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Evaluating Economic Impacts of Switchgrass Harvest Time

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ABSTRACT

This thesis deals with cost of production for cellulosic energy crops of switchgrass, miscanthus, and energy sorghum. The first chapter explains the rationale for development of decision support software called Energy Crop Analysis & Planning (ENCAP) and Switchgrass Harvest Date, Yield, Nutrient Removal Estimator (SHYNE). The second chapter examines harvest date implications on yield, nutrient removal, opportunity cost of modified sale dates, and post-harvest storage losses. This harvest date analysis leads to a profit maximizing harvest date from the perspective of the producer. While this harvest date may be optimal for the producer, biorefineries may be interested in sourcing switchgrass earlier and later than that profit-maximizing harvest date. Hence price premia that need to be paid to the producer for alternative harvest dates are calculated. The final chapter provides a brief summary, limitations and offers area for future research.

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Ultimately, I would like to thank all of the faculty and the staff in the Agricultural Economics Department at the University of Arkansas for their commitment to this program and its students.

DEDICATION

This thesis is dedicated to my lovely wife Erica and to my parents. Without their support over the past years, none of this would be possible. I would also like to dedicate this to the rest of my family who have shown me nothing but love and support while in graduate school.

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Chapter I

I. Introduction

Since the automobile industry began an era ago, oil has had a near monopoly as an energy source for transportation. Since the beginning of this era, global warming has slowly become a large concern for the United States due to its potential effects on agriculture and human health. As the automobile era proceeded, automobile emissions in the form of carbon dioxide (CO_2) have decreased per vehicle, but with an increase of automobiles on the road as well as an increase in average mileage traveled, CO_2 emissions have increased in aggregate (USDT, 2013).

In 1970, President Richard Nixon developed the Environmental Protection Agency (EPA) to develop regulations to improve air quality, protect the natural environment and take action on climate change. One of the major objectives of the EPA is the focus on the development of the use of alternative fuels in automobiles to reduce CO_2 emissions. While a major act that has recently been approved has come from the Department of Energy, the Energy Independence and Security Act of 2007 or EISA 2007, the EPA is responsible for implementing regulations and requirements stated within the bill.

Aims of EISA 2007 are to improve vehicle fuel economy and reduce U.S. dependence on domestic and foreign petroleum by increasing the production of clean renewable fuels (Rahall, 2007). Therefore, EISA 2007 includes provisions to increase the supply of renewable alternative fuel by setting a mandatory Renewable Fuel Standard (RFS) requiring a minimum of 36 billion gallons of renewable transportation fuels sold annually by 2022. Allocation of fuel sources require that 21 billion gallons be sourced from advanced biofuel, renewable fuels other ethanol derived from corn starch. To meet this goal, EISA 2007 includes grant programs to encourage the development of cellulosic biofuels (renewable fuels derived from cellulose, hemicellulose or lignin), plug-in hybrid electric vehicles, and other emerging electric technologies. The goal of this legislation in part is a projected greenhouse gas emissions reduction of 9% from 2020 to 2030 (EISA 2007).

With the requirement of such a large amount of renewable fuel in effect, the need to find a feedstock for this alternative fuel source is a concern. Corn (*Zea mays* L.) has been used since the 1970’s as a source of ethanol, but over the last two decades corn prices have risen drastically and, in part, due to growing demand for corn used for ethanol. Given increasing corn prices and resultant corn ethanol prices, alternative renewable feedstock sources to corn are thus showing promise to become financially feasible. Fuels from these alternative sources are thus termed second generation biofuels. These second generation biofuels are typically sourced from biomass high in cellulose and have become the focus of energy and food policy discussion. The desire for these biofuel source discussions are to i) decrease the dependence on low cost oil reserves, ii) recognize the concern of global warming and other environmental impacts of modified production and consumption, and iii) find a renewable energy source with lesser impact on the food, feed and fiber supply than the current practice of converting corn to ethanol. One such way to meet these needs is by the use of switchgrass (*Panicum virgatum* L.).

Literature Review

Switchgrass as a Biomass

Switchgrass is a warm season perennial grass indigenous to the North American tall-grass prairie but is widely distributed throughout the North America. Traditionally used as a livestock forage, switchgrass has grown in popularity for its use as a renewable fuel source because of its high biomass production and rapid perennial growth. The crop also has an extended harvest window starting in July, prior to yield maximum at high nutrient concentration in the harvested material all the way to March of the following year at low nutrient concentration at lower yields but also lower moisture content. In the short term, livestock and crop producers need information on how to integrate and manage switchgrass in their current production systems. Important to the economical production of switchgrass is defining how crop harvest management practices affect nutrient removal and biomass supply.

Studies conducted to determine an optimal harvest scheme (single or double harvest periods) showed that a single harvest in October removed less nitrogen than was applied at the beginning of the growing season in March (Kering et al. 2012, Reynolds et al. 2012, Guretzky et al. 2011). Further, harvests that occurred in July and October for the double harvest method removed more nutrients as expected. Other studies have focused on the amount of nitrogen to apply to attain a maximum yield. Lemus et al. (2008) and Kering et al. (2009) determined optimal nitrogen application rates of 50 to 100 pounds per acre to attain a maximum yield without over or under application for a harvest after first onset of frost.

While harvesting scheme and nitrogen application rate play a role in costs for a producer, one must consider the effects of storage loss. Larson et al. (2010) showed that conventional covered round bales have a total dry matter loss of 9% compared to a 13% loss after 360 days when uncovered. Mooney et al. (2012) and Sanderson, Egg and Wiselogel (1997) analyzed effects of storage losses on switchgrass profitability. Mooney et al. (2012), for example, showed that the breakeven price for the production of switchgrass decreases with increasing post-harvest storage as in-field losses are greater than post-harvest storage losses.

This suggests that an analysis of partial returns to switchgrass production is linked to harvest date as the yield harvested as well as nutrient concentrations in the harvested biomass change over the course of a growing season and into the following year. Producer profit thus changes with harvest date as a function of i) nutrient removal, ii) initial nitrogen application for yield potential, and iii) differential in-field vs. post-harvest storage losses. These factors should be considered by the producer when looking for an optimal harvest date to maximize profits.

Switchgrass Decision Tool

With increases in fuel and fertilizer prices, the potential for switchgrass production as an alternative fuel source has garnered increasing attention by producers and policy makers. Nonetheless, optimal harvest date and nutrient application rate decisions are important and the subject of analysis in this thesis. Further, the development of a decision aid that would allow producers to make more informed decisions by extending research findings is deemed important. While switchgrass production budgets are not hard to come by, most of the budgets that can be used by producers are shown as itemized budgets that are non-interactive – that is the user can modify the budgets only manually to adjust to their operations' conditions. An example of such a budget is the Iowa State University (ISU) Extension Service budget at http://www.extension.iastate.edu/agdm/cdcostsreturns.html. This particular budget lists several assumptions about the switchgrass stand and the land that it requires. The ISU budget assumes a yield of four tons per acre and that the stand life is eleven years. Field preparation is assumed with phosphorous and potassium already added as well as an application of lime before switchgrass is established. Other assumptions include storage of switchgrass along the side of the field and harvesting of the forage in the form of large square bales. While this budget is helpful, and gives producers a good foundation to improve upon, there are certainly many of the aforementioned assumptions that can, and will, be altered by the producer i.e. round baling instead of square baling as a way of harvest or multiple staging areas of the baled switchgrass. This method of multiple staging areas could lead to an increase of storage loss as bales can be delayed multiple days or weeks before being transported to a refinery for conversion.

The budget developed by The University of Tennessee Extension Service located at http://economics.ag.utk.edu/budgets/2009/Switchgrass2009.pdf, is similar to ISU's. It allows for a single type of harvest equipment and in this case the large round bale. Differences between the two budgets highlight greater herbicide use in Tennessee while the ISU budget accounts for the removal rates of phosphorous and potassium by charging for their replacement.

Another budget for switchgrass producers is the *Switchgrass vs. Hay Comparative Budgets* (2010) developed by the University of Kentucky and located at http://www2.ca.uky.edu/agecon/index.php?p=150. This computer based program is a tool for producers as it lets the producer input their own values for input prices and amount of fertilizers and pesticides to apply (Gregory, 2010). This particular budget is well developed but lacks the ability of the producer to choose different implements for production.

Objectives

To address both the tradeoff between harvest date and expected nutrient removal as well as enhanced user friendliness of budgeting software, this thesis provides a user manual of a newly developed spreadsheet based decision support software as well as a manuscript on optimal harvest date as affected by nutrient cost and yield. The Energy Crop Analysis and Planning (ENCAP) tool was developed to help producers make informed decisions and better understand cost of production from their operation. ENCAP allows users the ability to enter prices for various inputs for the production of biomass. While users have the ability to enter input prices, users also have the ability to select implements and tractors that most accurately represent their farming operation. This option of selecting implements and tractors is one characteristic that separates ENCAP from the other available budgets.

Another major way this program is different from other budgets is the inclusion of three different energy crop budgets, switchgrass, miscanthus (*Miscanthus* x *giganteus)*, and energy sorghum (*Sorghum bicolor*) to allow for ease of comparison in one package. While a user can conveniently compare across energy crop production methods, the program also allows users to select different harvest methods for each crop. The user has the option of choosing a round baler and tractor or a forage harvester (or silage chopper) with a single harvest annually. However, in the case of switchgrass, the user can select a double harvest system to compare costs to that of a single harvest. The user can also model the impact of used vs. new equipment and analyze the effect of using standard annual use hours vs. crop specific annual use.

Further, the user of ENCAP can determine optimal harvest date by using the Switchgrass Harvest Date, Yield, Nutrient Removal Estimator (SHYNE) to determine how much fertilizer needs to be added for each nutrient removed as this production input varies with the timing of harvest as harvest time in turn affects yield given crop maturity and plant senescence when nutrients relocate to the root system at the onset of plant dormancy for overwintering. In this program, the user can compare up to three different harvest dates. The first option the user sees is a calculated optimal harvest date based on switchgrass price and fertilizer cost. A second option allows the user to choose a harvest date using fertilizer recommendations based on optimal harvest date which leads to lower returns. The third option varies fertilizer use and switchgrass price such that producer profitability is the same as that under the first option but at a user specified date other than the profit maximizing choice in option one. The third option thus provides information for biorefineries about how much of a price premium they need to pay for a producer to modify harvest date.

ENCAP and SHYNE and their user manuals are two different programs soon to be available at http://agribus.uark.edu/2910.php. They should provide reasonably accurate cost estimates for switchgrass production for the producer under varying fertilizer and switchgrass price conditions as well as potential yield modified harvest dates. This sets switchgrass apart from the other two production budgets as more information for switchgrass production was available for this thesis.

With an understanding of the operation's cost structure and yield potential, the user has the ability to make better business decisions when considering changing harvest methods, harvest date or fertilizer application rates. It also provides the producer with information potentially required by lenders. As a result, producers can utilize ENCAP as an informative tool to evaluate different production methods and their impact on costs prior to committing to them.

