) in their biomass (McBee and Miller, 1990; Rooney et al., 2007; Hartley et al., 2009). Sorghum is a multipurpose C4 photosynthetic, annual grass that has been grown as a grain crop for food and feed and as a forage crop. More recently, forage and energy sorghum hybrids have been developed and identified as promising biomass crops. These sorghum types possess potential because of potentially high yields, efficient water-use efficiency, drought tolerance, seed reproduction, wide adaptability, and potential for genetic improvement (Rooney et al., 2007; Miller and McBe, 1993).

Forage sorghum includes sorghum x sudangrass and brown midrib hybrids that have been used primarily in the livestock industry (McCollum et al., 2005; Beyaert and Roy, 2005). Recent research and hybrid improvements, however, suggest that brown midrib forage sorghum and certain photoperiod-sensitive forage sorghum hybrids possess great biomass yield potential (Rooney et al., 2007; Venuto and Kindiger, 2008; Hallam et al., 2001). Because brown midrib
hybrids have relatively low levels of lignin, the cellulosic ethanol conversion process may be more efficient than with other sorghum hybrids containing higher levels of lignin (Propheter et al., 2010). Photoperiod-sensitive forage sorghum hybrids (as well as energy sorghums) will continue vegetative growth until day lengths are \( \leq 12 \text{ hrs 20 min} \) (Rooney and Aydin, 1999; McCollum et al., 2005). This ability to remain vegetative late into the growing season is also an advantage in dryland or rainfed agriculture because sorghums’ tolerance to drought is greater while growing vegetatively (Rooney et al., 2007) than reproductively when significant stress can occur (Prasad et al., 2008). Forage sorghum hybrids also have the ability to ‘rattoon’ or regrow after being harvested and can produce multiple cuttings in one season (Beyaert and Roy, 2005; Ketterings et al., 2007). Photoperiod-sensitive forage sorghum hybrids have reached mean dry biomass yields of 24.0 Mg dry matter (DM) ha\(^{-1}\) with only one cutting in Bushland, TX (McCollum et al., 2005), and 31.9 Mg DM ha\(^{-1}\) in College Station, TX (Miller and McBee, 1993). In a study in El Reno, OK a double cutting (Aug. and Nov.) of several forage sorghum hybrids yielded an average of 25.5 Mg DM ha\(^{-1}\) dry biomass whereas a single cutting of the same hybrids in Sept. yielded 27.0 Mg DM ha\(^{-1}\) (Venuto and Kindiger, 2008). In this study the highest yield was achieved from a single Sept. harvest of a photoperiod-sensitive forage sorghum hybrid that produced 40.3 Mg DM ha\(^{-1}\). However, multi-cut sorghum biomass total yields are usually greater than single cut sorghum biomass yields in tropical and subtropical regions (Rooney et al., 2007).

Energy sorghum hybrids have been developed from photoperiod-insensitive sorghum lines, are photoperiod-sensitive and similar to forage sorghum hybrids, but have been designed to be harvested once per year and possess even greater biomass yield potential than forage sorghum hybrids (Rooney and Aydin, 1999; Rooney et al., 2007; Sorghum Management Guide, 2010).
These energy sorghum hybrids contain large amounts of structural carbohydrates such as cellulose and hemicellulose in the leaves and stalks that can be converted to energy via combustion or into ethanol using cellulosic ethanol conversion methods (McBee and Miller, 1990; Hartley et al., 2009). Energy sorghum hybrids are photoperiod-sensitive, remain vegetative late into the growing season, have been shown to grow for more than 200 days in TX, and may grow 6 m tall (Sorghum Management Guide, 2010), while forage sorghum hybrids may reach heights greater than 4.3 m (Marsalis, 2011). An advantage of growing these photoperiod-sensitive forage and energy sorghum hybrids in more northern environments such as the upper Midwest, allows vegetative growth to continue until late in the growing season. Panicle and flower initiation triggers the end of vegetative biomass accumulation. As long as vegetative growth continues, biomass will continue to accumulate, which is ideal for a bioenergy crop that will be used as dry biomass feedstock (Katrin et al., 2009). No literature coming from IL has been published on forage and energy sorghum produced for biomass feedstock purposes. However, it is expected that when photoperiod-sensitive forage and energy sorghum hybrids are grown in IL, vegetative biomass accumulation will continue until mid or late Sept. because before this time period day lengths are longer than 12 hrs 20 min and the average date of the first fall frost ranges from 21 Oct. in the southwestern region to 7 Oct. in the northern region (IL State Water Survey, 2011, http://www.isws.illinois.edu/atmos/statecli/Frost/first_fall_frost.htm).

There have been studies that have investigated the N response of sorghum when grown for hay and silage, but information is scant regarding the response of forage and energy sorghum to N fertilizer when grown as a biomass feedstock crop. Studies evaluating N rates for sorghum have produced variable results, and as expected, are due in great part to site-to-site variation and different management practices that have been implemented. A management guide for forage
sorghum suggests that in irrigated environments with high yield potential, N rates as high as 269 kg N ha\(^{-1}\) may be needed, but under dryland conditions little to no N fertilizer may be required (Marsalis, 2011). In ON, Canada sorghum x sudangrass cut three times in July, Aug., and Sept. for hay reached maximum yields of 5.95 Mg DM ha\(^{-1}\) with an N application rate of 125 kg N ha\(^{-1}\), although economical optimum N rates were calculated at between 83 kg N ha\(^{-1}\) and 107 kg N ha\(^{-1}\) depending on the prices of N fertilizer and hay (Beyaert and Roy, 2005). Sweet sorghum and forage sorghum reached near maximum yields at 140 kg N ha\(^{-1}\) yr\(^{-1}\) when harvested once in Sept. and between 1988 and 1992 where forage sorghum mean biomass yields ranged from 14.6 to 16.7 Mg DM ha\(^{-1}\) at Ames, IA, and 12.6 to 21.8 Mg DM ha\(^{-1}\) at Chariton, IA (Hallam et al., 2001). In a study in NY, economic optimum N rates based upon a quadratic plus plateau model ranged between 137 and 192 kg ha\(^{-1}\) per cutting in four out of six site-years for brown midrib sorghum x sudangrass cut two times per year in July or Aug. and then again in Sept. (Ketterings et al., 2007). The other two sites had lower economical optimum N rates; 120 kg N ha\(^{-1}\) where a manure application in addition to the synthetic N fertilizer treatments had been applied, and < 56 kg N ha\(^{-1}\) when following a spring plow down of a long term grass and legume stand. In a KS study that evaluated several annual and perennial crops for biofuel feedstock production, photoperiod-sensitive sorghum reached dry biomass yield of 26.8 Mg DM ha\(^{-1}\) when fertilized with 180 kg N ha\(^{-1}\), while three other forage sorghum hybrids reached mean biomass yields ranging from 14.8 Mg DM ha\(^{-1}\) to 20.7 Mg DM ha\(^{-1}\) also with 180 kg N ha\(^{-1}\) (Propheter et al., 2010). Under limited irrigation in Lubbock, TX the optimum N rate for ethanol production from sweet sorghum and photoperiod-sensitive sorghum was 108 kg N ha\(^{-1}\) but the economical optimum N rate ranged between 59 and 101 kg N ha\(^{-1}\) (Tamang et al., 2011).
The overall objective of this study was to evaluate forage and energy sorghum grown for biomass feedstock production in IL. To meet this objective, two forage sorghum hybrids, and two energy sorghum hybrids were grown in four IL environments under different nitrogen rates. Measurements of biomass yield, plant height, leaf development, and leaf area index (LAI) were collected and the effects of environment, N rate, sorghum type, and sorghum hybrids were evaluated.

MATERIALS AND METHODS

This field study was conducted in Urbana, IL (40°04’ N, 88°12’W) in 2009 and 2010 and in Dixon Springs, IL (37°27’ N, 88°43’ W), and Perry, IL (39°48’ N, 90°49’W) in 2010, resulting in four environments in which the effects of N on the growth and yield of sorghum grown for biomass were evaluated. These sites are referred to as Urbana 2009, Urbana 2010, Dixon Springs 2010, and Perry 2010. The soils were a Flanagan series silt loam (Fine, smectitic, mesic Aquic Argiudolls) at Urbana, a Grantsburg silt loam (Fine-silty, mixed, active, mesic Oxyaquic Fragiudalfs) at Dixon Springs, and a Menfro silt loam (Fine-silty, mixed, superactive, mesic Typic Hapludalfs) at Perry. The experiment was arranged as a split-split-plot arrangement in a randomized complete block design with four replications with sorghum type as whole plots, sorghum hybrids as sub plots, and N fertilizer treatments as sub-sub plots. Two forage sorghum hybrids and two energy sorghum hybrids were planted each spring using a small plot drill (Great Plains No-Till Drill (606NT), Salina, KS). Planting dates ranged between 13 May and 9 June depending on the environment (Table 4.3). The energy hybrids, TAMUXH08001 and TX09007, both photoperiod-sensitive, were planted at 185,250 seeds ha\(^{-1}\) spaced at 0.76 m. The forage hybrids, Graze All (a photoperiod-insensitive hybrid) and Graze. n. Bale (and photoperiod-sensitive hybrid) were planted at 247,000 seeds ha\(^{-1}\) spaced at 0.19 m. All hybrids were obtained
from Dr. William Rooney’s breeding program at Texas A&M University. Prior to planting, the seeds had been treated with a herbicide safener, Concep II (Syngenta, Macquarie, NSW). In 2009, four N fertilizer treatments were applied at 0, 50, 100, and 150 kg N ha\(^{-1}\), while in 2010, five N fertilizer treatments were applied at 0, 56, 112, 168, and 224 kg N ha\(^{-1}\). The nitrogen fertilizer source, urea, was surface applied in each environment on the same day as planting (Table 4.3). The sub-sub plots were 5 m wide x 5 m long in 2009 and 5 m wide x 6.7 m long in 2010.

Preemergence herbicide, 2.2 kg a.i. ha\(^{-1}\) of atrazine (6-chloro-N-ethyl-N’-isopropyl-1,3,5-triazine-2,4-diamine) at Urbana and Perry, and 2.2 kg a.i. ha\(^{-1}\) of atrazine and 1.4 kg a.i. ha\(^{-1}\) s-Metolachor (Acetamide, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl]-,(S)) at Dixon Springs were applied to help control weeds. In addition, some manual weed removal was necessary at each site to minimize weed pressure and ensure proper establishment when weather conditions likely reduced the effectiveness of the pre-emergence herbicide. These conditions also resulted in slow, prolonged emergence. Weather data at Urbana were obtained at an on farm weather station for 2009 and 2010 growing season observations, while data for Dixon Springs, Perry, and 30-year weather averages were obtained from nearby weather stations from the Midwestern Regional Climate Center, a cooperative program of the Illinois State Water Survey and the National Climatic Data Center (Table 4.2). Accumulated growing-degree days were calculated with a base temperature of 11°C (Hammer et al., 1993).

Energy sorghum plant height was determined by measuring the height of the upper fully most expanded leaf on the main tiller of one-to-three randomly selected plants on four of five dates throughout the growing season (Table 4.3). On the same tillers, the number of fully expanded leaves was also determined by counting the number of nodes or visible leaves present
on each tiller. These measurements were collected during GS I (vegetative growth from emergence to initiation of reproductive structures) and GS II (panicle initiation through booting and heading) growth stages (Gerik et al., 2003; Sorghum Management Guide, 2010). The focus of these measurements was on the photoperiod-sensitive energy sorghum hybrids (TAMUXH08001, and TX09007) which remained in the GS I stage throughout most of the growing season and only reached the GS II stage near the end of Sept. For the energy sorghum hybrids (TAMUXH08001, and TX09007), leaf area index (LAI) and the proportion of photosynthetic active radiation (PAR, 400-700 nm) intercepted by the crop canopy were measured on four dates during the 2009 and 2010 growing seasons at Urbana. Sampling dates in 2009 were 13 July, 29 July, 29 Aug, and 18 Sept., while sampling dates in 2010 were 25 June, 14 July, 12 Aug., and 31 Aug. The measurements were collected by measuring the PAR above the crop canopy using an external sensor (Model Quantum, LI-COR Biosciences) connected to a linear ceptometer (Model PAR-80, Decagon Devices, Inc.) which was used to measure the amount of PAR not intercepted by the crop canopy. These measurements were taken beneath the crop canopy between 10:00 and 14:00 hrs on sunny or mostly sunny days. Two to three subsamples were taken in each plot for each measurement date and each subsample was the average of ~20 independent readings. Light interception was determined by calculating the proportion of PAR intercepted by the crop canopy. Leaf area index was calculated for each subsample using the observations of radiation interception beneath and above the canopy, and zenith angle and leaf angle distribution (Decagon, 1994). For LAI, only readings with above canopy PAR that were at least 1400 nm were used in the statistical analysis.

The forage sorghum hybrids had the capability of ratooning (regrowth after harvesting) and were harvested twice each season, once near the end of summer and a second time in the fall
This was done per recommendation of Dr. William Rooney at Texas A&M University, plant breeder of hybrids used in this experiment, who suggested that forage sorghum be harvested two times each season and energy sorghum harvested one time in the fall or after the end of the growing season. In 2009 at Urbana, a second harvest for the forage sorghum hybrids was not obtained because of late planting (9 June), a late first harvest (3 Sept), and a relatively short and cool growing season (Table 4.3) that resulted in a lack of harvestable biomass for a second harvest in the fall. Harvesting was done by cutting a 1.216 m wide pass down the middle of each plot using a small plot biomass harvester with an electronic scale for determining harvestable wet biomass (Wintersteiger Cibus S harvester mounted with a Kemper forage chopper, Ames, IA), expect for Perry 2010 where harvesting was done by hand by cutting a 0.76 m pass down the middle of each energy hybrid plot and a 1.1216 m pass down the middle of each forage sorghum hybrid plot. Subsamples were collected from the wet biomass of each plot to determine percent moisture and dry biomass. Subsamples were dried in a forced air oven for at least 48 hr at 60°C and % moisture was used to calculate dry biomass.

**Statistical Analysis**

In each environment, the experiment was arranged as a split-split-plot arrangement in a randomized complete block design with four replications with sorghum type as whole plots, sorghum hybrids as sub plots, and N fertilizer treatments as sub-sub plots. Data from Urbana 2009 were analyzed separately from the data obtained in 2010. Environments and blocks were considered random while the effects of sorghum type, hybrid, and N rate were considered fixed.

The non-linear function used to model the increase in energy sorghum plant height throughout the growing season was the logistic growth function,
Here, \( f(x) \) is energy sorghum plant height (meter units) measured throughout the growing season and \( x \) is the day of year (DOY). Three parameters describe the shape and spread of the function: 1) asymptote (\( \text{asym} \)) or maximum height achieved by the crop, 2) scale (\( \text{scal} \)) or the elapsed time between the crop achieving half and three quarters of its maximum height, and 3) inflection point (\( \text{xmid} \)) or DOY at which the crop achieves half of its maximum height.

Parameters for each experimental unit (i.e. plot) were derived by fitting a logistic function to the data for each environment using the ‘nlme’ package (Pinheiro et al., 2009) of R statistical software (R Core, v. 2.12.1, 2010) by following principles in Pinheiro and Bates (2000). The logistic curves fitted to the data in each experimental unit were plotted visually to evaluate the agreement between the observed and fitted values and to identify possible outliers. Residuals were checked for patterns by plotting standardized residuals against their fitted values and plots were obtained using the ‘graphics’ and ‘lattice’ packages of R (R Core, v. 2.12.1, 2010). Once the parameter estimates were derived they were analyzed in the GLIMMIX procedure of SAS (SAS Institute, 2007) to evaluate the effects of environment, hybrid, and N rate on each logistic growth function parameter.

Leaf area index, forage sorghum summer and fall harvest biomass yields, and total biomass yield analyzed in the GLIMMIX procedure of SAS (SAS Institute, 2007). Leaf area index measurements collected throughout the 2009 and 2010 growing seasons at Urbana were only used in if the above canopy PAR was at least 1400 nm. Before analysis, LAI values for each plot were averaged across subsamples before statistical analysis. Day of year was analyzed using a repeated measures technique with appropriate variance-covariance structure (Littell et al.,

\[
f(x) = \frac{\text{asym}}{1 + e^{\frac{x - \text{xmid}}{\text{scal}}}}
\]
Least square means from 2009 and 2010 were then plotted against DOY for each N rate (Fig. 4.2). Forage sorghum summer and fall biomass yields were analyzed to evaluate the effect of environment, N rate, and hybrid on the biomass yield of each cutting. Total dry biomass yield achieved during the growing season (summer + fall harvest for forage sorghum, and fall harvest for energy sorghum) were analyzed to consider the effects of environment, sorghum type, hybrid, and N rate on the seasons total biomass productivity.

For each variable that was analyzed in the GLIMMIX procedure of SAS (SAS Institute, 2007), it was assumed that the random effects of block and environment were independent normal random variables with expectations zero and their own respective variances, and that the errors had means of zero and common variances. Environments were considered random to account for different weather and other environmental conditions at each site which could not be controlled. Because of the split-split-plot arrangement sorghum hybrids were considered to be nested within sorghum type. Similarly, the blocks in each environment were unique to their associated environment and were thus considered to be nested in environment. Significance of random effects were calculated with a Wald Z test statistic using the COVTEST option in the GLIMMIX procedure of SAS (SAS Institute, 2007). Residuals were examined for normality and the assumption of common variances by inspection of residual plots. Preplanned comparisons and best linear unbiased predictions (i.e. means of random effects) and their interactions were calculated using estimate and contrast statements with appropriate degrees of freedom and standard errors in the GLIMMIX procedure of SAS (SAS Institute, 2007). Fisher’s least significant differences (LSD) were determined at the $\alpha = 0.5$ level using appropriate degrees of freedom and standard errors. Pearson correlation coefficients and their respective $P$-values were calculated using the CORR procedure of SAS (SAS Institute, 2007). Number of fully expanded
leaves accumulated throughout the growing season before harvesting of energy sorghum hybrids exhibited a linear relationship when plotted against GDD. Simple linear regression lines were fit to these data for each environment (Fig. 4.3) using the ‘xyplot’ function of R (R Core, v. 2.12.1, 2010). All other figures were created using the SGPLOT procedure of SAS (SAS Institute, 2007) and SigmaPlot (v. 11.2, Systat Software, inc.). Pearson correlations coefficients were calculated to evaluate end of season plant height, end of season expanded leaf number, and dry biomass yields of energy sorghum. This was done by correlating the average of the final plant height and expanded leaf number measurements collected in each environment (Table 4.3) with energy sorghum biomass yield.

RESULTS AND DISCUSSION

Plant Height

For energy sorghum plant height in Urbana 2009, the main effect of N rate was significant for the \( \text{asym} (P = 0.0007) \), \( \text{xmid} (P = 0.0036) \) and \( \text{scal} (P = 0.0012) \) parameters but not for the hybrid x N rate interaction \( (P \geq 0.3442) \) and main effect of hybrid \( (P \geq 0.2259) \). This suggests that both energy sorghum hybrids (TAMUXH08001 and TX09007) accumulated plant height similarly throughout the growing season and were influenced in the same manner by N rate. As the season progressed, the differences in plant height due to N rate became more and more apparent, and by the end of the season there was a large difference between the maximum height \( (\text{asym}) \) of plots receiving 0 kg N ha\(^{-1}\) and the plots receiving 50, 100, or 150 kg N ha\(^{-1}\) (Fig. 4.1). When the average of the 50, 100, and 150 kg N ha\(^{-1}\) rates were contrasted against the 0 kg N ha\(^{-1}\) rate, there was a significant difference for each logistic function parameter \( (P \leq 0.0018) \). More specifically, the \( \text{asym} \) or maximum height increased significantly from 0 kg N ha\(^{-1}\)
to 150 kg N ha$^{-1}$ ($P = 0.0002$) but the higher N rates (100 kg N ha$^{-1}$ and 150 kg N ha$^{-1}$) were not significantly different from each other ($P = 0.3124$).

For energy sorghum plant height in the 2010 environments, the effects of environment, N rate, and energy sorghum hybrid were evaluated for each logistic function parameters (eq. 1). It was found that the effect of environment was non-significant for the $asym$ ($P = 0.1753$), $xmid$ ($P = 0.2326$) and $scal$ ($P = 0.1642$) parameters, and that the hybrid x N rate interaction ($P \geq 0.5854$) and the main effect of hybrid ($P \geq 0.5785$) were also non-significant for each logistic function parameter. Plant height responded less favorably in 2010 than in 2009 to N rate. The main effect of N rate in 2010 was only significant for the $asym$ ($P < .0001$) but not for the $xmid$ ($P = 0.7286$) and $scal$ ($P = 0.8253$) parameters. The greatest plant heights achieved of the three 2010 environments occurred at the 168 kg N ha$^{-1}$ rate in each environment achieving 3.7 m in Dixon Springs 2010, 4.1 m in Perry 2010, and 3.8 m in Urbana 2010 (Fig. 4.1). This is contrasted with the greatest plant height in the Urbana 2009 environment which reached only 3 m at the 150 kg N ha$^{-1}$ rate (Fig. 4.1). The sorghum plants in 2010 likely grew taller than in 2009 because they were planted at least 2 weeks earlier (Table 4.3) and had a longer growing season. Additionally, the 2010 growing season was much warmer and had more precipitation during June through Sept. than the 2009 growing season (Table 4.2). Energy sorghum, can grow for 200 days in the right environment (typically southern environments like TX) and reach heights of 6 m (20 ft) (Sorghum Management Guide, 2010), however its ability to produce average heights up to 4.1 meters in Perry, IL is quite remarkable, considering that Perry, IL is over 1300 km northeast of College Station, TX (driving distance), the area where these hybrids were developed.
Leaf Area Index

Leaf area index expresses the ratio of surface leaf area to the ground area occupied by the crop. For LAI of the energy sorghum hybrids in the Urbana 2009 environment the N rate x DOY interaction \((P = 0.0058)\), N rate \((P = 0.0042)\), and DOY effects were significant \((P < .0001)\). As the energy sorghum hybrids grew throughout the growing season, LAI increased significantly from the first sampling date on 13 July to the third sampling date on 29 Aug. \((P < .0001)\) but then leveled off between the third sampling date and the fourth sampling date on 18 Sept. \((P = 0.7748)\) (Fig. 4.2). Throughout the growing season, LAI was lower for the 0 kg N ha\(^{-1}\) rate than for the other N rates (50 kg N ha\(^{-1}\), 100 kg N ha\(^{-1}\), and 150 kg N ha\(^{-1}\) \((P = 0.0014)\). In the Urbana 2010 environment, the only significant main effect was DOY \((P < .0001)\). Just as in 2009, LAI significantly increased in 2010 from the first sampling date on 25 June to the third sampling date on 12 Aug. \((P < .0001)\) but then leveled off between the third sampling date and the fourth sampling date on 31 Aug. \((P = 0.7985)\) (Fig. 4.2). The pattern of LAI responses to N rate was very similar to that of plant heights as the response of plant height was lower in 2010 than in 2009. Leaf area index values were highly correlated with the proportion of PAR intercepted by the crop canopy in 2009 \((\hat{\rho} = 0.93)\) \((P < .0001)\) and in 2010 \((\hat{\rho} = 0.95)\) \((P < .0001)\).

Leaf Expansion and Development

The number of fully expanded leaves produced by the photoperiod-sensitive energy sorghum hybrids (TAMUXH08001, and TX09007) was linearly associated with GDD, with greater a greater number of fully expanded leaves produced with greater heating units or GDD. The warmest environments, Dixon Springs 2010 and Perry 2010 accumulated 1906 and 1631 GDD, respectively (Table 4.3). These were the two environments which accumulated the greatest number of fully expanded leaves, each accumulating an average of 28 leaves on the
energy sorghum hybrids during the growing season. This is compared to typical grain sorghum hybrids (which are not photoperiod-sensitive) that accumulate between 15 and 19 leaves per plant depending on maturity group (Gerik et al., 2003). Even though the number of fully expanded leaves was similar for Dixon Springs 2010 and Perry 2010, plant height and biomass yield between the two environments were quite different (Fig. 4.1 and Table 4.4).

**Dry Biomass Yields**

For total dry biomass yields in the Urbana 2009 environment, the effects of type ($P = 0.0114$) and N rate ($P < .0001$) were significant. The effect of hybrid was non-significant ($P = 0.5445$) and estimates of dry biomass yield were calculated only for sorghum type (Table 4.4). In Urbana 2009, dry biomass yields were significantly greater for energy sorghum than for forage sorghum ($P = 0.0114$). Preplanned comparisons showed that an N linear response was significant ($P < 0.0001$) and the linear slope was the same both sorghum types ($P = 0.5924$). Forage sorghum was first harvested on 3 Sept. and a lack of harvestable biomass limited a second cutting in the fall. The energy sorghum hybrids were allowed to grow the entire season and were not harvested until 12 Nov. It appears that energy sorghum hybrids had greater overall biomass potential than forage sorghum hybrids even if forage sorghum hybrids were harvested both in summer and fall as occured in 2010 (Tables 4.4 and 4.5). Increasing N application from 0 kg N ha$^{-1}$ to 150 kg N ha$^{-1}$ improved energy sorghum biomass yields by 10.6 Mg ha$^{-1}$ and forage sorghum by 9.6 Mg ha$^{-1}$.

Biomass yields for forage sorghum in 2010 showed that summer harvest accounted for approximately 67%, 66%, and 79% of the total biomass (summer + fall harvest) yield in the Urbana 2010, Dixon Springs 2010, and Perry 2010 environments, respectively. For the summer forage sorghum harvest, the N rate effect was significant ($P = 0.0272$) but not for the fall forage
sorghum harvest \( (P = 0.2844) \). There was no difference among forage sorghum hybrids at the summer harvest \( (P = 0.7812) \), but there was a significant hybrid difference for the fall harvest \( (P = 0.0240) \) with Graze All re-growing approximately 0.65 Mg DM ha\(^{-1}\) more biomass than Graze. n. Bale since the summer harvest.

For total dry biomass yields in the 2010 environments, the effects of type \( (P = 0.0734) \) and N rate \( (P = 0.0062) \) were significant, and again as in the Urbana 2009 environment, the hybrid main effect was non-significant \( (P = 0.2489) \). Estimate statements showed that energy sorghum yields were significantly greater than forage sorghum yields in the Perry 2010 \( (P = 0.0018) \) and Urbana 2010 \( (P = 0.0311) \) environments but not in the Dixon Springs 2010 environment \( (P = 0.2104) \). Forage sorghum yields in each 2010 environment were quite similar and their response to increasing levels of N tended to follow a similar pattern (Table 4.4) and when contrasting forage sorghum dry biomass yields among environments the only significant difference was between Perry 2010 and Urbana 2010 \( (P = 0.0121) \). Overall in 2010, there was a significant increase in dry biomass yield for forage sorghum between the 0 kg N ha\(^{-1}\) rate and the 168 kg N ha\(^{-1}\) rate, but dry biomass yields did not increase from the 168 kg N ha\(^{-1}\) rate to the 224 kg N ha\(^{-1}\) rate (Table 4.4). Energy sorghum dry biomass yields were more influenced by environment than forage sorghum, and were less stable from environment to environment (Table 4.4). Energy sorghum yields were the highest in the Perry 2010 environment when compared with Urbana 2010 \( (P = 0.0811) \) and Dixon Springs 2010 \( (P = 0.0072) \) which was the lowest. The soil at Dixon Springs (southern IL) is generally of lower quality (i.e. lower organic matter, total N) than Urbana (east central IL) and Perry (west central IL) (Wander and Bollero, 1999). Also this environment had relatively low levels of P and K at planting compared to the other environments, and the precipitation in mid-to-late summer was very low totaling 74 mm
precipitation in July and Aug. In addition to being dry, the temperature was also very high during this time period with 15 days > 35°C (Table 4.2). It appears that this combination of lower soil quality and hot and dry conditions created an environment in which energy sorghum hybrids were unable to grow as well as in Perry 2010 and Urbana 2010. In addition to lower dry biomass yields, plant height was shorter for energy sorghum in the Dixon Springs 2010 environment (Fig. 4.1).

Correlations of end of season plant height, end of season fully expanded leaf number and energy sorghum biomass yield (Mg DM ha$^{-1}$) in 2009 showed positive linear relationships. In the Urbana 2009 environment end of season plant height and biomass yield was highly correlated ($\hat{\rho} = 0.87$) ($P < .0001$), while biomass yield and end of season fully expanded leaf number ($\hat{\rho} = 0.31$) ($P = 0.0815$), and end of season plant height and end of season fully expanded leaf number ($\hat{\rho} = 0.35$) ($P = 0.0477$) showed less positive relationships. The strong positive relationship end of season plant height and biomass yield in 2009 is likely related to the strong N rate response observed for both plant height and biomass yield (Fig. 4.1 and Table 4.4). In the 2010 environments, the relationship between these two variables was much less pronounced than in 2009, with the following correlations between end of season plant height and biomass yield: Urbana 2010 ($\hat{\rho} = 0.19$) ($P = 0.2903$), Dixon Springs 2010 ($\hat{\rho} = 0.39$) ($P = 0.0137$), and Perry 2010 ($\hat{\rho} = 0.19$) ($P = 0.2422$). However, end of season plant height and end of season fully expanded leaf number in 2010 was generally more positive than in 2009: Urbana 2010 ($\hat{\rho} = 0.65$) ($P < .0001$), Dixon Springs 2010 ($\hat{\rho} = 0.36$) ($P = 0.0243$), and Perry 2010 ($\hat{\rho} = 0.51$) ($P < .0007$).

