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

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This article analyzes economic tradeoffs among harvest date, fertilizer applied, nutrient removal, and switchgrass yield as they vary with respect to input and output prices. Economic sensitivity analyses suggest that higher biomass prices lead to earlier harvest. Optimal harvest time occurs beyond time of maximum yield because nutrient removal in the biomass is an important economic consideration. Switchgrass price premia that reflect the cost of non-optimal harvest time are driven by standing crop yield loss, nutrient removal, storage loss, and opportunity cost. These price premia could provide a mechanism to compensate producers for alternative harvest times and aid with logistics management.

Key Words: harvest date, nutrient use, switchgrass

JEL Classifications: Q15, Q16, Q42

Second-generation biofuels, generated from dedicated energy crops or waste materials with high cellulose content, have increasingly become a focus of energy and food policy discussion. The intent of these second-generation biofuels discussions is 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 impact on the food supply than the current practice of converting corn (*Zea mays* L.) to ethanol. Hence, the Energy Independence and Security Act (EISA) of 2007 (U.S. House, 2007) in the United States has set a target of 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

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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 with 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 per acre given its greater nitrogen use efficiency, high yield (approximately five tons at 75–90 gal of fuel per ton), lesser tillage given perennial growth, and lesser chemical use for weed control with a tradeoff 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. Growth, harvesting, production, and burning of switchgrass-derived biofuel are expected to 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 in farming operations. An important consideration, for both producers and biorefinery buyers, is how harvest management decisions affect nutrient removal and yield, because those two components would affect cost of production. Guretzky et al. (2011), Haque, Taliaferro, and Epplin (2009), and Kering et al. (2009, 2013) conducted studies based on harvest dates 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) fertilizer application rates, the double harvest system removed more N 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: 1) analyzing economic tradeoffs between initial fertilizer application and expected yield response; 2) N, phosphorus (P), and potassium (K) removal rates in the harvested biomass as related to timing of harvest; and 3) harvested yield levels as a function of timing of harvest. Although 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 commonly grown cultivar 'Alamo' in the southern United States 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 because nutrients need to be replaced and from a biomass to fuel conversion perspective because high nutrient loads negatively affect mainly thermal conversion processes (Adler et al., 2006; Johnson and Gresham, 2014). 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; Gouzaye et al., 2014; Parrish and Fike, 2005).

The comparison of delayed harvest or storage as a standing crop versus 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 by storage method on switchgrass profitability. Mooney et al. (2012), for example, showed that cost of production of switchgrass including storage increases at a decreasing rate as post-harvest storage losses occur early on, but they do not optimize harvest date in conjunction with storage method.

In summary, the tradeoff among 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 article. Also, price premia for earlier or later than profit-maximizing harvest dates are calculated to portray cost difference experienced by producers. This information could be used to develop a mechanism to compensate producers for these cost changes if a biorefinery custom harvests switchgrass for immediate processing and wishes to: 1) commence processing of biomass earlier in the year to lessen need for storage space at the refinery; 2) lessen peak hauling capacity by hauling over more days; or 3) target lower nutrient concentrations in the biomass by delaying harvest. A switchgrass producer that harvests material in baled form for intended storage also benefits from this information because they can see cost implications of alternative harvest dates. The article proceeds with a description of the available data from several field experiments, proceeds with a discussion of methods, and concludes with a discussion of findings and areas of needed additional research.

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 (long. 36°5′42″ N, lat. 94°10′25″ W) and at Haskell (long. 35°49′12″ N, lat. 95°40′37″ W). Harvest date and N rate trials at Fayetteville were conducted on eroded Pickwick gravelly loam at 3–8% slope. Litter application trials conducted at Fayetteville 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 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: 1) date of stand establishment; 2) amount of N applied in the form of commercial fertilizer or poultry litter in pounds per acre; 3) amount of N, P, and K removed in biomass harvested in pounds per acre; and 4) 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 three to six replicates depending on experiment. Established switchgrass stands occupied an area of 0.8 acres. Row and within-row spacing ranged from less than six to 24 inches and less than six inches, respectively. Trial sites received urea fertilizer in mid-to-late April of each year at rates of zero, 45, 54, 89, and 134 lbs of N per acre and poultry litter application rates that delivered zero, 100, and 200 lbs of total N per acre (average of zero, 1.2, and 2.4 tons of litter per acre). Annual harvests over the three-year period occurred in center rows of plots (three to four 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. Because data from three different experiments with three different experimental designs were used, the statistical analysis of the data thus represents a meta-analysis in an 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