The objectives of this work are thus to: i) explain the use and characteristics of ENCAP; ii) demonstrate the use of SHYNE within ENCAP; iii) determine a response in initial nutrient application and expected yield in conjunction with iv) N, P, and K removal rates in the harvested biomass as related to timing of harvest in switchgrass; v) determine harvested yield levels as a function of timing of harvest; and vi) estimate the switchgrass price premium needed to modify harvest date away from the profit maximizing time. These price premia could be used in later works to determine the profitability of in-field storage of standing switchgrass or earlier than profit maximizing harvest from the perspective the biorefinery. For example, biorefineries may be interested in extending the operating window of their hauling equipment or ascertaining different biomass nutrient concentrations caused by altered harvest dates.

Components of Thesis

This thesis is broken into several chapters. The first chapter serves as an introduction to the thesis. The second chapter is a paper which was submitted to the **Journal of Agricultural and Applied Economics** entitled: Switchgrass Harvest Time Effects on Nutrient Use and Yield: An Economic Analysis. This paper estimates profit-maximizing harvest dates by analyzing harvest date driven implications of yield, nutrient removal and the opportunity cost of delayed sales receipts as well as post-harvest storage losses avoided. In addition, producer profits are analyzed to determine price premia for switchgrass that would need to be offered to the producer to advance or delay harvest from the aforementioned profit maximizing harvest date. Chapter three provides conclusions about the use of the Switchgrass Harvest Date, Yield, Nutrient Removal Estimator and its interaction with ENCAP. It also discusses potential limitations of the tool and provides areas of interest for future research. The software and associated user manual will be made available to end-users in the near future and was a component of the research described in Chapter 2.

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Chapter II

Switchgrass Harvest Time Effects on Nutrient Use and Yield:
An Economic Analysis

By

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Alexandre Rocateli, Amanda Ashworth, and Rodney Farris

II. Switchgrass Harvest Time Effects on Nutrient Use and Yield: An Economic Analysis

Abstract

Switchgrass is a potential cellulosic feedstock for conversion to biofuel. This paper analyzes the economic relationship between day of harvest, nitrogen applied, nutrient removal, and yield as they vary with respect to input and output prices. Economic sensitivity analysis suggests that higher biomass prices lead to earlier harvest while a change in commercial fertilizer price only affects the amount of initial fertilizer applied. Optimal harvest time occurs beyond time of maximum yield suggesting that nutrient removal in the biomass is an important economic consideration for profit maximization. Price premia required to advance or delay harvest compared to the profit maximizing harvest date are calculated to assist feedstock buyers and producers.

Keywords: Harvest Date, Nutrient Use, Switchgrass

JEL Classifications: Q15, Q16, Q42

Introduction

Second generation biofuels, generated from dedicated energy crops or waste materials that are typically high in cellulose, have increasingly become a focus of energy and food policy discussion. The intent of these discussions are to 1) decrease the dependence on low cost oil reserves, 2) recognize the concern of global warming and other environmental impacts of modified production and consumption, and 3) find a renewable energy source with lesser disruption of the food supply than the current practice of converting corn (*Zea mays* L.) to ethanol. Hence the Energy Independence and Security Act of 2007 (EISA) mandated that 21 of the 36 billion gallons of renewable fuel be produced from sources other than corn by 2022. The United States thus needs substantial amounts of cellulosic biomass per year from various areas of agriculture to meet these targets.

One way to help meet EISA's goals is by the use of switchgrass (*Panicum virgatum* L.). Switchgrass is a warm season perennial grass indigenous to the North American tallgrass prairie but is widely distributed throughout the continent. Traditionally used as a livestock forage, switchgrass has strong potential as a cellulosic biomass producer because of its high biomass production and perennial growth habit, broad insect and disease resistance, high yields of cellulose, low fertilizer needs, drought tolerance, ability to grow in poor soils and efficient water use (Rinehart, 2006). When compared to other sources of renewable fuel such as ethanol from corn grain or sugarcane (*Saccharum* spp.), switchgrass is expected to lead to lesser greenhouse gas (GHG) emissions per ton of biomass harvested given its greater nitrogen use efficiency, high yield (~ 5 ton/acre at 75-90 gal of fuel per ton), lesser tillage given perennial growth and lesser chemical use for weed control at the cost of no feed production for the case of corn. As a renewable fuel source switchgrass use would hence not only displace fossil fuel but also reduce GHG emissions. Expectations are that growth, harvesting, production and burning of switchgrass derived biofuel would actually remove GHG from the atmosphere whereas use of conventional petroleum based fuels adds to GHG emissions. Also, switchgrass based biofuel compares favorably to renewable fuels sourced from corn (GHG reduction of 21%) or sugarcane (GHG reduction of 61%) using lower quality land resources that are not suitable for corn or sugarcane (USEPA, 2010).

Given these benefits, livestock and crop producers need information on how to economically integrate and manage switchgrass into farming operations. An important consideration, for both producers and biorefinery buyers is how harvest management decisions affect nutrient removal and yield, as those two components would affect cost of production. Guretzky et al. (2011), Kering et al. (2009), and Haque, Taliaferro, and Epplin (2009) conducted studies based on harvest rates of switchgrass at different fertilizer application rates. They compared a double harvest system (harvest at 'boot' stage in mid June to early July and after onset of first frost in mid-to-late October) to a single harvest system (harvest after onset of first frost). They showed that for all nitrogen (N) application rates, the double harvest system removed more nitrogen than was applied. Their determination for harvest management suggested that a single harvest should occur after the first frost when the forage is used for biofuel purposes. This single harvest method produces smaller total yields than observed for the double harvest method, but also reduces the amount of nutrients removed in the harvested biomass.

This study was conducted to determine optimal time of a single harvest in the fall by: i) analyzing economic tradeoffs between initial nutrient application and expected yield response; ii) nitrogen, phosphorus (P), and potassium (K) removal rates in the harvested biomass as related to timing of harvest; and iii) harvested yield levels as a function of timing of harvest. While the initial fertilizer levels shift the yield curve -- the relationship between harvested yield and the date of harvest -- up or down, nutrient removal changes along with yield as the producer changes the harvest date. Biomass yields of switchgrass peak during the period of full panicle emergence to the onset of plant senescence (Parrish and Fike, 2005), which for the cultivar 'Alamo' in the southern U.S occurs from August to October (Ashworth, 2010; Sanderson et al., 1996) However, these early harvest dates are also at relatively high nutrient concentrations, which are undesirable both from a cost of production perspective as nutrients need to be replaced, and from a biomass to fuel conversion perspective as high nutrient loads negatively affect mainly thermal conversion processes (Johnson and Gresham, 2013; Adler et al., 2006). First frost signals the onset of switchgrass senescence, when the plant goes dormant and mobile nutrients are translocated to plant roots and crown (Parrish and Fike, 2005). Hence delaying harvest dates past yield maximum results in lower biomass yield along with lesser nutrient removal (Adler et al., 2006; Parrish and Fike, 2005).

The comparison of delayed harvest or storage as a standing crop vs. earlier harvest with post-harvest storage losses thus poses a challenging problem for growers and end users of switchgrass. Mooney et al. (2012) and Sanderson, Egg and Wiselogel (1997) analyzed effects of storage losses on switchgrass profitability. Mooney et al., for example, showed that the breakeven price for the production of switchgrass decreases with increasing post-harvest storage as in-field losses are greater than post-harvest storage losses. In summary, the tradeoff between yield, initial fertilizer application levels and nutrient removal as driven by the harvest date, at varying input and output price levels, is the assessment objective of this paper. Also, price premia required to advance or delay harvest date compared to the profit maximizing date are calculated to provide guidelines for biorefinery buyers about economic outcomes associated with sourcing feedstock at different times in the year. Nutrient concentrations in the harvested biomass and biomass yield levels also impact biorefinery returns via their impact on processing costs and transport distances, respectively.

Data

Production data on switchgrass from two different trials in northwest Arkansas and one trial in northeast Oklahoma were collected to compare N, P, and K uptake (removal) and dry matter yield by harvest date under varying commercial fertilizer and poultry litter application rates. These studies were conducted from 2009 to 2011 on switchgrass stands that were planted no later than 2008. The production sites were located at the University of Arkansas Research and Extension Center in Fayetteville, AR (36° 5’ 42” N, 94° 10’ 25” W) and at Haskell, OK (35 49’ 12” N, 95 40’ 37” W). Harvest date and N rate trials at Fayetteville, AR were conducted on eroded Pickwick gravelly loam at 3-8% slope. Litter application trials conducted at Fayetteville, AR were on Captina silt loam at 1-3% slope with silt-loam texture in the top 20 inches and clay fragipan (root-restrictive layer) at 20-24 inches. Litter applications for Haskell, OK were conducted on Taloka silt loam at 1-3% slope with silt-loam texture in the top 20 inches and no root restrictive layer down to 80 inches. Plot locations had the following variables tracked throughout production: i) date of stand establishment; ii) amount of N applied in the form of commercial fertilizer or poultry litter in pounds per acre; iii) amount of N, P, and K removed in biomass harvested in pounds per acre; and iv) dry matter yield in tons per acre across several harvest dates in a crop year. Collection of these variables commenced May 1, 2009 and concluded December 15, 2011.

Plots were arranged in randomized complete block designs with harvest date, N application rate, or litter application rate as the main effect. Yield and nutrient removal data for a particular harvest date were reported as the average of 3 to 6 replicates depending on experiment. Established switchgrass stands occupied an area of 0.8 acres. Row and within row spacing ranged from less than 6 to 24 inches and less than 6 inches, respectively. Trial sites received urea fertilizer in mid-to-late April each year at rates of 0, 45, 54, 89 and 134 lbs of N per acre and poultry litter application rates that delivered 0, 100 and 200 lbs of total N per acre (average of 0, 1.2, and 2.4 tons of litter per acre). Annual harvests over the 3 year period occurred in center rows of plots (3 to 4 feet wide, depending on the row spacing) to avoid potential border effects. A summary of harvest dates and fertilizer application rates by location and year is provided in Table 1. Table 2 highlights the number of observations for each independent variable used in this study. Since data from three different experiments with three different experimental designs were used, the statistical analysis of the data thus represents a meta analysis in attempt to provide economic insight about a range of field observations that are a function of both changes in nutrient application levels and type of fertilizer applied as well as harvest date for locations that have similar weather patterns as shown in Table 3.

Methods

Yield and Nutrient Removal Estimation

To determine the effects of location, year of production, date of harvest and fertilizer application on yield (Y in dry tons/acre), multiple linear regression in EViews® v6 (Lilien et al., 2007) was used as follows:

$$(1) \qquad Y = \alpha_0 + \alpha_1\, LOC + \alpha_2 YEAR10 + \alpha_3 YEAR11 + \alpha_4 D + \alpha_5 D^2 + \alpha_6 N + \alpha_7 N^2 + + \alpha_8 L + \varepsilon$$

where α_0 is the constant term, *LOC* is a location dummy variable for Haskell, OK (*LOC* = 1 and 0 otherwise), *YEAR10* and *YEAR11* are year of harvest dummy variables (*YEAR10* = 1 for 2010 and 0 otherwise, *YEAR11* = 1 for 2011 and 0 otherwise), day harvested past end of winter dormancy or March 1 (*D*), commercial nitrogen (*N*) and poultry litter (*L*) application rates in lbs of N/acre and ε is an error term. The base production year and location were 2009 and Fayetteville, AR, respectively. In addition to the quadratic functional form shown here, square root and linear functional forms were tested for goodness of fit on the basis of adjusted R^2 and number of individual t-statistics that added explanatory power (| t –stat | >1). Once the functional form was selected, heteroskedasticity was evaluated using White's test and corrected by using the White's heteroskedasticity consistent covariance standard error and *p*-value option in EViews 6. Harvest days analyzed ranged from 61 days past March 1 (May 1) to 354 days past the beginning of new growth (February 18 of the following year) using 71 observations. In essence, equation 1 describes the yield curve with intercept shifters of location and year along with yield responses to *N* or *L* applications.