Plant height accumulation and biomass yield response to N in each of the 2010 environments were less pronounced than in the Urbana 2009 environment likely because the residual soil NO$_3^-$ present in the soil in the Urbana 2009 environment at planting was very low
(5.5 mg kg\(^{-1}\) in the upper 23 cm of soil). This was due to a wetter than normal spring (Table 4.2) which limited early planting and probably caused some N loss via leaching. Thus, the plants in the Urbana 2009 environment responded very favorably to N fertilizer application, thus creating a larger disparity between shorter plants with lower yields and taller plants with greater yields. In 2010, each environment had higher residual NO\(_3\) levels than Urbana 2009, which likely limited the N response from being greater than it was. Due to the strong linear response of dry biomass yield to N rate in the Urbana 2009 environment and the variability in dry biomass yields among the 2010 environments it is difficult to suggest an optimal N rate recommendation when growing forage or energy sorghum for biomass in IL. These results suggest the need to continue evaluating sorghum grown for biomass in these IL sites as well as other sites to increase the number of site-years to predict dry biomass yield potential and recommended N rates.

**CONCLUSIONS**

The results of this study show that forage and energy sorghum possess great potential as biomass crops for IL. Environment had a major impact on plant growth and total biomass yields, and the degree to which sorghum responded to N fertilizer rate. In some cases these differences were explained by differences in leaf area index and plant height accumulation. Even though forage sorghum was harvested twice annually (summer and fall), energy sorghum harvested once in the fall had greater biomass yields in each environment. Biomass yield, LAI, and plant height response to N rate were observed up to 150 kg N ha\(^{-1}\) in 2009 and up to at least 168 kg N ha\(^{-1}\) in 2010. Photoperiod-sensitive forage and energy sorghum allow vegetative growth to continue late into until late Sept. in IL and therefore continue accumulating biomass until late Sept. Because forage and energy sorghum are annual crops they provide a unique crop option to IL producers and stakeholders interested in biomass crop production.
Acknowledgments

The authors acknowledge the Energy Biosciences Institute and the Energy Biosciences Institute Energy Farm at the University of Illinois Urbana-Champaign for providing funding, land, and labor support for this study.

REFERENCES


**Tables**

**Table 4.1.** Soil properties from environments in 2009 and 2010 (Urbana 2009, Urbana 2010, Dixon Springs 2010, and Perry 2010). Samples were obtained either within the plots before fertilization occurred or adjacent to the plots at planting or early in the growing season and are expressed as mean values ± standard deviation.

<table>
<thead>
<tr>
<th>Environment</th>
<th>depth cm</th>
<th>pH</th>
<th>SOM †</th>
<th>P (mg kg⁻¹)</th>
<th>K (mg kg⁻¹)</th>
<th>NH₄-N (mg kg⁻¹)</th>
<th>NO₃-N (mg kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urbana 2009</td>
<td>0-23</td>
<td>6.5 (0.3) ‡</td>
<td>2.8 (0.6)</td>
<td>38 (12)</td>
<td>207 (41)</td>
<td>-</td>
<td>5.5 (1.7)</td>
</tr>
<tr>
<td>Urbana 2010</td>
<td>0-23</td>
<td>6.4 (0.6)</td>
<td>3.3 (0.5)</td>
<td>51 (29)</td>
<td>200 (412)</td>
<td>5.6 (1)</td>
<td>23.8 (6.2)</td>
</tr>
<tr>
<td>Dixon Springs 2010</td>
<td>0-15</td>
<td>7.1 (0.1)</td>
<td>2.4 (0.2)</td>
<td>41 (15)</td>
<td>110 (8)</td>
<td>10.6 (2)</td>
<td>30.5 (7.7)</td>
</tr>
<tr>
<td></td>
<td>15-30</td>
<td>6 (0.5)</td>
<td>1.4 (0.2)</td>
<td>13 (3)</td>
<td>81 (4)</td>
<td>11.4 (2.2)</td>
<td>22.6 (5.8)</td>
</tr>
<tr>
<td>Perry 2010</td>
<td>0-10</td>
<td>6.1 (0.2)</td>
<td>2.2 (0.1)</td>
<td>24 (2)</td>
<td>175 (13)</td>
<td>11.2 (1.8)</td>
<td>23.3 (8.7)</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>6.5 (0)</td>
<td>1.7 (0.2)</td>
<td>14 (3)</td>
<td>130 (20)</td>
<td>9.9 (1.6)</td>
<td>7.9 (1.4)</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>6.2 (0.2)</td>
<td>1.4 (0.2)</td>
<td>16 (3)</td>
<td>160 (4)</td>
<td>8.9 (1.1)</td>
<td>4.9 (0.8)</td>
</tr>
</tbody>
</table>

† soil organic matter (SOM)
‡ standard deviation in parenthesis, and n=4, 5, 3, and 4 respectively for Urbana-2009, Urbana-2010, Dixon Springs-2010, and Perry-2010.
Table 4.2. Monthly average minimum (min.) and maximum (max.) air temperature, 30-yr temperature averages, number of days with temperature > 35°C, and precipitation in each environment (Urbana 2009, Urbana 2010, Dixon Springs 2010, and Perry 2010) during the growing season (May-October).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Urbana 2009</td>
<td>average min. (°C)</td>
<td>11.1</td>
<td>16.7</td>
<td>15.7</td>
<td>15.5</td>
<td>12.9</td>
<td>5.3</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>30-yr average min. (°C)</td>
<td>10.6</td>
<td>15.8</td>
<td>18.0</td>
<td>16.9</td>
<td>12.4</td>
<td>6.1</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>average max. (°C)</td>
<td>22.5</td>
<td>27.7</td>
<td>25.2</td>
<td>26.3</td>
<td>24.0</td>
<td>14.8</td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td>30-yr average max. (°C)</td>
<td>23.1</td>
<td>28.1</td>
<td>29.6</td>
<td>28.4</td>
<td>25.3</td>
<td>18.4</td>
<td>25.5</td>
</tr>
<tr>
<td></td>
<td>no. days temp. &gt; 35°C</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>precipitation, mm</td>
<td>145</td>
<td>92</td>
<td>137</td>
<td>94</td>
<td>22</td>
<td>201</td>
<td>692</td>
</tr>
<tr>
<td></td>
<td>30-year average precipitation, mm</td>
<td>122</td>
<td>107</td>
<td>119</td>
<td>111</td>
<td>82</td>
<td>71</td>
<td>612</td>
</tr>
<tr>
<td>Urbana 2010</td>
<td>average min. (°C)</td>
<td>12</td>
<td>18.1</td>
<td>18.6</td>
<td>17.9</td>
<td>12.3</td>
<td>5.6</td>
<td>14.1</td>
</tr>
<tr>
<td></td>
<td>30-yr average min. (°C)</td>
<td>10.6</td>
<td>15.8</td>
<td>18</td>
<td>16.9</td>
<td>12.4</td>
<td>6.1</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>average max. (°C)</td>
<td>23.3</td>
<td>28.4</td>
<td>29.6</td>
<td>30.2</td>
<td>26.1</td>
<td>21</td>
<td>26.4</td>
</tr>
<tr>
<td></td>
<td>30-yr average max. (°C)</td>
<td>23.1</td>
<td>28.1</td>
<td>29.6</td>
<td>28.4</td>
<td>25.3</td>
<td>18.4</td>
<td>25.5</td>
</tr>
<tr>
<td></td>
<td>no. days temp. &gt; 35°C</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>precipitation, mm</td>
<td>75</td>
<td>199</td>
<td>82</td>
<td>55</td>
<td>75</td>
<td>34</td>
<td>519</td>
</tr>
<tr>
<td></td>
<td>30-year average precipitation, mm</td>
<td>122</td>
<td>107</td>
<td>119</td>
<td>111</td>
<td>82</td>
<td>71</td>
<td>612</td>
</tr>
<tr>
<td>Dixon Springs 2010</td>
<td>average min. (°C)</td>
<td>16.1</td>
<td>19.4</td>
<td>20.4</td>
<td>18</td>
<td>14.2</td>
<td>6.7</td>
<td>15.8</td>
</tr>
<tr>
<td></td>
<td>30-yr average min. (°C)</td>
<td>12.8</td>
<td>17.3</td>
<td>19.6</td>
<td>18.4</td>
<td>14.5</td>
<td>8.2</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>average max. (°C)</td>
<td>26.7</td>
<td>32.8</td>
<td>34</td>
<td>34.4</td>
<td>29.8</td>
<td>25</td>
<td>30.4</td>
</tr>
<tr>
<td></td>
<td>30-yr average max. (°C)</td>
<td>26.1</td>
<td>30.4</td>
<td>32.4</td>
<td>32</td>
<td>28.6</td>
<td>22.8</td>
<td>28.7</td>
</tr>
<tr>
<td></td>
<td>no. days temp. &gt; 35°C</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>precipitation, mm</td>
<td>18</td>
<td>104</td>
<td>51</td>
<td>23</td>
<td>86</td>
<td>25</td>
<td>306</td>
</tr>
<tr>
<td></td>
<td>30-year average precipitation, mm</td>
<td>131</td>
<td>104</td>
<td>95</td>
<td>91</td>
<td>83</td>
<td>80</td>
<td>585</td>
</tr>
<tr>
<td>Perry 2010</td>
<td>average min. (°C)</td>
<td>11.4</td>
<td>17.8</td>
<td>19.2</td>
<td>18.1</td>
<td>13.1</td>
<td>4.9</td>
<td>14.1</td>
</tr>
<tr>
<td></td>
<td>30-yr average min. (°C)</td>
<td>11.4</td>
<td>16.7</td>
<td>18.7</td>
<td>17.2</td>
<td>12.4</td>
<td>6.2</td>
<td>13.8</td>
</tr>
<tr>
<td></td>
<td>average max. (°C)</td>
<td>24.2</td>
<td>31.4</td>
<td>32.4</td>
<td>31.8</td>
<td>26.8</td>
<td>21.9</td>
<td>28.1</td>
</tr>
<tr>
<td></td>
<td>30-yr average max. (°C)</td>
<td>23.1</td>
<td>27.8</td>
<td>30.2</td>
<td>29.3</td>
<td>25.4</td>
<td>19.2</td>
<td>25.8</td>
</tr>
<tr>
<td></td>
<td>no. days temp. &gt; 35°C</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>precipitation, mm</td>
<td>143</td>
<td>292</td>
<td>301</td>
<td>26</td>
<td>62</td>
<td>52</td>
<td>876</td>
</tr>
<tr>
<td></td>
<td>30-year average precipitation, mm</td>
<td>104</td>
<td>84</td>
<td>103</td>
<td>77</td>
<td>82</td>
<td>72</td>
<td>523</td>
</tr>
</tbody>
</table>
Table 4.3. Planting date, dates of plant height and fully expanded leaf number measurements, accumulated growing degree days, and harvest dates for each environment (Urbana 2009, Urbana 2010, Dixon Springs 2010, and Perry 2010).

<table>
<thead>
<tr>
<th>Environment</th>
<th>planting date</th>
<th>plant height and fully expanded leaf number measurements</th>
<th>GDD†</th>
<th>summer‡</th>
<th>fall§</th>
</tr>
</thead>
</table>

† growing degree days (GDD) with a base temperature of 11°C accumulated since planting until fall harvest or first fall frost, whichever occurred first.
‡ forage sorghum was cut two times, once in summer and once in the fall.
§ energy sorghum was only cut one time in the fall.
¶ measurements were taken during the fall harvest, but it was assumed that these final plant heights and number of fully expanded leaves were achieved the day before the first killing frost. The first killing frost for these two environments occurred on 5 Oct. and 4 Oct. for Dixon Springs 2010 and Perry 2010, respectively.
### Table 4.4

Total sorghum biomass yield (Mg DM ha\(^{-1}\)) obtained from each environment in 2009 (Urbana 2009) and 2010 (Urbana 2010, Dixon Springs 2010, and Perry 2010) for each N rate (kg N ha\(^{-1}\)) and their respective ANOVA. Biomass yields were obtained using least square means and in the case of the 2010 environments were estimated as best linear unbiased predictors (aka means of random variables).

<table>
<thead>
<tr>
<th>environment</th>
<th>sorghum type</th>
<th>LSD†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Urbana 2009</td>
<td>energy</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>forage</td>
<td>7.0</td>
</tr>
<tr>
<td>Urbana 2010</td>
<td>energy</td>
<td>22.6</td>
</tr>
<tr>
<td></td>
<td>forage</td>
<td>16.9</td>
</tr>
<tr>
<td>Dixon Springs 2010</td>
<td>energy</td>
<td>17.8</td>
</tr>
<tr>
<td></td>
<td>forage</td>
<td>15.7</td>
</tr>
<tr>
<td>Perry 2010</td>
<td>energy</td>
<td>27.6</td>
</tr>
<tr>
<td></td>
<td>forage</td>
<td>14.4</td>
</tr>
<tr>
<td>all 2010 environments</td>
<td>energy</td>
<td>22.7</td>
</tr>
<tr>
<td></td>
<td>forage</td>
<td>15.7</td>
</tr>
</tbody>
</table>

#### ANOVA and P-values

<table>
<thead>
<tr>
<th></th>
<th>Urbana 2009 ANOVA</th>
<th>2010 environments ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>0.0114</td>
<td>environment† &gt; 0.99</td>
</tr>
<tr>
<td>hybrid</td>
<td>0.5445</td>
<td>Type 0.0734</td>
</tr>
<tr>
<td>N rate</td>
<td>&lt;.0001</td>
<td>hybrid 0.2489</td>
</tr>
<tr>
<td>type x N rate</td>
<td>0.9056</td>
<td>N rate 0.0062</td>
</tr>
<tr>
<td>N rate x hybrid</td>
<td>0.6613</td>
<td>type x N rate 0.2311</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N rate x hybrid 0.3240</td>
</tr>
</tbody>
</table>

† LSD values for comparing dry biomass yield values across N rate within sorghum type. Differences greater than LSD values are significantly different at the α = 0.05 level.
‡ environment is a random effect and when its covariance parameter estimate was equal to zero it’s p-value (based upon a Wald Z statistic) was set to > 0.99.
Table 4.5. Forage sorghum biomass yields for summer harvest and fall harvests for each 2010 environment (Urbana 2010, Dixon Springs 2010, and Perry 2010) and ANOVA for each harvest. Biomass yields were obtained using least square means and in the case of individual environments were estimated as best linear unbiased predictors (aka means of random variables).

<table>
<thead>
<tr>
<th>Environment/source</th>
<th>N rate kg ha(^{-1})</th>
<th>summer Mg DM ha(^{-1})</th>
<th>fall Mg DM ha(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urbana 2010</td>
<td>0</td>
<td>10.5</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>12.6</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>112</td>
<td>13.1</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>168</td>
<td>14.1</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>224</td>
<td>14.0</td>
<td>6.7</td>
</tr>
<tr>
<td>Dixon Springs 2010</td>
<td>0</td>
<td>10.2</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>12.0</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>112</td>
<td>11.9</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>168</td>
<td>13.0</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>224</td>
<td>13.0</td>
<td>6.4</td>
</tr>
<tr>
<td>Perry 2010</td>
<td>0</td>
<td>10.9</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>12.7</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>112</td>
<td>13.0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>168</td>
<td>14.2</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>224</td>
<td>14.0</td>
<td>3.7</td>
</tr>
<tr>
<td>all 2010 environments</td>
<td>0</td>
<td>10.6</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>12.4</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>112</td>
<td>12.7</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>168</td>
<td>13.8</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>224</td>
<td>13.6</td>
<td>5.6</td>
</tr>
</tbody>
</table>

**ANOVA**

<table>
<thead>
<tr>
<th></th>
<th>(P)-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>environment</td>
<td>0.2986 0.1632</td>
</tr>
<tr>
<td>hybrid</td>
<td>0.7812 0.0240</td>
</tr>
<tr>
<td>N rate</td>
<td>0.0272 0.2844</td>
</tr>
<tr>
<td>hybrid x N rate</td>
<td>0.1743 0.7145</td>
</tr>
</tbody>
</table>

† LSD values for comparing dry biomass yield of the 2010 environments grouped together by N rate.
Figure 4.1. Energy sorghum plant height (m) plotted against day of year (DOY) and fit with logistic growth functions averaged across hybrids for each N rate at each location in each year.
Figure 4.2. Energy sorghum leaf area index (LAI) and interception of photosynthetic active radiation (PAR) plotted against day of year (DOY) and averaged across hybrids for each N rate at Urbana in 2009 and 2010.
Figure 4.3. Number of fully expanded leaves of photoperiod-sensitive energy sorghum hybrids plotted against growing degree days (GDD) with a base temperature of 11°C accumulated since planting, and simple linear regression lines for each environment (Urbana 2009, Urbana 2010, Dixon Springs 2010, and Perry 2010).
CHAPTER 5
Supplementary Information to Ch. 4

This chapter summarizes some additional analysis from the forage and energy sorghum field study in Ch. 4.

In an effort to develop an understanding of the N response that sorghum exhibits, quadratic plus plateau curves were fit to the total biomass yield data when possible. A quadratic plus plateau as opposed to a quadratic model, was implemented because of research in corn (Zea mays L.) that has shown recommendations based on and quadratic model result in biases and over predictions (Bullock and Bullock, 1994a). The quadratic function tends to predict a decline in crop yield with increasing levels of N beyond the optimal N rate (Bullock and Bullock, 1994a), calculated by setting the first derivative equal to zero. This prediction is generally not true unless extremely excessive N rates are applied that may ultimately cause lodging or other crop problems due to excessive N application. Additionally, the quadratic response model may overestimate yields for the predicted optimum N rate (Cerrato and Blackmer, 1990).

The quadratic plus plateau model has been shown to best describe yield responses to N in corn when compared to several other N response functions (linear-plus-plateau, quadratic, exponential, and square root) (Cerrato and Blackmer, 1990). Extending this model to sorghum grown for biomass is reasonable due to the similarities between the two crops. In the context of dry biomass production the quadratic plus-plateau model can be described as:

\[
Y = a + bX + cX^2 \text{ if } X < C \\
Y = P \quad \text{ if } X \geq C
\]  
[eq. 2]
where $Y$ is the biomass yield (Mg DM ha$^{-1}$) and $X$ is the N application rate (kg N ha$^{-1}$), $a$ is the intercept, $b$ is the linear coefficient, $c$ is the quadratic coefficient, and $C$ is the rate of N fertilization which occurs at the intersection of the quadratic response and the plateau ($P$) portions of the model. The critical rate of fertilizer can be defined as the N rate required to achieve maximum dry biomass yield (Max N).

Where model convergence was possible, a quadratic plus plateau curve was fit to each sorghum type in each 2010 environment using the NLMIXED procedure of SAS (SAS Institute, 2007). Plateau dry biomass yields and Max N rates were derived from each response function and are shown in Table 5.1. Max N rates are assumed to be the N rates that maximize dry biomass yields, and not profits, since they do not consider input costs, risk, or other stochastic events that can optimize or minimize a farmer’s production objective (Bullock and Bullock, 1994b). Where convergence of a quadratic plus plateau model could not be achieved, or it was observed that the relationship between dry biomass yield and N rate was linear, a linear model was fit to the data. This was the case for both sorghum types in the Urbana 2009 environment and for energy sorghum in the Perry 2010 environment (Fig. 5.1). Residuals (observed yields minus predicted yields) were plotted against N rate for each environment (Fig. 5.1). Based upon the price of Mar. urea (46% N) from 2006 to 2011 (USDA/ERS, 2011), three prices of urea ($362 \text{ ton}^{-1} (\$328.3 \text{ Mg}^{-1})$, $448 \text{ ton}^{-1} (\$406.3 \text{ Mg}^{-1})$, and $552 \text{ ton}^{-1} (\$500.6 \text{ Mg}^{-1})$) and respective unit prices of a kg of N ($0.87 \text{ kg}^{-1} \text{ N}$, $1.07 \text{ kg}^{-1} \text{ N}$, and $1.32 \text{ kg}^{-1} \text{ N}$), economical optimum N rates (EONR) were calculated by considering three theoretical prices of a Mg of dry biomass: $35 \text{ Mg}^{-1}$, $50 \text{ Mg}^{-1}$, and $65 \text{ Mg}^{-1}$ (Table 5.1). These economical optimum N rates were calculated ex post (after the fact) (Bullock and Bullock, 1994b) using the following equation:
where $w$ is the cost of N fertilizer ($\text{kg}^{-1}$), $p$ is the price of dry biomass ($\text{Mg}^{-1}$), $b$ is the linear coefficient from eq. 2, and $c$ is the quadratic coefficient from eq. 2. Generally, it is recommended that an ex ante (expected before the event) economical optimum N rate be calculated based upon several years of ex post rates calculated for a given site or location (Bullock and Bullock, 1994b), but this was not possible due to the limited amount of data available for each site. The variation within and among environments, shown by the varying levels of plateau yields, Max N, EONR, and the difference in functional form (linear vs. quadratic plus plateau) fit to the data suggest the need to continue researching sorghum biomass production in IL so that sufficient data is available to make reliable predictions of yield and economical optimum N rates that should be applied to meet farmers objectives. In addition, plant breeding efforts may continue to improve dry biomass yield potential, but also increase the ability of the crop to respond favorably and more consistently to agronomic inputs such as N fertilizer. It is apparent, however that the price of a Mg of dry biomass and a the price of N fertilizer can alter the rate of N that should be applied to meet an economic goal. As the price of N increased, the EONR decreased, however as the price of a Mg of dry biomass increased, the EONR also increased (Table 5.1).

Measurements of leaf greenness for all hybrids were taken using a SPAD meter (Minolta Camera Co., Ltd., Japan) at 3 different time periods (14-15 July, 30 July, and 20 Aug.) heretofore referred to as early-summer, mid-summer, and late-summer, respectively. In 2010, SPAD readings were taken at two different time periods in the Urbana 2010 (25 June, and 21-22 July), Dixon Springs 2010 (30 June, and 19 July), and Perry 2010 (11 July, and 23 July), heretofore referred to as early-summer and mid-summer, respectively. The sampling time
periods in 2009 and 2010 each occurred during the GSI and GSII growth stages for photoperiod-sensitive hybrids and the into the GSIII stage for the single photoperiod-insensitive hybrid (Graze All) (Gerik et al., 2003; Sorghum Management Guide, 2010). On each sampling date, eight SPAD reading were taken from each plot on eight separate tillers from eight representative plants and then averaged to produce one SPAD reading per plot. Readings were taken from the upper fully most expanded leaf of each selected tiller. From approximately the same location the SPAD readings were collected, three-one cm diameter leaf disc samples were taken across the leaf (one on the midrib and two on either side of the midrib) using a leaf puncher (Precision Machine Co., Lincoln, NE). This resulted in 24 leaf disks that were aggregated for each plot and were weighed wet and dried in a forced air oven at 48°C for at least 48 hours. Dried samples were ground and TN and TC were determined us a CHN analyzer (Costech Analytical Elemental Combustion System, Costech 4010 model, Valencia, CA). Leaf TC and leaf TN were determined by combustion in the presence of oxygen and appropriate standard curves and verification of proper analysis were determined using acetanilide and apple leaf samples (National Institute of Standards and Technology, Gaithersburg, MD). Subsamples that had been collected at harvest were dried in a forced air oven were then ground and used to determine harvest TN and TC following the same protocol as described above for the leaf punch samples. For forage sorghum, only samples coming from the first harvest were used in the statistical analysis.

SPAD, leaf TN, leaf TC, harvest TN, and harvest TC were each analyzed in the GLIMMIX procedure of SAS (SAS Institute, 2007). For SPAD, leaf N, and leaf C, statistical analysis, time of sampling (sampling period) was considered a fixed variable and was modeled as a split in time, because in 2010 there were only two sampling periods in each environment, reducing the
need to consider this variable as a repeated measurement. In the Urbana 2009 environment, the first sampling period (14-15 July) for leaf TN and leaf TC was not used in the analysis because of errors resulting from the CHN analysis. Each of these variables were analyzed in the GLIMMIX procedure of SAS (SAS Institute, 2007), and statistical analysis followed the same protocol as in Ch. 4.

SPAD meter readings allow the relative comparison of plants showing varying levels of leaf greenness and chlorophyll concentration (Bullock and Anderson, 1998; Markwell et al., 1995). SPAD readings can indicate plant N stress (Ruiz Diaz et al., 2008) and have been related to yield response to N in corn (Zea mays. L) (Scharf et al., 2006) and leaf TN in switchgrass (Panicum virgatum L.) (Madakadze et al., 1999). In the Urbana 2009 environment there was a moderate, yet positive significant correlation between SPAD and N rate ($\hat{\rho} = 0.69$) ($P < .0001$) throughout the growing season. The correlation between SPAD and leaf TN during the last two sampling periods (mid-summer and late-summer) was also significant ($P < .0001$) but the correlation was much lower ($\hat{\rho} = 0.41$). Correlations between SPAD meter readings and leaf TN have also been shown in corn, although correlations were low early in the season and increased as the crop moved into the reproductive stage (Bullock and Anderson, 1998). For SPAD, there was a significant N rate x time period x type interaction ($P = 0.035$) and a significant type x time period interaction ($P < .0001$), although readings generally declined from the early-summer to late summer for both sorghum types and almost all hybrids (Table 5.2). Each hybrid responded similarly to N, but was slightly different for each time period (Table 5.2). SPAD meter readings and leaf TN increased significantly from 0 kg N ha$^{-1}$ to 100 kg N ha$^{-1}$ but then leveled off between 100 kg N ha$^{-1}$ and 150 kg N ha$^{-1}$ (Table 5.2). SPAD meter readings also differed among sorghum hybrids (Table 5.2) which has also been shown in corn (Bullock and Anderson, 1998).
There was a significant N rate x time period interaction for leaf TN \((P < .0001)\) which increased from mid-summer to late-summer for each hybrid (Table 5.2). The only significant effect for leaf TC was time period \((P = 0.0051)\) and leaf TC increased significantly for the energy sorghum hybrids from mid-summer to late-summer, but not for the forage sorghum hybrids (Table 5.2).

For the 2010 environments, there were moderate, yet positive significant correlations between SPAD and TN \((\hat{\rho} = 0.49)\) \((P < .0001)\), and SPAD and N rate \((\hat{\rho} = 0.60)\) \((P < .0001)\) at the early-summer measurements. The correlation between SPAD and TN \((\hat{\rho} = 0.30)\), and SPAD and N rate \((\hat{\rho} = 0.51)\) decreased in mid-summer although the correlation were still significant \((P < .0001)\). The effect of environment was non-significant for SPAD \((P > .99)\), leaf TN \((P = 0.2817)\), and leaf TC \((P = 0.4285)\). For SPAD, there was a significant time period x hybrid interaction \((P = 0.0925)\) and SPAD measurements increased from early-summer to mid-summer for each hybrid although there were differences between hybrids (Table 5.3). SPAD meter readings and leaf TN increased significantly from 0 kg N ha\(^{-1}\) to 112 kg N ha\(^{-1}\) but then leveled off between 112 kg N ha\(^{-1}\) and 168 kg N ha\(^{-1}\) (Table 5.3). Leaf TN also differed at each sampling period and decreased from early-summer to late-summer for each sorghum type and each sorghum hybrid. All leaf TC effects were non-significant (Table 5.3).

Harvest TN levels were at least half of the leaf TN levels taken during the growing season (Tables 5.2, 5.3, and 5.4). Harvest TN samples were a composite sample of the entire plant including stems, leaves, and in some cases panicles, while leaf TN samples only contained leaf material. Harvest TN was significant only for N rate \((P = 0.0876)\) in the Urbana 2009 environment, while only type was significant for the 2010 environments \((P = 0.0589)\). Harvest TN increased significantly from 0 kg N ha\(^{-1}\) to 150 kg N ha\(^{-1}\) in the Urbana 2009 environment and from 0 kg N ha\(^{-1}\) to 150 kg N ha\(^{-1}\) in the 2010 environments. The effect of environment was
non-significant for the 2010 environments, but energy sorghum had significantly lower harvest
TN levels than forage sorghum. This is likely because the forage sorghum harvest samples came
from the summer harvest when the plants were still green, while the energy sorghum harvest
samples came from the fall harvest, which, for Dixon Springs and Perry, had begun field drying
at harvest time.

REFERENCES


J. 86: 921-923.

Extension publication, Texas A&M University.

Madakadze, I.C., K.A. Stewart, R.M. Madakadze, P.R. Peterson, B.E. Coulman, and D.L. Smith.
1999. Field Evaluation of the Chlorophyll Meter to Predict Yield and Nitrogen Concentration


665.

Sorghum Management Guide. 2010. Managing High-Biomass Sorghum as a Dedicated Energy
Crop. Blade Energy Crops. Available online at
May 2011; verified 22 June 2011).

USDA/ERS. 2011. Average U.S. farm prices of selected fertilizers. Available at
### Table 5.1. Plateau biomass yields based upon quadratic plus plateau response curves and associated N rate (max N) required to achieve plateau biomass yields at each 2010 environment for each sorghum type. Ex post economic optimum N rates using based upon three prices of a unit of N ($0.87 kg⁻¹ N, $1.07 kg⁻¹ N, and $1.32 kg⁻¹ N) and three prices for a Mg of dry biomass ($35 Mg⁻¹, $50 Mg⁻¹, and $65 Mg⁻¹).