Table 1. Summary of Nitrogen (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 and 2011	2009	2010	2011
		N Application Rate Used[d]				
Fayetteville, AR	150–175 July 29–August 23	54	54	—	—	—
	176–200 August 24–September 17	54	54	—	—	—
	201–225 September 18–October 12	54	54	0, 100, 200	0, 100, 200	0, 100, 200
	226–250 October 13–November 6	0, 45, 54, 89, 134	0, 45, 54, 89, 134	—	—	—
	251–275 November 7–December 1	54	54	—	—	—
	276–300 December 2–December 26	54	54	—	—	—
	301–325 December 27–January 20	—	54	—	—	—
	326–354 January 21–February 18	—	54	—	—	—
Haskell, OK	150–175 July 29–August 23					
	176–200 August 24–September 17			—	—	—
	201–225 September 18–October 12			—	—	0, 100, 200
	226–250 October 13–November 6			—	0, 100, 200	—
	251–275 November 7–December 1	NA[e]		—	—	—
	276–300 December 2–December 26			—	—	—
	301–325 December 27–January 20			—	—	—
	326–354 January 21–February 18			—	—	—

[a] Seventy-one observations were used. Row spacing ranged from less than six inches to 24 inches. Spacing of plants within rows was less than six 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 six feet × 15 feet and eight feet × 30 feet depending on location. Harvest areas for commercial fertilizer trials were four feet ×10 feet and six feet × 30 feet, respectively.
[c] Plots size for poultry litter trials were 10 feet × 23 feet with harvest areas of four feet × 18 feet and three feet × 15 feet.
[d] N application rates in the form of urea or litter are in pounds of elemental N per acre.
[e] Not applicable because no commercial fertilizer was applied at Haskell, OK.

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

Variable	Description	Observations
Year	2009	20
	2010	28
	2011	23
Harvest date[a]	61–149 May 1—July 28	9
	150–175 July 29—August 23	2
	176–200 August 24—September 17	3
	201–225 September 18—October 12	26
	226–250 October 13—November 6	21
	251–275 November 7—December 1	3
	276–300 December 2—December 26	3
	301–325 December 27—January 20	2
	326–354 January 21—February 18	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

[a] Harvest date was calculated as days past March 1 each year or the time of year when switchgrass returns from winter dormancy. Numerical days correspond with calendar dates as shown using the 2009–2010 growing season as an example.

[b] Numbers in parentheses represent nutrient concentrations in percent of nitrogen–phosphorus (P)–potassium (K), respectively. One hundred lbs of urea applied would thus represent 46 lbs of N. Note that although N represents elemental N concentration, P and K actually represent phosphate (P_2O_5) and potash (K_2O) concentrations. This was considered for nutrient cost calculations for estimating nutrient replacement cost as shown in Table 4.

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), generalized least squares in EViews® v6 (Lilien et al., 2007) was used on the panel data with year and location modeled as random and fixed effects, respectively:

$$Y_{it} = \alpha_0 + \alpha_1 LOC_{it} + \alpha_2 D_{it} + \alpha_3 D_{it}^{0.5} + \alpha_4 N_{it} + \alpha_5 N_{it}^{2} + \alpha_6 L_{it} + \varepsilon_{it} \quad (1)$$

where the parameter α_0 is the constant term, LOC_{it} is a location binary variable for Haskell (LOC_{it} = one and zero otherwise), D_{it} is the number of days to harvest past the end of winter dormancy or March 1, N_{it} is commercial N (elemental pounds per acre in the form of urea), L_{it} is N (elemental pounds per acre in the form of poultry litter), and ε_{it} is an error term. Observations on the variables are for the i^{th} experimental plot (averaged across factor replicates) and year t. The base location is Fayetteville (LOC_{it} = 0). In addition to the square root and quadratic functional forms shown here, transcendental and Mitscherlich-Baule functional forms were also estimated to compare goodness of fit on the basis of adjusted R^2 and number of individual t-statistics that added explanatory power ($|$ t –stat $| > 1.0$) for N_{it}, L_{it}, and D_{it}. A Hausman test indicated random effects were preferred to fixed effects for year. Harvest days analyzed ranged from