Nutrient removal rates were estimated to determine the cost of nutrient replacement for partial profit (π) calculations. Three equations for nitrogen (*NR*), phosphorus (*PR*), and potassium (*KR*) removal rates were regressed utilizing similar variables and methods as described above as follows:

$$(2) \qquad NR = \beta_0 + \beta_1 LOC + \beta_2 YEAR10 + \beta_3 YEAR11 + \beta_4 D + \beta_5 Y + \theta$$

$$(3) \qquad PR = \gamma_0 + \gamma_1 LOC + \gamma_2 YEAR10 + \gamma_3 YEAR11 + \gamma_4 D + \gamma_5 Y + \lambda$$

$$(4) \qquad KR = \delta_0 + \delta_1 LOC + \delta_2 YEAR10 + \delta_3 YEAR11 + \delta_4 D + \delta_5 Y + \mu$$

where β_0, γ_0, and δ_0 are the constant terms, β_5, γ_5, and δ_5 are the Y coefficients, and θ, λ, and μ are the error terms for *NR*, *PR*, and *KR*, respectively. Data analyzed were limited to 38 observations for each nutrient removed as fewer observations were available and targeted at seasonally later harvest dates when nutrient translocation to the roots would occur. Table 4 shows the prices per pound of nutrient applied with the assumption that producers would likely apply twice per year. Once in the spring for nitrogen application when timely application of plant available nitrogen is critical for achieving yield potential and another time for replacing P and K on the basis of soil test. Note that the amount of fertilizer applied per acre would not affect the applied price as the trip across the field is considered a sunk cost. Further, the producer limits litter applications to meet but not exceed *PR* to avoid excess nutrient loadings of P that are an environmental problem in the production area analyzed (Delaune et al., 2004).

Profit Maximizing Harvest Date and Initial Nitrogen Application

Optimal day of harvest (D^*) and initial amount of nitrogen applied (N^*) were determined from Eqs. 1 to 4. Differentiating the yield function with respect to N and multiplying by the switchgrass price (s) yielded the marginal value of switchgrass from an extra pound of N applied and was set equal to the cost of N (n) to determine the optimal commercial N application rate (N^*). Given the linear yield response to L, or the amount of litter applied which contains N, P and K (3-3-3), economically optimal litter application per acre is thus either i) zero if the cost of P applied sourced from litter exceeds that of commercial fertilizer; or ii) restricted to the amount of P that needs to be replaced on the basis of harvest-date driven *PR* to avoid negative environmental impacts.

The optimal harvest date was determined by setting the change in switchgrass value per harvest day equal to the cost of daily interest foregone with delayed sale (*i*), daily, post- harvest storage losses avoided with delayed harvest (*c*) as well as daily changes in nutrient removal as a function of both yield and harvest date. Larson et al. (2010) determined that round bales have a total dry matter loss of 9% while covered compared to 13% loss after 360 days when uncovered. For this study, post-harvest storage losses are based on a 6 month loss of 10%. This value is thus relatively high compared to the literature but it is stipulated that most storage losses would occur early on. Post-harvest storage losses affect optimal harvest date in the sense that high post-harvest loss rates would make harvest delays more attractive as in-field losses may be lower than post-harvest storage losses. Somewhat complicating the issue, however, is the question of who bears the cost of those losses. In this paper the producer considers the potential implications of these costs relative to the yield maximizing harvest date whereas the biorefinery is assumed to bear the cost of losses beyond harvest date. Further discussion surrounding ramifications of changing the post-harvest storage loss rate is presented in the results section.

Optimal fertilizer application in the spring is separated in time from nutrient removal rates in the harvested material, and the decision maker would not apply different amounts of N fertilizer to manage nutrient removal but only to shift the yield curve. This holds if no statistically significant P and K yield responses are observed (Ashworth, 2010). That is, increasing N application does not imply attendant, increased requirement of P and K in the spring as P and K are not yield drivers and their application is not as time-sensitive as N application. Hence, for urea applications containing N only, the cost of P and K removed (Eqs. 3 and 4) is based on nutrient removal rates as a function of harvest date, whereas appropriate N application is determined by estimated yield response (Eq. 1). For litter applications (containing all three nutrients), economically optimal application is a function of yield response and limited by environmental restrictions as discussed above. Hence, first order conditions for urea and day of harvest using Equations 1 to 4 are:

(5) $(\alpha_6 + 2\alpha_7 N)\, s = n$

(6) $(\alpha_4 + 2\alpha_5 D)\,(s - \gamma_5 p - \delta_5 k) = i\, s\, Y_{max} - c\, s\, Y_{max} + \gamma_4 p + \delta_4 k$ when applying urea, and

(7) $(\alpha_4 + 2\alpha_5 D)\,(s - \gamma_5 p_L - \delta_5 k) = i\, s\, Y_{max} - c\, s\, Y_{max} + \gamma_4 p_L + \delta_4 k$ when applying litter and urea, where *p* and *k* are the commercial fertilizer prices per pound of P and K, respectively, using variable and coefficient descriptions as presented above. In equation 7, p_L represents the cost per pound of phosphate from litter net of a credit for N and K based on their respective commercial fertilizer prices as well as relative N response on yield between litter and urea as follows:

(8) $p_L = (\, l - (\mathrm{N_{conc}}\, N_{eff}\, n + \mathrm{K_{conc}}\, k)) / \mathrm{P_{conc}}$

where *l* is the litter cost per lb, N_{eff} is the ratio of *L* yield response from litter (α_8) divided by *N* yield response from urea ($\alpha_6 + 2\alpha_7 N$) as per eq. 1, $\mathrm{N_{conc}}$, 0.03, is the fraction of N in a pound of litter, $\mathrm{K_{conc}}$, 0.015, is the fraction of K in a pound of litter and $\mathrm{P_{conc}}$, 0.006, is the fraction of P in a pound of litter.

The first order condition for equation 5 thus sets the benefit of extra nutrient use equal to its cost. We also set the value of yield changes with alternative harvest dates ($\partial Y/\partial D$) ($s - \partial PR/\partial Y\, p - \partial KR/\partial Y\, k$) or the daily marginal revenue net of yield driven changes in nutrient removal equal to attendant changes in cost due to daily opportunity cost associated with delayed cash receipt net of savings associated with avoided post-harvest storage losses ($- c\, s\, Y_{max}$) and daily nutrient removal changes ($\partial PR/\partial D\, p + \partial KR/\partial D\, k$ -- both γ_4 and δ_4 are expected to have negative coefficients). It is stipulated here that most producers would choose maximum yield, $Y_{max,}$ as a first rule of thumb for harvest time and therefore post-harvest storage loss and opportunity cost of delayed cash receipts are a function of Y_{max} calculated at the yield maximizing harvest date or $D_{max} = \alpha_4/(-2\alpha_5)$ where $\partial Y/\partial D = 0$ (Debertin, 1986).

Solving the above first order condition for N^* gives the profit maximizing fertilizer application rate for urea:

(9) $N^* = (n - \alpha_6 s) / (2\alpha_7 s)$

Profit maximizing litter application, on the other hand, is a function of phosphate removed in the harvested biomass as discussed above or:

(10) $L^* = \widehat{PR} / 12$ if $p_L < p$

$L^* = 0$ if $p_L \geq p$

as litter contains 12 lbs of P per ton of litter. The profit maximizing harvest day (D^*) occurs when solving for D in Eqs. 6 and 7 and leads to:

(11) $D^* = (\mathrm{w} - \alpha_4 \mathrm{x}) / 2\alpha_5 \mathrm{x}$

where $\mathrm{w} = (i\text{-}c)\, s\, Y_{max} + \gamma_4 p + \delta_4 k$ or the marginal cost of harvest date changes as driven by daily post-harvest storage loss savings and opportunity cost as well as daily change in nutrients removed and $\mathrm{x} = s - \gamma_5 p - \delta_5 k$ or the marginal cost of yield changes with harvest date changes as a function of switchgrass price and the yield effect on nutrients removed. In eq. 11, the price of p depends on the litter cost so the cheapest source of P is used. Note that at the fertilizer prices shown in Table 4, $p_L < p$ when litter is available for \$45.20 or less.

In summary, optimal harvest date is independent of urea price but does depend on daily opportunity cost (i) and post-harvest storage loss savings (c) as well as nutrient removal of P and K.

With the above determined D^*, N^* and L^*, the partial profit (π) equation is:

(12) $\pi^* = Y^* s - (D^* - D_{max})\,(i - c)\, s\, Y_{max} - N^* n - \widehat{PR}\, p_L - \widehat{KR}\, k$

where Y^* is the profit maximizing, estimated yield on harvest day D^* using N^* and L^*, while $\widehat{PR}$ and $\widehat{KR}$ are estimated nutrient removal as a function of Y^* and D^*. Note further that L^* takes care of PR but also supplies N and K credits toward N and K fertilizer cost. We thus report N_L and K_L in the results tables as long as $p_L < p$. While L^* and l are not in the equation directly, p_L takes the litter cost into consideration. So both N^* and $\widehat{KR}$ are nutrient totals applied and removed with some of those nutrients supplied by litter. Finally, we present sensitivity analyses with respect to changes in s, n, k, l and c on D^* and π^* and rank their relative importance using elasticities.

Price Premia for Non-optimal Harvest Dates

Modifying the harvest date in Eq. 12 allows for calculation of price premia needed at newly estimated Y_a by calculating the switchgrass price (s_a) needed to make partial returns equal between D^* and a modified harvest date (D_a) as follows:

(13) $s_a = (\pi^* + N_a\, n + \widehat{PR}_a\, p_L + \widehat{KR}_a\, k\,) / (Y_a - (D_a - D_{max})\,(i - c)\, Y_{opp})$

where Y_a is the yield estimate as a function of D_a, N_a and L_a while N_a and L_a are the profit maximizing urea and litter application levels using s_a as opposed to s, respectively. The $\widehat{PR}_a$ and $\widehat{KR}_a$ are estimates of nutrient replacement using Y_a and D_a.. Finally, Y_{opp} is used to determine storage losses and opportunity cost foregone at harvest dates other than D_{max}. If the chosen day of harvest, D_a, is less than D_{max}, then Y_{opp} is Y_a. However, if D_a is greater than D_{max}, Y_{opp} is Y_{max}. Graphically, this is depicted in Figure 1. We solve for the price the producer needs to receive for switchgrass so his or her profitability is not affected by the change in harvest date. Further, the harvest date alternative is known at the time of spring fertilizer application and hence affects N_a and L_a. However, if harvest date is not determined until after the beginning of the growing season, N^* and L^* is used in equation 13. Price premia for both conditions are presented below.