#### Plateau biomass yields (Mg DM ha⁻¹)

<table>
<thead>
<tr>
<th>environment</th>
<th>sorghum type</th>
<th>plateau yield</th>
<th>max N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mg DM ha⁻¹</td>
<td>kg N ha⁻¹</td>
</tr>
<tr>
<td>Urbana 2010</td>
<td>energy</td>
<td>28.4</td>
<td>187.4</td>
</tr>
<tr>
<td></td>
<td>forage</td>
<td>21.1</td>
<td>193.7</td>
</tr>
<tr>
<td>Dixon Springs 2010</td>
<td>energy</td>
<td>21.2</td>
<td>41.8</td>
</tr>
<tr>
<td></td>
<td>forage</td>
<td>18.3</td>
<td>47.8</td>
</tr>
<tr>
<td>Perry 2010</td>
<td>energy†</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>forage</td>
<td>17.9</td>
<td>214.9</td>
</tr>
</tbody>
</table>

#### Economic optimum N rate (kg N ha⁻¹)

<table>
<thead>
<tr>
<th>environment</th>
<th>sorghum type</th>
<th>$ kg⁻¹ N</th>
<th>$35</th>
<th>$50</th>
<th>$65</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urbana 2010</td>
<td>energy</td>
<td>$0.87</td>
<td>115.42</td>
<td>137.02</td>
<td>148.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.07</td>
<td>98.87</td>
<td>125.43</td>
<td>139.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.32</td>
<td>78.18</td>
<td>110.95</td>
<td>128.60</td>
</tr>
<tr>
<td></td>
<td>forage</td>
<td>$0.87</td>
<td>96.63</td>
<td>125.75</td>
<td>141.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.07</td>
<td>74.32</td>
<td>110.13</td>
<td>129.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.32</td>
<td>46.43</td>
<td>90.61</td>
<td>114.39</td>
</tr>
<tr>
<td>Dixon Springs 2010</td>
<td>energy</td>
<td>$0.87</td>
<td>35.66</td>
<td>37.48</td>
<td>38.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.07</td>
<td>34.25</td>
<td>36.50</td>
<td>37.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.32</td>
<td>32.50</td>
<td>35.28</td>
<td>36.77</td>
</tr>
<tr>
<td></td>
<td>forage</td>
<td>$0.87</td>
<td>35.66</td>
<td>37.48</td>
<td>38.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.07</td>
<td>34.25</td>
<td>36.50</td>
<td>37.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.32</td>
<td>32.50</td>
<td>35.28</td>
<td>36.77</td>
</tr>
<tr>
<td>Perry 2010</td>
<td>energy</td>
<td>$0.87</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.07</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.32</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>forage</td>
<td>$0.87</td>
<td>62.16</td>
<td>107.97</td>
<td>132.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.07</td>
<td>27.05</td>
<td>83.40</td>
<td>113.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.32</td>
<td>na‡</td>
<td>52.68</td>
<td>90.11</td>
</tr>
</tbody>
</table>

† a quadratic plus plateau response curve was not fit for the energy sorghum type at Perry 2010.
‡ economical optimum N rate calculated was less than 0.
Table 5.2. SPAD, leaf TN, and leaf TC measurements from Urbana 2009 showing results by N rate, for the type x time period, and time period x hybrid(type) interaction. Analysis of variance (ANOVA) for each variable is shown at bottom of table.

<table>
<thead>
<tr>
<th>N rate, kg N ha⁻¹</th>
<th>SPAD no units</th>
<th>leaf TN g kg⁻¹</th>
<th>leaf TC g kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>34.5</td>
<td>1.87</td>
<td>38.5</td>
</tr>
<tr>
<td>50</td>
<td>38.1</td>
<td>1.91</td>
<td>40.0</td>
</tr>
<tr>
<td>100</td>
<td>43.0</td>
<td>2.37</td>
<td>41.4</td>
</tr>
<tr>
<td>150</td>
<td>44.9</td>
<td>2.23</td>
<td>42.6</td>
</tr>
<tr>
<td>LSD†</td>
<td>1.96</td>
<td>0.354</td>
<td>4.25</td>
</tr>
</tbody>
</table>

**type x time period**

| Energy, early-summer | 42.5 | - | - |
| Energy, mid-summer   | 41.2 | 1.96 | 38.6 |
| Energy, late-summer  | 39.2 | 2.17 | 44.0 |
| Forage, early-summer | 41.6 | - | - |
| Forage, mid-summer   | 37.5 | 2.06 | 38.6 |
| Forage, late-summer  | 38.6 | 2.19 | 41.3 |
| LSD‡                 | 3.37 | 0.561 | 4.32 |

**time period x hybrid**

| TAMUXH08001, early-summer | 42.3 | - | - |
| TAMUXH08001, mid-summer   | 41.9 | 2.04 | 40.2 |
| TAMUXH08001, late-summer  | 39.7 | 2.29 | 42.8 |
| TX09007, early-summer     | 42.8 | - | - |
| TX09007, mid-summer       | 40.6 | 1.88 | 37.0 |
| TX09007, late-summer      | 38.7 | 2.05 | 45.3 |
| Graze All, early-summer   | 42.5 | - | - |
| Graze All, mid-summer     | 39.0 | 2.30 | 38.1 |
| Graze All, late-summer    | 42.2 | 2.59 | 40.3 |
| Graze, n. Bale, early-summer | 40.8 | - | - |
| Graze, n. Bale, mid-summer | 36.0 | 1.82 | 39.0 |
| Graze, n. Bale, late-summer | 35.0 | 1.79 | 42.2 |
| LSD§                     | 2.97 | 0.599 | 5.87 |

ANOVA

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>0.175</td>
<td>0.7542</td>
<td>0.3855</td>
</tr>
<tr>
<td>hybrid</td>
<td>0.0008</td>
<td>0.0016</td>
<td>0.7816</td>
</tr>
<tr>
<td>N rate</td>
<td>&lt;.0001</td>
<td>0.0136</td>
<td>0.245</td>
</tr>
<tr>
<td>type x N rate</td>
<td>0.3166</td>
<td>0.327</td>
<td>0.7843</td>
</tr>
<tr>
<td>N rate x hybrid</td>
<td>0.3994</td>
<td>0.3042</td>
<td>0.4382</td>
</tr>
<tr>
<td>time period</td>
<td>&lt;.0001</td>
<td>0.1469</td>
<td>0.0051</td>
</tr>
<tr>
<td>type x time period</td>
<td>&lt;.0001</td>
<td>0.7276</td>
<td>0.3297</td>
</tr>
<tr>
<td>time period x hybrid</td>
<td>&lt;.0001</td>
<td>0.6014</td>
<td>0.355</td>
</tr>
<tr>
<td>N rate x time period</td>
<td>&lt;.0001</td>
<td>0.01</td>
<td>0.5687</td>
</tr>
<tr>
<td>type x N rate x time period</td>
<td>0.035</td>
<td>0.6463</td>
<td>0.3943</td>
</tr>
<tr>
<td>N rate x time period x hybrid</td>
<td>0.3697</td>
<td>0.1118</td>
<td>0.8613</td>
</tr>
</tbody>
</table>

† LSD values for comparing within N rate.
‡ LSD values for comparing values within type x time period interaction.
§ LSD values for comparing values within time period x hybrid(type) interaction.
Differences greater than LSD values are significantly different at the α = 0.05 level
Table 5.3. SPAD, leaf TN, and leaf TC measurements from all 2010 environments (Urbana 2010, Dixon Springs 2010, and Perry 2010) showing results by N rate, for the type x time period, and time period x hybrid(type) interaction. Analysis of variance (ANOVA) for each variable is shown at bottom of table.

<table>
<thead>
<tr>
<th>N rate, kg N ha⁻¹</th>
<th>SPAD no units</th>
<th>leaf TN g kg⁻¹</th>
<th>leaf TC g kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>38.6</td>
<td>1.94</td>
<td>34.5</td>
</tr>
<tr>
<td>56</td>
<td>42.2</td>
<td>2.12</td>
<td>35.0</td>
</tr>
<tr>
<td>112</td>
<td>45.0</td>
<td>2.44</td>
<td>35.3</td>
</tr>
<tr>
<td>168</td>
<td>46.0</td>
<td>2.61</td>
<td>34.6</td>
</tr>
<tr>
<td>224</td>
<td>46.3</td>
<td>2.60</td>
<td>35.2</td>
</tr>
<tr>
<td>LSD†</td>
<td>1.78</td>
<td>0.205</td>
<td>2.39</td>
</tr>
</tbody>
</table>

**type x time period**
- Energy, early-summer: 43.9, 2.83, 37.1
- Energy, mid-summer: 46.1, 1.97, 34.0
- Forage, early-summer: 41.0, 2.41, 35.5
- Forage, mid-summer: 43.4, 2.14, 33.1
- LSD‡: 4.18, 0.714, 19.95

**time period x hybrid**
- TAMUXH08001, early-summer: 43.4, 2.81, 37.7
- TAMUXH08001, mid-summer: 46.1, 2.00, 34.7
- TX09007, early-summer: 44.4, 2.85, 36.5
- TX09007, mid-summer: 46.2, 1.95, 33.3
- Graze All, early-summer: 42.0, 2.49, 35.4
- Graze All, mid-summer: 45.5, 2.46, 33.1
- Graze. n. Bale, early-summer: 39.9, 2.33, 35.6
- Graze. n. Bale, early-summer: 41.3, 1.83, 33.0
- LSD§: 4.15, 0.527, 20.39

**ANOVA**

<table>
<thead>
<tr>
<th>P-values</th>
<th>environment¶</th>
<th>Type</th>
<th>hybrid</th>
<th>N rate</th>
<th>type x N rate</th>
<th>N rate x hybrid</th>
<th>time period</th>
<th>type x time period</th>
<th>time period x hybrid</th>
<th>N rate x time period</th>
<th>type x N rate x time period</th>
<th>N rate x time period x hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;0.99</td>
<td>0.002</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>0.4057</td>
<td>0.5058</td>
<td>0.196</td>
<td>0.8334</td>
<td>0.0925</td>
<td>0.3085</td>
<td>0.8907</td>
<td>0.6106</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2817</td>
<td>0.0532</td>
<td>0.3691</td>
<td>0.7051</td>
<td>0.9563</td>
<td>0.0666</td>
<td>&lt;.0001</td>
<td>0.0325</td>
<td>0.1908</td>
<td>0.9649</td>
<td>0.8876</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.4285</td>
<td>0.2024</td>
<td>0.9458</td>
<td>0.9824</td>
<td>0.932</td>
<td>0.6069</td>
<td>0.7202</td>
<td>0.9821</td>
<td>0.6689</td>
<td>0.7227</td>
<td>0.8173</td>
</tr>
</tbody>
</table>

† LSD values for comparing within N rate.
‡ LSD values for comparing values within type x time period interaction.
§ LSD values for comparing values within time period x hybrid(type) interaction.
Differences greater than LSD values are significantly different at the α = 0.05 level.
¶ environment is a random effect and when its covariance parameter estimate was equal to zero its p-value (based upon a Wald Z statistic) was set to > 0.99.
Table 5.4. Harvest TN and harvest TC samples from Urbana 2009 and all 2010 environments (Urbana 2010, Dixon Springs 2010, and Perry 2010) showing results by N rate and for the type x N rate interaction. Analysis of variance (ANOVA) for each variable is shown at bottom of table.

<table>
<thead>
<tr>
<th>N rate, kg N ha(^{-1})</th>
<th>harvest TN</th>
<th>harvest TC</th>
<th>N rate, kg N ha(^{-1})</th>
<th>harvest TN</th>
<th>harvest TC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g kg(^{-1})</td>
<td>g kg(^{-1})</td>
<td></td>
<td>g kg(^{-1})</td>
<td>g kg(^{-1})</td>
</tr>
<tr>
<td>0</td>
<td>0.79</td>
<td>33.3</td>
<td>0</td>
<td>0.91</td>
<td>39.7</td>
</tr>
<tr>
<td>50</td>
<td>0.80</td>
<td>32.3</td>
<td>56</td>
<td>0.97</td>
<td>39.9</td>
</tr>
<tr>
<td>100</td>
<td>0.82</td>
<td>34.9</td>
<td>112</td>
<td>1.09</td>
<td>41.7</td>
</tr>
<tr>
<td>150</td>
<td>0.99</td>
<td>34.1</td>
<td>168</td>
<td>1.04</td>
<td>40.7</td>
</tr>
<tr>
<td>LSD(^\dagger)</td>
<td>0.180</td>
<td>4.07</td>
<td></td>
<td>224</td>
<td>39.9</td>
</tr>
<tr>
<td>type x N rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>energy, 0</td>
<td>0.76</td>
<td>31.6</td>
<td></td>
<td>0.68</td>
<td>39.6</td>
</tr>
<tr>
<td>energy, 50</td>
<td>0.77</td>
<td>32.1</td>
<td></td>
<td>0.67</td>
<td>39.4</td>
</tr>
<tr>
<td>energy, 100</td>
<td>0.67</td>
<td>34.2</td>
<td></td>
<td>0.74</td>
<td>41.3</td>
</tr>
<tr>
<td>energy, 150</td>
<td>0.86</td>
<td>35.0</td>
<td></td>
<td>0.73</td>
<td>40.2</td>
</tr>
<tr>
<td>forage, 0</td>
<td>0.81</td>
<td>35.1</td>
<td></td>
<td>0.74</td>
<td>40.1</td>
</tr>
<tr>
<td>forage, 50</td>
<td>0.83</td>
<td>32.6</td>
<td></td>
<td>1.14</td>
<td>39.8</td>
</tr>
<tr>
<td>forage, 100</td>
<td>0.96</td>
<td>35.5</td>
<td></td>
<td>1.27</td>
<td>40.3</td>
</tr>
<tr>
<td>forage, 150</td>
<td>1.12</td>
<td>33.2</td>
<td></td>
<td>1.45</td>
<td>42.1</td>
</tr>
<tr>
<td>LSD(^\dagger)</td>
<td>0.322</td>
<td>6.04</td>
<td></td>
<td>1.35</td>
<td>41.1</td>
</tr>
<tr>
<td>ANOVA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>type x N rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>energy, 0</td>
<td>0.1838</td>
<td>0.6199</td>
<td></td>
<td>0.4035</td>
<td>0.1641</td>
</tr>
<tr>
<td>energy, 50</td>
<td>0.9024</td>
<td>0.9451</td>
<td></td>
<td>0.0589</td>
<td>0.2007</td>
</tr>
<tr>
<td>energy, 100</td>
<td>0.0876</td>
<td>0.6038</td>
<td></td>
<td>0.5728</td>
<td>0.1358</td>
</tr>
<tr>
<td>energy, 150</td>
<td>0.4032</td>
<td>0.621</td>
<td></td>
<td>0.1389</td>
<td>0.505</td>
</tr>
<tr>
<td>forage, 0</td>
<td>0.8204</td>
<td>0.2918</td>
<td></td>
<td>0.1773</td>
<td>0.845</td>
</tr>
<tr>
<td>forage, 50</td>
<td>0.3918</td>
<td>0.5652</td>
<td></td>
<td>0.3918</td>
<td>0.5652</td>
</tr>
</tbody>
</table>

\(^\dagger\) LSD values for comparing within N rate.

\(^\ddagger\) LSD values for comparing values of type x N rate interaction.

Differences greater than LSD values are significantly different at the \(\alpha = 0.05\) level.
Figure 5.1. Biomass yields (Mg DM ha$^{-1}$) and residuals of energy and forage sorghum in each environment fit with quadratic plus plateau response curves and linear response curves where quadratic plus plateau response curves could not be fitted to the data. Both sorghum types at Urbana 2009 and energy sorghum at Perry 2010 were fitted with linear response curves, while the others were fit with quadratic plus plateau response curves.
CONCLUDING REMARKS

When considering biomass production of switchgrass, *M. x giganteus*, and forage and energy sorghum, the effects of the environment and field management practices are very critical elements that can greatly affect biomass yield and productivity. Because these crops were not evaluated in the same experiment no direct comparisons about these crops can be discussed, although each individual study provides valuable information about these three crops. Future research could also benefit from a comparison of these crops in side-by-side experiments.

In Ch. 2, an evaluation of data from 106 sites and 45 studies from the eastern two thirds of the USA and southeastern Canada revealed that N rate, region, spring precipitation, growing season, ecotype, and harvest timing each had a significant effect on biomass yields of switchgrass. Results of this study also revealed that N response varies from site-to-site, that the lower and upper central USA regions tend to produce greater biomass yields than the northern or southern regions of the USA, and that the lowland ecotype tends to yield better than the upland ecotype, although this depends on the region in which it is grown. Several issues made the compilation of the database for this study and its statistical analysis challenging. First, management practices and methods of reporting biomass yields were different from study-to-study and provided a challenge in classifying data into a discrete set of categories. This often resulted in the exclusion of valuable data. In several cases, data from certain studies were excluded from the database because rather than reporting biomass yield for specific management practices (that were of interest in this study) such as N rate and harvest timing, biomass yields were often reported as averages across these variables. A random coefficients model was implemented that allowed several variables of interest to be considered together in a single model. Because the number of variables of interest was relatively high, it was not possible to
estimate the variance (i.e. standard error of the differences of means, confidence intervals, standard deviations, coefficient of variation) within and among studies in way that was consistent or standardized from study-to-study. Based upon the results of this study, there are several areas of that could benefit from future research, some of which are already in progress. First, continued development of new switchgrass cultivars with improved biomass yield potential and broad adaptation is necessary to provide reliable and high biomass yielding switchgrass crops. Secondly, one of the most important decisions a producer can make is selecting the proper ecotype and cultivar suited for biomass production in his or her area. For example, Cave-in-Rock is a cultivar that originates from southern IL. This cultivar may be a front runner candidate for biomass production in northern IL, but other cultivars such as Kanlow may possess greater biomass yield potential in southern and central IL. It is necessary that local scientists and agronomists evaluate potential cultivars for a specific area and develop recommendations that will help producers make informed cultivar selection decisions.

In Ch. 3, *M. x giganteus* was grown for three years (establishment years) in four environments ranging from the western Corn Belt in Mead, NE to the Atlantic Coast in Adelphia, NJ. It was observed that late planting and cold winter temperatures may limit the production range for this clone. *M. x giganteus* biomass yields did not respond significantly to N application during this study, but according to the literature, response to N application in future production years (beyond establishment) is more likely. Biomass yields were greatly impacted by environment, with low yields associated with poor soil conditions and hot dry conditions, and high biomass yields associated with high levels of well distributed rainfall (throughout the growing season) and warm growing conditions as were observed in NE in 2010. One of the major limitations of this study was the limited number of sites that were established and the
broad range of geography that was evaluated. This limitation was due to a lack of sufficient *M. x giganteus* rhizome material available for establishing replicated experiments at more sites. Four areas of potential production were evaluated (NE, IL, KY, and NJ), but only one location in each of these areas was established with a replicated experiment. This made the evaluation of these specific production areas difficult, because in each year, production area was confounded with environment, due to a lack of replication within area. For example, it may have been better for IL if replicated experiments had been set up at six locations at the main University of Illinois research and extension centers (Urbana, Brownstown, Dixon Springs, Perry, Monmouth, and Dekalb). A further step would have been to set up multiple replicated experiments at or near each of these research and education centers so that different soil types and potentially different environment effects could have been observed. This would have provided a hierarchical experimental design which includes the effects of area, location within area, and site within location. Because there is still limited published research available on *M. x giganteus* biomass production in the USA, many more sites and years of production are needed to suggest an optimal production region and how it performs under different management practices such as harvest timing and response to fertilizer application. One specific management practice that needs further evaluation is the effect of N fertilization on fully productive stands of *M. x giganteus*, or *M. x giganteus* stands that are at least 3 to 5 years old.

In Ch. 4, forage and energy sorghum hybrids were grown in four IL environments under different N rates. It was observed that environment had a major impact on plant growth and total biomass yields, and in each environment forage sorghum harvested twice annually (summer and fall) yielded less than energy sorghum harvested once in the fall. Biomass yield, leaf area index, and plant height response to N rate were observed up to 150 kg N ha$^{-1}$ in 2009 and up to at least
168 kg N ha\(^{-1}\) in 2010. Photoperiod sensitivity allowed the energy sorghum hybrids to continue vegetative growth until late Sept. which allowed them to continue accumulating plant height and biomass throughout the majority of the growing season. Future research would benefit from more sites and more years of production. This study was limited to three locations, two years, and a total of four environments. Multiple years of production for a given site would provide more useful information for calculating optimal N rates than a single year of production at that site (Bullock and Bullock, 1994). If agronomists were to continue evaluating sorghum in IL for biomass production, a couple of research areas should be pursued. First, continue evaluating energy and forage sorghum hybrids under a wide range of N rates, and establish trials at several locations (i.e. six main research and extension centers in IL) for two or three or even more years. Of course, this should be done under soil conditions that have adequate levels phosphorous, potassium and other essential macro and micro nutrients. One major foreseen challenges in dealing with sorghum biomass is the high moisture content of the biomass material. Even when harvested in Nov., the biomass still had approximately 60% moisture. The process of baling and hauling this material to a conversion facility would require that this biomass be dried down to a level that would allow long term storage. Baled biomass with high moisture content, stored for even a short period of time, can result in rapid decomposition and even spontaneous combustion. Biomass harvesters with conditioners could potentially provide a means to crack and break apart the sorghum stems so that significant field drying would occur. Also, harvesting earlier in the season could provide sufficient time for the crop to dry in the field when there is still plenty of warm late summer and early fall weather. In each case, the biomass would likely need to be spread out evenly on the field (for drying purposes) or windrowed in a way that allows the
biomass to be turned over with equipment such as a hay rake that can expose the underside of the
windrow to the sun and air.

REFERENCES

APPENDIX A

Selected SAS and R code for Ch. 2

Cultivar means, SEM, min, max-Ch.2, Table 2.4.

```sas
options ps=100 ls=100 nodate nocompress nonumber formdlim='*';
data SW;
length Cultivar$ 30;
infile 'C:\Documents and Settings\maughan2\My Documents\My Dropbox\Switchgrass Meta-Analysis\SW database June 18, 2011, no Europe, no Irrigation.csv'
dlm='",' firstobs=2;
input PubName$ Category$ Publication$ Experiment sites$ Country$ Location$ Region$ Latitude Longitude soil$ establishment$ SeedRate$ Precip spring Irrigation$ year$ season$ Cultivar$
Ecotype$ Cuttings$ harvest$ Nrate$ biomass notes$;
if Nrate > 300 then delete;
cards;
run;
proc print; run;
```

```sas
data SW; set SW;
if cultivar="mean" then delete;
if cultivar="NA" then delete;
if cultivar="unknown" then delete;
if cultivar="average" then delete;
if cultivar="Mean" then delete;
if cultivar="average of 3 varieties" then delete;
*if cuttings=2 then delete;
if season=1 then delete;
*if season=2 then delete;
run; proc print; run;
```

```sas
proc sort data=SW; by season region cultivar; run;
proc means data=SW noprint mean std min max; by season region cultivar;
output out=culmean mean=meanbiomass std=stdbiomass min=minbiomass max=maxbiomass;
run; proc print data=culmean; run;
```

Descriptive statistics, model development-Ch.2, Fig. 2.2, Fig. 2.3, Fig. 2.4, Fig. 2.5, Fig. 2.6, Table 2.5, Table 2.6 in part.

```r
## Load packages
library(nlme) #library(help = nlme)
library(Hmisc)
library(lattice) #library(help = lattice)
library (graphics) #library(help = graphics)
##library(help = nlme)
## Load file
sw <- read.csv("./SW database June 18, 2011, no Europe, no Irrigation.csv")

head(sw)
sw.NR <-sw[sw$Region == "North",]
unique(sw.NR[,5])
sw.UCR <-sw[sw$Region == "Upper-Central",]
unique(sw.UCR[,5])
sw.LCR <-sw[sw$Region == "Lower-Central",]
unique(sw.LCR[,5])
sw.SR <-sw[sw$Region == "South",]
unique(sw.SR[,5])
unique(sw[,3]) #45 studies
unique(sw[,5]) #106 site or location combinations
sw

#which varieties are yielding greater than 26? Kanlow, Alamo.
```
which varieties are yielding greater than 30? Kanlow, Alamo.

which varieties are yielding greater than 35? Kanlow, Alamo.

Removing data with N rates higher than 300. can cause lodging and most recommended N rates have been much lower.

Removing lowland upper north

Get rid of SeedRate

# I will average over varieties before I do the analysis

Averaged switchgrass biomass over varieties

write.csv(sw.b, "./sw-meta June 18, 2011.csv", row.names=FALSE)

rm(list=ls())

sw.b <- read.csv("./sw-meta June 18, 2011.csv")

manually removing observations from NA's associated with N rates higher than 280 if the above code is rerun, this will have to be done again.

season 2 yields by ecotype

mean(sw.b$biomass) #0 to 33.4

season 2 yields by ecotype

mean(sw.b$biomass) #11.1
For lowland ecotypes

Removing lowland upper north, b/c few observation exist in the north region

Mean for the north upland is 7
Mean for the north lowland is 10.23
Mean for the upper central upland is 9.7
Mean for the upper central lowland is 9.9
Mean for the lower central upland is 11.9
Mean for the lower central lowland is 14.4

# Yield increases from season 2 to seasons >=3

# Biomass yield ranges by ecotype

Range (sw.b$region == "North", "biomass") = #0 to 30.4
Range (sw.b$region == "Lower-Central", "biomass") = #4.6 to 33.4
Range (sw.b$region == "Upper-Central", "biomass") = #2.5 to 26
Range (sw.b$region == "South", "biomass") = #1.1 to 14.5

# Biomass yield ranges by region

Range (sw.b$region == "South", "biomass") = #0 to 30.4
Range (sw.b$region == "Lower-Central", "biomass") = #4.6 to 33.4
Range (sw.b$region == "Upper-Central", "biomass") = #2.5 to 26
Range (sw.b$region == "North", "biomass") = #1.1 to 14.5

# Biomass yields by season

Mean (sw.b$season == "1", "biomass") = #6.6
Mean (sw.b$season == "2", "biomass") = #3
Mean (sw.b$season == "3", "biomass") = #10.9
Mean (sw.b$season == "4", "biomass") = #5.2

# Yield increases from season 2 to seasons >=3

Mean (sw.b$season == "2", "biomass") = #11.1
Mean (sw.b$season == "3", "biomass") = #12.6
Mean (sw.b$season == "4", "biomass") = #9.3
Mean (sw.b$season == "5", "biomass") = #10.1

# What are the mean values by region

Mean (sw.b$region == "South", "biomass") = 10.3
Mean (sw.b$region == "Upper-Central", "biomass") = 14.4
Mean (sw.b$region == "Upper-Central", "biomass") = 11.9
Mean (sw.b$region == "Upper-Central", "biomass") = 9.7
Mean (sw.b$region == "North", "biomass") = 10.23
Mean (sw.b$region == "North", "biomass") = 7

# Removing lowland upper north, b/c few observation exist in the north region

For lowland ecotypes

sw.b$region == "North", "biomass" = 5
sw.b[sw.b$Region == "North" & sw.b$Ecotype == "L",5] <- NA

unique(sw.b$Ecotype)

sw.b$Region <- factor(sw.b$Region,
  levels = c("South", "Lower-Central", "Upper-Central", "North"))

bwplot(biomass ~ Region | Ecotype*season, data = sw.b,
  xlab="Region",
  ylab="Dry Biomass Yield (Mg/ha)",
  fill="yellow",
  panel = function(...) {
    panel.grid(v = 0, h=-1)
    panel.bwplot(...)
  },
  layout = c(1,2))

## This suggests that yield is higher in the lower central region vs the
## upper central for lowland ecotypes but they
## are about the same for upland
## ecotypes

data(sw.b)

##FIGURE 3
png("./manuscript figures/season1.png",width=600, height=1200, res=120)
sw.b.one <- sw.b[sw.b$season == "1",]
print(bwplot(biomass ~ Region | Ecotype, data = sw.b.one,
  xlab="Region",
  ylab=list(expression(paste("Dry biomass yield ","(Mg ",ha"-1,")"))),
  ylim=c(0,35),
  main = "growing season 1",
  fill="ivory2",
  panel = function(...) {
    panel.grid(v = 0, h=-1)
    panel.bwplot(...)
  },
  layout = c(1,2))
dev.off()

##FIGURE 3
png("./manuscript figures/season2.png",width=600, height=1200, res=120)
sw.b.two <- sw.b[sw.b$season == "2",]
print(bwplot(biomass ~ Region | Ecotype, data = sw.b.two,
  xlab="Region",
  ylab=list(expression(paste("Dry biomass yield ","(Mg ",ha"-1,")"))),
  ylim=c(0,35),
  main = "growing season 2",
  fill="ivory3",
  panel = function(...) {
    panel.grid(v = 0, h=-1)
    panel.bwplot(...)
  },
  layout = c(1,2))
dev.off()

mean(sw.b.two[sw.b.two$Region == "South" & sw.b.two$Ecotype == "L","biomass"])
## The mean for the south lowland is 9.3
mean(sw.b.two[sw.b.two$Region == "South" & sw.b.two$Ecotype == "U","biomass"])
## The mean for the south upland is 5.5
mean(sw.b.two[sw.b.two$Region == "Lower-Central" & sw.b.two$Ecotype == "L","biomass"])
## The mean for the lower central lowland is 14.3
median(sw.b.two[sw.b.two$Region == "Lower-Central" & sw.b.two$Ecotype == "L","biomass"])
## The median for the lower central lowland is 10.3
mean(sw.b.two[sw.b.two$Region == "Lower-Central" & sw.b.two$Ecotype == "U","biomass"])
## The mean for the lower central upland is 12.9
median(sw.b.two[sw.b.two$Region == "Upper-Central" & sw.b.two$Ecotype == "L","biomass"])
## The median for the upper central lowland is 11.1
mean(sw.b.two[sw.b.two$Region == "Upper-Central" & sw.b.two$Ecotype == "U","biomass"])
## The mean for the upper central upland is 8.2
## The mean for the north lowland is NA
mean(sw.b.two[sw.b.two$Region == "North" & sw.b.two$Ecotype == "U","biomass"])