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

	Temperature in Degrees Fahrenheit							
	Fayetteville				Haskell			
Month	2009	2010	2011	Avg.	2009	2010	2011	Avg.
January	32.4	38.7	29.1	33.4	35.5	33.5	33.6	34.2
February	43.0	29.7	44.6	39.1	46.0	35.6	38.9	40.2
March	53.4	47.1	50.0	50.2	52.3	49.0	52.0	51.1
April	56.1	62.2	58.3	58.9	58.2	62.0	62.5	60.9
May	63.5	67.6	62.4	64.5	66.1	68.9	66.7	67.2
June	76.5	77.9	79.7	78.0	78.5	80.0	81.9	80.1
July	77.4	79.5	85.8	80.9	78.9	81.4	88.1	82.8
August	76.6	82.9	84.0	81.2	77.2	83.0	85.0	81.7
September	66.6	74.3	66.2	69.0	69.0	72.8	68.7	70.2
October	54.5	58.6	60.8	58.0	55.2	60.4	61.0	58.9
November	51.4	54.3	50.4	52.0	53.2	50.8	50.4	51.5
December	38.5	32.7	33.8	35.0	34.2	38.2	41.4	37.9
	Precipitation in Inches							
	Fayetteville				Haskell			
Month	2009	2010	2011	Avg.	2009	2010	2011	Avg.
January	0.0	0.0	0.3	0.1	1.7	1.9	0.3	1.3
February	1.5	0.2	2.49	1.4	2.5	2.6	1.5	2.2
March	0.6	1.2	1.29	1.0	2.5	2.5	0.7	1.9
April	1.1	0.9	10.53	4.2	4.8	1.8	8.7	5.1
May	1.5	2.6	5.46	3.2	4.5	5.9	4.6	5.0
June	2.4	0.1	0.65	1.6	2.4	4.0	1.0	2.5
July	1.3	9.5	0.36	3.7	1.8	4.5	0.3	2.2
August	2.2	0.0	2.05	1.4	3.2	1.2	4.7	3.0
September	3.1	8.5	3.73	5.1	7.4	5.9	3.6	5.6
October	8.4	0.7	1.97	3.7	9.8	1.0	1.9	4.2
November	0.4	0.3	5.96	2.2	1.8	1.8	9.0	4.2
December	0.0	0.0	0.04	0.01	2.7	0.4	1.9	1.7

Source: National Oceanic and Atmospheric Administration and Oklahoma Mesonet.

61 days past March 1 (May 1) to 354 days past the beginning of new growth (February 18 of the next year) using 71 observations. In essence, equation (1) specifies the yield curve with intercept shifters for location as a fixed effect and a random year effect along with yield responses to N sourced from urea *N* or poultry litter *L*.

Nutrient removal rates, as affected by harvest date and yield, were estimated 1) to determine the cost of nutrient replacement for partial profit (π) calculations for P and K; and 2) to track nutrient removal in harvested biomass for N. Three equations for N (*NR*), P (*PR*), and K (*KR*) removal rates were regressed using similar variables and methods as described previously:

$$(2) \quad NR_{it} = \beta_0 + \beta_1 LOC_{it} + \beta_2 D_{iy} + \beta_3 Y_{it} + \theta_{it}$$

$$(3) \quad PR_{it} = \gamma_0 + \gamma_1 LOC_{it} + \gamma_2 D_{it} + \gamma_3 Y_{it} + \lambda_{it}$$

$$(4) \quad KR_{it} = \delta_0 + \delta_1 LOC_{it} + \delta_2 D_{it} + \delta_3 Y_{it} + \mu_{it}$$

where β_0, γ_0, and δ_0 are the constant terms and θ_{it}, λ_{it}, and μ_{it} are the error terms for NR_{it}, PR_{it}, and KR_{it}, respectively. Data analyzed were limited to 38 observations for each nutrient removed, because 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 N application

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	$0.00[c]

[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. Note that P and K concentrations are in percent of phosphate (P_2O_5) and potash (K_2O) in the "N–P–K" column, respectively, whereas "Cost/lb" information is stoichiometrically converted to cost per pound of elemental P or phosphorus (0–20–0) for Triple S phosphate and cost per pound of elemental K or potassium (0–0–50) for potash. Litter yields (3–1.31–2.49).