Results

Yield, Yield Curve and Nutrient Removal

Analysis of the statistical regression of the yield response function described in Eq. 1 and shown in Table 5, reveals significant effects for the location, production year, harvest date, *N* and litter (*L*) application rates. The coefficient estimates on *D* support a yield curve consistent with field observations (increasing yields until mid-October and steady declines due to increased leaf shedding later in the season). Increasing the amount of N fertilizer application increased yields at a decreasing rate, whereas poultry litter application increased biomass yield linearly but at a significantly lower rate than urea (compare $\alpha_6 + \alpha_7 N$ to α_8). This result is not surprising as lesser N efficiency of poultry litter compared to urea is likely a function of uncertain timing of nutrient release as plant available N and greater N losses due to volatilization and leaching than typically observed with urea. Yield in 2010 was greater than in 2009 and slightly greater than in 2011, likely because of weather conditions (Table 3). It can also be noted that harvested yield increased from 2009 with the age of the stand which is similar to findings by Holman et al. (2011). Similar to Ashworth (2010), statistically significant coefficients on *D* resulted in an estimable yield curve. The positive location effect associated with Haskell, OK suggests an important role for effective water supply on switchgrass biomass production and use of fertilizer nutrients as the soil at Haskell was deeper and likely afforded greater water holding capacity than the soils tested at Fayetteville, AR. Note that Haskell, OK and Fayetteville, AR have similar weather patterns as they are of similar latitude and within 100 miles of each other (Table 3) and hence soil effects are the likely cause of alternative nutrient uptake and yield expectations.

Table 6 summarizes the nutrient removal equations. For all nutrients, date of harvest was statistically significant. As the harvest is delayed, the amount of N, P, and K removed per acre decreased which is consistent with nutrient translocation to the root system at the time of year when nutrient removal observations were made (late in the production season). Haskell, OK results, where only poultry litter was applied, showed lower N and K uptake compared to Fayetteville, AR. This supports the contention of uncertain timing of N nutrient release stipulated above. Higher P uptake at Haskell is relatively small and may be confounded with higher yields observed at Haskell compared to Fayetteville. Interestingly, yield played a major role in the determination of N and K removed but not for P removed. As yield increased the amount of N and K removal increased with no statistical increase observed for the amount of P removed. This lack of significance found on P removal suggests that switchgrass is a low user of P or very efficient in P use and hence may explain why relatively high amounts of P applied in litter did not enhance yield.

Economically Optimal Harvest Date

Table 7 illustrates how partial profitability (π^* = switchgrass revenue - relevant fertilizer and harvest date dependent storage and opportunity costs) varies by switchgrass price per ton (s) and urea price per pound of N (n) for the baseline scenario of Fayetteville, AR, 2009. Other locations and production years are not shown as the yield curve as shown in

Figure 2 would only shift up or down and hence marginal changes in performance due to changes in *s* and *n* would be the same. As expected, profitability increased as *s* increased and decreased as *n* increased. The optimal harvest date (D^*) approaches the maximum yield achieved on day 235 or October 22 at a decreasing rate as *s* increases. Hence, the lower the cost of leaf shedding (or standing yield loss) as well as interest foregone and post-harvest storage loss avoided as would be observed at low *s*, the greater the importance of nutrient removal of P and K with altered harvest day.

Table 8 shows similar findings to table 7 but uses p_L instead of *p*. Allowing the use of litter in conjunction with commercial N and K increased partial profitability since poultry litter is a cheaper source of P than commercial P. It also led to earlier profit maximizing harvest dates as the cost of nutrient removal in the harvested biomass took on a lesser role.

Figure 2 captures this relationship, by showing estimated *Y*, *NR*, *PR*, *KR* and partial profit (π) for the baseline of Fayetteville, AR, 2009. Note that while the *D* coefficients on *NR*, *PR*, *KR* are all linear in Eqs. 2 to 4, *NR*, *PR* and *KR* in Figure 1 are curvilinear as nutrient uptake is also affected by yield. At *s* = \$50/ton, *n* = \$0.63/lb of N, *p* = \$1.59/lb of P, *k* = \$0.59/lb of K, operating interest rate *i* = 4% per annum (p.a.) and storage losses *c* = 10% over 6 months, maximum yield (D_{max}) occurs in mid-October. Profit maximizing N fertilizer application was at N^* = 63 lb/ac. This finding is similar to studies conducted by Reynolds, Walker, and Kirchner (2000) and Haque, Taliaferro, and Epplin (2009). Partial profit maximizing harvest date (D^*) occurs later than point D_{max} as nutrient savings with delayed harvest are possible after senescence.

To assess the relative importance of the cost of N applied (*n*) versus the impact of switchgrass price (*s*), calculated elasticities of *s* on π^* ($\frac{\Delta\pi}{\Delta s}\cdot\frac{\bar{s}}{\bar{\pi}}$ = 1.43 at n = 0.63 and *s* varying from \$40 to \$60 per ton) in comparison to the elasticity of *n* on π^* ($\frac{\Delta\pi}{\Delta s} \cdot \frac{\bar{s}}{\pi}$ = -0.18 at *s* = \$50 per ton and *n* varying from \$400 to \$800 per ton) showed that changes in *s* have a larger effect on profitability than changes induced by modifying *n*. Further, only changes in *s* as opposed to *n* affected the optimal harvest day.

Similar to Tables 7 and 8, Table 9 is an illustration of the impact of the cost of K or *k* on partial profitability. Compared to changes in *s* that drive N^* and hence harvest date as reported in Table 6, *k* cost changes had a larger effect on harvest date as *KR* is greater than N^*. Depending on *k* and *s* price, harvest date occurred from day 252 to 270. This suggests that while N is a yield driver, *k* is a major factor for determining the optimal date of harvest.

Table 10 assesses the importance of a change in post-harvest storage losses (*c*) associated with a change in the switchgrass price (*s*) relative to the baseline. Similar to findings in Table 9, storage losses have a large effect on D^*. As expected, the smaller the post-harvest storage loss rate, the earlier the harvest date. Also, the greater the post-harvest storage loss rate the greater the harvest delay as standing crop yield losses are smaller than post-harvest storage losses. Also, earlier harvest leads to a decrease in expected partial returns as greater nutrient removal with earlier harvest as well as reduced storage loss savings, relative to the yield-maximizing harvest date, ultimately lead to lower producer returns even at higher harvested yield. These results need to be interpreted carefully. The opportunity cost of post-harvest storage losses enters the optimal harvest date decision as they are calculated relative to the yield-maximizing harvest date. However, actual post-harvest storage losses borne by the biorefinery are not considered in the partial return equation of the producer in this analysis. Nonetheless, the table is included to provide insight about how post-harvest storage loss rates affect optimal harvest date with attendant implications for nutrient concentrations in the biomass harvested but includes only producer return implications.

Finally, Table 11 compares the effect that the price of litter, *l*, and hence p_L has on partial profits. As expected, the cheaper the price of litter, the earlier the harvest. Relative to *k* and *n*, a price change in p_L leads to greater harvest date ramifications since N_L and K_L also play a role even at low $\widehat{PR}$.

Price Premia for Alternate Harvest Dates

Since partial returns are mainly a function of *s* and *s* also significantly affects the optimal harvest date as well as initial N fertilizer application rate, price premia were calculated to inform producers about implications of alternative harvest dates (Table 12). Assuming a biorefinery has a multi-year contract and has a target price of *s* = \$50/ton, they set their annual delivery schedule in advance and would like producer x to harvest on day 175 as opposed to the producer's economic optimum of day 261. Table 12 shows that a producer would be indifferent between the optimum harvest day of 258 at *s* = \$50/ton and day 175 at s_a= \$59.80/ton, or a premium of \$9.80 per ton for switchgrass to cover lower yield and higher nutrient removal. Knowing this premium ahead of time, producer x also adjusts his N application rate (from 62.6 lbs/acre to 68.1 lbs/acre) to obtain a higher yield on harvest day 175 than what would have occurred with a switchgrass price expectation of \$50/ton. Given the quadratic yield response, the price premia needed, and estimated yields, optimal N application rates, N^*, deviate more or less symmetrically from the optimal harvest date. Figure 1 depicts the above scenario graphically. To maintain the partial return prior to the harvest date change at D^* for a known harvest date alternative, D_a, *s* has to increase which also shifts the partial return curve up given higher N application. Alternatively, considering that a biorefinery may want to alter the harvest date after N has already been applied, Table 13 shows price premia needed without altering N application. The differences between Table 12 and Table 13 are deemed marginal.

Nonetheless, nutrient removal of P and K decline with harvest delays and hence lesser premia are required for later than profit maximizing harvest dates compared to earlier than profit maximizing harvest dates. This illustration shows the cost to refineries to advance or delay harvest as they may wish to: i) commence hauling of biomass earlier in the year to lessen need for storage space at the refinery; ii) lessen peak hauling capacity by hauling over more days; or iii) target lower nutrient concentrations in the biomass by delaying harvest. Optimization of harvest date given storage cost, yield and processing cost differences as a function of nutrient concentrations in the biomass are beyond the scope of this analysis.

Discussions

The objectives of this paper were to: i) analyze the economic tradeoffs between yield, initial fertilizer application and nutrient removal as driven by harvest date at varying input and output price levels and ii) provide insight for biorefinery buyers about effects of changing the optimal harvest date. Properties of the switchgrass yield curve were determined by estimating a yield function with respect to harvest date, and linear N, P, and K removal functions with respect to harvest day and yield. Urea fertilizer enhanced yield at a decreasing rate whereas litter application provided a less efficient but cheaper form of yield enhancement that was capped to avoid excessive P application. Use of litter, while economically attractive, led to lower N use efficiency compared to commercial N fertilizer applications that lead to enhanced plant available N during the key growth period. Also, the use of litter provided insufficient N and K with the P limit imposed.

Optimal N fertilization was a function of switchgrass price. Optimal harvest dates varied by switchgrass price, nutrient removal, storage loss, and opportunity cost of delayed sale time. Optimal day of harvest was shown to occur later than the maximum yield date with greater delays at lower switchgrass prices as nutrient removal took on a greater economic role than yield loss with delayed harvest. Price premia of approximately 20% were needed to push harvest dates earlier to mid-August, and slightly lesser premia were needed to delay harvest to mid-January. These premia were calculated with the producer adjusting fertilizer application at the onset of the season or by utilizing optimal levels of fertilizer and adjusting the premia for extra nutrient removal. Our results deviate marginally from those of Mooney et al (2012) as we considered the cost of nutrient replacement.

While not analyzed specifically, this paper also demonstrated location and year effects on switchgrass yields for two different locations. Adding more locations to the analysis should provide insight on further location effects particularly as they pertain to the optimal harvest date in terms of yield and nutrient removal as changes in latitude would affect date of plant senescence. Switchgrass growth modeling efforts accounting for differences in soil and precipitation are expected to extend predictive ability of our results to a broad geographic range for Alamo switchgrass (Rocateli et al. 2013).