## The mean for the north upland is NA

##FIGURE 3-PART 3

png("./manuscript figures/season3.png",width=600, height=1200, res=120)
sw.b.three <- sw.b[sw.b$season == "3-5",]
print(bwplot(biomass ~ Region | Ecotype, data = sw.b.three,
  xlab="Region",
  ylab=list(expression(paste("Dry biomass yield ","(Mg ",ha^-1,"))")),
  ylim=c(0,35),
  main = "growing seasons >=3",
  fill=c("ivory4"),
  panel = function(...) {
    panel.grid(v = 0, h=-1)
    panel.bwplot(...)
  },
  layout = c(1,2))
dev.off()

mean(sw.b.three[sw.b.three$Region == "South" & sw.b.three$Ecotype == "L","biomass"])
  ## 16.9
mean(sw.b.three[sw.b.three$Region == "South" & sw.b.three$Ecotype == "U","biomass"])
  ## 5.1
mean(sw.b.three[sw.b.three$Region == "Lower-Central" & sw.b.three$Ecotype == "L","biomass"])
  ## 14.6
median(sw.b.three[sw.b.three$Region == "Lower-Central" & sw.b.three$Ecotype == "L","biomass"])
  ## 15.6
mean(sw.b.three[sw.b.three$Region == "Lower-Central" & sw.b.three$Ecotype == "U","biomass"])
  ## 11.9
mean(sw.b.three[sw.b.three$Region == "Upper-Central" & sw.b.three$Ecotype == "L","biomass"])
  ## 10.4
median(sw.b.three[sw.b.three$Region == "Upper-Central" & sw.b.three$Ecotype == "L","biomass"])
  ## 10.7
mean(sw.b.three[sw.b.three$Region == "Upper-Central" & sw.b.three$Ecotype == "U","biomass"])
  ## 10
mean(sw.b.three[sw.b.three$Region == "North" & sw.b.three$Ecotype == "L","biomass"])
  ## NA
mean(sw.b.three[sw.b.three$Region == "North" & sw.b.three$Ecotype == "U","biomass"])
  ## NA

library(latticeExtra)
sw.b$harvest.timing <- factor(sw.b$harvest.timing, levels = c("PSC", "ES"))
png("./manuscript figures/harvesttimimg-ellipse.png",width=1500, height=600, res=120)
xypplot(biomass ~Nrate | Region, groups=harvest.timing, data = sw.b,
  xlab=list(expression(paste("N rate ","(kg ",ha^-1,"))")),
  ylab=list(expression(paste("Dry biomass yield ","(Mg ",ha^-1,"))")),
  cex=1.2,
  col=c("Green","Brown"),
  layout=c(4,1),
  panel = function(x,y,...){
    panel.xypplot(x,y, type = c("p"), pch=c(15,25), fill="transparent",
    cex=1.2,...)
    panel.ellipse(x,y, lwd = 2, lty=c(1,2), center.pch=NULL, level=0.80,...)
  },
  key=list(text=list(c("PSC","ES")),
    x=0.8, y=.9, cex.title=1.2, pch=c(15,25),
    points=TRUE, cex=1.2, lty=c(1,2), lwd=2, lines=TRUE,
    col=c("Green","Brown"))
}
dev.off()

# yield increases from season 2 to seasons >=3
mean(sw.b[sw.b$Region == "South" & sw.b$harvest.timing == "PSC","biomass"])
  ## 11.1
sd(sw.b[sw.b$Region == "South" & sw.b$harvest.timing == "PSC","biomass"])
  ## 6.3
mean(sw.b[sw.b$Region == "South" & sw.b$harvest.timing == "ES","biomass"])
  ## 8.2
sd(sw.b[sw.b$Region == "South" & sw.b$harvest.timing == "ES","biomass"])
  ## 5

mean(sw.b[sw.b$Region == "North" & sw.b$harvest.timing == "PSC","biomass"])
  ## 6.4
sd(sw.b[sw.b$Region == "North" & sw.b$harvest.timing == "PSC","biomass"])
  ## 3
mean(sw.b[sw.b$Region == "North" & sw.b$harvest.timing == "ES","biomass"])
  ## 7.8
sd(sw.b[sw.b$Region == "North" & sw.b$harvest.timing == "ES","biomass"])
  ## 3.2

## it appears that in the south, PSC yields better than ES, but in the North it is
## the other way around. This may have to do with early harvesting injuring the crop
## long term in the north, being unprepared for winter due to early harvest.
## The south appears to have some recovery time due to lack of temperatures excessively below freezing

```r
png("./manuscript figures/spring precip.png",width=1200, height=600, res=120)
xyplot(biomass ~ Apr.June.precip..mm., group=Ecotype, data = sw.b, 
  ylab=list(expression(paste("Dry biomass yield ","(Mg ",ha^-1","))}), cex=1.2), 
  xlab = list("April-June Precipitation (mm)"), cex=1.2), 
  pch=c(1,17), col=c("black", "grey"), fill="transparent", lty=c(2,1), lwd = 2, 
  type = c("p", "l"), cex=1, 
  xlim=c(50,1020), 
  key=list(x=0.5, y=1, cex.title=1.2, 
    pch=c(1,17), cex=1.2, 
    lty=c(2,1), lwd=2, points=TRUE, lines=TRUE, 
    col=c("black", "grey"), 
    text=list(c("Lowland", "Upland"))))
dev.off()

# biomass yields tend to be higher with greater amounts of early season precipitation
# lowland yield better than upland

sw.b[sw.b$biomass > 34,]
sw.b[sw.b$biomass > 34,10] <- NA
sw.b.n <- na.omit(sw.b)
sw.b.n$G <- groupedData(biomass ~ Nrate | sites, data = sw.b.n)
unique(sw.b.n$sites)
xyplot(biomass ~ Nrate | sites, type = c("p","a"), data = sw.b.n)

## MODEL BUILDING

## model without random Nrate effects
quad.lme <- lme(biomass ~ Nrate + I(Nrate^2) , 
  random = ~ 1 | sites, data = sw.b.n$G, 
  na.action="na.omit")
quad.lme
anova(quad.lme)
plot(ranef(quad.lme))
plot(intervals(quad.lme))

## model with random effect for the quadratic term
fitquad.lme <- lme(biomass ~ Nrate + I(Nrate^2) , 
  random = ~ 1 + Nrate + I(Nrate^2) | sites, data = sw.b.n$G, 
  na.action="na.omit")
fitquad.lme
anova(fitquad.lme)
plot(ranef(fitquad.lme))
plot(intervals(fitquad.lme))

## A simpler model does not have random effect for the quadratic term
fitsimple.lme <- lme(biomass ~ Nrate + I(Nrate^2) , 
  random = ~ 1 + Nrate | sites, data = sw.b.n$G, 
  na.action="na.omit")
fitsimple.lme
anova(quad.lme,fitquad.lme,fitsimple.lme)

#              Model df      AIC      BIC    logLik   Test  L.Ratio p-value
#quad.lme          1  5 3490.786 3512.788 -1740.393 
#fitquad.lme       2 10 3485.885 3529.888 -1732.943 1 vs 2 14.901160  0.0108
#fitsimple.lme     3  7 3480.126 3510.928 -1733.063 2 vs 3  0.241361  0.9707

anova(fitsimple.lme)
plot(ranef(fitsimple.lme))

## The simpler model is better, rather parsimony is better here.
\texttt{coef(fitsimple.lme)}
\texttt{plot(augPred(fitsimple.lme, level=0:1, data=sw.b.nG))}

\#NOW WE ADD IN VARIABLES and use a backward elimination method. IF p-value larger
\#than 0.1 then drop. adding all main effects and suspected interactions that
\#could have valid interpretations, based upon literature and xyplots.
\texttt{fit.lme <- lme(biomass ~ Nrate +}
\texttt{I(Nrate^2) +}
\texttt{Region +}
\texttt{Apr.June.precip..mm. +}
\texttt{season +}
\texttt{Ecotype +}
\texttt{harvest.timing +}
\texttt{Cuttings +}
\texttt{Apr.June.precip..mm.:Region +}
\texttt{Apr.June.precip..mm.:Ecotype +}
\texttt{Apr.June.precip..mm.:season +}
\texttt{Nrate:Ecotype +}
\texttt{I(Nrate^2):Ecotype +}
\texttt{Region:harvest.timing +}
\texttt{season:Ecotype,}
\texttt{random = ~ 1 + Nrate | sites,}
\texttt{data = sw.b.nG)}

\#other potential interactions that result in singularity or don't makes sense.
\#Region:Ecotype clearly is significant in reality but it is suspected that the
\#unbalanced nature of the data render this interaction a singularity problem.
\texttt{anova(fit.lme)}
\begin{verbatim}
#                             numDF denDF  F-value p-value
#(Intercept)                      1   487 918.5267  <.0001
#Nrate                            1   487  34.8070  <.0001
#I(Nrate^2)                       1   487   4.3686  0.0371
#Region                           3    93  16.7507  <.0001
#Apr.June.precip..mm.             1   487  14.7192  0.0001
#season                           2   487   3.1355  0.0444
#Ecotype                          1   487 104.6983  <.0001
#harvest.timing                   1   487   3.1562  0.0763
#Region:April.June.precip..mm.    3   487   1.5727  0.1951
#April.June.precip..mm.:Ecotype   1   487   8.7157  0.0033
#April.June.precip..mm.:season    2   487   7.6962  0.0005
#Nrate:Ecotype                    1   487   3.3621  0.0673
#I(Nrate^2):Ecotype               1   487   0.2175  0.6411
#Region:harvest.timing            3   487   2.2997  0.0766
#season:Ecotype                   2   487   0.4422  0.6429
\end{verbatim}

\#now removing non-significant terms
\texttt{fit2.lme <- lme(biomass ~ Nrate +}
\texttt{I(Nrate^2) +}
\texttt{Region +}
\texttt{Apr.June.precip..mm. +}
\texttt{season +}
\texttt{Ecotype +}
\texttt{harvest.timing +}
\texttt{Apr.June.precip..mm.:Ecotype +}
\texttt{Apr.June.precip..mm.:season +}
\texttt{Nrate:Ecotype +}
\texttt{Region:harvest.timing,}
\texttt{random = ~ 1 + Nrate | sites,}
\texttt{data = sw.b.nG)}

\texttt{anova(fit2.lme)}
coefficient (fit2.lme)
summary(fit2.lme)
fixed.effects(fit2.lme)
intervals(fit2.lme)

## Spring precipitation seems to interact strongly with season, this means
## that biomass responds differently to precipitation depending on the
## season. As the crop matures from season 1 to season 2 and seasons >=3,
## similar precipitation
## levels result in higher biomass yields

#also spring precipitation interacts with ecotype, and this makes since since lowland ecotypes
#tend to come from wetter environments than upland ecotypes, and likely do better under wetter
#conditions than upland ecotypes.

#Lowland and upland ecotypes may have slightly different N requirements. This has been suggested
#in the old literature

## in the south, PSC harvests tend to result in greater biomass yields, but not so in the north.
## in the north, PSC harvest likely injured the stands by removing nutrients needed for winter
## survival, causing yields to decline over time. This is just one possible explanation for
## this interaction

plot(fit2.lme)
qqnorm(fit2.lme, abline=c(0,1))

## final model
unique(sw.b.nG$sites)
## Sort the sites
sw.b.nG$sites <- factor(sw.b.nG$sites, levels = unique(sw.b.nG$sites))
unique(sw.b.nG$sites)
augpred <- augPred(fit2.lme, level=0:1, group=Region, data=sw.b.nG)
augpred$groups <- factor(augpred$groups, levels = unique(sw.b.nG$sites))
png("./manuscript figures/site_predictions.png", width=1200, height=1600, res=140)
plot(augpred, xlab=list(expression(paste("N rate ","(kg \(\cdot\)ha\(^{-1}\))"))), cex=1.2),
ylab=list(expression(paste("Dry biomass yield ","(Mg \(\cdot\)ha\(^{-1}\))"))), cex=1.2),
as.table = TRUE,
layout = c(8,13),
ltc=c(1,2), col="Black",
key=list(text=list(c("fixed","experimental unit")),lty=c(1,2),lines=1))
dev.off()

#plotting predictions 300mm SPRING PRECIPITATION, PSC, growing seasons >=3
rgn <- c("South","Lower-Central","Upper-Central","North")
nd <- expand.grid(Region = rgn, season = ">=3", Nrate = c(0,50,100,150,200,250),
Ecotype = c("L","U"), Apr.June.precip..mm.=300,
harvest.timing = "PSC")
pp <- predict(fit2.lme, newdata = nd, level = 0)
preds <- data.frame(pp=pp, nd)
preds$type <- "predicted"
names(preds) <- c("biomass", "Region", "season", "Nrate", "Ecotype", "Precip",
harvest.timing", "type")
sw.psc <- sw.b.nG[sw.b.nG$harvest.timing == "PSC" & sw.b.nG$season == ">=3",]
sw.b.nG$Apr.June.precip..mm. >=200 & sw.b.nG$Apr.June.precip..mm. <=400,]
obs <- with(sw.psc, data.frame(biomass = biomass, Region = Region, season = season, Nrate = Nrate, Ecotype = Ecotype, Precip = Apr.June.precip..mm., harvest.timing = harvest.timing, type = "observed"))

pred.obs <- rbind(preds, obs)
pred.obs$Region <- factor(pred.obs$Region, levels = c("South", "Lower-Central", "Upper-Central", "North"))
pred.obs$type <- factor(pred.obs$type)
pred.obs$type.Ecotype <- with(pred.obs, type:Ecotype)
pred.obs[pred.obs$type == 'predicted' & pred.obs$Region == 'North' & pred.obs$Ecotype == 'L', 'biomass'] <- NA

png('./manuscript figures/predicted-and-observed-PSC-300mm.png', width=1500, height=600, res=120)
xyplot(biomass ~ Nrate | Region, data = pred.obs, main="growing seasons >=3, PSC harvest, 300mm spring precipitation", cex.title=1.2, pch = c(1,17), fill="transparent", cex=1.2, groups = type.Ecotype, layout = c(4,1), xlab=list(expression(paste("N rate ", "(kg ha^{-1})"))), ylab=list(expression(paste("Dry biomass yield ", "(Mg ha^{-1})"))), col = c("black", "grey"), ylim=c(0,35), panel = function(x,y,...){ panel.superpose.2(x,y,type=c('p','p','l','l','l','l'), lty=c(2,1), lwd=2,...) }, key = list(x=0.8, y=.9, cex.title=1.2, pch=c(1,17), cex=1.2, lty=c(2,1), lwd=2, points=TRUE, lines=TRUE, col=c("black", "grey"), text=list(c("Lowland", "Upland"))))
dev.off()

#plotting predictions 300mm SPRING PRECIPITATION, ES, growing seasons >=3
rgn <- c("South","Lower-Central","Upper-Central","North")
nd <- expand.grid(Region = rgn, season = ">=3", Nrate = c(0,50,100,150,200,250), Ecotype = c("L","U"), Apr.June.precip..mm.>=300, harvest.timing="ES")
pp <- predict(fit2.lme, newdata = nd, level = 0)
preds <- data.frame(pp=pp, nd)
preds$type <- "predicted"
names(preds) <- c("biomass", "Region", "season", "Nrate", "Ecotype", "Precip", "harvest.timing", "type")
sw.es <- sw.b.nG[sw.b.nG$harvest.timing == "ES" & sw.b.nG$season == ">=3",]
# & sw.b.nG$Apr.June.precip..mm.>=200 & sw.b.nG$Apr.June.precip..mm.<=400]
obs <- with(sw.es, data.frame(biomass = biomass, Region = Region, season = season, Nrate = Nrate, Ecotype = Ecotype, Precip = Apr.June.precip..mm., harvest.timing = harvest.timing, type = "observed"))
pred.obs <- rbind(preds, obs)
pred.obs$Region <- factor(pred.obs$Region, levels = c("South","Lower-Central","Upper-Central","North"))
pred.obs$type <- factor(pred.obs$type)
pred.obs$type.Ecotype <- with(pred.obs, type:Ecotype)
pred.obs[pred.obs$type == 'predicted' & pred.obs$Region == 'North']
& pred.obs$Ecotype == 'L', 'biomass'] <- NA

png('./manuscript figures/predicted-and-observed-ES-300mm.png', width=1500, height=600, res=120)
xyplot(biomass ~ Nrate | Region,
data = pred.obs, main="growing seasons >=3, ES harvest, 300mm spring precipitation",
cex.title=1.2, pch = c(1,17), fill="transparent",
cex=1.2, groups = type.Ecotype, layout = c(4,1),
xlab=list(expression(paste("N rate ","(kg ",ha^-1,")))), cex=1.2),
ylab=list(expression(paste("Dry biomass yield ","(Mg ",ha^-1,")))), cex=1.2),
col = c("black", "grey"),
ylab=c(0,35),
panel = function(x,y,...){
  panel.superpose.2(x,y,type=c('p','p','l','l','l','l'), lty=c(2,1), lwd=2,...)
},
key = list(x=0.8, y=.9, cex.title=1.2,
pch=c(1,17), cex=1.2, lty=c(2,1), lwd=2, points=TRUE, lines=TRUE,
col=c("black", "grey"),
text=list(c("Lowland", "Upland")))
dev.off()

##removing outliers for supplementary results
## beginnning with final model
fit2.lme <- lme(biomass ~ Nrate + I(Nrate^2) + Region + Apr.June.precip..mm. + season + Ecotype + harvest.timing + Apr.June.precip..mm.:Ecotype + Apr.June.precip..mm.:season + Nrate:Ecotype + Region:harvest.timing,
  random = ~ 1 + Nrate | sites,
  data = sw.b.nG)
anova(fit2.lme)
#   numDF denDF  F-value p-value
# (Intercept)         1  494  899.7931 <.0001
# Nrate              1  494  34.9935  <.0001
# I(Nrate^2)         1  494   4.4053   0.0363
# Region             3   93  16.2564  <.0001
# Apr.June.precip..mm.  1  494  14.7079   0.0001
# season            2  494   3.0845   0.0466
# Ecotype            1  494  104.9683   <.0001
# harvest.timing    1  494   3.1382   0.0771
# Apr.June.precip..mm.:Ecotype  1  494   6.8370   0.0092
# Apr.June.precip..mm.:season 2  494   7.4240   0.0007
# Nrate:Ecotype     1  494   3.4461   0.0640
# Region:harvest.timing 3  494   2.2497   0.0817

plot(fit2.lme) ##residuals look OK, some outliers

## checking the residuals for outliers
rnm <- row.names(na.omit(sw.b.nG[,,-3]))
plot(fit2.lme, id = 0.08, idLabels = rnm)
qqnorm(fit2.lme, abline=c(0,1))

sw.b.nmd <- na.omit(sw.b.nG)

141
sw.b.n2 <- sw.b.nmd[row.names(sw.b.nmd) %in% c(233, 387, 29, 617, 235),]

## What are these outliers?
unique(sw.b.nmd[row.names(sw.b.nmd) %in% c(233, 387, 29, 617, 235),]$sites)
sw.b.nmd[row.names(sw.b.nmd) %in% c(233, 387, 29, 617, 235),]

<table>
<thead>
<tr>
<th></th>
<th>sites</th>
<th>Region</th>
<th>Apr.June.precip..mm.</th>
<th>season</th>
<th>Ecotype</th>
<th>Cuttings</th>
<th>harvest.timing</th>
<th>Nrate</th>
<th>biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>#29</td>
<td>10a</td>
<td>South</td>
<td>393</td>
<td>&gt;=3</td>
<td>L</td>
<td>1</td>
<td>ES</td>
<td>150</td>
<td>24.36441</td>
</tr>
<tr>
<td>#233</td>
<td>24a</td>
<td>Lower-Central</td>
<td>379</td>
<td>2</td>
<td>L</td>
<td>2</td>
<td>ES</td>
<td>0</td>
<td>33.40000</td>
</tr>
<tr>
<td>#235</td>
<td>24a</td>
<td>Lower-Central</td>
<td>379</td>
<td>2</td>
<td>L</td>
<td>2</td>
<td>ES</td>
<td>224</td>
<td>29.50000</td>
</tr>
<tr>
<td>#387</td>
<td>10a</td>
<td>South</td>
<td>243</td>
<td>&gt;=3</td>
<td>L</td>
<td>2</td>
<td>ES</td>
<td>84</td>
<td>28.63500</td>
</tr>
<tr>
<td>#617</td>
<td>10a</td>
<td>Lower-Central</td>
<td>475</td>
<td>&gt;=3</td>
<td>L</td>
<td>2</td>
<td>ES</td>
<td>67</td>
<td>25.97100</td>
</tr>
</tbody>
</table>

fit2b.lme <- lme(biomass ~ Nrate + I(Nrate^2) + Region + Apr.June.precip..mm. + season + Ecotype + harvest.timing + Apr.June.precip..mm.:Ecotype + Apr.June.precip..mm.:season + Nrate:Ecotype + Region:harvest.timing, random = ~ 1 + Nrate | sites, data = sw.b.n2)

anova(fit2b.lme)

#                             numDF denDF  F-value p-value
#(Intercept)                      1   489 938.0432 <.0001
#Nrate                            1   489 38.0413 <.0001
#I(Nrate^2)                       1   489  7.6106  0.0060
#Region                            3    93 17.2381 <.0001
#Apr.June.precip..mm.             1   489 18.0897 <.0001
#season                           2   489  3.8675  0.0216
#Ecotype                          1   489 110.0736 <.0001
#harvest.timing                   1   489  3.8717  0.0497
#Apr.June.precip..mm.:Ecotype     1   489  5.9813  0.0148
#Apr.June.precip..mm.:season      2   489  8.7673  0.0002
#Nrate:Ecotype                    1   489  4.7955  0.0290
#Region:harvest.timing            3   489  2.5163  0.0576

plot(fit2b.lme)  ## residuals look pretty good

plot(augPred(fit2b.lme, level=0:1))
qqnorm(fit2b.lme, abline=c(0,1))
APPENDIX B

Selected SAS and R code for Ch. 3

Plant height-Ch.3, Table 3.6, Fig. 3.1

```r
library(nlme)
library(Hmisc)
library(lattice)
library(graphics)

#2009 & 2010 ht data
growth <- read.csv(file = "../2009 2010 ht data.csv", skip = 2, na.strings=".")
head(growth)
growth <- growth[-373:-426,] #getting rid of Illinois
head(growth)
unique(growth$Year)
growth$Year <- as.factor(growth$Year)
head(growth)

xyplot(growth[,8] ~ growth[,10],
  ylab = "Height",
  xlab = "day of year",
  groups = growth[,1],
  auto.key=TRUE)

growth2 <- data.frame(env=growth[,11],
  doy = growth[,10],
  Nrate = growth[,6],
  height = growth[,8],
  TT = growth[,9])

## developing a model
expu <- with(growth, Environment:factor(Rep):factor(N.rate.kg.ha))
growthG <- groupedData(height ~ doy | expu, data = growth2)
head(growthG)
fit.nls <- nlsList(height ~ SSlogis(doy, Asym, xmid, scal),
                   data = growthG)
fit.nlme <- nlme(fit.nls)
anova(fit.nlme)
plot(augPred(fit.nlme, level = 0:1))

fix2 <- fixef(fit.nlme)
fix2
fit2.nlme <- update(fit.nlme, fixed = Asym + xmid + scal ~ Nrate,
                      start = c(fix2[1], 0, fix2[2], 0, fix2[3], 0))
anova(fit2.nlme)

#                 numDF denDF   F-value p-value
#Asy
#m.(Intercept)     1   379  6453.716  <.0001
#Asym.Nrate           1   379     0.001  0.9725
#xmid.(Intercept)     1   379 14449.984  <.0001
#xmid.Nrate           1   379     0.001  0.9717
#scal.(Intercept)     1   379  2782.442  <.0001
#scal.Nrate           1   379     0.155  0.6940

## Add the effect of env
fix3 <- fixef(fit2.nlme)
fix3
fit3.nlme <- update(fit.nlme, fixed = Asym + xmid + scal ~ Nrate + env,
                      start = c(fix3[1:2], 0, 0, 0, 0, fix3[3:4], 0, 0, 0, 0, fix3[5:6], 0, 0, 0, 0))
anova(fit3.nlme)
```

```
Add the interaction of $Nrate \times loc$

```r
fix4 <- fixef(fit3.nlme)
fit4.nlme <- update(fit3.nlme, fixed = Asym + xmid + scal ~ Nrate * env,
                 start = c(fix4[1:7], 0, 0, 0, 0, 0, fix4[8:14], 0, 0, 0, 0, 0, fix4[15:21], 0, 0, 0, 0, 0))
```  

```r
anova(fit4.nlme)
#                 numDF denDF   F-value p-value
#Asym.(Intercept)     1   349 14528.41  <.0001
#Asym.Nrate           1   349      1.21  0.2713
#Asym.env             5   349   1039.42  <.0001
#Asym.Nrate:env       5   349      3.08  0.0099
#xmid.(Intercept)     1   349 167106.08  <.0001
#xmid.Nrate           1   349      0.02  0.8942
#xmid.env             5   349     96.82  <.0001
#xmid.Nrate:env       5   349      0.74  0.5913
#scal.(Intercept)     1   349   3552.38  <.0001
#scal.Nrate           1   349      0.40  0.5276
#scal.env             5   349     11.61  <.0001
#scal.Nrate:env       5   349      0.25  0.9382
```

Simplify error structure

```r
fit5.nlme <- update(fit4.nlme, random = pdDiag(list(Asym + xmid + scal ~ 1)))
fit5.nlme #the std. deviations for xmid and scale are very small here and could be eliminated
anova(fit4.nlme, fit5.nlme)
```

Simpler model is better

```r
fit6.nlme <- update(fit5.nlme, random = pdDiag(Asym ~ 1))
anova(fit5.nlme, fit6.nlme)
```

```r
fit7.nlme <- update(fit6.nlme, weights = varPower())
fit7.nlme
```

```r
anova(fit6.nlme, fit7.nlme)
#          Model df       AIC       BIC   logLik   Test     L.Ratio p-value
#fit6.nlme     1 38 -422.4554 -265.8007 249.2277
#fit7.nlme     2 39 -420.4606 -259.6834 249.2303 1 vs 2 0.005209665  0.9425
```

Investigating the effect, especially the interaction, now that our error structure is settled?

```r
anova(fit6.nlme)
#                 numDF denDF   F-value p-value
#Asym.(Intercept)     1   349   7945.70  <.0001
#Asym.Nrate           1   349      0.60  0.4392
#Asym.env             5   349   827.98  <.0001
#Asym.Nrate:env       5   349      1.74  0.1249
#xmid.(Intercept)     1   349 168312.32  <.0001
#xmid.Nrate           1   349      0.02  0.8832
#xmid.env             5   349     97.36  <.0001
#xmid.Nrate:env       5   349      0.74  0.5954
#scal.(Intercept)     1   349   3537.96  <.0001
#scal.Nrate           1   349      0.41  0.5247
#scal.env             5   349   11.61  <.0001
#scal.Nrate:env       5   349      0.26  0.9369
```

The interaction is only somewhat significant for the asymptote,
the effect of $N$ is inconsistent from location to location, and appears generally to not be important.
# I will reduce down to just Nrate + env

```r
fit8.nlme <- update(fit6.nlme, fixed = Asym + xmid + Nrate + env, 
start = c(fix3[1:2], 0, 0, 0, 0, fix3[3:4], 0, 0, 0, 0, fix3[5:6], 0, 0, 0, 0))
plot(fit8.nlme)
qqnorm(fit8.nlme, abline=c(0,1))
#residuals look are not too bad

fit8.ss <- summary(fit8.nlme)
```

```r
fit8.ss$tTable
# Value Std.Error DF t-value  p-value
#Asym.(Intercept)  3.079769e+00  0.0491411709 364  62.67186833 4.178050e-197
#Asym.Nrate         -1.515855e-05  0.0002937831 364  -0.05159775 9.588775e-01
#Asym.envNY-2010   3.110370e-01  0.0569491855 364  5.46165884 8.755655e-08
#Asym.envNE-2009    -2.336358e-01  0.0698799919 364  -3.34338555 9.136065e-04
#Asym.envNE-2010    7.111425e-01  0.0558585500 364  12.73113115 5.792894e-31
#Asym.envNJ-2009    2.901095e-01  0.0574492388 364  5.49840173 7.005466e-07
#Asym.envNW-2010    -7.862059e-02  0.0550167145 364  -1.42904501 1.538489e-01
#Asym.(Intercept)  3.154565e+00  2.4543087333 364  121.60792785 7.872212e-297
#xmid.Nrate         -2.976600e-03  0.0075318111 364  -0.27850673 7.807815e-01
#xmid.envNY-2010    -7.948429e+00  1.4510276017 364  -5.50250872 7.073680e-08
#xmid.envNE-2009    2.000777e+01  1.9235455543 364  10.40150308 2.334178e-22
#xmid.envNE-2009    1.028235e+01  1.3937302031 364  7.37757353 1.100905e+12
#xmid.envNE-2010    8.788309e+00  1.4790677464 364  6.09664740 3.220649e-09
#xmid.envNW-2010    -4.613128e+00  1.3984866305 364  -3.29780847 1.070451e-03
#scal.(Intercept)   2.477236e-01  1.1817792625 364  20.48184901 1.446951e-62
#scal.Nrate         9.955716e-04  0.0067791685 364  0.13652959 8.914781e-01
#scal.envNY-2010    -8.905931e+00  1.2483827914 364  -0.71335423 4.760837e-01
#scal.envNW-2010    2.477236e+00  1.6164154659 364  1.53254920 1.262556e-01
#scal.envNE-2010    8.951866e+00  1.1837697880 364  7.807815e-01
#scal.envNW-2009    1.927412e+00  1.2862373772 364  -1.49844575 1.348842e-01
#scal.envNW-2010    -6.366202e+00  1.2409978986 364  -5.12990539 4.723678e-07
```

```r
intervals(fit8.ss, level=0.95, which="fixed")
# lower est. upper
#Asym.(Intercept)  2.985384e+00  3.079769e+00  3.154565e+00
#Asym.Nrate       -5.794241e-04  -1.515855e-05   0.0002937831
#Asym.envNY-2010   2.016554e-01  3.110370e-01   4.20418615
#Asym.envNE-2009   -3.678534e-01  -2.336358e-01  -0.09941824
#Asym.envNE-2010   6.038575e-01  7.111425e-01   8.18429349
#Asym.envNW-2010   1.797674e-01  2.901095e-01   4.00451512
#Asym.envNW-2010   -1.842895e-02  -7.862059e-02   0.02704829
#scal.(Intercept)  1.490644e+02  1.514565e+02  153.84859643
#scal.Nrate       -1.077126e+00  -7.948429e+00  -5.19732136
#scal.envNY-2010   1.631323e+01  2.000777e+01  23.70229504
#scal.envNW-2010   7.605427e+00  1.028235e+01  12.95926733
#scal.envNW-2010   6.007332e+00  8.788309e+00  11.56928518
#scal.envNW-2010   -7.299876e+00  -4.613128e+00  -1.92638092
#scal.(Intercept)  1.970969e+01  2.174922e+01   23.78875908
#scal.Nrate       -1.209511e-02  9.255716e-04   0.01394622
#scal.envNY-2010   -3.288292e+00  -8.905931e-01  1.507214158
#scal.envNW-2010   -6.273929e-01  2.477236e+00   5.58186531
#scal.envNW-2010   -2.184133e+00  8.951866e-02   2.363170778
#scal.envNW-2010   -4.397942e+00  -1.927412e+00  0.543118617
#scal.envNW-2010   -8.749771e+00  -6.366202e+00  -3.982632569
```

```r
unique(grwth2$env)
growth2$env <- factor(grwth2$env, 
unique(grwth2$env)
```

```r
newdat <- expand.grid(Nrate = unique(grwth2$Nrate), env = unique(grwth2$env), doy = 50:290)
preds <- predict(fit6.nlme , newdata = newdat, level = 0)
```
### Nebraska 2010
plot3 <- prds.NE.2009
obs.NE.2009 <- obs.NE.2009
pred.obs <- obs.NE.2009
## Nebraska 2009
plot2 <- prds.KY.2010
obs.KY.2010 <- obs.KY.2010
## Kentucky 2010
plot1 <- obs.KY.2009
prds.KY.2009 <- prds.KY.2009
## Kentucky 2009

## Do one plot at a time and then combine them
### Kentucky 2009

plot1 <- xyplot(height ~ doy, data = obs.KY.2009, groups = Nrate,
    col = 'black', fill = 'transparent',
    panel = function(x, y, ...){
        panel.xyplot(x, y, type = 'p', pch = c(17,19,22), ...)
        panel.xyplot(prds.KY.2009[prds.KY.2009$Nrate == 0,]$doy, 
            prds.KY.2009[prds.KY.2009$Nrate == 0,]$preds, type = 'l', lty = 1,...)
        panel.xyplot(prds.KY.2009[prds.KY.2009$Nrate == 60,]$doy, 
            prds.KY.2009[prds.KY.2009$Nrate == 60,]$preds, type = 'l', lty = 2,...)
        panel.xyplot(prds.KY.2009[prds.KY.2009$Nrate == 120,]$doy, 
            prds.KY.2009[prds.KY.2009$Nrate == 120,]$preds, type = 'l', lty = 3,...)
        panel.text(170, 4, labels = 'KY-2009', cex = 1.2)
        }, ylab = list('height, m', cex=1), ylim = c(0,4.2), 
        xlim = c(50,290), xlab = list('DOY', cex=1), cex=1.2 
    }

### Kentucky 2010
obs.KY.2010 <- obs.KY.2010[obs.KY.2010$env == 'KY-2010',]
prds.KY.2010 <- prds.KY.2010[prds.KY.2010$env == 'KY-2010',]

plot2 <- xyplot(height ~ doy, data = obs.KY.2010, groups = Nrate,
    col = 'black', fill = 'transparent',
    panel = function(x, y,...){
        panel.xyplot(x, y, type = 'p', pch = c(17,19,22), ...)
        panel.xyplot(prds.KY.2010[prds.KY.2010$Nrate == 0,]$doy, 
            prds.KY.2010[prds.KY.2010$Nrate == 0,]$preds, type = 'l', lty = 1,...)
        panel.xyplot(prds.KY.2010[prds.KY.2010$Nrate == 60,]$doy, 
            prds.KY.2010[prds.KY.2010$Nrate == 60,]$preds, type = 'l', lty = 2,...)
        panel.xyplot(prds.KY.2010[prds.KY.2010$Nrate == 120,]$doy, 
            prds.KY.2010[prds.KY.2010$Nrate == 120,]$preds, type = 'l', lty = 3,...)
        panel.text(170, 4, labels = 'KY-2010', cex = 1.2)
        }, ylab = list('height, m', cex=1), ylim = c(0,4.2), 
        xlim = c(50,290), xlab = list('DOY', cex=1), cex=1.2 
    }

### Nebraska 2009
obs.NE.2009 <- obs.NE.2009[obs.NE.2009$env == 'NE-2009',]
prds.NE.2009 <- prds.NE.2009[prds.NE.2009$env == 'NE-2009',]

plot3 <- xyplot(height ~ doy, data = obs.NE.2009, groups = Nrate,
    col = 'black', fill = 'transparent',
    panel = function(x, y,...){
        panel.xyplot(x, y, type = 'p', pch = c(17,19,22), ...)
        panel.xyplot(prds.NE.2009[prds.NE.2009$Nrate == 0,]$doy, 
            prds.NE.2009[prds.NE.2009$Nrate == 0,]$preds, type = 'l', lty = 1,...)
        panel.xyplot(prds.NE.2009[prds.NE.2009$Nrate == 60,]$doy, 
            prds.NE.2009[prds.NE.2009$Nrate == 60,]$preds, type = 'l', lty = 2,...)
        panel.xyplot(prds.NE.2009[prds.NE.2009$Nrate == 120,]$doy, 
            prds.NE.2009[prds.NE.2009$Nrate == 120,]$preds, type = 'l', lty = 3,...)
        panel.text(170, 4, labels = 'NE-2009', cex = 1.2)
        }, ylab = list('height, m', cex=1), ylim = c(0,4.2), 
        xlim = c(50,290), xlab = list('DOY', cex=1), cex=1.2 
    }

### Nebraska 2010
obs.NE.2010 <- obs[obs$env == 'NE-2010',]
prds.NE.2010 <- prds[prds$env == 'NE-2010',]

plot4 <- xyplot(height ~ doy, data = obs.NE.2010, groups = Nrate,
                col = 'black', fill = 'transparent',
                panel = function(x,y,...){
                  panel.xyplot(x,y, type = 'p', pch=c(17,19,22), ...)
                  panel.xyplot(prds.NE.2010$prds.NE.2010$Nrate == 0,$doy,
                                prds.NE.2010[prds.NE.2010$Nrate == 0,]$preds, type='l', lty = 1,...)
                  panel.xyplot(prds.NE.2010$prds.NE.2010$Nrate == 60,$doy,
                                prds.NE.2010[prds.NE.2010$Nrate == 60,]$preds, type='l', lty = 2,...)
                  panel.xyplot(prds.NE.2010$prds.NE.2010$Nrate == 120,$doy,
                                prds.NE.2010[prds.NE.2010$Nrate == 120,]$preds, type='l', lty = 3,...)
                  panel.text(170,4, labels = 'NE-2010, cex = 1.2)
                },
                ylim = list('height, m', cex=1), ylim = c(0,4.2),
                xlim = c(50,290), xlab = list('DOY', cex=1), cex=1.2
                )

## New Jersey 2009

obs.NJ.2009 <- obs[obs$env == 'NJ-2009',]
prds.NJ.2009 <- prds[prds$env == 'NJ-2009',]

plot5 <- xyplot(height ~ doy, data = obs.NJ.2009, groups = Nrate,
                col = 'black', fill = 'transparent',
                panel = function(x,y,...){
                  panel.xyplot(x,y, type = 'p', pch=c(17,19,22), ...)
                  panel.xyplot(prds.NJ.2009$prds.NJ.2009$Nrate == 0,$doy,
                                prds.NJ.2009[prds.NJ.2009$Nrate == 0,]$preds, type='l', lty = 1,...)
                  panel.xyplot(prds.NJ.2009$prds.NJ.2009$Nrate == 60,$doy,
                                prds.NJ.2009[prds.NJ.2009$Nrate == 60,]$preds, type='l', lty = 2,...)
                  panel.xyplot(prds.NJ.2009$prds.NJ.2009$Nrate == 120,$doy,
                                prds.NJ.2009[prds.NJ.2009$Nrate == 120,]$preds, type='l', lty = 3,...)
                  panel.text(170,4, labels = 'NJ-2009, cex = 1.2)
                },
                ylim = list('height, m', cex=1), ylim = c(0,4.2),
                xlim = c(50,290), xlab = list('DOY', cex=1), cex=1.2
                )

## New Jersey 2010

obs.NJ.2010 <- obs[obs$env == 'NJ-2010',]
prds.NJ.2010 <- prds[prds$env == 'NJ-2010',]

plot6 <- xyplot(height ~ doy, data = obs.NJ.2010, groups = Nrate,
                col = 'black', fill = 'transparent',
                panel = function(x,y,...){
                  panel.xyplot(x,y, type = 'p', pch=c(17,19,22), ...)
                  panel.xyplot(prds.NJ.2010$prds.NJ.2010$Nrate == 0,$doy,
                                prds.NJ.2010[prds.NJ.2010$Nrate == 0,]$preds, type='l', lty = 1,...)
                  panel.xyplot(prds.NJ.2010$prds.NJ.2010$Nrate == 60,$doy,
                                prds.NJ.2010[prds.NJ.2010$Nrate == 60,]$preds, type='l', lty = 2,...)
                  panel.xyplot(prds.NJ.2010$prds.NJ.2010$Nrate == 120,$doy,
                                prds.NJ.2010[prds.NJ.2010$Nrate == 120,]$preds, type='l', lty = 3,...)
                  panel.text(170,4, labels = 'NJ-2010, cex = 1.2)
                },
                ylim = list('height, m', cex=1), ylim = c(0,4.2),
                xlim = c(50,290), xlab = list('DOY', cex=1), cex=1.2
                )

png('/.../figs/ht 2009 2010.png', width=2200, height=2800, res=225)
print(plot1, c(0, 0.666, 0.5, 1), more = TRUE)
print(plot2, c(0.5, 0.666, 1, 1), more = TRUE)
print(plot3, c(0, 0.333, 0.5, 0.666), more = TRUE)

147
## Plot predictions

```
print(plot4, c(0.5, 0.333, 1, 0.666), more = TRUE)
print(plot5, c(0, 0, 0.5, 0.333), more = TRUE)
print(plot6, c(0.5, 0, 1, 0.333))
dev.off()
```

```
## Plot predictions

png('../figs/augPred-final 2009 2010 ht.nlme.png', width=1600, height=1600, res=145)
plot(augPred(fit6.nlme, level = 0:1),
     lty=c(1,2), col=c("black"), as.table=T,
     key=list(text=list(c("fixed", "random")), lty=c(1,2), lines=T),
     ylab=list('height, m', cex=1.2), xlab=list('day of year', cex=1.2))
dev.off()
```

### Biomass yields - Ch.3, Table 3.7

*Doe miscanthus manuscript, 2nd and 3rd year biomass yield; options ls=120 ps=100 nodate nocenter formdlim="-";

```
data biomass;
length location$ 10;
length harvest$ 10;
infile 'F:\PhD\Miscanthus fertility study\DOE 2009 2010 growth and yield manuscript\2009 2010 season biomass yields, NE, KY, NJ, IL.csv'
dlm='," firstobs=4;
input year location$ block subsample Nrate biomass harvest$;
label Nrate="N rate (kg N/ha)";
label biomass="Dry Biomass (Mg/ha)";
*if location="Illinois" then delete;
*if location="Illinois" and year="2009" then Env="IL09";
*if location="Illinois" and year="2010" then Env="IL10";
if location="Kentucky" and year="2009" then Env="KY09";
if location="Kentucky" and year="2010" then Env="KY10";
if location="Nebraska" and year="2009" then Env="NE09";
if location="Nebraska" and year="2010" then Env="NE10";
if location="New Jersey" and year="2009" then Env="NJ09";
if location="New Jersey" and year="2010" then Env="NJ10";
*dropping IL, b/c in poor winter survival in 2008-2009 required ~80% replanting. As of 2010 the IL
stand is a mixture of 2 and 3 year old plants. This is not on par with the other 3 sites, all of
which are 3 year old stands as of 2010.;
cards;
run; proc print; run;
```

data Il; set biomass;
if location ne "Illinois" then delete;
run;
```
proc sort data=IL; by year Nrate; run;
proc means data=IL mean noprint; var biomass; by year Nrate;
output out=Ilmeans mean=biomass; run; proc print data=Ilmeans; run;
```

*running a model with location and year combined into an environment effect.
model:
```
random: Environment(E) = KY09 KY10 NE09 NE10 NJ09 NJ10 i=1,2,3
random: block(B) = 1,2,3,4 j=1,2,3,4
fixed: N rate- (N) = 0,60,120 k=1,2,3
random: subsample-(S) = 1 to 4 depending on site l=1 to 4
```

*main questions:

Is there an N response, what type (linear/quadratic), what locations?
Is there a significant increase or decrease in yield from 2009 to 2010 at each site;;
```
proc mixed data=biomass covtest method=REML;
class Env Nrate block;
model biomass=Nrate/ddfm-kr outpred=temp;
random Env block(Env) Env*Nrate Nrate*block(Env);
*should block be nested in Env? We know it is nested in location.;
estimate "KY09 vs KY10"|Env 1 -1 0 0 0 0;
estimate "NE09 vs NE10"|Env 0 0 1 -1 0 0;
estimate "NJ09 vs NJ10"|Env 0 0 0 0 1 -1;
```
*BLUP Env lsmeans;
estimate "KY09" intercept 1 | Env 1 0 0 0 0 0;
estimate "KY10" intercept 1 | Env 0 1 0 0 0 0;
estimate "NE09" intercept 1 | Env 0 0 1 0 0 0;
estimate "NE10" intercept 1 | Env 0 0 0 1 0 0;
estimate "NJ09" intercept 1 | Env 0 0 0 0 1 0;
estimate "NJ10" intercept 1 | Env 0 0 0 0 0 1;

*BLUP Env*Nrate lsmeans;
estimate "KY09 Nrate 0" intercept 1 Nrate 1 | Env 1 Env*Nrate 1;
estimate "KY09 Nrate 60" intercept 1 Nrate 0 1 | Env 1 Env*Nrate 0 1;
estimate "KY09 Nrate 120" intercept 1 Nrate 0 0 1 | Env 1 Env*Nrate 0 0 1;
estimate "KY10 Nrate 0" intercept 1 Nrate 1 | Env 0 1 Env*Nrate 0 0 0 1;
estimate "KY10 Nrate 60" intercept 1 Nrate 0 1 | Env 0 1 Env*Nrate 0 0 0 1;
estimate "KY10 Nrate 120" intercept 1 Nrate 0 0 1 | Env 0 1 Env*Nrate 0 0 0 1;
estimate "NE09 Nrate 0" intercept 1 Nrate 1 | Env 0 0 1 Env*Nrate 0 0 0 0 0 0 1;
estimate "NE09 Nrate 60" intercept 1 Nrate 0 1 | Env 0 0 1 Env*Nrate 0 0 0 0 0 0 1;
estimate "NE09 Nrate 120" intercept 1 Nrate 0 0 1 | Env 0 0 1 Env*Nrate 0 0 0 0 0 0 0 1;
estimate "NE10 Nrate 0" intercept 1 Nrate 1 | Env 0 0 0 1 Env*Nrate 0 0 0 0 0 0 0 0 1;
estimate "NE10 Nrate 60" intercept 1 Nrate 0 1 | Env 0 0 0 1 Env*Nrate 0 0 0 0 0 0 0 0 1;
estimate "NE10 Nrate 120" intercept 1 Nrate 0 0 1 | Env 0 0 0 1 Env*Nrate 0 0 0 0 0 0 0 0 0 0 1;
estimate "NJ09 Nrate 0" intercept 1 Nrate 1 | Env 0 0 0 0 1 Env*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 0 1;
estimate "NJ09 Nrate 60" intercept 1 Nrate 0 1 | Env 0 0 0 0 1 Env*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 0 1;
estimate "NJ09 Nrate 120" intercept 1 Nrate 0 0 1 | Env 0 0 0 0 1 Env*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1;

*Linear effect within environment;
estimate "KY-09 linear" Nrate 1 0 -1 | Env*Nrate 1 0 -1;
estimate "KY-10 linear" Nrate 1 0 -1 | Env*Nrate 0 0 0 1 0 -1;
estimate "NE-09 linear" Nrate 1 0 -1 | Env*Nrate 0 0 0 0 0 1 0 -1;
estimate "NE-10 linear" Nrate 1 0 -1 | Env*Nrate 0 0 0 0 0 0 0 0 0 0 0 1 0 -1;
estimate "NJ-09 linear" Nrate 1 0 -1 | Env*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 -1;
estimate "NJ-10 linear" Nrate 1 0 -1 | Env*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 -1;

*Nquad effect within environment;
estimate "KY-09 quad" Nrate 1 -2 | Env*Nrate 1 -2 1;
estimate "KY-10 quad" Nrate 1 -2 | Env*Nrate 0 0 0 1 -2 1;
estimate "NE-09 quad" Nrate 1 -2 | Env*Nrate 0 0 0 0 0 1 -2 1;
estimate "NE-10 quad" Nrate 1 -2 | Env*Nrate 0 0 0 0 0 0 1 -2 1;
estimate "NJ-09 quad" Nrate 1 -2 | Env*Nrate 0 0 0 0 0 0 0 1 -2 1;
estimate "NJ-10 quad" Nrate 1 -2 | Env*Nrate 0 0 0 0 0 0 0 0 0 0 1 -2 1;

run;
goptions reset=all; symbol v=plus color=blue h=1.5;

proc gplot data=temp;
plot resid*pred/ vref=0 vaxis=-10 to 10 by 2;
run;
symbol v=circle color=blue h=2;
proc univariate data=temp normal plot resid;
var resid;
probplot resid/
normal(mu=est sigma=est color=black w=3);
inset n mean median min max skewness kurtosis var probn;
run;

Tiller density-Ch.3, Table 3.7.
*2009 end of season stems;
options ls=100 ps=100 nodate nocenter formdlim="-";
data grwth09;
length loc$ 10;
length month$ 10;
infile 'F:\PhD\Miscanthus fertility study\DOE manuscript, 2nd year growth\2009 growth data\2009 growth data, NE, KY, NJ.csv'
dlm="", firstobs=4;
input year$ loc$ block month$ date$ Nrate Nlb ht stems leaves TT;
*keeping final sampling dates at each location for stem #;
if loc="Nebraska" and month="May" then delete;
if loc="Nebraska" and month="June" then delete;
if loc="Nebraska" and month="July" then delete;
if loc="Nebraska" and month="August" then delete;
if loc="Kentucky" and month="April" then delete;
if loc="Kentucky" and month="May" then delete;
if loc="Kentucky" and month="June" then delete;
if loc="Kentucky" and month="July" then delete;
if loc="New Jersey" and month="May" then delete;
if loc="New Jersey" and month="June" then delete;
if loc="New Jersey" and month="July" then delete;
if loc="New Jersey" and month="August" then delete;
if loc="New Jersey" and month="September" then delete;
drop date Nlb ht leaves TT;
sqstems=sqrt(stems);
run;
proc print data=grwth09; run;
data shoot09; set grwth09;
drop month;
run; proc print data=shoot09; run;

*2010 stem number for KY, NE, IL, NJ;
Data stemnum;
length loc$ 10;
infile 'F:\PhD\Miscanthus fertility study\DOE 2009 2010 growth and yield manuscript\2010 stem number.csv'
dlm=",", firstobs=4;
input location$ year$ plotID$ block grass Nrate harvest$ plant_sub stems biomass;
drop grass plotID harvest plant_sub;
if location="IL" then delete;
if location="KY" then loc= "Kentucky";
if location="NE" then loc= "Nebraska";
if location="NJ" then loc= "New Jersey";
sqstems=sqrt(stems);
run; proc print data=stemnum; run;

*
*means of stem number;
proc sort data=data-stemnum; by loc year block Nrate; run;
proc means data=data-stemnum noprint mean; var stems sqrtstems;
by loc year block Nrate;
output out=shoots mean=stems sqstems; run;
proc print data=shoots; run;
data shoot10; set shoots;
drop _TYPE_ _FREQ_;
run; proc print data=shoot10; run;

*combining 2009 2010 shoot number;
proc sort data=shoot10; by loc year block Nrate; run;
proc sort data=shoot09; by loc year block Nrate; run;
data shoot; merge shoot10 shoot09;
by loc year block Nrate; run; proc print data=shoot; run;
data stem; set shoot;
if loc="Kentucky" and year="2009" then Env="KY09";
if loc="Kentucky" and year="2010" then Env="KY10";
if loc="Nebraska" and year="2009" then Env="NE09";
if loc="Nebraska" and year="2010" then Env="NE10";
if loc="New Jersey" and year="2009" then Env="NJ09";
if loc="New Jersey" and year="2010" then Env="NJ10";
run; proc print data=stem; run;
ods html;
ods graphics on;
proc glimmix data=stem plots=(residualpanel pearsonpanel studentpanel);
class Env Nrate block;
model stems=Nrate/dist=Poisson ddfm=kr;
random Env block(Env) Env*Nrate Nrate*block(Env);
covtest glm/wald;
estimate "KY09 vs KY10"|Env 1 -1 0 0 0 0/ilink;
estimate "NE09 vs NE10"|Env 0 0 1 -1 0 0;
estimate "NJ09 vs NJ10"|Env 0 0 0 0 1 -1;
*BLUP Env lsmeans;
estimate "KY09" intercept 1|Env 1 0 0 0 0 0/ilink;
estimate "KY10" intercept 1|Env 0 1 0 0 0 0/ilink;
estimate "NE09" intercept 1|Env 0 0 1 0 0 0/ilink;
estimate "NE10" intercept 1|Env 0 0 0 1 0 0/ilink;
estimate "NJ09" intercept 1|Env 0 0 0 0 1 0/ilink;
estimate "NJ10" intercept 1|Env 0 0 0 0 0 1/ilink;
*BLUP Env*Nrate lsmeans;
estimate "KY09 Nrate 0" intercept 1 Nrate 1|
  Env 1 Env*Nrate 1/ilink cl;
estimate "KY09 Nrate 60" intercept 1 Nrate 0 1|
  Env 1 Env*Nrate 0 1/ilink cl;
estimate "KY09 Nrate 120" intercept 1 Nrate 0 0 1|
  Env 1 Env*Nrate 0 0 1/ilink cl;
estimate "KY10 Nrate 0" intercept 1 Nrate 1|
  Env 0 1 Env*Nrate 0 0 0 1/ilink cl;
estimate "KY10 Nrate 60" intercept 1 Nrate 0 0 1|
  Env 0 1 Env*Nrate 0 0 0 1/ilink cl;
estimate "KY10 Nrate 120" intercept 1 Nrate 0 0 1|
  Env 0 1 Env*Nrate 0 0 0 0 1/ilink cl;
estimate "NE09 Nrate 0" intercept 1 Nrate 1|
  Env 0 0 1 Env*Nrate 0 0 0 0 0 1/ilink;
estimate "NE09 Nrate 60" intercept 1 Nrate 0 1|
  Env 0 0 1 Env*Nrate 0 0 0 0 0 1/ilink;
estimate "NE09 Nrate 120" intercept 1 Nrate 0 0 1|
  Env 0 0 1 Env*Nrate 0 0 0 0 0 0 1/ilink;
estimate "NE10 Nrate 0" intercept 1 Nrate 1|
  Env 0 0 0 1 Env*Nrate 0 0 0 0 0 0 1/ilink;
estimate "NE10 Nrate 60" intercept 1 Nrate 0 1|
  Env 0 0 0 1 Env*Nrate 0 0 0 0 0 0 1/ilink;
estimate "NE10 Nrate 120" intercept 1 Nrate 0 0 1|
  Env 0 0 0 1 Env*Nrate 0 0 0 0 0 0 0 1/ilink;
estimate "NJ09 Nrate 0" intercept 1 Nrate 1;
   Env 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1/Ilink;
estimate "NJ09 Nrate 60" intercept 1 Nrate 0;
   Env 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1/Ilink;
estimate "NJ09 Nrate 120" intercept 1 Nrate 0 0 1;
   Env 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1/Ilink;
estimate "NJ10 Nrate 0" intercept 1 Nrate 1;
   Env 0 0 0 0 0 1 Env*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 0 1/Ilink;
estimate "NJ10 Nrate 60" intercept 1 Nrate 0;
   Env 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1/Ilink;
estimate "NJ10 Nrate 120" intercept 1 Nrate 0 0 1;
   Env 0 0 0 0 0 1 Env*Nrate 0 0 0 0 0 0 0 0 0 0 0 1/Ilink;
run;
ods graphics off;
ods html close;

Correlations among variables and scatter plot-Ch.3, Fig. 3.2

*2009 end of season ht, stems;
options ls=100 ps=100 nodate nocenter formdlim="-";
data grwth09;
length loc$ 10;
length month$ 10;
infile 'F:\PhD\Miscanthus fertility study\DOE manuscript, 2nd year growth\2009 growth data\2009 growth data, NE, KY, NJ, IL.csv'
dlm="," firstobs=4;
input year$ loc$ block month$ date$ Nrate Nlb ht stems leaves TT;
*keeping final sampling dates at each location for stem #;
if loc="Nebraska" and month="May" then delete;
if loc="Nebraska" and month="June" then delete;
if loc="Nebraska" and month="July" then delete;
if loc="Nebraska" and month="August" then delete;
if loc="Kentucky" and month="April" then delete;
if loc="Kentucky" and month="May" then delete;
if loc="Kentucky" and month="June" then delete;
if loc="Kentucky" and month="July" then delete;
if loc="New Jersey" and month="May" then delete;
if loc="New Jersey" and month="June" then delete;
if loc="New Jersey" and month="July" then delete;
if loc="New Jersey" and month="August" then delete;
if loc="New Jersey" and month="September" then delete;
run;
proc print data=grwth09; run;

proc sort data=grwth09; by loc year block Nrate;
proc means data=grwth09 noprint mean; var ht stems;
by loc year block Nrate;
output out=height09 mean=ht_mean shoot_mean; run;
proc print data=height09; run;
data htstem09; set height09;
drop _TYPE_ _FREQ_;run;
proc print data=htstem09; run;

*2010 end of season ht;
data grwth10;
length loc$ 10;
length month$ 10;
infile 'F:\PhD\Miscanthus fertility study\DOE 2009 2010 growth and yield manuscript\2010 growth data, KY, NE, NJ, IL.csv'
dlm="," firstobs=4;
input year$ loc$ block month$ date$ Nrate Nlb ht TT;
*keeping final sampling dates at each location for stem #;
if loc="Illinois" then delete;
if loc="Kentucky" and month="April" then delete;
if loc="Kentucky" and month="May" then delete;
if loc="Kentucky" and month="June" then delete;
if loc="Kentucky" and month="July" then delete;
if loc="Kentucky" and month="August" then delete;
if loc="Kentucky" and month="September" then delete;
if loc="Nebraska" and month="April" then delete;
if loc="Nebraska" and month="May" then delete;
if loc="Nebraska" and month="June" then delete;
if loc="Nebraska" and month="July" then delete;
if loc="Nebraska" and month="August" then delete;
if loc="Nebraska" and month="September" then delete;
if loc="New Jersey" and month="May" then delete;
if loc="New Jersey" and month="June" then delete;
if loc="New Jersey" and month="July" then delete;
if loc="New Jersey" and month="August" then delete;
if loc="New Jersey" and month="September" then delete;
if loc="New Jersey" and month="October" then delete;
run; proc print data=grwth10; run;
proc sort data=grwth10; by loc year block Nrate;
proc means data=grwth10 noprint mean; var ht;
by loc year block Nrate;
output out=height10 mean=ht_mean;
proc print data=height10; run;
data ht10; set height10;
drop _TYPE_ _FREQ_; run; proc print data=ht10; run;
*2010 end of season KY, NE, IL, NJ;
Data stem10;
length loc$ 10;
Infile 'F:\PhD\Miscanthus fertility study\DOE 2010 yield components\2010 stem number.csv' firstobs=4 dlm=',';
input location$ year$ plotID$ block grass Nrate harvest$ plant_sub shoots;
drop grass;
if location="IL" then delete;
if location="KY" then loc= "Kentucky";
if location="NE" then loc= "Nebraska";
if location="NJ" then loc= "New Jersey";
run; proc print data=stem10; run;
*means of stem number;
proc sort data=stem10; by loc year block Nrate; run;
proc means data=stem10 noprint mean; var shoots;
by loc year block Nrate;
output out=shoots mean=shoot_mean;
proc print data=shoots; run;
data shoot10; set shoots;
drop _TYPE_ _FREQ_; run; proc print data=shoot10; run;
*combining 2010 ht shoot number;
data comb10; merge shoot10 ht10;
by loc year block Nrate; run; proc print data=comb10; run;
* 2nd and 3rd year biomass yield;
options ls=120 ps=100 nodate nocenter formdlim="-";
data biomass;
  length loc$ 10;
  length harvest$ 10;
infile 'F:\PhD\Miscanthus fertility study\DOE 2009 2010 growth and yield manuscript\2009 2010 season biomass yields, NE, KY, NJ, IL.csv' dlm="", firstobs=4;
input year$ loc$ block subsample Nrate biomass harvest$;
  label Nrate="N rate (kg N/ha)";
  label biomass="Dry Biomass (Mg/ha)";
  if loc="Illinois" then delete;
  if loc="Kentucky" and year="2009" then Env="KY09";
  if loc="Kentucky" and year="2010" then Env="KY10";
  if loc="Nebraska" and year="2009" then Env="NE09";
  if loc="Nebraska" and year="2010" then Env="NE10";
  if loc="New Jersey" and year="2009" then Env="NJ09";
  if loc="New Jersey" and year="2010" then Env="NJ10";
cards;
run; proc print; run;
data biomass09; set biomass;
if year=2010 then delete;
run; proc print data=biomass09; run;
*means of biomass 2009;
proc sort data=biomass09; by loc year block Nrate; run;
proc means data=biomass09 noprint mean; var biomass;
by loc year block Nrate;
output out=bio09 mean=bio_mean; run;
data biom09; set bio09;
drop _TYPE_ _FREQ_; run; proc print data=biom09; run;
data biomass10; set biomass;
if year=2009 then delete;
run; proc print data=biomass10; run;
*means of biomass 2010;
proc sort data=biomass10; by loc year block Nrate; run;
proc means data=biomass10 noprint mean; var biomass;
by loc year block Nrate;
output out=bio10 mean=bio_mean; run;
data biom10; set bio10;
drop _TYPE_ _FREQ_; run; proc print data=biom10; run;
*combining 2009 ht, shoot, biomass;
data all2009;
  label loc=location;
  label ht_mean=plant ht (m);
  label shoot_mean=tiller density (tillers/sq. m);
  label bio_mean=dry biomass (Mg/ha);
  merge htstem09 biom09;
by loc year block Nrate; run;
proc print data=all2009; run;
data all2009; set all2009;
if loc="Kentucky" and year="2009" then Env="KY-2009";
if loc="Nebraska" and year="2009" then Env="NE-2009";
if loc="New Jersey" and year="2009" then Env="NJ-2009";
label env=environment;
run; proc print data=all2009; run;
proc sgscatter data=all2009;
title "2009 season";
matrix ht_mean shoot_mean bio_mean/group=env;
run;
proc corr data=all2009;
var ht_mean shoot_mean bio_mean; run;
*combining 2010 ht, shoot, biomass;
data all2010;
  label loc=location;
  label ht_mean=plant ht (m);
  label shoot_mean=tiller density (tillers/sq. m);
  label bio_mean=dry biomass (Mg/ha);
  merge comb10 biom10;
  by loc year block Nrate;
run; proc print data=all2010; run;
data all2010; set all2010;
  if loc="Kentucky" and year="2010" then Env="KY-2010";
  if loc="Nebraska" and year="2010" then Env="NE-2010";
  if loc="New Jersey" and year="2010" then Env="NJ-2010";
  label env=environment;
run; proc print data=all2010; run;
proc sgscatter data=all2010;
title "2010 season";
  matrix ht_mean shoot_mean bio_mean/group=env;
run;
proc corr data=all2010;
  var ht_mean shoot_mean bio_mean; run;
APPENDIX C