Our findings, especially with respect to post-harvest storage loss rates, nutrient concentrations, and price premia needed to modify producer harvest date, provide a starting point for analyses that could be conducted by biorefineries as they attempt to minimize post-harvest storage losses, maximize hauling equipment efficiency and adjust for modifications in nutrient concentrations in the harvested biomass in their conversion process.

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Table 1. Summary of N Application Rates by Commercial Fertilizer or Poultry Litter Applied Along with Harvest Day Range to Determine Nutrient Removal and Yield.

		Commercial Fertilizer[b] Year			Poultry Litter[c] Year		
Location	Harvest Day Range[a]	2009	2010	2011	2009	2010	2011
		N Application Rate Used[d]					
Fayetteville, AR	150-175	54	54	54	-	-	-
	176-200	54	54	54	-	-	-
	201-225	54	54	54	0, 100, 200	0, 100, 200	0, 100, 200
	226-250	0, 45, 54, 89, 134	0, 45, 54, 89, 134	0, 45, 54, 89, 134	-	-	-
	251-275	54	54	54	-	-	-
	276-300	54	54	54	-	-	-
	301-325	-	54	54	-	-	-
	326-356	-	54	54	-	-	-
Haskell, OK	150-175						
	176-200				-	-	-
	201-225				-	-	0, 100, 200
	226-250		Na		-	0, 100, 200	-
	251-275				-	-	-
	276-300				-	-	-
	301-325				-	-	-
	326-356				-	-	-

Notes:

[a] 71 observations were utilized. Row spacing ranged from less than 6 inches to 24 inches. Spacing of plants within rows was less than 6 inches. Stands for all locations were established no later than 2008. Application of nitrogen fertilizer and litter for all locations was mid-May.

[b] Plot size for commercial fertilizer trials were 6’ x 15’ and 8’ x 30’ depending on location. Harvest areas for commercial fertilizer trials were 4’ x 10’ and 6’ x 30’, respectively.

[c] Plots size for poultry litter trials were 10’ x 23’ with harvest areas of 4’ x 18’ and 3’ x 15’.

[d] N application rates in the form of urea or litter are in pounds of elemental N per acre.

Table 2. Frequency of Observations by Harvest Date Range, Location, Source and Amount of N Fertilizer Application.

Variable	Description	Observations
Year	2009	20
	2010	28
	2011	23
Harvest Date[a]	61-149	9
	150-175	2
	176-200	3
	201-225	26
	226-250	21
	251-275	3
	276-300	3
	301-325	2
	326-354	2
Location	Haskell, OK	12
	Fayetteville, AR	59
Source of N	Poultry Litter (3-3-3)[b]	30
	Urea (46-0-0)	41
Amount of N Applied (lb/acre)	0	13
	45	3
	54	29
	89	3
	100	10
	134	3
	200	10

Notes:

[a] Harvest date was calculated as days past March 1st each year or the time of year when switchgrass returns from winter dormancy. 61 days corresponds with a harvest date of May 1and 354 days past March 1st corresponds with February 18 of the following year.

[b] Numbers in parentheses represent nutrient concentrations in percent of N – P – K, respectively. 100 lbs of urea applied would thus represent 46 lbs of N.

Table 3. Weather for Fayetteville, AR and Haskell, OK, 2009-2011.

	Temperature in degree Fahrenheit							
	Fayetteville, AR				Haskell, OK			
Month	2009	2010	2011	Avg.	2009	2010	2011	Avg.
January	37.9	35.8	37.4	37.0	35.5	33.5	33.6	34.2
February	47.2	35.8	43.7	42.2	46.0	35.6	38.9	40.2
March	52.4	50.2	52.4	51.7	52.3	49.0	52.0	51.1
April	59.5	63.3	63.4	62.1	58.2	62.0	62.5	60.9
May	67.3	71.2	67.2	68.6	66.1	68.9	66.7	67.2
June	78.8	81.8	81.7	80.8	78.5	80.0	81.9	80.1
July	77.6	82.1	84.8	81.5	78.9	81.4	88.1	82.8
August	76.6	84.2	83.2	81.3	77.2	83.0	85.0	81.7
September	71.0	74.9	70.5	72.1	69.0	72.8	68.7	70.2
October	56.4	62.8	60.6	59.9	55.2	60.4	61.0	58.9
November	54.1	52	53.2	53.1	53.2	50.8	50.4	51.5
December	37.9	38.6	43.1	39.9	34.2	38.2	41.4	37.9
	Precipitation in inches							
	Fayetteville, AR				Haskell, OK			
Month	2009	2010	2011	Avg.	2009	2010	2011	Avg.
January	3.0	4.1	1.6	2.9	1.7	1.9	0.3	1.3
February	2.7	3.5	4.2	3.5	2.5	2.6	1.5	2.2
March	5.3	3.1	2.7	3.7	2.5	2.5	0.7	1.9
April	5.1	3.1	10.4	6.2	4.8	1.8	8.7	5.1
May	11.4	6.1	8.5	8.7	4.5	5.9	4.6	5.0
June	2.7	2.5	1.6	2.2	2.4	4.0	1.0	2.5
July	7.4	4.5	2.1	4.6	1.8	4.5	0.3	2.2
August	3.4	1.7	4.2	3.1	-	1.2	4.7	2.9
September	8.8	3.3	2.5	4.9	7.4	5.9	3.6	5.6
October	14.4	1.4	2.6	6.1	9.8	1.0	1.9	4.2
November	1.7	4.4	8.6	4.9	1.8	1.8	9.0	4.2
December	7.0	1.5	6.9	5.1	2.7	0.4	1.9	1.6

Source: National Oceanic and Atmospheric Administration and Oklahoma Mesonet.

Table 4. Fayetteville, AR, 2012 Fertilizer Prices.

Fertilizer Name	N – P – K	Cost/ton[a]	Cost/lb[b]
Urea	46-0-0	$575.00	$0.63
Triple S Phosphate	0-45-0	$635.00	$1.59
Potash	0-0-60	$590.00	$0.59
Poultry Litter	3-3-3	$35.00	$0.02[c]

Notes:

[a] Fertilizer prices were local, Northwest Arkansas quotes for the summer of 2012. Note that application cost does not vary with quantity applied per acre.

[b] Costs per pound are per pound of active ingredient. For nitrogen from urea, for example, the cost per pound of N is $575/2000 lbs per ton/0.46 N concentration or $0.63 per lb of N.

[c] Cost per pound of litter applied. Cost of P per pound from litter is thus $2.92 less nutrient credit for N of $0.70 and nutrient credit for K of $1.48 or a net cost of $0.74 per pound P from litter.

Table 5. Yield Response to Location, Year, Harvest Date, Commercial Fertilizer and Poultry Litter, 2009 to 2011 for Fayetteville, AR and Haskell, OK.

Dependent Variable[a]		Yield (Y)	Mean = 5.43
Independent Variable		Coefficient[b]	Standard Error
Constant	α_0	-6.35***	1.07
LOC	α_1	1.30***	0.34
YEAR10	α_2	1.51***	0.27
YEAR11	α_3	0.72**	0.28
D	α_4	0.089272***	0.009832
D^2	α_5	-0.000190***	0.000024
N	α_6	0.035634***	0.009956
N^2	α_7	-0.000185*	0.000084
L	α_8	0.005425***	0.001843
Adj. R^2		0.74	
Number of Observations		71	

Notes:

[a] Y is switchgrass yield in tons/acre at day of harvest (*D*) under commercial nitrogen application rate (N) in lbs acre or poultry litter nitrogen (L) application rate in lbs per acre. All remaining variable are zero/one dummy variables set to zero except for LOC = 1 for Haskell, OK, YEAR10 = 1 for 2010, and YEAR11 = 2011. Base calculations are for Fayetteville, AR in 2009.

[b] *, **, and *** indicate significance at $p = 0.05$, 0.01 and < 0.01, respectively.

Table 6. N, P, and K Removal Rates, 2009 to 2011 for Fayetteville, AR and Haskell, OK.

Dependent Variable[a]	Independent Variable		Coefficient Estimate[b]	Standard Error	Adj. R^2
Nitrogen Removed (*NR*) Mean = 58.11	*Constant*	β_0	65.02***	11.95	0.77
	LOC	β_1	-14.07***	4.94	
	YEAR10	β_2	8.68*	3.81	
	YEAR11	β_3	12.95***	4.07	
	D	β_4	-0.30***	0.04	
	Y	β_5	10.33***	1.54	
Phosphate Removed (*PR*) Mean = 12.08	*Constant*	γ_0	27.77***	4.61	0.41
	LOC	γ_1	5.59***	1.90	
	YEAR10	γ_2	-0.01	1.47	
	YEAR11	γ_3	0.53	1.57	
	D	γ_4	-0.07***	0.02	
	Y	γ_5	0.02	0.59	
Potassium Removed (*KR*) Mean = 75.50	*Constant*	δ_0	60.37**	22.92	0.65
	LOC	δ_1	-36.54***	9.47	
	YEAR10	δ_2	-2.04	7.29	
	YEAR11	δ_3	25.14*	7.80	
	D	δ_4	-0.39***	0.08	
	Y	δ_5	17.96***	2.95	

Notes:

[a] NR, PR, and KR are the nutrient removal rates in lbs/acre at day of harvest (*D*) for the observed yield (*Y*). All remaining variable are zero/one dummy variables set to zero except for LOC = 1 for Haskell, OK, D10 = 1 for 2010, and D11 = 2011. Base calculations are for Fayetteville, AR in 2009. Number of observations was 38 for each equation.

[b] *, **, and *** indicate significance at the P = 0.05, 0.01 and < 0.01, respectively.

Table 7. Impact of N Fertilizer Prices (n) and Switchgrass Prices (s) on Profit maximizing Yield, Harvest Date, N, P, and K Removal for Fayetteville, 2009 using Urea Fertilizer Only.

s (*$/dry ton*)	*Variable*[a]	*n (adjusted to $/ton)* $400	$500	**$575**	$700	$800
	D^*	273	273	**273**	273	273
	N^*	67	60	**54**	45	38
	Y^*	5.41	5.32	**5.24**	5.08	4.94
$40	π^*	$145	$139	**$135**	$130	$127
	$\widehat{NR}$	39	39	**38**	36	35
	$\widehat{PR}$	10	10	**10**	10	10
	$\widehat{KR}$	52	50	**49**	46	44
	D^*	265	265	**265**	265	265
	N^*	73	67	**63**	55	49
	Y^*	5.57	5.51	**5.46**	5.36	5.27
$50	π^*	$200	$193	**$188**	$181	$177
	$\widehat{NR}$	44	43	**42**	41	41
	$\widehat{PR}$	10	10	**10**	10	10
	$\widehat{KR}$	58	57	**56**	54	53
	D^*	260	260	**260**	260	260
	N^*	77	72	**68**	62	57
	Y^*	5.65	5.61	**5.58**	5.51	5.44
$60	π^*	$257	$249	**$244**	$235	$230
	$\widehat{NR}$	46	45	**45**	44	44
	$\widehat{PR}$	11	11	**11**	11	11
	$\widehat{KR}$	61	61	**60**	59	58

Notes:

p = $1.59/lb, k = $0.59/lb, i = 4% p.a. and c = 10% over 6 months. Maximum yield day of harvest is 235. Note that, comparisons across switchgrass price, s, and nitrogen price, n, are appropriate but are not estimated producer returns from switchgrass production. Values in bold are baseline comparison values.