Selected SAS and R code for Ch. 4

Plant height and expanded leaf number-Ch.4, Fig. 4.1, Fig. 4.3

library(nlme)
library(Hmisc)
library(lattice)
library (graphics)

#2009 & 2010 sorghum ht, leafno data
htleaf$height <- htleaf$h..cm. / 100
head(htleaf)

htleaf <- htleaf[,2] #getting rid of Date
htleaf <- htleaf[,4] #getting rid of sample
htleaf <- htleaf[,7] #getting rid of nitrogen lb/acre
htleaf <- htleaf[,7] #getting rid of plot
htleaf <- htleaf[,8] #getting rid of comments
htleaf <- na.omit(htleaf) #getting rid of observations with missing ht and leafno data
head(htleaf)

UrbanE90 <-htleaf[htleaf$Environment == “Urbana-2009” & htleaf$type == ”Energy”,]
urbanE90 <-htleaf[htleaf$Environment == “Urbana-2010” & htleaf$type == ”Energy”,]
unique(UrbanE90$doy) #194 210 231 261 260
UrbanE10 <-htleaf[htleaf$Environment == “Urbana-2010” & htleaf$type == ”Energy”,]
unique(UrbanE10$doy) #176 202 243 270
DSE10 <-htleaf[htleaf$Environment == “Dixon Springs-2010” & htleaf$type == ”Energy”,]
unique(DSE10$doy) #181 200 217 277
PerE10 <-htleaf[htleaf$Environment == ”Perry-2010” & htleaf$type == ”Energy”,]
unique(PerE10$doy) #182 204 229 276

#plotting for leaf number
energy <-htleaf[htleaf$type == ”Energy”,]
forage <-htleaf[htleaf$type == ”Forage” & htleaf$variety == ”Graze. n. Bale”], #dropping photoperiod insensitive variety, Graze All
forage[forage$doy > 242,2]
forage[forage$doy > 242,2] <- NA #getting rid of leafno beyond the first harvest
forage <- na.omit(forage)
head(forage)
leafno <- rbind(energy, forage)
head(leafno)

unique(leafno$Environment) #Dixon Springs-2010 Perry-2010 Urbana-2009 Urbana-2010

xyplot(leafno ~ GDD11, data = energy, type=c(“p”, “r”), groups = Environment, auto.key=TRUE)

xyplot(leafno ~ GDD11, data = forage, type=c(“p”, “r”), groups = Environment, auto.key=TRUE)

png("./2009 & 2010 analysis for manuscript 1/leafno.png",width=600, height=600, res=80)

xyplot(leafno ~ GDD11, data = energy, groups = Environment,
xlab=lab(“GDD”,cex=1.2),
ylab=lab(“expanded leaf number”,cex=1.3),
pch=c(17, 19, 22, 8), col=c(“darkgreen”,”darkred”,”midnightblue”,”black”),
fill = ’transparent’, lty = c(1,2,3,4), lwd=2,
type=c(“p”,”r”), cex = 1.2,
key=list(x=0.3, y=1, cex.title=1.3,
pch = c(17, 19, 22, 8), cex=1.3,
lty = c(1,2,3,4), points = TRUE, lines = TRUE, lwd=2,
col=c(”darkgreen”,”darkred”,”midnightblue”,”black”),
text=list(c(“Dixon Springs 2010”, “Perry 2010”, “Urbana 2009”, “Urbana 2010”)))

dev.off()

mean(leafno[leafno$doy == “277” & leafno$Environment == ”Dixon Springs-2010”,”leafno”]) #28.25
mean(leafno[leafno$doy == “276” & leafno$Environment == ”Perry-2010”,”leafno”]) #28.42
## dataframe for Urbana Energy 2009

```r
UrbE09.1 <- data.frame(env = UrbE09[,1],
                   doy = UrbE09[,2],
                   variety = UrbE09[,5],
                   Nrate = UrbE09[,6],
                   leafno = UrbE09[,7],
                   GDD10 = UrbE09[,8],
                   GDD11 = UrbE09[,9],
                   height = UrbE09[,10])

head(UrbE09.1)
```

## developing a model Urbana Energy 2009 height

```r
expu <- with(UrbE09, Environment:factor(block):factor(variety):factor(Nrate))
UrbE09G <- groupedData(height ~ doy | expu, data = UrbE09)

UrbE09ht.nls <- nlsList(height ~ SSlogis(doy, Asym, xmid, scal), data = UrbE09G)
UrbE09ht.nlme <- nlme(UrbE09ht.nls)

anova(UrbE09ht.nlme)
plot(augPred(UrbE09ht.nlme, level = 0:1))
coef(UrbE09ht.nlme)
```

## dataframe for Urbana Energy 2010

```r
UrbE10.1 <- data.frame(env = UrbE10[,1],
                   doy = UrbE10[,2],
                   variety = UrbE10[,5],
                   Nrate = UrbE10[,6],
                   leafno = UrbE10[,7],
                   GDD10 = UrbE10[,8],
                   GDD11 = UrbE10[,9],
                   height = UrbE10[,10])

head(UrbE10.1)
```

## developing a model Urbana Energy 2010 height

```r
expu <- with(UrbE10, Environment:factor(block):factor(variety):factor(Nrate))
UrbE10G <- groupedData(height ~ doy | expu, data = UrbE10)

UrbE10ht.nls <- nlsList(height ~ SSlogis(doy, Asym, xmid, scal), data = UrbE10G, start = c(Asym = 3.5, xmid = 220, scal = 25))
UrbE10ht.nlme <- nlme(UrbE10ht.nls)

anova(UrbE10ht.nlme)
plot(augPred(UrbE10ht.nlme, level = 0:1))
coef(UrbE10ht.nlme)
```

## dataframe for Dixon Springs Energy 2010

```r
DSE10.1 <- data.frame(env = DSE10[,1],
                     doy = DSE10[,2],
                     variety = DSE10[,5],
                     Nrate = DSE10[,6],
                     leafno = DSE10[,7],
                     GDD10 = DSE10[,8],
                     GDD11 = DSE10[,9],
                     height = DSE10[,10])

head(DSE10.1)
```

## developing a model Dixon Springs Energy 2010 height

```r
expu <- with(DSE10, Environment:factor(block):factor(variety):factor(Nrate))
DSE10G <- groupedData(height ~ doy | expu, data = DSE10)

xyplot(height ~ doy, data = DSE10G, groups = Nrate, auto.key=TRUE)
DSE10ht.nls <- nlsList(height ~ SSlogis(doy, Asym, xmid, scal), data = DSE10G, start = c(Asym = 3.5, xmid = 230, scal = 20))
DSE10ht.nlme <- nlme(DSE10ht.nls)
anova(DSE10ht.nlme)
plot(augPred(DSE10ht.nlme, level = 0:1))
coef(DSE10ht.nlme)
```

## dataframe for Perry Energy 2010

deprecated
```r
## developing a model Perry Energy 2010 height
```
PerE10.1 <- data.frame(env = PerE10[,1],
                      doy = PerE10[,2],
                      variety = PerE10[,5],
                      Nrate = PerE10[,6],
                      leafno = PerE10[,7],
                      GDD10 = PerE10[,8],
                      GDD11 = PerE10[,9],
                      height = PerE10[,10])

head(PerE10.1)

## developing a model Perry Energy 2010 height
expu <- with(PerE10, Environment:factor(block):factor(variety):factor(Nrate))
PerE10G <- groupedData(height ~ doy | expu, data = PerE10.1)
head(PerE10G)

xyplot(height ~ doy, data = PerE10G, groups = Nrate, auto.key=TRUE)

PerE10ht.nls <- nlsList(height ~ SSlogis(doy, Asym, xmid, scal),
                        data = PerE10G,
                        start = c(Asym = 3.9, xmid = 230, scal = 30))
PerE10ht.nlme <- nlme(PerE10ht.nls)
anova(PerE10ht.nlme)
plot(augPred(PerE10ht.nlme, level = 0:1))
coef(PerE10ht.nlme)

*Bringing in logistic fitted parameters for energy sorghum height
options ls=120 ps=150 nodate nocenter formdlim="-";
data locyr;
length loc$ 14;
length hybrid$ 11;
infile 'C:\Documents and Settings\maughan2\My Documents\My Dropbox\sorghum fertility trial\2009 & 2010 analysis for manuscript 1\Energy sorghum logistic fits, LOC=yr.csv'
dl="", firstobs=3;
input loc$ yr block hybrid$ Nrate Asym xmid scal;
if loc="Urbana" and yr=2010 then env="Urb2010";
if loc="Dixon Springs" and yr=2010 then env="DS2010";
if loc="Perry" and yr=2010 then env="Per2010";
cards;
run; proc print; run;

*Urbana 2009 analyzed alone;
data Urbana09; set locyr;
if loc ne "Urbana" then delete;
if yr ne 2009 then delete;
run; proc print data=Urbana09; run;

*Asym;
ods html;
ods graphics on;
proc glimmix data=Urbana09 plots=RESIDUALPANEL;
class block hybrid Nrate;
model Asym=hybrid Nrate hybrid*Nrate/dist=normal ddfm=kr;
random block block*hybrid;
covtest glm/wald;
lsmeans Nrate/pdiff;
contrast "0 vs all N" Nrate 1 -.33333 -.33333 -.33333;
contrast "0 vs 50" Nrate 1 -1;
contrast "0 vs 100" Nrate 1 0 -1;
contrast "0 vs 150" Nrate 1 0 0 -1;
contrast "50 vs 100" Nrate 0 1 -1 0;
contrast "50 vs 150" Nrate 0 1 0 -1;
contrast "100 vs 150" Nrate 0 0 1 -1;
run;
ods graphics off;
ods html close;

*xmid;
ods html;
ods graphics on;
**proc glimmix data=Urbana09 plots=RESIDUALPANEL;**
class block hybrid Nrate;
model xmid=hybrid Nrate hybrid*Nrate/dist=normal ddfm=kr;
random block block*hybrid;
covtest glm/wald;
lsmeans Nrate/pdiff;
contrast "0 vs all N" Nrate 1 -.33333 -.33333 -.33333;
contrast "0 vs 50" Nrate 1 -1;
contrast "0 vs 100" Nrate 1 0 -1;
contrast "0 vs 150" Nrate 1 0 0 -1;
contrast "50 vs 100" Nrate 0 1 -1 0;
contrast "50 vs 150" Nrate 0 1 0 -1;
contrast "100 vs 150" Nrate 0 0 1 -1;
run;
ods graphics off;
ods html close;

*Asym;
ods html;
ods graphics on;
**proc glimmix data=Urbana09 plots=RESIDUALPANEL;**
class block hybrid Nrate;
model scal=hybrid Nrate hybrid*Nrate/dist=normal ddfm=kr;
random block block*hybrid;
covtest glm/wald;
lsmeans Nrate/pdiff;
contrast "0 vs all N" Nrate 1 -.33333 -.33333 -.33333;
contrast "0 vs 50" Nrate 1 -1;
contrast "0 vs 100" Nrate 1 0 -1;
contrast "0 vs 150" Nrate 1 0 0 -1;
contrast "50 vs 100" Nrate 0 1 -1 0;
contrast "50 vs 150" Nrate 0 1 0 -1;
contrast "100 vs 150" Nrate 0 0 1 -1;
run;
ods graphics off;
ods html close;

*2010 data considering environments random;
data env2010; set locyr;
if yr=2009 then delete;
run; proc print;

*Asym;
ods html;
ods graphics on;
**proc glimmix data=env2010 plots=RESIDUALPANEL;**
class env block hybrid Nrate;
model Asym=hybrid Nrate hybrid*Nrate/dist=normal ddfm=kr;
random env block(env) env*hybrid hybrid*Nrate env*Nrate env*hybrid*Nrate;
covtest glm/wald;
estimate "DS 0" intercept 1 Nrate 1|env 1 env*Nrate 1;
estimate "DS 56" intercept 1 Nrate 0 1|env 1 env*Nrate 0 1;
estimate "DS 112" intercept 1 Nrate 0 0 1|env 1 env*Nrate 0 0 1;
estimate "DS 168" intercept 1 Nrate 0 0 0 1|env 1 env*Nrate 0 0 0 1;
estimate "DS 224" intercept 1 Nrate 0 0 0 0 1|env 1 env*Nrate 0 0 0 0 1;
estimate "PE 0" intercept 1 Nrate 1|env 0 1 env*Nrate 0 0 0 0 1;
estimate "PE 56" intercept 1 Nrate 0 1|env 0 1 env*Nrate 0 0 0 0 1;
estimate "PE 112" intercept 1 Nrate 0 0 1|env 0 1
env*Nrate 0 0 0 0 0 1;
estimate "PE 168" intercept 1 Nrate 0 0 0 1|env 0 1
env*Nrate 0 0 0 0 0 0 1;
estimate "PE 224" intercept 1 Nrate 0 0 0 0 1|env 0 1
env*Nrate 0 0 0 0 0 0 0 1;
estimate "UR 0" intercept 1 Nrate 1|env 0 1
env*Nrate 0 0 0 0 0 0 0 1;
estimate "UR 56" intercept 1 Nrate 0 1|env 0 1
env*Nrate 0 0 0 0 0 0 0 1;
estimate "UR 112" intercept 1 Nrate 0 0 1|env 0 1
env*Nrate 0 0 0 0 0 0 0 0 1;

159
estimate "UR 169" intercept 1 Nrate 0 0 0 1|env 0 1
  env*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;
estimate "UR 224" intercept 1 Nrate 0 0 0 0 1|env 0 0 1
  env*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;
contrast "ON vs. Napp" Nrate 1 -.25 -.25 -.25 -.25;
contrast "0 vs 56" Nrate 1 -1;
contrast "0 vs 112" Nrate 1 0 -1;
contrast "0 vs 168" Nrate 1 0 0 -1;
contrast "0 vs 224" Nrate 1 0 0 -1;
contrast "56 vs 112" Nrate 0 1 -1 0 0;
contrast "56 vs 168" Nrate 0 1 0 -1 0;
contrast "56 vs 224" Nrate 0 1 0 0 -1;
contrast "112 vs 168" Nrate 0 0 1 -1 0;
contrast "112 vs 224" Nrate 0 0 1 0 -1;
contrast "168 vs 224" Nrate 0 0 0 1 -1;
run;
ods graphics off;
ods html close;

*scal;
ods html;
ods graphics on;
proc glimmix data=env2010 plots=RESIDUALPANEL;
class env block hybrid Nrate;
model scalp hybrid*Nrate/dist=normal ddfm=kr;
random env block(env) env*hybrid hybrid*block(env) env*Nrate env*hybrid*Nrate;
      cvtest glm/wald;
estimate "DS 0" intercept 1 Nrate 1|env 1 env*Nrate 1;
estimate "DS 56" intercept 1 Nrate 0 1|env 1 env*Nrate 0 1;
estimate "DS 112" intercept 1 Nrate 0 0 1|env 1 env*Nrate 0 0 1;
estimate "DS 168" intercept 1 Nrate 0 0 0 1|env 1 env*Nrate 0 0 0 1;
estimate "DS 224" intercept 1 Nrate 0 0 0 0 1|env 1 env*Nrate 0 0 0 0 1;
estimate "PE 0" intercept 1 Nrate 1|env 0 1 env*Nrate 0 0 0 0 1;
estimate "PE 56" intercept 1 Nrate 0 1|env 0 1 env*Nrate 0 0 0 0 1;
estimate "PE 112" intercept 1 Nrate 0 0 1|env 0 1
  env*Nrate 0 0 0 0 0 0 1;
estimate "PE 168" intercept 1 Nrate 0 0 0 1|env 0 1
  env*Nrate 0 0 0 0 0 0 0 1;
estimate "PE 224" intercept 1 Nrate 0 0 0 0 1|env 0 1
  env*Nrate 0 0 0 0 0 0 0 0 1;
estimate "UR 0" intercept 1 Nrate 1|env 0 0 1
  env*Nrate 0 0 0 0 0 0 0 0 0 1;
estimate "UR 56" intercept 1 Nrate 0 1|env 0 0 1
  env*Nrate 0 0 0 0 0 0 0 0 0 1;
estimate "UR 112" intercept 1 Nrate 0 0 1|env 0 0 1
  env*Nrate 0 0 0 0 0 0 0 0 0 1;
estimate "UR 168" intercept 1 Nrate 0 0 0 1|env 0 0 1
  env*Nrate 0 0 0 0 0 0 0 0 0 1;
estimate "UR 224" intercept 1 Nrate 0 0 0 0 1|env 0 0 1
  env*Nrate 0 0 0 0 0 0 0 0 0 1;
contrast "ON vs. Napp" Nrate 1 -.25 -.25 -.25 -.25;
contrast "0 vs 56" Nrate 1 -1;
contrast "0 vs 112" Nrate 1 0 -1;
contrast "0 vs 168" Nrate 1 0 0 -1;
contrast "0 vs 224" Nrate 1 0 0 -1;
contrast "56 vs 112" Nrate 0 1 -1 0 0;
contrast "56 vs 168" Nrate 0 1 0 -1 0;
contrast "56 vs 224" Nrate 0 1 0 0 -1;
contrast "112 vs 168" Nrate 0 0 1 -1 0;
contrast "112 vs 224" Nrate 0 0 1 0 -1;
contrast "168 vs 224" Nrate 0 0 0 1 -1;
run;
ods graphics off;
ods html close;
random env block(env) env*hybrid hybrid*block(env) env*Nrate env*hybrid*Nrate;
correct glm/wald;
estimate "DS 0" intercept Nrate |env 1 env*Nrate 1;
estimate "DS 56" intercept Nrate 0 |env 1 env*Nrate 0 1;
estimate "DS 112" intercept Nrate 0 0 1 |env 1 env*Nrate 0 0 1;
estimate "DS 168" intercept Nrate 0 0 0 1 |env 1 env*Nrate 0 0 0 1;
estimate "DS 224" intercept Nrate 0 0 0 0 1 |env 1 env*Nrate 0 0 0 0 1;
estimate "PE 0" intercept Nrate 1 |env 0 1 env*Nrate 0 0 0 0 1;
estimate "PE 56" intercept Nrate 0 1 |env 0 1
env*Nrate 0 0 0 0 1;
estimate "PE 112" intercept Nrate 0 0 0 1 |env 0 1
env*Nrate 0 0 0 0 0 0 1;
estimate "PE 168" intercept Nrate 0 0 0 1 |env 0 1
env*Nrate 0 0 0 0 0 0 0 1;
estimate "PE 224" intercept Nrate 0 0 0 0 1 |env 0 1
env*Nrate 0 0 0 0 0 0 0 0 1;
estimate "UR 0" intercept Nrate 1 |env 0 0 1
env*Nrate 0 0 0 0 0 0 0 0 1;
estimate "UR 56" intercept Nrate 0 1 |env 0 0 1
env*Nrate 0 0 0 0 0 0 0 0 0 1;
estimate "UR 112" intercept Nrate 0 0 1 |env 0 0 1
env*Nrate 0 0 0 0 0 0 0 0 0 1;
estimate "UR 168" intercept Nrate 0 0 0 1 |env 0 0 1
env*Nrate 0 0 0 0 0 0 0 0 0 1;
estimate "UR 224" intercept Nrate 0 0 0 0 1 |env 0 0 1
env*Nrate 0 0 0 0 0 0 0 0 0 1;
contrast "GN vs. Napp" Nrate 1 -.25 -.25 -.25 -.25
contrast "0 vs 56" Nrate 1 -1;
contrast "0 vs 112" Nrate 0 1 -1;
contrast "0 vs 168" Nrate 1 0 0 -1;
contrast "0 vs 224" Nrate 1 0 0 0 -1;
contrast "56 vs 112" Nrate 0 1 -1 0 0;
contrast "56 vs 168" Nrate 0 1 0 -1 0;
contrast "56 vs 224" Nrate 0 1 0 0 -1;
contrast "112 vs 168" Nrate 0 0 0 1 -1 0;
contrast "112 vs 224" Nrate 0 0 1 0 -1;
contrast "168 vs 224" Nrate 0 0 0 1 0 -1;
run;
ods graphics off;
ods html close;

Leaf area index-Ch.4, Fig. 4.2
"Urbana 2009 and Urbana 2010 LAI;" options la=120 ps=150 nodate nocenter formdlim="";
data lai;
length yr$ 11;
length hybrid$ 14;
infile 'C:\Documents and Settings\maughan2\My Documents\My Dropbox\sorghum fertility trial\2009 &
2010 analysis for manuscript 1\sorghum LAI 2009 & 2010.csv'
dlm="", firstobs=7;
input yr$ day$ doy block type$ hybrid$ Nrate sub plot abovePAR Par1 tao1 lai zenith hours$ month$ comment$ GDD11 intpar;
penetr=100-intpar;
drop day sub plot Par1 tao1 lai zenith hours month comment;
if type="Forage" then delete;
if abovePAR le 1400 then delete;
cards;
run; proc print; run;

*averaging sub samples;
proc sort data=lai; by yr doy block hybrid Nrate GDD11;
proc means data=lai mean noprnt; by yr doy block hybrid Nrate GDD11; var lai intpar;
output out=lai mean=lai intpar; run; proc print data=lai mean; run;
data laimean; set laimean;
drop _TYPE_; drop _FREQ_; run; proc print data=lai mean; run;
data lai109; set laimean;
if yr ne "Urbana 2009" then delete;
run; proc print;
proc corrx data=lai09;
var lai intpar; run;
data lai10; set laimean;
if yr ne "Urbana 2010" then delete;
run; proc print;
proc corrx data=lai10;
var lai intpar; run;

*2009 LAI;
ods html;
ods graphics on;
proc glimmix data=lai09 plots=all;
model lai = hybrid Nrate hybrid*Nrate doy hybrid*doy Nrate*doy/dist=normal
ddfm=KR;
random block block*hybrid block*hybrid*Nrate;
random doy/type=arh(1) subject=block*hybrid*Nrate residual;
covtest glm/wald;
lsmeans Nrate*doy/plot=meanplot(sliceby=Nrate ilink join);
lsmeans Nrate*doy/pdiff;
contrast "DOY July 13 vs Aug. 29" DOY 1 0 -1 0;
contrast "DOY Aug. 29 vs Sept 18" DOY 0 0 1 -1;
contrast "Nrate 0 vs. rest" Nrate 1 -.33333 -.33333 -.33333;
run;
ods graphics off;
ods html close;
proc sort data=lai09; by Nrate doy;
proc means data=lai09 mean noprint; by Nrate doy; var lai intpar;
output out=lai09mean mean=lai intpar; run; proc print data=lai09mean; run;

*2010 LAI;
ods html;
ods graphics on;
proc glimmix data=lai10 plots=all;
class block hybrid Nrate doy;
model lai = hybrid Nrate hybrid*Nrate doy hybrid*doy Nrate*doy/dist=normal
ddfm=KR;
random block block*hybrid block*hybrid*Nrate;
random doy/type=arh(1) subject=block*hybrid*Nrate residual;
covtest glm/wald;
lsmeans Nrate*doy/plot=meanplot(sliceby=Nrate ilink join);
lsmeans Nrate*doy/pdiff;
contrast "DOY 25 June vs Aug. 12" DOY 1 0 -1 0;
contrast "DOY Aug. 12 vs Aug. 31" DOY 0 0 1 -1;
run;
ods graphics off;
ods html close;
proc sort data=lai10; by Nrate doy;
proc means data=lai10 mean noprint; by Nrate doy; var lai intpar;
output out=lai10mean mean=lai intpar; run; proc print data=lai10mean; run;

Biomass yields-Ch.4, Table 4.4, Table 4.5.
options ls=150 ps=150 nodate nocenter formdlim="-";
data biom10;
length env$ 18;
length hybrid$ 14;
infile "C:\Users\maughan2\Documents\My Dropbox\sorghum fertility trial\2009 & 2010 analysis for
manuscript 1\sorghum dry biomass yield 2010.csv"
dlmt="," firstobs=7;
input env$ block type$ hybrid$ Nrate lbs Nrate plot summer fall tons biomass comments$;
drop Nrate lbs comments;
*if env ="Urbana 2010" and block=1 and hybrid="TX09007" then biomass=.; *poor planting in 106-
and some flooding;
*if env ="Dixon Springs 2010" and plot=301 then biomass=.; *no second harvest;
*if env ="Perry 2010" and plot=401 then biomass=.;
early-summer=2.24;
late=fall*2.24;
run; proc print; run;
proc sort data=biom10; by env type hybrid block Nrate; run; proc print;
*means by cutting and total biomass production;
proc sort data=biom10; by env type Nrate; run;
proc means data=biom10 noprint mean; var early; by env type Nrate;
output out=summer mean=summerbiom; run; proc print data=summer; run;
data summer; set summer;
drop _TYPE_ _FREQ_; run;
proc means data=biom10 noprint mean; var late; by env type Nrate;
output out=fall mean=fallbiom; run; proc print data=fall; run;
data fall; set fall;
drop _TYPE_ _FREQ_; run;
data all; merge summer fall;
by env type Nrate; run; proc print data=all; run;
data all; set all;
if summerbiom= then summerbiom=0;
total=summerbiom+fallbiom; run;
proc print data=all; run;
*modeling 2010 total dry biomass yields;
*blup estimate statements calculating dry biomass yield in each environment by type and Nrate;
ods html;
ods graphics on;
proc glimmix data=biom10 plots=all;
class env block type Nrate;
model biomass=type hybrid(type) Nrate type*Nrate Nrate*hybrid(type)/dist=normal ddfm=kr;
random env block(env) env*type type*block(env) env*hybrid(type) env*Nrate env*Nrate*hybrid(type);
covtest glm/wald;
*lsmeans type*Nrate/plot=meanplot(sliceby=type join);
estimate "DS energy 0" intercept 1 type 1 0 Nrate 1 0 0 0 0 type*Nrate 1|env 1 0
  env*type 1 0 0 0 0 env*type*Nrate 1;
estimate "DS energy 56" intercept 1 type 1 0 Nrate 0 1 0 0 0 type*Nrate 0 1|env 1 0
  env*type 1 0 0 0 0 env*type*Nrate 0 1;
estimate "DS energy 112" intercept 1 type 1 0 Nrate 0 0 1 0 0 type*Nrate 0 0 1|env 1 0
  env*type 1 0 0 0 0 env*type*Nrate 0 0 1;
estimate "DS energy 168" intercept 1 type 1 0 Nrate 0 0 0 1 0 type*Nrate 0 0 0 1|env 1 0
  env*type 1 0 0 0 0 env*type*Nrate 0 0 0 1;
estimate "DS energy 224" intercept 1 type 1 0 Nrate 0 0 0 0 1 type*Nrate 0 0 0 0 1|env 1 0
  env*type 1 0 0 0 0 env*type*Nrate 0 0 0 0 1;
estimate "DS forage 0" intercept 1 type 0 1 Nrate 1 0 0 0 0 type*Nrate 0 0 0 0 0 1|env 1 0
  env*type 0 1 0 0 0 env*type*Nrate 0 0 0 0 0 1;
estimate "DS forage 56" intercept 1 type 0 1 Nrate 0 1 0 0 0 type*Nrate 0 0 0 0 0 1|env 1 0
  env*type 0 1 0 0 0 env*type*Nrate 0 0 0 0 0 1;
estimate "DS forage 112" intercept 1 type 0 1 Nrate 0 0 1 0 0 type*Nrate 0 0 0 0 0 1|env 1 0
  env*type 0 1 0 0 0 env*type*Nrate 0 0 0 0 0 1;
estimate "DS forage 168" intercept 1 type 0 1 Nrate 0 0 0 1 0 type*Nrate 0 0 0 0 0 1|env 1 0
  env*type 0 1 0 0 0 env*type*Nrate 0 0 0 0 0 1;
estimate "DS forage 224" intercept 1 type 0 1 Nrate 0 0 0 0 1 type*Nrate 0 0 0 0 0 0 0 1|env 1 0
  env*type 0 1 0 0 0 env*type*Nrate 0 0 0 0 0 0 0 1;
estimate "PE energy 0" intercept 1 type 1 0 Nrate 1 0 0 0 0 type*Nrate 1|env 0 1
  env*type 0 0 1 0 0 env*type*Nrate 0 0 0 0 0 0 0 0 1;
estimate "PE energy 56" intercept 1 type 1 0 Nrate 0 1 0 0 0 type*Nrate 0 1|env 0 1
163
estimate "PE energy 112"
  intercept 1 type 1 1 Nrate 0 1 0 0 0 type*Nrate 0 1 0 0 0 env 0 1
  env*type 0 0 1 0 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "PE energy 168"
  intercept 1 type 1 1 Nrate 0 0 0 1 0 type*Nrate 0 0 0 1 0 env 0 1
  env*type 0 0 1 0 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "PE energy 224"
  intercept 1 type 1 1 Nrate 0 0 0 1 1 type*Nrate 0 0 0 1 1 env 0 1
  env*type 0 0 1 0 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "PE forage 0"
  intercept 1 type 0 1 Nrate 1 0 0 0 0 type*Nrate 0 0 0 0 0 env 0 1
  env*type 0 0 1 0 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "PE forage 56"
  intercept 1 type 0 1 Nrate 0 1 0 0 0 type*Nrate 0 0 0 0 0 env 0 1
  env*type 0 0 1 0 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "PE forage 112"
  intercept 1 type 0 1 Nrate 0 0 1 0 0 type*Nrate 0 0 0 1 0 env 0 1
  env*type 0 0 1 0 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "PE forage 168"
  intercept 1 type 0 1 Nrate 0 0 0 1 0 type*Nrate 0 0 0 0 0 env 0 1
  env*type 0 0 1 0 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "PE forage 224"
  intercept 1 type 0 1 Nrate 0 0 0 1 1 type*Nrate 0 0 0 0 0 env 0 1
  env*type 0 0 1 0 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "UR energy 0"
  intercept 1 type 1 1 Nrate 1 0 0 0 0 type*Nrate 1 0 0 0 0 env 0 1
  env*type 0 0 0 1 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "UR energy 56"
  intercept 1 type 1 1 Nrate 0 1 0 0 0 type*Nrate 0 1 0 0 0 env 0 1
  env*type 0 0 0 1 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "UR energy 112"
  intercept 1 type 1 1 Nrate 0 0 1 0 0 type*Nrate 0 0 1 0 0 env 0 1
  env*type 0 0 0 1 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "UR energy 168"
  intercept 1 type 1 1 Nrate 0 0 0 1 0 type*Nrate 0 0 0 1 0 env 0 1
  env*type 0 0 0 1 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "UR energy 224"
  intercept 1 type 1 1 Nrate 0 0 0 1 1 type*Nrate 0 0 0 1 1 env 0 1
  env*type 0 0 0 1 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "UR forage 0"
  intercept 1 type 0 1 Nrate 1 0 0 0 0 type*Nrate 0 0 0 0 0 env 0 1
  env*type 0 0 0 1 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "UR forage 56"
  intercept 1 type 0 1 Nrate 0 1 0 0 0 type*Nrate 0 0 0 0 0 env 0 1
  env*type 0 0 0 1 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "UR forage 112"
  intercept 1 type 0 1 Nrate 0 0 1 0 0 type*Nrate 0 0 0 0 0 env 0 1
  env*type 0 0 0 1 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "UR forage 168"
  intercept 1 type 0 1 Nrate 0 0 0 1 0 type*Nrate 0 0 0 0 0 env 0 1
  env*type 0 0 0 1 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "UR forage 224"
  intercept 1 type 0 1 Nrate 0 0 0 1 1 type*Nrate 0 0 0 0 0 env 0 1
  env*type 0 0 0 1 0 env*type*Nrate 0 0 0 0 0 0 0 0 0 0 0 0 1;

estimate "N 0 vs 56" Nrate 1 -1 0 0 0;

estimate "N 0 vs 112" Nrate 1 0 -1 0 0;

estimate "N 0 vs 168" Nrate 1 0 0 -1 0;

estimate "N 56 vs 224" Nrate 1 0 0 -1;

estimate "N 56 vs 112" Nrate 0 1 -1 0 0;
estimate "N 56 vs 168" Nrate 0 1 0 -1;
estimate "N 56 vs 224" Nrate 0 1 0 0 -1;
estimate "N 112 vs 168" Nrate 0 0 1 -1 0;
estimate "N 112 vs 224" Nrate 0 0 1 0 -1;
estimate "N 168 vs 224" Nrate 0 0 0 1 -1;
estimate "energy 0" intercept 1 type 1 Nrate 1 type*Nrate 1;
estimate "energy 56" intercept 1 type 1 Nrate 0 1 type*Nrate 0 1;
estimate "energy 112" intercept 1 type 1 Nrate 0 0 1 type*Nrate 0 0 1;
estimate "energy 168" intercept 1 type 1 Nrate 0 0 0 1 type*Nrate 0 0 0 1;
estimate "energy 224" intercept 1 type 1 Nrate 0 0 0 0 1 type*Nrate 0 0 0 0 1;
estimate "forage 0" intercept 1 type 0 1 Nrate 1 type*Nrate 0 0 0 0 0 1;
estimate "forage 56" intercept 1 type 0 1 Nrate 0 1 type*Nrate 0 0 0 0 0 1;
estimate "forage 112" intercept 1 type 0 1 Nrate 0 0 1 type*Nrate 0 0 0 0 0 1;
estimate "forage 168" intercept 1 type 0 1 Nrate 0 0 0 1 type*Nrate 0 0 0 0 0 1;
estimate "forage 224" intercept 1 type 0 1 Nrate 0 0 0 0 1 type*Nrate 0 0 0 0 0 1;
estimate "energy 0 vs 56" Nrate 1 -1 type*Nrate 1 -1;
estimate "energy 0 vs 112" Nrate 1 0 -1 type*Nrate 1 0 -1;
estimate "energy 0 vs 168" Nrate 1 0 0 -1 type*Nrate 1 0 0 -1;
estimate "energy 0 vs 224" Nrate 1 0 0 0 -1 type*Nrate 1 0 0 0 -1;
estimate "energy 56 vs 112" Nrate 0 1 -1 0 type*Nrate 0 1 -1 0;
estimate "energy 56 vs 168" Nrate 0 1 0 -1 type*Nrate 0 1 0 -1;
estimate "energy 56 vs 224" Nrate 0 1 0 0 -1 type*Nrate 0 1 0 0 -1;
estimate "energy 112 vs 168" Nrate 0 0 1 -1 0 type*Nrate 0 0 1 -1 0;
estimate "energy 112 vs 224" Nrate 0 0 1 0 -1 type*Nrate 0 0 1 0 -1;
estimate "energy 168 vs 224" Nrate 0 0 0 1 -1 type*Nrate 0 0 0 1 -1;
estimate "forage 0 vs 56" Nrate 1 -1 type*Nrate 0 0 0 0 1 -1;
estimate "forage 0 vs 112" Nrate 1 0 -1 type*Nrate 0 0 0 0 1 -1;
estimate "forage 0 vs 168" Nrate 1 0 0 -1 type*Nrate 0 0 0 0 1 -1;
estimate "forage 0 vs 224" Nrate 1 0 0 0 -1 type*Nrate 0 0 0 0 1 -1;
estimate "forage 56 vs 112" Nrate 0 1 -1 0 type*Nrate 0 0 0 0 1 -1;
estimate "forage 56 vs 168" Nrate 0 1 0 -1 type*Nrate 0 0 0 0 1 -1;
estimate "forage 56 vs 224" Nrate 0 1 0 0 -1 type*Nrate 0 0 0 0 1 -1;
estimate "forage 112 vs 168" Nrate 0 0 1 -1 0 type*Nrate 0 0 0 0 1 -1;
estimate "forage 112 vs 224" Nrate 0 0 1 0 -1 type*Nrate 0 0 0 0 1 -1;
estimate "forage 168 vs 224" Nrate 0 0 0 1 -1 type*Nrate 0 0 0 0 1 -1;
estimate "Dixon Springs 2010 type difference" type 1 -1|env 1 env*type 1 -1;
estimate "Perry 2010 type difference" type 1 -1|env 0 1 env*type 0 0 1 -1;
estimate "Urbana 2010 type difference" type 1 -1|env 0 0 1 env*type 0 0 0 1 -1;
estimate "DS vs PE energy vs. forage" type 1 -1|env 1 -1 0 env*type 1 -1 -1 1;
estimate "DS vs UR energy vs. forage" type 1 -1|env 1 0 -1 env*type 1 -1 1 0 -1;
estimate "PE vs UR energy vs. forage" type 1 -1|env 0 1 -1 env*type 0 0 1 -1 1 1;
estimate "DS vs PE energy" |env 1 -1 0 env*type 1 0 -1 0 0 0;
estimate "PE vs UR energy" |env 0 1 -1 env*type 0 0 1 0 -1 0;
output out=out1 residual=resid predicted=pred;
run;
ods graphics off;
ods html close;

*checking outliers;
data outlout; set out1;
if resid le 5 then delete;
run; proc print data=outlout;
run;

*removing outliers;
data new; set out1;
if resid ge 10 then delete;
run;
ods html;
ods graphics on;
proc glimmix data=new plots=all;
class env block type hybrid Nrate;
model biomass=type hybrid(type) Nrate type*Nrate Nrate*hybrid(type) /dist=normal ddfm=kr;
random env block(env) env*type*block(env) env*hybrid(type) block*hybrid(env type) env*Nrate
env*type*Nrate env*Nrate*hybrid(type);
*Running the model without these outliers did not change the significance of any of the
day factors or parameter estimates in a way that would warrant leaving them out. The residuals
looked better but the model did not change significantly so I will keep them in the model.

*Based upon the results of the model only the effect of Nrate and Type are significant at
the alpha=.1 level, ;

*2010 forage sorghum harvest 1, harvest 2 analysis;
data forage; set biom10;
if type = "Energy" then delete;
run; proc print data=forage; run;

*2010 summer forage sorghum harvest analysis;
ods html;
ods graphics on;
proc glimmix data=forage plots=all;
class env block hybrid Nrate;
model early=hybrid Nrate hybrid*Nrate; ddfm=kr ;
random env block(env) env*Nrate env*Nrate*hybrid;
covtest glim/wald;
lsmeans Nrate/pdiff;
estimate "DS 0" intercept 1 Nrate 1 0 0 0 0|env 1 0 0 env*Nrate 1;
estimate "DS 56" intercept 1 Nrate 0 1 0 0 0|env 1 0 0 env*Nrate 0 1;
estimate "DS 112" intercept 1 Nrate 0 0 1 0 0|env 1 0 0 env*Nrate 0 0 1;
estimate "DS 168" intercept 1 Nrate 0 0 0 1 0|env 1 0 0 env*Nrate 0 0 0 1;
estimate "DS 224" intercept 1 Nrate 0 0 0 0 1|env 1 0 0 env*Nrate 0 0 0 0 1;
estimate "PE 0" intercept 1 Nrate 1 0 0 0 0|env 0 1 0 env*Nrate 0 0 0 0 0 1;
estimate "PE 56" intercept 1 Nrate 0 1 0 0 0|env 0 1 0 env*Nrate 0 0 0 0 0 1;
estimate "PE 112" intercept 1 Nrate 0 0 1 0 0|env 0 1 0 env*Nrate 0 0 0 0 0 1;
estimate "PE 168" intercept 1 Nrate 0 0 0 1 0|env 0 1 0 env*Nrate 0 0 0 0 0 1;
estimate "PE 224" intercept 1 Nrate 0 0 0 0 1|env 0 1 0 env*Nrate 0 0 0 0 0 1;
estimate "UR 0" intercept 1 Nrate 1 0 0 0 0|env 0 0 1 env*Nrate 0 0 0 0 0 0 0 1;
estimate "UR 56" intercept 1 Nrate 0 1 0 0 0|env 0 0 1 env*Nrate 0 0 0 0 0 0 0 1;
estimate "UR 112" intercept 1 Nrate 0 0 1 0 0|env 0 0 1 env*Nrate 0 0 0 0 0 0 0 1;
estimate "UR 168" intercept 1 Nrate 0 0 0 1 0|env 0 0 1 env*Nrate 0 0 0 0 0 0 0 1;
estimate "UR 224" intercept 1 Nrate 0 0 0 0 1|env 0 0 1 env*Nrate 0 0 0 0 0 0 0 1;
run;
ods graphics off;
ods html close;

*2010 fall forage sorghum harvest analysis;
ods html;
ods graphics on;
proc glimmix data=forage plots=all;
class env block hybrid Nrate;
model late=hybrid Nrate hybrid*Nrate; ddfm=kr ;
random env block(env) env*Nrate hybrid*block(env) env*Nrate env*Nrate*hybrid;
covtest glim/wald;
lsmeans Nrate/pdiff;
estimate "DS 0" intercept 1 Nrate 1 0 0 0 0|env 1 0 0 env*Nrate 1;
estimate "DS 56" intercept 1 Nrate 0 1 0 0 0|env 1 0 0 env*Nrate 0 1;
estimate "DS 112" intercept 1 Nrate 0 0 1 0 0|env 1 0 0 env*Nrate 0 0 1;
estimate "DS 168" intercept 1 Nrate 0 0 0 1 0|env 1 0 0 env*Nrate 0 0 0 1;
estimate "DS 224" intercept 1 Nrate 0 0 0 0 1|env 1 0 0 env*Nrate 0 0 0 0 1;
estimate "PE 0" intercept 1 Nrate 1 0 0 0 0|env 0 1 0 env*Nrate 0 0 0 0 0 1;
estimate "PE 56" intercept 1 Nrate 0 1 0 0 0|env 0 1 0 env*Nrate 0 0 0 0 0 1;
estimate "PE 112" intercept 1 Nrate 0 0 1 0 0|env 0 1 0 env*Nrate 0 0 0 0 0 1;
estimate "PE 168" intercept 1 Nrate 0 0 0 1 0|env 0 1 0 env*Nrate 0 0 0 0 0 1;
estimate "PE 224" intercept 1 Nrate 0 0 0 0 1|env 0 1 0 env*Nrate 0 0 0 0 0 1;
estimate "UR 0" intercept 1 Nrate 1 0 0 0 0 | env 0 0 1 env*Nrate 0 0 0 0 0 0 0 0 0 1;
estimate "UR 56" intercept 1 Nrate 0 1 0 0 0 | env 0 0 1 env*Nrate 0 0 0 0 0 0 0 0 0 1;
estimate "UR 112" intercept 1 Nrate 0 0 1 0 0 | env 0 0 1 env*Nrate 0 0 0 0 0 0 0 0 0 1;
estimate "UR 168" intercept 1 Nrate 0 0 0 1 0 | env 0 0 1 env*Nrate 0 0 0 0 0 0 0 0 0 0 0 1;nestimate "UR 224" intercept 1 Nrate 0 0 0 0 1 | env 0 0 1 env*Nrate 0 0 0 0 0 0 0 0 0 0 0 1;
estimate "graze all" intercept 1 hybrid 1 0;estimate "graze. n. bale" intercept 1 hybrid 0 1;estimate "graze all vs graze. n. bale" hybrid 1 -1;run;ods graphics off;ods html close;

*2009 biomass data;
data biom09;length env$ 18;length hybrid$ 14;infile 'C:\Users\maughan2\Documents\My Dropbox\sorghum fertility trial\2009 & 2010 analysis for manuscript 1\sorghum dry biomass yield 2009.csv'dlm='",' firstobs=5;input env$ block type$ hybrid$ Nrate plot tons;biomass-tons*2.24;run;proc print;run;proc sort data=biom09 by env type hybrid block Nrate;run;proc print;
proc sort data=biom09 by env type Nrate;run;proc means data=biom09 noprint mean;var biomass;by env type Nrate;output out=mean09 mean=biomass;run;proc print data=mean09;run;
ods graphics on;proc glimmix data=biom09 plots=RESIDUALPANEL;class block type hybrid Nrate;model biomass=type hybrid(type) Nrate type*Nrate Nrate*hybrid(type);random block*type block*hybrid(type);covtest glmwald;lsmeans type*Nrate/pdiff;estimate "energy 0 vs 50" Nrate 1 -1 type*Nrate 1 -1;estimate "energy 0 vs 100" Nrate 1 0 -1 type*Nrate 1 0 -1;estimate "energy 0 vs 150" Nrate 1 0 0 -1 type*Nrate 1 0 0 -1;estimate "energy 50 vs 100" Nrate 0 1 -1 0 type*Nrate 0 1 -1 0;estimate "energy 50 vs 150" Nrate 0 1 0 -1 type*Nrate 0 1 0 -1;estimate "energy 100 vs 150" Nrate 0 0 1 -1 type*Nrate 0 0 1 -1;estimate "forage 0 vs 50" Nrate 1 -1 -1 type*Nrate 0 0 0 1 -1;estimate "forage 0 vs 100" Nrate 1 0 -1 type*Nrate 0 0 0 1 0 -1;estimate "forage 0 vs 150" Nrate 1 0 0 -1 type*Nrate 0 0 0 1 0 0 -1;estimate "forage 50 vs 100" Nrate 0 1 -1 0 type*Nrate 0 0 0 0 1 0 1 -1;estimate "forage 50 vs 150" Nrate 0 1 0 -1 type*Nrate 0 0 0 0 1 0 -1;estimate "forage 100 vs 150" Nrate 0 0 1 -1 type*Nrate 0 0 0 0 1 -1 -1;contrast "linear N rate" Nrate -3 -1 1 3;contrast "linear N rate energy vs forage" type*Nrate -3 -1 1 3 1 -1 3 -3;run;ods graphics off;

Correlations among plant height, expanded leaf number, and biomass yield

*2010 energy sorghum biomass yields;
options ls=150 ps=150 nodate nocenter formdlim="-";
data biom10;length env$ 18;length hybrid$ 14;infile 'C:\Users\maughan2\Documents\My Dropbox\sorghum fertility trial\2009 & 2010 analysis for manuscript 1\sorghum dry biomass yield 2010.csv'dlm='",' firstobs=7;
input env$ block type$ hybrid$ Nratelbs Nrate plot summer fall tons biomass comments$;
if type="Forage" then delete;
drop Nrate Nratelbs summer fall tons comments;
run; proc print data=biom10; run;

*2009  energy sorghum biomass data;
data biom09;
length env$ 18;
length hybrid$ 14;
infile 'C:\Users\maughan2\Documents\My Dropbox\sorghum fertility trial\2009 & 2010 analysis for
manuscript 1\sorghum dry biomass yield 2009.csv'
dlm="," firstobs=5;
input env$ block type$ hybrid$ Nrate plot tons;
biomass=tons*2.24;
if type="Forage" then delete;
drop tons;
run;
proc print data=biom09; run;

*2009 & 2010 leaf number and height;
data htleafno;
length env$ 18;
length hybrid$ 14;
infile 'C:\Users\maughan2\Documents\My Dropbox\sorghum fertility trial\2009 & 2010 analysis for
manuscript 1\sorghum ht-leafno 2009 & 2010 for correlations.csv'
dlm="," firstobs=6;
input env$ date$ doy block sample type$ hybrid$ Nrate Nratelbs plot leaf htcm GDD10 GDD11
comment$;
htm=htcm/100;
if type="Forage" then delete;
drop date sample Nratelbs htcm GDD10 GDD11 comment;
run;
proc print data=htleafno; run;

*Urbana 2009 end of season ht and leaf number;
data htleaf09; set htleafno;
if env ne "Urbana 2009" then delete;
if doy ne 280 then delete;
run; proc print; run;

proc sort data=htleaf09 by env block type hybrid Nrate plot; run;
proc means data=htleaf09 mean noprint; var leaf htm; by env block type hybrid Nrate plot;
output out=new09 mean=leaf htm; run; proc print data=new09; run;
data new09; set new09;
drop _TYPE_ _FREQ_; run; proc print data=new09; run;

*2010 end of season ht and leaf number;
data htleaf10; set htleafno;
if env ="Urbana 2009" then delete;
if env="Urbana 2010" and doy ne 270 then delete;
if env="Dixon Springs 2010" and doy ne 277 then delete;
if env="Perry 2010" and doy ne 276 then delete;
run; proc print; run;

proc sort data=htleaf10 by env block type hybrid Nrate plot; run;
proc means data=htleaf10 mean noprint; var leaf htm; by env block type hybrid Nrate plot;
output out=new10 mean=leaf htm; run; proc print data=new10; run;
data new10; set new10;
drop _TYPE_ _FREQ_; run; proc print data=new10; run;

*merging 2009 info;
proc sort data=biom09 by env block type hybrid Nrate plot; run;
data all10; merge biom09 new09;
by env block type hybrid Nrate;
run;
proc print data=all10; run;

*Correlations among biomass, leaf number, and height for Urbana 2009;
proc corr data=all09;
var biomass leaf htm; run;
proc sgscatter data=all09;
title "Urbana 2009";
matrix htm leaf biomass/group=Nrate;
run;

*merging 2010 info;
proc sort data=biom10 by env block type hybrid Nrate plot; run;
data all10; merge biom10 new10; by env block type hybrid Nrate; run;
proc print data=all10; run;

*Correlations among biomass, leaf number, and height for 2010;
proc corr data=all10;
var biomass leaf htm;
by env; run;
proc sgscatter data=all10;
title "2010 environments";
matrix htm leaf biomass/group=env;
run;
APPENDIX D

Selected SAS code for Ch. 5

Nitrogen response curves, EONR-Ch.5, Fig. 5.1, Table 5.1.

```sas
options ls=150 ps=150 nodate nocenter formdlim="-";
data biom10;
length env$ 18;
length hybrid$ 14;
infile 'C:\Users\maughan2\Documents\My Dropbox\sorghum fertility trial\2009 & 2010 analysis for manuscript\sorghum dry biomass yield 2010.csv' dlm=" " firstobs=7;
input env$ block type$ hybrid$ Nratelbs Nrate plot summer fall tons biomass comments$;
drop Nratelbs summer fall tons comments;
run;
proc print;
run;
proc sort data=biom10; by env type hybrid block Nrate;
run;
proc print;
run;
*URBANA 2010 ENERGY SORGHUM;
data urbenergy; set biom10;
if type ne "Energy" then delete;
if env ne "Urbana 2010" then delete;
*if block=1 and hybrid="TX09007" then delete; *poor planting in 106-110 and some flooding;
X=Nrate;
X2=X*X;
run;
proc print data=urbenergy;
run;
proc sort data=urbenergy; by env hybrid block type Nrate;
proc print data=urbenergy;
run;
proc sort data=urbenergy; by block;
run;
proc nlmixed data=urbenergy;
parms alpha=-22.5 beta=.075 gamma=-.0001 /*s2blk=1*/ s2e=45;
x0 = -.5*beta / gamma;
y = (x<x0)*(alpha+beta*x + gamma*x*x) + (x>=x0)*(alpha+beta*x0+gamma*x0*x0)/ + blk */;
plateau =alpha + beta*x0 + gamma*x0*x0;
EONR1a=((.87/35)-beta)/(2*gamma);
EONR2a=((.87/50)-beta)/(2*gamma);
EONR3a=((.87/65)-beta)/(2*gamma);
EONR1b=((1.07/35)-beta)/(2*gamma);
EONR2b=((1.07/50)-beta)/(2*gamma);
EONR3b=((1.07/65)-beta)/(2*gamma);
EONR1c=((1.32/35)-beta)/(2*gamma);
EONR2c=((1.32/50)-beta)/(2*gamma);
EONR3c=((1.32/65)-beta)/(2*gamma);
model biomass ~ normal(y,s2e);
*random blk ~ NORMAL(0,s2blk) SUBJECT=block;
estimate 'X0' X0;
estimate 'plateau' plateau;
estimate "$35a" EONR1a;
estimate "$50a" EONR2a;
estimate "$65a" EONR3a;
estimate "$35b" EONR1b;
estimate "$50b" EONR2b;
estimate "$65b" EONR3b;
estimate "$35c" EONR1c;
estimate "$50c" EONR2c;
estimate "$65c" EONR3c;
predict y out=response1;
run;
proc print data=response1; run;
```

```sas
data response1; set response1;
residuals=biomass-pred;
run;
proc print data=response1; run;
data ce;
do i=0 to 224 by 0.5;
do n=187.42;
yielde = (i <n)*(22.3700+0.06470*i -0.00017*i*i) +
```

170
(i>=n)*(22.3700+0.06470*n -0.00017*n*n);
output;
end;
end;
proc print data=ce; run;

*URBANA 2010 FORAGE SORGHUM;
data urbforage; set biom10;
if type ne "Forage" then delete;
if env ne "Urbana 2010" then delete;
X=Nrate;
X2=X*X;
run; proc print data=urbforage; run;
proc sort data=urbforage; by env hybrid block type Nrate;
proc print data=urbforage; run;
proc sort data=urbforage; by block;
proc print;
proc nlmixed data=urbforage;
parms alpha=16.25 beta=.049 gamma=-.0001 /*s2blk=1*/ s2e=45;
x0 = -.5*beta / gamma; /*estimate of joint point;*/
y = (x <x0)*(alpha+beta*x +gamma*x*x) + (x>=x0)*(alpha+beta*x0+gamma*x0*x0) /* + blk */;
plateau =alpha + beta*x0 + gamma*x0*x0;
EONR1a=((.87/35)-beta)/(2*gamma);
EONR2a=((.87/50)-beta)/(2*gamma);
EONR3a=((.87/65)-beta)/(2*gamma);
EONR1b=((1.07/35)-beta)/(2*gamma);
EONR2b=((1.07/50)-beta)/(2*gamma);
EONR3b=((1.07/65)-beta)/(2*gamma);
EONR1c=((1.32/35)-beta)/(2*gamma);
EONR2c=((1.32/50)-beta)/(2*gamma);
EONR3c=((1.32/65)-beta)/(2*gamma);
model biomass ~ normal(y,s2e);
*random blk ~ NORMAL(0,s2blk) SUBJECT=block;
estimate 'X0' X0;
estimate 'plateau' plateau;
estimate "$35a" EONR1a;
estimate "$50a" EONR2a;
estimate "$65a" EONR3a;
estimate "$35b" EONR1b;
estimate "$50b" EONR2b;
estimate "$65b" EONR3b;
estimate "$35c" EONR1c;
estimate "$50c" EONR2c;
estimate "$65c" EONR3c;
predict y out=response2;
run;
proc print data=response2; run;
data response2; set response2;
residuals=biomass-pred; run; proc print data=response2; run;
data cf;
do j=0 to 224 by 0.5;
do n=193.69;
yieldf = (j <n)*((16.2596+0.0496*j) -0.00013*j*j) +
        (j>=n)*((16.2596+0.0496*n -0.00013*n*n));
output;
end;
end;
proc print data=cf; run;

*PLOTTING RESPONSE CURVES FOR URBANA 2010;
data all; merge urbenergy urbforage;
by env hybrid block type Nrate biomass X X2;
run; proc print data=all; run;
proc sort data=all; by type; run; proc print data=all; run;
data urb; merge all ce cf; run; proc print data=urb; run;
proc sort data=urb; by i j; run; proc print data=urb; run; proc sgplot data=urb noautolegend; title "Urbana 2010"; yaxis label="Biomass (Mg/ha)" values=(0 to 50 by 10); xaxis label="N rate (kg/ha)" values=(0 to 225 by 25); scatter y=biomass x=x/group=type markerattrs=(size=8) name="obs" NOMISSINGGROUP; series y=yieldx x=i/lineattrs=(pattern=longdash thickness=2px color=blue) name="E" legendlabel="Energy"; series y=yieldf x=j/lineattrs=(pattern=solid thickness=2px color=darkred) name="F" legendlabel="Forage"; discretelegend "obs" "E" "F" /across=1 position=topleft location=inside; run;
*plotting residuals; data Urb10; merge response1 response2; by type; run; proc print data=Urb10; run; proc sgplot data=Urb10 noautolegend; title "Urbana 2010"; yaxis label="Residuals (observed yield - predicted yield)"; xaxis label="N rate (kg/ha)" values=(0 to 225 by 25); scatter y=residuals x=x/group=type markerattrs=(size=8) name="obs" NOMISSINGGROUP; refline 0/axis=y; run;

*DIXON SPRINGS 2010 ENERGY SORGHUM; data dsenergy; set biom10; if type ne "Energy" then delete; if env ne "Dixon Springs 2010" then delete; *if plot=311 then delete; *if plot=109 then delete; *if plot=204 then delete; X=Nrate; X2=X*X; run; proc print data=dsenergy; run; proc sort data=dsenergy; by env hybrid block type Nrate; proc print data=dsenergy; run; proc sort data=dsenergy; by block; run; proc nlmixed data=dsenergy; parms alpha=17 beta=.18 gamma=-.00247 /*s2blk=1*/ s2e=8.5; x0 = -.5*beta / gamma; y = (x <x0)*(alpha+beta*x + gamma*x*x) + (x>=x0)*(alpha+beta*x0 + gamma*x0*x0)/* + blk */; plateau =alpha + beta*x0 + gamma*x0*x0; EONR1a=(.87/35-beta)/(2*gamma); EONR2a=(.87/50-beta)/(2*gamma); EONR3a=(.87/65-beta)/(2*gamma); EONR1b=(1.07/35-beta)/(2*gamma); EONR2b=(1.07/50-beta)/(2*gamma); EONR3b=(1.07/65-beta)/(2*gamma); EONR1c=(1.32/35-beta)/(2*gamma); EONR2c=(1.32/50-beta)/(2*gamma); EONR3c=(1.32/65-beta)/(2*gamma); model biomass ~ normal(y,s2e); *random blk ~ NORMAL(0,s2blk) SUBJECT=block; estimate 'X0' X0; estimate 'plateau' plateau; estimate "$35a" EONR1a; estimate "$50a" EONR2a; estimate "$65a" EONR3a; estimate "$35b" EONR1b; estimate "$50b" EONR2b; estimate "$65b" EONR3b; estimate "$35c" EONR1c;
estimate "$50c" EONR2c;
estimate "$65c" EONR3c;
predict y out=response3;
run;
proc print data=response3; run;
data response3; set response3;
residuals=biomass-pred; run; proc print data=response3; run;
data ce;
do i=0 to 224 by 0.5;
do n=41.7536;
yield = (i <n)* (17.6916 + 0.1702*i - 0.00204*i*i) + (i>=n)* (17.6916 + 0.1702*n - 0.00204*n*n);
output;
end;
end;
proc print data=ce; run;
data dsforage;
set biom10;
if type ne "Forage" then delete;
if env ne "Dixon Springs 2010" then delete;
if plot=301 then delete; *no second harvest;
*if plot=114 then delete;
*if plot=115 then delete;
*if plot=306 then delete;
*if plot=403 then delete;
X=Nrate;
X2=X*X;
run;
proc print data=dsforage; run;
proc sort data=dsforage; by env hybrid block type Nrate; run;
proc print data=dsforage; run;
proc sort data=dsforage; by block; run;
proc nlmixed data=dsforage;
parms alpha=16 beta=.09 gamma=-.0008 /*s2blk=1*/ s2e=3.5;
x0 = -.5*beta / gamma;
y = (x <x0)* (alpha+beta*x + gamma*x*x) + (x>=x0)* (alpha+beta*x0+gamma*x0*x0) /* + blk */;
plateau = alpha + beta*x0 + gamma*x0*x0;
EONR1a=((.87/35)-beta)/(2*gamma);
EONR2a=((.87/50)-beta)/(2*gamma);
EONR3a=((.87/65)-beta)/(2*gamma);
EONR1b=((1.07/35)-beta)/(2*gamma);
EONR2b=((1.07/50)-beta)/(2*gamma);
EONR3b=((1.07/65)-beta)/(2*gamma);
EONR1c=((1.32/35)-beta)/(2*gamma);
EONR2c=((1.32/50)-beta)/(2*gamma);
EONR3c=((1.32/65)-beta)/(2*gamma);
model biomass ~ normal(y,s2e);
*random blk ~ NORMAL(0,s2blk) SUBJECT=block;
estimate 'X0' X0;
estimate 'plateau' plateau;
estimate "$35a" EONR1a;
estimate "$50a" EONR2a;
estimate "$65a" EONR3a;
estimate "$35b" EONR1b;
estimate "$50b" EONR2b;
estimate "$65b" EONR3b;
estimate "$35c" EONR1c;
estimate "$50c" EONR2c;
estimate "$65c" EONR3c;
predict y out=response4;
run;
proc print data=response4; run;
data response4; set response4;
residuals=biomass-pred; run; proc print data=response4; run;
data cf;
do j=0 to 224 by 0.5;
do n=47.8261;
yieldf = (j <n)*(16.6889+0.06675*j -0.00070*j*j) + (j>=n)*(16.6889+0.06675*n -0.00070*n*n);
output;
end;
end;
proc print data=cf; run;