[a] N^* and D^*, the profit maximizing N fertilizer application rates in lb/acre and harvest in days after March 1 are calculated using Eqs. 9 and 11. . The estimated yield, Y^*, is calculated using Eq. 1 for Fayetteville, AR in 2009 utilizing the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield and nutrient removal rates using Eq. 13 with N^*, $\widehat{PR}(Y^*, D^*)$ and $\widehat{KR}(Y^*, D^*)$. $\widehat{NR}(Y^*, D^*)$ rates are shown to demonstrate difference in nutrient application vs. nutrient removal.

Table 8. Impact of N Fertilizer Prices (n) and Switchgrass Prices (*s*) on Profit maximizing Yield, Harvest Date, N, P, and K Removal for Fayetteville, 2009 using Urea and Litter.

s (*$/dry ton*)	*Variable*[a]	*n (adjusted to $/ton)* $400	$500	**$575**	$700	$800
	D^*	266	266	**266**	265	265
	N^*	67	60	**54**	45	38
	L^*	0.85	0.85	**0.85**	0.85	0.85
	(N_L, K_L)	(25,25)	(20,25)	**(18,25)**	(15,26)	(13,26)
$40	Y^*	5.50	5.41	**5.34**	5.18	5.03
	π^*	$157	$151	**$147**	$142	$139
	$\widehat{NR}$	43	42	**41**	39	38
	$\widehat{PR}$	10	10	**10**	10	10
	$\widehat{KR}$	56	55	**54**	51	48
	D^*	259	258	**258**	258	258
	N^*	73	67	**63**	55	49
	L^*	0.89	0.89	**0.89**	0.89	0.89
	(N_L, K_L)	(33,27)	(27,27)	**(23,27)**	(19,27)	(17,27)
$50	Y^*	5.64	5.58	**5.53**	5.43	5.33
	π^*	$216	$209	**$204**	$197	$192
	$\widehat{NR}$	46	46	**45**	44	43
	$\widehat{PR}$	11	11	**11**	11	11
	$\widehat{KR}$	62	61	**60**	58	56

Table 8 (*cont.*). Impact of N Fertilizer Prices (n) and Switchgrass Prices (*s*) on Profit maximizing Yield, Harvest Date, N, P, and K Removal for Fayetteville, 2009 using Urea and Litter.

s (\$/dry ton)	*Variable*[a]	*n (adjusted to \$/ton)* \$400	\$500	**\$575**	\$700	\$800
	D^*	254	254	**254**	254	254
	N^*	77	72	**68**	62	57
	L^*	0.91	0.91	**0.91**	0.91	0.91
	(N_L, K_L)	(41,27)	(32,27)	**(29,27)**	(24,27)	(21,27)
\$60	Y^*	5.71	5.67	**5.63**	5.56	5.49
	π^*	\$276	\$268	**\$263**	\$254	\$249
	$\widehat{NR}$	48	48	**47**	47	46
	$\widehat{PR}$	11	11	**11**	11	11
	$\widehat{KR}$	65	64	**63**	62	61

Notes:

k = \$0.59/lb, l = \$35/ton, i = 4% p.a. and c = 10% over 6 months. Maximum yield day of harvest is 235. Note that, comparisons across switchgrass price, *s*, and nitrogen price, *n*, are appropriate but are not estimated producer returns from switchgrass production. Values in bold are baseline comparison values.

[a] N^*, L^* and D^*, the profit maximizing N fertilizer application rates in lb/acre, L application rate in tons/acre and harvest in days after March 1 are calculated using Eqs. 9, 10 and 11. N_L and K_L are N and K supplied from L. The estimated yield, Y^*, is calculated using Eq. 1 for Fayetteville, AR in 2009 utilizing the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield and nutrient removal rates using Eq. 13 with N^*, $\widehat{PR}(Y^*, D^*)$ and $\widehat{KR}$ (Y^*, D^*). $\widehat{NR}$ (Y^*, D^*) rates are shown to demonstrate difference in nutrient application vs. nutrient removal.

Table 9. Impact of K Fertilizer Prices (k) and Switchgrass Prices (s) on Profit maximizing Yield, Harvest Date, N, P, and K Removal for Fayetteville, 2009 using Urea and Litter.

s (*$/dry ton)*	*Variable*[a]	*k (adjusted to $/ton)* $300	$400	**$590**	$600	$700
$40	D^*	256	259	**266**	266	270
	N^*	54	54	**54**	54	54
	L^*	0.90	0.89	**0.85**	0.85	0.82
	(N_L, K_L)	(19, 27)	(18, 27)	**(18,25)**	(18, 25)	(17, 25)
	Y^*	5.43	5.40	**5.34**	5.33	5.28
	π^*	$156	$153	**$147**	$147	$144
	$\widehat{NR}$	45	44	**41**	41	39
	$\widehat{PR}$	11	11	**10**	10	10
	$\widehat{KR}$	59	57	**54**	53	51
$50	D^*	252	254	**258**	259	261
	N^*	63	63	**63**	63	63
	L^*	0.93	0.92	**0.89**	0.89	0.87
	(N_L, K_L)	(24, 28)	(24, 27)	**(23,27)**	(23, 27)	(23, 26)
	Y^*	5.58	5.57	**5.53**	5.53	5.50
	π^*	$214	$210	**$204**	$204	$200
	$\widehat{NR}$	48	47	**45**	45	44
	$\widehat{PR}$	11	11	**11**	11	10
	$\widehat{KR}$	63	62	**60**	60	58

Table 9 (*cont.*). Impact of K Fertilizer Prices (k) and Switchgrass Prices (s) on Profit maximizing Yield, Harvest Date, N, P, and K Removal for Fayetteville, 2009 using Urea and Litter.

s (*$/dry ton*)	*Variable*[a]	*k (adjusted to $/ton)* $300	$400	**$590**	$600	$700
	D^*	249	251	**254**	254	256
	N^*	68	68	**68**	68	68
	L^*	0.94	0.94	**0.91**	0.91	0.90
	(N_L, K_L)	(29, 28)	(29, 28)	**(29,27)**	(29,27)	(28,27)
$60	Y^*	5.66	5.65	**5.63**	5.63	5.61
	π^*	$273	$270	**$263**	$262	$259
	$\widehat{NR}$	49	49	**47**	47	47
	$\widehat{PR}$	11	11	**11**	11	11
	$\widehat{KR}$	66	65	**63**	63	62

Notes:

n = $0.63/lb, l = $35/ton, i = 4% p.a. and c = 10% over 6 months. Maximum yield day of harvest is 235. Note that, comparisons across switchgrass price, s, and potassium price, k, are appropriate but are not estimated producer returns from switchgrass production. Values in bold are baseline comparison values.

[a] N^*, L^* and D^*, the profit maximizing N fertilizer application rates in lb/acre, L application rate in tons/acre and harvest in days after March 1 are calculated using Eqs. 9, 10 and 11. N_L and K_L are N and K supplied from L. The estimated yield, Y^*, is calculated using Eq. 1 for Fayetteville, AR in 2009 utilizing the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield and nutrient removal rates using Eq. 13 with N^*, $\widehat{PR}(Y^*, D^*)$ and $\widehat{KR}$ (Y^*, D^*). $\widehat{NR}$ (Y^*, D^*) rates are shown to demonstrate difference in nutrient application vs. nutrient removal.

Table 10. Impact of Storage Loss Rate (*c*) and Switchgrass Prices (*s*) on Profit maximizing Yield, Harvest Date, N, P, and K Removal for Fayetteville, 2009 using Urea and Litter.

s (*$/dry ton)*	*Variable*[a]	*Storage Losses, c (adjusted to daily loss rate)*				
		5%	7%	**10%**	13%	15%
	D^*	261	263	**266**	269	271
	N^*	54	54	**54**	54	54
	L^*	0.87	0.87	**0.85**	0.83	0.82
	(N_L, K_L)	(18, 26)	(18,26)	**(18,25)**	(17, 25)	(17, 24)
$40	Y^*	5.39	5.37	**5.34**	5.30	5.27
	π^*	$146	$146	**$147**	$148	$149
	$\widehat{NR}$	43	42	**41**	40	39
	$\widehat{PR}$	11	10	**10**	10	10
	$\widehat{KR}$	57	55	**54**	52	51
	D^*	254	256	**258**	261	263
	N^*	63	63	**63**	63	63
	L^*	0.92	0.91	**0.89**	0.88	0.86
	(N_L, K_L)	(24, 27)	(24, 27)	**(23,27)**	(23, 26)	(23, 26)
$50	Y^*	5.57	5.55	**5.53**	5.50	5.48
	π^*	$202	$203	**$204**	$205	$206
	$\widehat{NR}$	47	46	**45**	44	43
	$\widehat{PR}$	11	11	**11**	11	10
	$\widehat{KR}$	62	61	**60**	58	57

Table 10 (*cont.*). Impact of Storage Loss Rate (*c*) and Switchgrass Prices (*s*) on Profit maximizing Yield, Harvest Date, N, P, and K Removal for Fayetteville, 2009 using Urea and Litter.

s (*$/dry ton)*	*Variable*[a]	*Storage Losses, c (adjusted to daily loss rate)* 5%	7%	**10%**	13%	15%
	D^*	249	251	**254**	257	259
	N^*	68	68	**68**	68	68
	L^*	0.94	0.93	**0.91**	0.90	0.89
	(N_L, K_L)	(29, 28)	(29, 28)	**(29,27)**	(28, 27)	(28, 27)
$60	Y^*	5.66	5.65	**5.63**	5.61	5.59
	π^*	$261	$262	**$263**	$264	$264
	$\widehat{NR}$	49	49	**47**	46	46
	$\widehat{PR}$	11	11	**11**	11	11
	$\widehat{KR}$	66	65	**63**	62	61

Notes:

n = $0.63/lb, k = $0.59/lb, l = $35/ton, and i = 4% p.a. Maximum yield day of harvest is 235. Note that, comparisons across switchgrass price, *s*, and storage loss rate, *c*, are appropriate but are not estimated producer returns from switchgrass production. Values in bold are baseline comparison values.

[a] N^*, L^* and D^*, the profit maximizing N fertilizer application rates in lb/acre, L application rate in tons/acre and harvest in days after March 1 are calculated using Eqs. 9, 10 and 11. N_L and K_L are N and K supplied from L. The estimated yield, Y^*, is calculated using Eq. 1 for Fayetteville, AR in 2009 utilizing the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield and nutrient removal rates using Eq. 13 with N^*, $\widehat{PR}(Y^*, D^*)$ and $\widehat{KR}(Y^*, D^*)$. $\widehat{NR}(Y^*, D^*)$ rates are shown to demonstrate difference in nutrient application vs. nutrient removal.