*PLOTTING RESPONSE CURVES FOR Dixon springs 2010;
data allds; merge dsenergy dsforage; by env hybrid block type Nrate biomass X X2;
run; proc print data=allds; run;
proc sort data=allds; by type;
run;
proc print data=allds; run;
data ds; merge allds ce cf;
run;
proc sort data=ds; by i j;
run;
proc print data=ds; run;
proc sgplot data=ds noautolegend;
title "Dixon Springs 2010";
yaxis label="Biomass (Mg/ha)" values=(0 to 50 by 10);
xaxis label="N rate (kg/ha)" values=(0 to 225 by 25);
scatter y=biomass x=X/group=type markerattrs=(size=8) name="obs" NOMISSINGGROUP;
series y=yieldf x=X2/lineattrs=(pattern=longdash thickness=2px color=blue) name="E" legendlabel="Energy";
series y=yieldf x=X1/lineattrs=(pattern=solid thickness=2px color=darkred) name="F" legendlabel="Forage";
discretelegend "obs" "E" "F"/across=1 position=topleft location=inside;
run;

*plotting residuals;
data DS10; merge response3 response4; by type;
run; proc print data=DS10; run;
proc sgplot data=DS10 noautolegend;
title "Dixon Springs 2010";
yaxis label="Residuals (observed yield- predicted yield)";
xaxis label="N rate (kg/ha)" values=(0 to 225 by 25);
scatter y=residuals x=X/group=type markerattrs=(size=8) name="obs" NOMISSINGGROUP;
refline 0/axis=y;
run;

*FERRY 2010 ENERGY SORGHUM;
data perenergy; set biomi10;
if type ne "Energy" then delete;
if env ne "Perry 2010" then delete;
*if plot=310 then delete;
*if plot=311 then delete;
*if plot=110 then delete;
*if plot=206 then delete;
*if plot=311 then delete;
*if plot=420 then delete;
*if plot=108 then delete;
*if plot=309 then delete;
X=Nrate;
X2=X*X;
run; proc print data=perenergy; run;
proc sort data=perenergy; by env hybrid block type Nrate;
proc print data=perenergy; run;

/*
proc sort data=perenergy; by block; run; proc print;
proc nlmixed data=perenergy;
 parms alpha=18 beta=-.01 gamma=-.0001 s2e=10;
x0 = -.5*beta / gamma;
y = (x <x0)*(alpha+beta*x + gamma*x*x) + (x>=x0)*(alpha+beta*x0+gamma*x0*x0);
plateau =alpha + beta*x0 + gamma*x0*x0;
EONR1=((1.1638/35)-beta)/(2*gamma);
EONR2=((1.1638/50)-beta)/(2*gamma);
EONR3=((1.1638/65)-beta)/(2*gamma);
model biomass ~ normal(y, s2e);
*random blk ~ NORMAL(0, s2blk) SUBJECT=block;
estimate 'X0' X0;
estimate 'plateau' plateau;
estimate "$35" EONR1;
estimate "$50" EONR2;
estimate "$65" EONR3;
predict y out=response;
run;
proc print data=response; run;
data ce;
do i=0 to 224 by 0.5;
do n=41.7536;
yield = (i <n)*(17.6916+0.1702*i -0.00204*i*i) + (i>=n)*(17.6916+0.1702*n -0.00204*n*n);
output;
end;
end;
proc print data=ce; run;
*/
*running it as a linear equation;
proc sort data=perenergy; by block; run;
proc print;
proc nlmixed data=perenergy;
  parms alpha=28 beta=.03 s2e=42;
y=alpha + beta*x;
model biomass ~ normal(y, s2e);
predict y out=response5;
run;
proc print data=response5; run;
data response5; set response5;
residuals=biomass-pred; run;
proc print data=response5; run;
data ce;
do i=0 to 224 by 0.5;
yield = 27.1121+0.04319*i;
output;
end;
proc print data=ce; run;
*/

*Perry 2010 FORAGE SORGHUM;
data perforage; set biom10;
if type ne "Forage" then delete;
if env ne "Perry 2010" then delete;
*if plot=401 then delete; extremely high for 0 N, something not correct;
X=Nrate;
X2=X*X;
run;
proc print data=perforage; run;
proc sort data=perforage; by env hybrid block type Nrate;
proc print data=perforage; run;
proc sort data=perforage; by block; run;
proc print;
proc nlmixed data=perforage;
  parms alpha=14 beta=-.05 gamma=-.0001 /*s2blk=1*/ s2e=9;
x0 = -.5*beta / gamma;
y = (x <x0)*(alpha+beta*x + gamma*x*x) + (x>=x0)*(alpha+beta*x0+gamma*x0*x0)/ + blk */;
plateau =alpha + beta*x0 + gamma*x0*x0;
EONR1a={(.87/35)-beta)/(2*gamma);
EONR2a={(.87/50)-beta)/(2*gamma);
EONR3a={(.87/65)-beta)/(2*gamma);
EONR1b={(1.07/35)-beta)/(2*gamma);
EONR2b={(1.07/50)-beta)/(2*gamma);
EONR3b={(1.07/65)-beta)/(2*gamma);
EONR1c={(1.32/35)-beta)/(2*gamma);
EONR2c={(1.32/50)-beta)/(2*gamma);
EONR3c={(1.32/65)-beta)/(2*gamma);
model biomass ~ normal(y,s2e);
*random blk ~ NORMAL(0,s2blk) SUBJECT=block;
estimate 'X0' X0;
estimate 'plateau' plateau;
estimate "$35a" EONR1a;
estimate "$50a" EONR2a;
estimate "$65a" EONR3a;
estimate "$35b" EONR1b;
estimate "$50b" EONR2b;
estimate "$65b" EONR3b;
estimate "$35c" EONR1c;
estimate "$50c" EONR2c;
estimate "$65c" EONR3c;
predict y out=response6;
run;
proc print data=response6; run;
data response6; set response6;
residuals=biomass-pred; proc print data=response6; run;
data cf;
do j=0 to 224 by 0.5;
do n=214.88;
yield = (j <n)*((14.1348+0.03497*j -0.00008*j*j) +
(n>=n)*((14.1348+0.03497*n -0.00008*n*n));
output;
end;
end;
proc print data=cf; run;
*PLOTTING RESPONSE CURVES FOR Perry 2010;
data allper; merge perenergy perforage; by env hybrid block type Nrate plot biomass X X2;
run; proc print data=allper; run;
proc sort data=allper; by type; run; proc print data=allper; run;
data per; merge allper ce cf; run; proc print data=per; run;
proc sgplot data=per noautolegend;
title "Perry 2010";
yaxis label="Biomass (Mg/ha)" values=(0 to 50 by 10);
xaxis label="N rate (kg/ha)" values=(0 to 225 by 25);
scatter y=biomass x=i/group=type markerattrs=(size=8) name="obs" NOMISSINGGROUP;
series y=yields x=i/lineattrs=(pattern=longdash thickness=2px color=blue) name="E"
legendlabel="Energy";
series y=yields x=j/lineattrs=(pattern=solid thickness=2px color=darkred) name="F"
legendlabel="Forage";
discretelegend "obs" "E" "F"/across=1
   position=topleft location=inside;
run;
*plotting residuals;
data PE10; merge response5 response6; by type;
run; proc print data=PE10; run;
proc sgplot data=PE10 noautolegend;
title "Perry 2010";
yaxis label="Residuals (observed yield- predicted yield)";
xaxis label= "N rate (kg/ha)" values=(0 to 225 by 25);
scatter y=residuals x=x/group=type markerattrs=(size=8) name="obs" NOMISSINGGROUP;
refline 0/axis=y;
run;

*2009 biomass data;
data biom09;
length env$ 18;
length hybrid$ 14;
infile 'C:\Users\maughan2\Documents\My Dropbox\sorghum fertility trial\2009 & 2010 analysis for manuscript 1\sorghum dry biomass yield 2009.csv'
dlm="," firstobs=5;
input env$ block type$ hybrid$ Nrate plot tons;
biomass=tons*2.24;
run; proc print; run;
proc sort data=biom09; by env type hybrid block Nrate; run; proc print;

*Urbana 2009 ENERGY SORGHUM;
data urbenergy; set biom09;
if type ne "Energy" then delete;
X=Nrate; X2=X*X;
run; proc print data=urbenergy; run;
proc sort data=urbenergy; by env hybrid block type Nrate;
proc print data=urbenergy;

*running it as a linear equation;
proc sort data=urbenergy; by block; run; proc print;
proc nlmixed data=urbenergy;
parms alpha=13 beta=.07 s2e=22;
y=alpha + beta*x;
model biomass ~ normal(y, s2e);
predict y out=response7;
run;
proc print data=response7; run;
data response7; set response7;
residuals=biomass-pred; run; proc print data=response7; run;

data ce;
do i=0 to 150 by 0.5;
yield = 12.7240+0.07618*i;
output;
end;
proc print data=ce; run;

*Urbana 2009 FORAGE SORGHUM;
data urbforage; set biom09;
if type ne "Forage" then delete;
X=Nrate; X2=X*X;
run; proc print data=urbforage; run;
proc sort data=urbforage; by env hybrid block type Nrate;
proc print data=urbforage;

*running it as a linear equation;
proc sort data=urbforage; by block; run; proc print;
proc nlmixed data=urbforage;
parms alpha=7 beta=.07 s2e=5;
y=alpha + beta*x;
model biomass ~ normal(y, s2e);
predict y out=response8;
run;
proc print data=response8; run;
data response8; set response8;
residuals=biomass-pred; run; proc print data=response8; run;
data cf;
do i=0 to 150 by 0.5;
yield = 6.8105+0.06752*i;
output;
end;
proc print data=cf; run;

*PLOTTING CURVES FOR Urbana 2009;
data allur;
merge urbenergy urbforage;
by env hybrid block type Nrate plot biomass X X2;
run;
proc print data=allur; run;
proc sort data=allur; by type; run;
proc print data=allur; run;
data ur;
merge allur ce cf;
run;
proc print data=ur; run;
proc sort data=ur; by i j; run;
proc print data=ur; run;
proc sgplot data=ur noautolegend;
title "Urbana 2009";
axis label="Biomass (Mg/ha)" values=(0 to 50 by 10);
axis label="N rate (kg/ha)" values=(0 to 225 by 25);
scatter y=biomass x=i/group=type markerattrs=(size=8) name="obs" NOMISSINGGROUP;
series y=yieldf x=j/lineattrs=(pattern=longdash thickness=2px color=blue) name="E" legendlabel="Energy";
series y=yieldf x=j/lineattrs=(pattern=solid thickness=2px color=darkred) name="F" legendlabel="Forage";
discretelegend "obs" "E" "F"/across=1 position=topleft location=inside;
run;

*plotting residuals;
data UR09; merge response7 response8; by type;
run; proc print data=UR09; run;
proc sgplot data=UR09 noautolegend;
title "Urbana 2009";
axis label="Residuals (observed yield- predicted yield)";
axis label="N rate (kg/ha)" values=(0 to 225 by 25);
scatter y=residuals x=i/group=type markerattrs=(size=8) name="obs" NOMISSINGGROUP;
reline 0/axis=y;
run;

SPAD, leaf TN, and leaf TC-Ch.5, Table 5.2, Table 5.3.
*SPAD, leaf TN, leaf TC;
options ls=150 ps=150 nodate nocenter formdlim="-";
data TN;
length env$ 18;
length date$ 16;
length hybrid$ 14;
length time$ 12;
infile 'C:\Users\maughan2\Documents\My Dropbox\sorghum fertility trial\2009 & 2010 analysis for man. 2\2009 2010 TN TC SPAD.csv' dlm="" firstobs=14;
input env$ date$ doy time$ block sample type$ hybrid$ Nrate plot TN TC SPAD SLA;
drop date sample plot doy;
*if env=Urbana 2009" and doy=232 then delete;
run; proc print; run;
proc sort data=TN; by env time type hybrid block Nrate SLA; run; proc print;
proc sort data=TN; by env time type hybrid Nrate;
proc means data=TN noprint mean std; var TN TC SPAD SLA; by env time type hybrid Nrate; output out=means mean=mean_TN mean_TC mean_SPAD mean_SLA; run; proc print data=means; run;

*URBANA 2009;
data Urb2009; set TN;
if env ne "Urbana 2009" then delete;
if time = "early-summer" then time=1;
if time = "mid-summer" then time=2;
if time = "late-summer" then time=3;
run; proc sort data=Urb2009; by env time type hybrid Nrate; run; proc print data=Urb2009; run;

*SPAD;
ods html;
ods graphics on;
proc glimmix data=Urb2009 plots=residualpanel;
class block type hybrid Nrate time;
model SPAD=type hybrid(type) Nrate type*Nrate Nrate*hybrid(type) time type*time time*hybrid(type) Nrate*time type*Nrate*time Nrate*time*hybrid(type)/dist=normal ddfm=kr;
random block block*type block*hybrid(type) block*Nrate*hybrid(type);
covtest glm/wald;
lsmeans time*hybrid(type)/pdiff;
lsmeans type*hybrid(type)/pdiff;
lsmeans Nrate*type/pdiff;
lsmeans Nrate*pdiff;
estimate "linear N" Nrate -3 1 1 3;
estimate "quad N" Nrate 1 -1 -1 1;
lsmeans time*type*Nrate/pdiff plot=meanplot(sliceby=type*time join ilink);
run;
ods graphics off;
ods html close;

proc corr data=Urb2009;
var SPAD Nrate; run;

data TotalN; set Urb2009;
if time = 1 then delete; *this run for total N is mest up;
run; proc print data=TotalN; run;

proc corr data=TotalN;
var SPAD TN Nrate; run;

*TN;
ods html;
ods graphics on;
proc glimmix data=TotalN plots=residualpanel;
class block type hybrid Nrate time;
model TN=type hybrid(type) Nrate type*Nrate Nrate*hybrid(type) time type*time time*hybrid(type) Nrate*time type*Nrate*time Nrate*time*hybrid(type)/dist=normal ddfm=kr;
random block block*type block*hybrid(type) block*Nrate*hybrid(type);
covtest glm/wald;
lsmeans time*hybrid(type)/pdiff;
lsmeans type*hybrid(type)/pdiff;
lsmeans Nrate*time/pdiff;
lsmeans Nrate*pdiff;
estimate "linear N" Nrate -3 1 1 3;
estimate "quad N" Nrate 1 -1 -1 1;
run;
ods graphics off;
ods html close;

*TC;
ods html;
ods graphics on;
proc glimmix data=TotalN plots=residualpanel;
class block type hybrid Nrate time;
model TC=type hybrid(type) Nrate type*Nrate Nrate*hybrid(type) time type*time time*hybrid(type) Nrate*time type*Nrate*time Nrate*time*hybrid(type)/dist=normal ddfm=kr;
random block block*type block*hybrid(type) block*Nrate*hybrid(type);
covtest glm/wald;
lsmeans time*hybrid(type)/pdiff;
lsmeans time*type/pdiff;
lsmeans Nrate*time/pdiff;
lsmeans Nrate/pdiff;
estimate "linear N" Nrate -3 -1 1 3;
estimate "quad N" Nrate 1 -1 -1 1;
run;
ods graphics off;
ods html close;

*URBANA 2010;
data Urb2010; set TN;
if env ne "Urbana 2010" then delete;
run; proc print data=Urb2010; run;

proc corr data=Urb2010;
var SPAD TN Nrate; run;

*Dixon Springs 2010;
data DS2010; set TN;
if env ne "Dixon Springs 2010" then delete;
run; proc print data=DS2010; run;

proc corr data=DS2010;
var SPAD TN; run;

*Perry 2010;
data PE2010; set TN;
if env ne "Perry 2010" then delete;
run; proc print data=PE2010; run;

proc corr data=PE2010;
var SPAD TN; run;

data data2010; set TN;
if env="Urbana 2009" then delete;
run; proc print data=data2010; run;

*SPAD;
ods html;
ods graphics on;
proc glmix data=data2010 plots=residualpanel;
class env block type hybrid Nrate time;
model spad type hybrid Nrate Nrate*hybrid(time) time type time*hybrid Nrate*time Nrate*time Nrate*hybrid(time)/dist=normal
ddfm=kr;
random env block(env) env*type*block(env) env*hybrid(type) block*hybrid(env type) env*Nrate env*Nrate*hybrid(type) block*hybrid*Nrate(env type)
env*time env*time env*time*hybrid(type) env*Nrate*time env*time*hybrid(type) env*Nrate*time
estime Nrate*time*hybrid(type);
covtest glm/wald;
lsmeans time*hybrid(type)/pdiff;
lsmeans time*type/pdiff;
lsmeans Nrate/pdiff;
estimate "linear N" Nrate -2 -1 0 1 2;
estimate "quad N" Nrate 2 -1 -2 -1 2;
run;
ods html;
ods graphics on;

*TN;
ods html;
ods graphics on;
proc glmix data=data2010 plots=residualpanel;
class env block type hybrid Nrate time;
model TN type hybrid Nrate type*Nrate Nrate*hybrid(type)
time type*time time*hybrid(type) Nrate*time type*Nrate*time Nrate*hybrid(type)/
dist=normal
ddfm=kr;
random env block(env) env*type block*hybrid(env type) env*Nrate
evtype*Nrate*hybrid(type) block*hybrid*Nrate(env type)
env*type*time env*type*hybrid(type) env*hybrid(time) env*Nrate*time
ev*Nrate*type*hybrid(type) env*Nrate*time*hybrid(type) env*Nrate*time*Nrate*time
env*Nrate*time*hybrid(type) env*Nrate*time*Nrate*time
env*Nrate*time*hybrid(type);
covtest glm/wald;
lsmeans time*hybrid(type)/pdiff;
lsmeans time*type/pdiff;
lsmeans Nrate/pdiff;
estimate "linear N" Nrate -2 -1 0 1 2;
estimate "quad N" Nrate 2 -1 -2 -1 2;
run;
ods html;
ods graphics on;
*TC;
ods html;
ods graphics on;
proc glimmix data=data2010 plots=residualpanel;
class env block type hybrid Nrate time;
model TC=type hybrid(type) Nrate type*Nrate Nrate*hybrid(type) time type*time time*hybrid(type) Nrate*time type*Nrate*time Nrate*time*hybrid(type)/
dist=normal
ddfm=kr;
random env block(env) env*type block*hybrid(env type) env*Nrate
evtype*Nrate*hybrid(type) block*hybrid*Nrate(env type)
env*type*time env*type*hybrid(type) env*hybrid(time) env*Nrate*time
ev*Nrate*type*hybrid(type) env*Nrate*time*Nrate*time
env*Nrate*time*hybrid(type);
covtest glm/wald;
lsmeans time*hybrid(type)/pdiff;
lsmeans time*type/pdiff;
lsmeans Nrate/pdiff;
estimate "linear N" Nrate -2 -1 0 1 2;
estimate "quad N" Nrate 2 -1 -2 -1 2;
run;
ods html;
ods graphics on;

*early-summer correlations;
data early; set data2010;
if time="mid-summer" then delete;
run; proc print data=early; run;
proc corr data=early;
var SPAD TN Nrate; run;

*mid-summer correlations;
data mid; set data2010;
if time="early-summer" then delete;
run; proc print data=mid; run;
proc corr data=mid;
var SPAD TN Nrate; run;

Harvest TN and harvest TC-Ch.5, Table 5.4.
options ls=150 ps=150 nodate nocenter formdlim="-";
data harvest;
length env$ 18;
length hybrid$ 14;
infile 'C:\Users\maughan2\Documents\My Dropbox\sorghum fertility trial\2009 & 2010 analysis for man. 2\2009 2010 TN TC harvest samples.csv'
dlm="," firstobs=9;
input env$ block type$ hybrid$ Nrate plot position wt pos wt TN TC;
drop plot position wt pos;
run; proc print; run;
*URBANA 2009:
data Urbana2009; set harvest;
if env ne "Urbana 2009" then delete;
run; proc print data=Urbana2009; run;

*TN:
ods html;
ods graphics on;
proc glimmix data=Urbana2009 plots=residualpanel;
class block type hybrid Nrate;
model TN=type hybrid(type) Nrate type*type Nrate*hybrid(type)/dist=normal ddfm=kr;
random block block*block*hybrid(type);
covtest glm/wald;
lsmeans type*Nrate/pdiff;
lsmeans Nrate/pdiff;
run;
ods graphics off;
ods html close;

*TC:
ods html;
ods graphics on;
proc glimmix data=Urbana2009 plots=residualpanel;
class block type hybrid Nrate;
model TC=type hybrid(type) Nrate type*type Nrate*hybrid(type)/dist=normal ddfm=kr;
random block block*block*hybrid(type);
covtest glm/wald;
lsmeans type*Nrate/pdiff;
lsmeans Nrate/pdiff;
run;
ods graphics off;
ods html close;

*2010:
data envs2010; set harvest;
if env = "Urbana 2009" then delete;
run; proc print data=envs2010; run;

*TN:
ods html;
ods graphics on;
proc glimmix data=envs2010 plots=residualpanel;
class env block type hybrid Nrate;
model TN=type hybrid(type) Nrate type*type Nrate*hybrid(type)/dist=normal ddfm=kr;
random env block(env) env*block(env) env*hybrid(env) block*hybrid(env) env*Nrate env*Nrate*type env*Nrate*hybrid(type);
covtest glm/wald;
lsmeans type*Nrate/pdiff;
lsmeans Nrate/pdiff;
run;
ods graphics off;
ods html close;

*TC:
ods html;
ods graphics on;
proc glimmix data=envs2010 plots=residualpanel;
class env block type hybrid Nrate;
model TC=type hybrid(type) Nrate type*type Nrate*hybrid(type)/dist=normal ddfm=kr;
random env block(env) env*type block(env) env*hybrid(env) block*hybrid(env) env*Nrate env*Nrate*type env*Nrate*hybrid(type);
covtest glm/wald;
lsmeans type*Nrate/pdiff;
lsmeans Nrate/pdiff;
run;
ods graphics off;
ods html close;
CURRICULUM VITAE

Matthew W. Maughan, Ph.D. candidate

Education

University of Illinois Urbana-Champaign
Ph.D. in Crop Sciences, summer 2011 (expected)

University of Illinois Urbana-Champaign
M.S. in Crop Sciences, May 2008

Brigham Young University-Idaho

Work Experience

Research Assistant (while Ph.D. student) Aug. 2008 – present
Department Crop Sciences, University of Illinois Urbana-Champaign
Supervised by Dr. Germán Bollero, Dr. D.K. Lee and Dr. Tom Voigt.
Major research projects:
• Meta-analysis of switchgrass: management and environmental factors that affect biomass yields in the US and southern Canada.
• Field experimentation of Miscanthus x giganteus productivity in Nebraska, Illinois, Kentucky, and New Jersey, and the impacts of nitrogen rate, season of growth, and environmental conditions on morphology, plant growth, and biomass yield.
• Management of biomass sorghum hybrids for biomass feedstock production under different nitrogen rates in four Illinois environments.

Research Assistant (while M.S. student) Aug. 2006 – May 2008
Department Crop Sciences, University of Illinois Urbana-Champaign
Supervised by Dr. Germán Bollero and Dr. Benjamin Tracy.
Replicated farm scale study investigating the impact of an integrated crop-livestock system that includes perennial pastures and winter cover crops on soil physical and biological properties, and corn grain yield.

Teaching Assistant 2007-2010
Supervised by Dr. Germán Bollero and Dr. Donald Bullock.
Teaching assistant for following courses:
3) Regression Analysis (Fall 2009).
Responsibilities for these three courses included:
1) Preparing teaching material used in weekly laboratory sessions where I taught and reviewed lecture material, and provided statistical examples applicable to assigned homework, exams, and quizzes.
2) Taught procedures and coding in Statistical Analysis Software (SAS).
3) Administered and graded scheduled quizzes, graded homework assignments, and helped to grade midterms and final exam.
4) Held weekly office hours, and interacted and taught students through Web CT (Compass).

Farm Hand/Supervisor, Maughan Farms, Inc. 1996-2006
Maughan Farms Inc. is a seed potato, corn, small grain, and hay farm near Fort Benton, MT. This is a family farm operation on which I have worked at different times between 1996 and 2006. Responsibilities and tasks related to this farm business have included:
• Planting and harvesting of seed potatoes, wheat, and corn.
• Fertilizer and chemical application.
• Center pivot, wheel line, and hand line irrigation of crops
• Solid set irrigation of potatoes on corners of center pivots.
• Supervision and participation in potato rogueing crew for disease identification and removal.
• Wheat rogueing, primarily for wild oat and rye.
• Haying, raking, baling, and stacking hay.
• Extensive field and farm equipment operation including tractors, implements, and harvesters.
• Various other jobs and responsibilities included: feeding and tending livestock, and light mechanical work on farm equipment (i.e. oil changes and general maintenance).

Publications, peer reviewed


Manuscripts in preparation or submitted


Invited Presentations


Abstracts at Professional meetings


Maughan, M., F. Miguez, T. Voigt, S. Bonos, J. Murphy, R. Gaussoin, D. Williams, and G. Bollero. 2009. Miscanthus x giganteus growth and survival in IL, IN, KY, NE, and NJ. Pittsburgh, PA. In annual meeting abstracts. ASA-CSSA-SSSA, Madison, WI.


Awards/Fellowships

- 2009-2010 Lawrence E. Schrader and Elfriede Massier Plant Physiology Fellowship, Dept. of Crop Sciences, Univ. of Illinois.
- 2008-2009 University Fellowship, Block Grant, Univ. of Illinois.
- Recognized at the Univ. of Illinois on the “Incomplete List of Teachers Ranked as Excellent by their Students” during 4 semesters (Fall 2007, Spring 2009, Fall 2009, Spring 2010).
- 2006 Rutger-Harper Walker Agriculture Leadership Award, BYU-Idaho.
- 2005 Outstanding Agricultural Science Award & Grant, BYU-Idaho.
- Eagle Scout Award. 2000.

Leadership/Service

- Crop Science Graduate Organization, Vice President (2009-2010), and Treasurer (2007-2009), Dept. of Crop Sciences, Univ. of Illinois.

International Experience & Languages

- Citizen Ambassador (October 9-19, 2009). Participated in an Agronomy Delegation Trip to the People’s Republic of China representing the Agronomy Society of America to participate in bicultural exchanges and discussions with Chinese Agronomists and Ag Professionals regarding various aspects of Chinese agriculture including soils, crop geography, and agricultural production practices.
- Lived and served in Brazil for 2 years (2001-2003) as a volunteer missionary, becoming immersed in Brazilian culture and the Portuguese language.
- Bilingual-Portuguese. Speaking & Conversation – advanced level. Reading & Writing – intermediate level.
Computer and statistical software skills

Microsoft office (Word, Excel, PowerPoint)
Statistical Analysis Software (SAS)
R-software for statistical computing
SigmaPlot-data analysis and graphing software

Professional & Honor Societies

American Society of Agronomy (2007 - present)
Crop Science Society of America (2007 - present)
Soil Science Society of America (2007 - present)
Gamma Sigma Delta (2008-present)
Phi Theta Kappa Society (2005-present)

Certificates

Completed a Certificate in Business Administration
Spring 2011 program (http://www.business.illinois.edu/cib/) at the Univ. of Illinois Urbana-Champaign in which I strengthened my understanding and abilities in the functional areas of business.

References

Germán Bollero. Department Head and Professor of Biometry and Cropping Systems. Dept. of Crop Sciences. Univ. of Illinois. Mail: W-201 Turner Hall, 1102 S. Goodwin Ave, Urbana, IL 61801. E-mail: gbollero@illinois.edu. Phone: (217) 333-9475.

DoKyoung "D.K." Lee. Assistant Professor of Biomass and Bioenergy Crop Production. Dept. of Crop Sciences. Univ. of Illinois. Mail: S-320 Turner Hall, 1102 S. Goodwin Ave, Urbana, IL 61801. E-mail: leedk@illinois.edu. Phone: (217) 333-7736.

Thomas B. Voigt. Associate Professor and Extension Turfgrass Specialist, Dept. of Crop Sciences. Univ. of Illinois. Mail S-416 Turner Hall, 1102 S. Goodwin Ave, Urbana, IL 61801. E-mail: tvoigt@illinois.edu. Phone: (217) 333-7847.