Table 11. Impact of Litter Prices (*l*) and Switchgrass Prices (*s*) on Profit maximizing Yield, Harvest Date, N, P, and K Removal for Fayetteville, 2009 using Urea and Litter.

s (*$/dry ton)*	*Variable*[a]	*l (adjusted to $/ton)* $25	$30	**$35**	$40	$45
$40	D^*	261	263	**266**	268	271
	N^*	54	54	**54**	54	54
	L^*	0.88	0.86	**0.85**	0.84	0.82
	(N_L, K_L)	(28, 26)	(18,26)	**(18,25)**	(17, 25)	(17, 25)
	Y^*	5.39	5.36	**5.34**	5.31	5.27
	π^*	$156	$152	**$147**	$143	$139
	$\widehat{NR}$	43	42	**41**	40	39
	$\widehat{PR}$	11	10	**10**	10	10
	$\widehat{KR}$	56	55	**54**	52	50
$50	D^*	255	257	**258**	260	262
	N^*	63	63	**63**	63	63
	L^*	0.91	0.90	**0.89**	0.88	0.87
	(N_L, K_L)	(24, 27)	(23, 27)	**(23,27)**	(23, 26)	(23, 26)
	Y^*	5.56	5.55	**5.53**	5.51	5.49
	π^*	$213	$208	**$204**	$200	$195
	$\widehat{NR}$	47	46	**45**	44	44
	$\widehat{PR}$	11	11	**11**	11	10
	$\widehat{KR}$	62	61	**60**	59	58

Table 11 (*cont.*). Impact of Litter Prices (l) and Switchgrass Prices (s) on Profit maximizing Yield, Harvest Date, N, P, and K Removal for Fayetteville, 2009 using Urea and Litter.

s (\$/dry ton)	*Variable*[a]	l (adjusted to \$/ton)				
		\$25	\$30	**\$35**	\$40	\$45
	D^*	251	253	**254**	256	257
	N^*	68	68	**68**	68	68
	L^*	0.93	0.92	**0.91**	0.90	0.90
	(N_L, K_L)	(29, 28)	(29, 28)	**(29,27)**	(28, 27)	(28, 27)
\$60	Y^*	5.65	5.64	**5.63**	5.62	5.61
	π^*	\$272	\$267	**\$263**	\$258	\$254
	$\widehat{NR}$	49	48	**47**	47	46
	$\widehat{PR}$	11	11	**11**	11	11
	$\widehat{KR}$	65	64	**63**	63	62

Notes:

n = \$0.63/lb, k = \$0.59/lb, i = 4% p.a. and c = 10% over 6 months. Maximum yield day of harvest is 235. Note that, comparisons across switchgrass price, s, and potassium price, k, are appropriate but are not estimated producer returns from switchgrass production. Values in bold are baseline comparison values.

[a] N^*, L^* and D^*, the profit maximizing N fertilizer application rates in lb/acre, L application rate in tons/acre and harvest in days after March 1 are calculated using Eqs. 9, 10 and 11. N_L and K_L are N and K supplied from L. The estimated yield, Y^*, is calculated using Eq. 1 for Fayetteville, AR in 2009 utilizing the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield and nutrient removal rates using Eq. 13 with N^*, $\widehat{PR}(Y^*, D^*)$ and $\widehat{KR}$ (Y^*, D^*). $\widehat{NR}$ (Y^*, D^*) rates are shown to demonstrate difference in nutrient application vs. nutrient removal.

Table 12. Impact of Changing Harvest Date to match the Partial Profits of the Optimal Harvest Date on Price Premia Needed, Yield, Optimal N Application Rate, Optimal P Application Rate, P, and K removal for Fayetteville, 2009.

			Altered Day of Harvest (D_a)						
Optimal Harvest Date Conditions		*Non-Optimal Harvest Date*[b]	175	200	225	Yield Max D_{max} = 235	275	300	325
s	**$40**	s_a	$48.94	$44.38	$41.63		$40.09	$41.33	$44.63
Y^*	5.34	Y_a	4.95	5.35	5.52		5.21	4.73	4.04
N^*	54.1	N_a	61.9	58.3	55.8		54.2	55.5	58.5
L^*	0.85	L_a	1.35	1.21	1.08	$\boldsymbol{D^* = 266}$	0.80	0.66	0.52
(NL,KL)	(18, 25)	(NL_a, KL_a)	(34, 41)	(28, 36)	(23, 32)		(17, 24)	(14, 20)	(12, 16)
$\widehat{PR}$	10	$\widehat{PR}_a$	16	15	13		10	8	6
$\widehat{KR}$	54	$\widehat{KR}_a$	82	79	73		48	29	7
s	**$50**	s_a	$59.80	$54.49	$51.42		$50.37	$52.53	$57.50
Y^*	5.34	Y_a	5.02	5.44	5.63		5.33	4.85	4.14
N^*	62.6	N_a	68.1	65.4	63.5		62.8	64.2	67.0
L^*	0.89	L_a	1.35	1.21	1.08	$\boldsymbol{D^* = 258}$	0.80	0.66	0.52
(NL,KL)	(23, 27)	(NL_a, KL_a)	(42, 41)	(34, 36)	(29, 32)		(21, 24)	(18, 20)	(16, 16)
$\widehat{PR}$	11	$\widehat{PR}_a$	16	15	13		10	8	6
$\widehat{KR}$	60	$\widehat{KR}_a$	83	81	75		50	32	9

Table 12 (*cont.*)**.** Impact of Changing Harvest Date to match the Partial Profits of the Optimal Harvest Date on Price Premia Needed, Yield, Optimal N Application Rate, Optimal P Application Rate, P, and K removal for Fayetteville, 2009.

			Altered Day of Harvest (D_a)						
Optimal Harvest Date Conditions		*Non-Optimal Harvest Date*[b]	175	200	225	Yield Max D_{max} **= 235**	275	300	325
s	**$60**	s_a	$70.85	$64.74	$61.33		$60.72	$63.80	$70.46
Y^*	5.63	Y_a	5.06	5.49	5.69		5.40	4.91	4.20
N^*	68.2	N_a	72.5	70.3	68.8		68.6	69.9	72.4
L^*	0.92	L_a	1.35	1.21	1.08	$\boldsymbol{D^* = 254}$	0.80	0.66	0.52
(NL,KL)	(29, 27)	(NL_a, KL_a)	(50, 41)	(41, 36)	(34, 32)		(25, 24)	(22, 20)	(19, 16)
$\widehat{PR}$	11	$\widehat{PR}_a$	16	15	13		10	8	6
$\widehat{KR}$	63	$\widehat{KR}_a$	84	82	76		51	33	10

Notes: n = $0.63, k = $0.59/lb, l = $35/ton, i = 4% p.a. and c = 10% over 6 months. Maximum yield day of harvest is 235.

[a] N^* and D^*, the profit maximizing N fertilizer application rates in lb/acre and harvest in days after March 1 are calculated using Eqs. 9 and 11. The estimated yield, Y^*, in dry tons/acre is calculated using Eq. 1 for Fayetteville, AR in 2009 utilizing the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield and nutrient removal rates in lbs/acre using Eq. 13 with N^*, $\widehat{PR}$ (Y^*, D^*) and $\widehat{KR}$ (Y^*, D^*).

[b] s_a is the breakeven price in $/dry ton needed to achieve π^*, the level of partial returns at the optimal harvest date, D^* given an alternative harvest day, D_a. Y_a, N_a, $\widehat{PR}_a$, and $\widehat{KR}_a$ are a function of s_a and D_a. NL_a and KL_a are the nitrogen and potassium supplied by litter, respectively.

Partial profits for $40, $50, and $60 are $147.24, $203.96, and $262.61, respectively.

Table 13. Impact of Changing Harvest Date to match the Partial Profits of the Optimal Harvest Date on Price Premia Needed at the Optimal N Application Rate for Fayetteville, 2009.

Optimal Harvest Date Conditions		*Non-Optimal Harvest Date*[b]	Alternative Day of Harvest (D_a) 175	200	225	Yield Max D_{max} **= 235**	275	300	325
s	**$40**	s_a	$49.61	$44.61	$41.69		$40.09	$41.35	$44.70
Y^*	5.34	Y_a	4.84	5.29	5.50		5.21	4.71	3.97
N^*	54.1	N_a	54.1	54.1	54.1		54.1	54.1	54.1
L^*	0.85	L_a	0.85	0.85	0.85	D^* **= 266**	0.85	0.85	0.85
(NL,KL)	(18, 25)	(NL_a, KL_a)	(18, 25)	(18, 25)	(18, 25)		(18, 25)	(18, 25)	(18, 25)
$\widehat{PR}$	10	$\widehat{PR}_a$	16	15	13		10	8	6
$\widehat{KR}$	54	$\widehat{KR}_a$	80	78	72		48	29	6
s	**$50**	s_a	$60.61	$54.76	$51.49		$50.38	$52.60	$57.71
Y^*	5.34	Y_a	4.95	5.40	5.62		5.33	4.83	4.09
N^*	62.6	N_a	62.6	62.6	62.6		62.6	62.6	62.6
L^*	0.89	L_a	0.89	0.89	0.89	D^* **= 258**	0.89	0.89	0.89
(NL,KL)	(23, 27)	(NL_a, KL_a)	(23, 27)	(23, 27)	(23, 27)		(23, 27)	(23, 27)	(23, 27)
$\widehat{PR}$	11	$\widehat{PR}_a$	16	15	13		10	8	6
$\widehat{KR}$	60	$\widehat{KR}_a$	82	80	74		50	31	8

Table 13 (*cont.*)**.** Impact of Changing Harvest Date to match the Partial Profits of the Optimal Harvest Date on Price Premia Needed at the Optimal N Application Rate for Fayetteville, 2009.

Optimal Harvest Date Conditions		*Non-Optimal Harvest Date*[b]	Alternative Day of Harvest (D_a)						
			175	200	225	Yield Max **D_{max}= 235**	275	300	325
s	**$60**	s_a	$71.78	$65.05	$61.40		$60.75	$63.93	$70.82
Y^*	5.63	Y_a	5.02	5.47	5.68		5.39	4.89	4.16
N^*	68.2	N_a	68.2	68.2	68.2		68.2	68.2	68.2
L^*	0.92	L_a	0.92	0.92	0.92	**D^* = 254**	0.92	0.92	0.92
(NL,KL)	(29, 27)	(NL_a, KL_a)	(29, 27)	(29, 27)	(29, 27)		(29, 27)	(29, 27)	(29, 27)
$\widehat{PR}$	11	$\widehat{PR}_a$	16	15	13		10	8	6
$\widehat{KR}$	63	$\widehat{KR}_a$	83	81	75		51	32	9

Notes: n = $0.63, p = $1.59/lb, k = $0.59/lb, i = 4% p.a. and c = 10% over 6 months. Maximum yield day of harvest is 235.

[a] N^* and D^*, the profit maximizing N fertilizer application rates in lb/acre and harvest in days after March 1 are calculated using Eqs. 9 and 11. The estimated yield, Y^*, in dry tons/acre is calculated using Eq. 1 for Fayetteville, AR in 2009 utilizing the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield and nutrient removal rates in lbs/acre using Eq. 13 with N^*, $\widehat{PR}(Y^*, D^*)$ and $\widehat{KR}(Y^*, D^*)$.

[b] s_a is the breakeven price in $/dry ton needed to achieve π^*, the level of partial returns at the optimal harvest date, D^* given an alternative harvest day, D_a. Y_a, N_a, $\widehat{PR}_a$, and $\widehat{KR}_a$ are a function of s_a and D_a. NL_a and KL_a are the nitrogen and potassium supplied by litter, respectively.

Partial profits for $40, $50, and $60 are $147.24, $203.96, and $262.61, respectively.

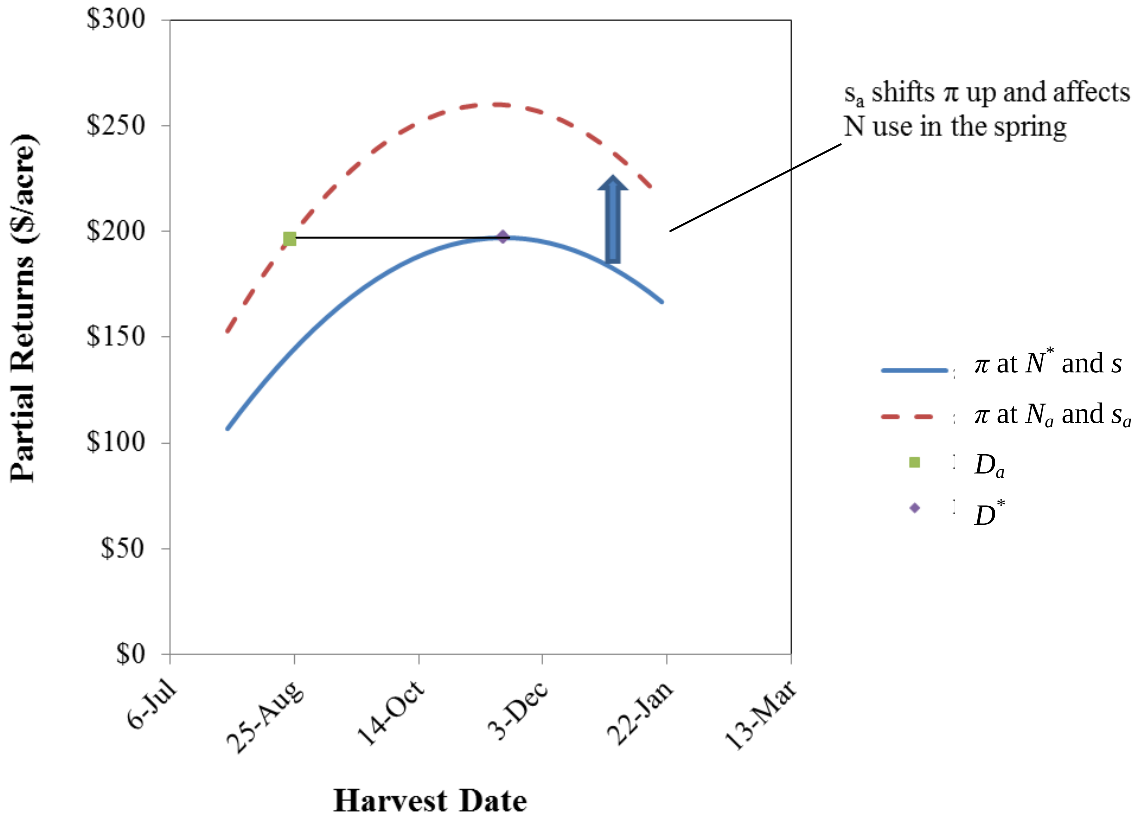

Figure 1. Alternative Harvest Date Driven Price Premium Effects on Nitrogen Application and Partial Returns at Fayetteville, AR, 2009 given nitrogen fertilizer price n = \$0.63/lb of N, phosphorus fertilizer price p = \$1.59/lb of P, potassium fertilizer price k = \$0.59/lb of K, operating interest rate i = 4% p.a. and storage losses c = 10% over 6 months at initial s = \$50/ton and N^* = 63 lb/ac and alternative harvest date switchgrass price s_a = \$62.48/ton and N_a = 69 lb/ac.

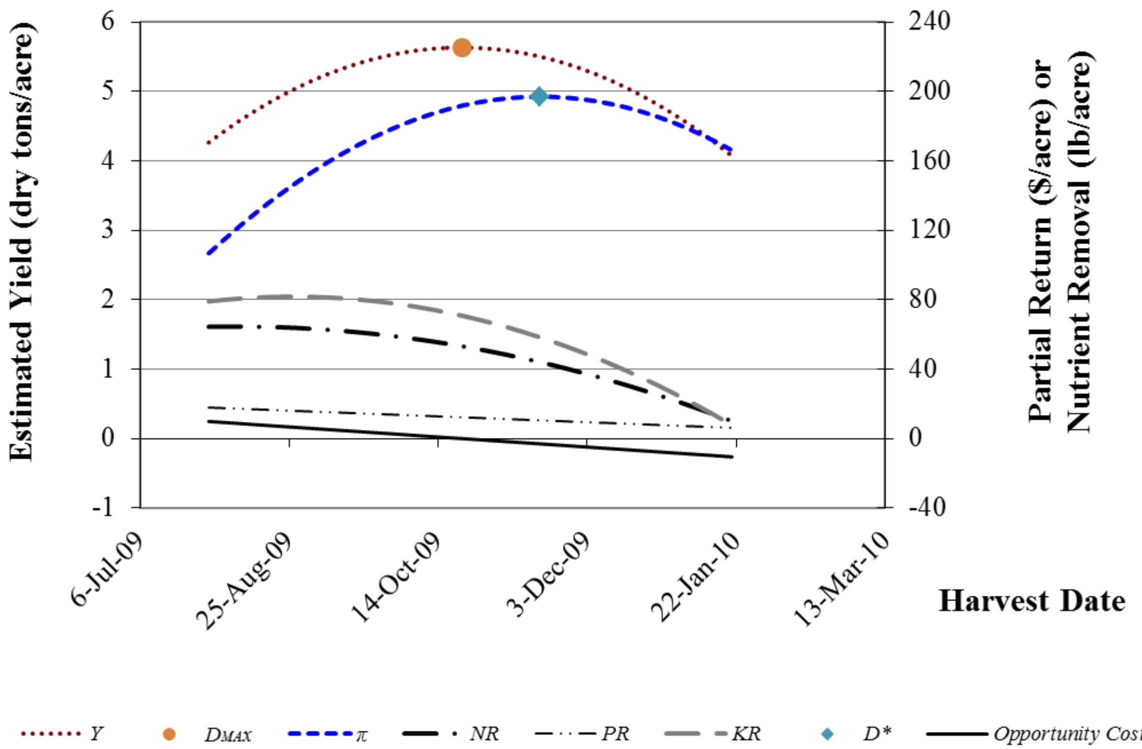

Figure 2. Relationship between Estimated Yield, Nutrient Removal and Resultant Partial Returns for Fayetteville, AR, 2009 at switchgrass price s = \$50/ton, nitrogen fertilizer price n = \$0.63/lb of N, optimal N fertilizer application rate of N^* = 63 lb/ac, phosphorus fertilizer price p = \$1.59/lb of P, potassium fertilizer price k = \$0.59/lb of K, operating interest rate i = 4% p.a. and storage losses c = 10% over 6 months. Day of maximum yield, D_{MAX}, occurs before the partial profit maximizing harvest date, D^*.

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M E M O

From: Michael Popp

To: Graduate School

Date: November 14, 2013

Subject: Nathanial Cahill M.Sc Thesis

This memorandum is to certify that Nathanial E. Cahill has performed at least 51% of the work associated with work entitled "Evaluating Economic Impacts of Switchgrass Harvest Time". Should you have any questions, please feel free to contact me at 479-575-6838 or mpopp@uark.edu.

Chapter III

III. Conclusion

Based on information presented in this thesis, biomass producers were deemed in need of a tool that would allow them the opportunity to analyze economic implications of modifying production practices prior to field implementation. Given that there are a multitude of production practices that can be assessed, estimated costs for a given production scheme will differ from farm to farm. This thesis focused on an optimal harvest date given tradeoffs of costs of nutrient replacement and the value of the biomass at time of harvest.

The Energy Crop Analysis and Planning (ENCAP) tool was developed to assist biomass producers in understanding the economic aspects of their operation and how changing a management practice and equipment complement can affect costs before implementing the practice in question. The Switchgrass Harvest Date, Yield, Nutrient Removal Estimator (SHYNE) is a separate tool that producers are encouraged to use within ENCAP to accurately estimate costs. SHYNE calculates the optimal harvest date and nitrogen application rate needed to maximize potential profits when utilizing urea or a combination of urea and litter to provide nitrogen. It also calculates the amount of nutrients removed that need to be replaced before the following growing season to maintain the soil's nutrient profile. Comparisons between nutrient removal and harvested yield are a function of changing harvest date. A profit maximizing date was calculated on the basis of switchgrass price, storage loss, opportunity cost of capital and nutrient costs. Price premia needed to modify the harvest date area calculated to provide insight for biorefinery managers and producers interested in profitability and nutrient concentration repercussions in the harvested biomass. Nutrient concentration and harvest date are expected to alter biorefinery profitability. These impacts are mentioned in this thesis but not included here.

Limitations

Since any farming operation can vary significantly in management practices and harvest schemes, even with the detail considered in ENCAP, it is difficult for a user to fully define their operation using the tool. While the user can use ENCAP to define their operation as closely as possible, the user may still encounter problems associated with actual production results. For example, a drought could adversely affect stand establishment. Equipment can break down unexpectedly and so on. The Switchgrass Nutrient Removal and Yield Estimator is based on nitrogen, phosphorus, potassium, and yield tradeoffs from Fayetteville, AR and Haskell, OK. Hence, regional specific tradeoffs are not captured by this study which limits the degree to which results can be generalized to a larger production region.

Further Research

Further research is needed to be able to add alternative regional effects of tradeoffs between nutrient removal and yield. Adding more locations to the analysis may also provide more insight on location effects on the optimal harvest date. While analysis was conducted for switchgrass, additionally energy sorghum and miscanthus producers would benefit from research conducted to determine an optimal harvest date in a similar way as switchgrass. Growth modeling efforts linked to ALMANAC or DSAT offer opportunities for linkage into SHYNE as yield curves for different growing conditions may soon be able to be modeled for the post senescence growth stage of switchgrass and energy sorghum. Likewise, transport, storage and processing cost implications borne by the biorefinery are likely to affect harvest date choice. It may be possible to add components to ENCAP that would entertain some of these factors. For example, transportation can be an underlying cost that ultimately decides the profit margin that a producer can achieve. Yield per acre and moisture content affect transport cost to the biorefinery. Yield in the sense that higher yields lower the amount of acres needed to meet the plant's capacity and thereby transport distance. Moisture content of the harvested biomass (especially when using a forage harvester) affects transport cost in the sense that material may need to be dried to levels safe for storage and because moisture content implies added cost of transporting water rather than biomass. In sum, the cost of alternative harvest date has only been analyzed from the perspective of the producer in this analysis. Cost and revenue ramifications are also likely determinants for optimal harvest dates and need to be analyzed in future work.