[c] Cost of P per pound from litter is $1.34 ($35 per ton/26.2 lbs of P per ton of litter) less nutrient credit for N of $0.22 per pound of P applied from litter (76.3 lbs of litter/one lb of P * 0.03 N per pound of litter yields 2.3 lbs of N per lb of P applied from litter at $0.63 per lb of N and is adjusted for relative N efficiency as a result of added leaching and volatilization with litter compared with urea and hence each lb of P applied from litter receives a credit of 2.3 lbs of N * $0.63/lb of N at 15% efficiency as an example = $0.22) and nutrient credit for K of $1.12 per pound of P applied (76.3 lbs of litter/one lb of P yields 1.9 lbs of K at $0.59 per lb or $1.12) or a zero net cost per pound of P from litter.

N, nitrogen; P, phosphorus; K, potassium.

when timely application of plant-available N is critical for achieving yield potential, and another time, for replacing P and K on the basis of soil tests. Note that the amount of fertilizer applied per acre does not affect the applied price because the cost of fertilizer application involves a trip across the field and the trip cost does not vary with application rate. Furthermore, 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 N applied (N^*) were determined from equations (1–4). 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 1) zero if the cost of P applied sourced from litter exceeds that of commercial fertilizer; or 2) 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. Note that the estimated amount of N removed also varies by harvest day and yield, but optimal N application is modeled on expected yield response before harvest and not post-harvest on the basis of *NR*. Larson et al. (2010) determined that round bales have a total dry matter loss of 9% while covered compared with 13% loss after 360 days when uncovered. For this study, post-harvest storage losses are based on a six-month loss of 10%. Compared with the literature, this value is thus relatively high. Post-harvest storage losses affect optimal harvest date in the sense that high post-harvest loss rates would make harvest delays more attractive because in-field losses as a standing crop 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 article, 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 instead to shift the yield curve. This holds if no statistically significant P and K nutrient removal changes occur across N rate applications as observed by Ashworth (2010). That is, increasing N application does not imply attendant, increased requirement of P and K in the Spring, because 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 (equations [3] and [4]) is based on nutrient removal rates as a function of harvest date, whereas appropriate N fertilizer application is determined by estimated yield response (equation [1]). For litter applications (containing all three nutrients), economically optimal application is a function of yield response and limited by environmental restrictions as discussed previously. Hence, first-order conditions for urea and day of harvest using equations (1–4) are:

$$(5) \qquad (\alpha_4 + 2\alpha_5 N)\, s = n$$

$$(6) \qquad (\alpha_2 + 0.5\alpha_3 D^{-0.5})(s - \gamma_3 p - \delta_3 k) = i\, s\, Y_{max} - c\, s\, Y_{max} + \gamma_2 p + \delta_2 k$$

when applying only urea; and

$$(7) \qquad (\alpha_2 + 0.5\alpha_3 D^{-0.5})(s - \gamma_3 p_L - \delta_3 k) = i\, s\, Y_{max} - c\, s\, Y_{max} + \gamma_2 p_L + \delta_2 k$$

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 previously. 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:

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

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 ($\alpha_6 + \alpha_7 N$) as per equation (1), $\mathrm{N_{conc}}$, 0.03, is the fraction of N in a pound of litter, $\mathrm{K_{conc}}$, 0.0249, is the fraction of K in a pound of litter, and $\mathrm{P_{conc}}$, 0.0131, is the fraction of P in a pound of litter.

The first-order condition for N fertilizer (equation [5]) thus sets the benefit of extra N use equal to its cost in the Spring and determines the yield potential. We also set the value of yield changes with alternative harvest dates in the Fall ($\partial Y/\partial D$) ($s - \partial PR/\partial Y\, p - \partial KR/\partial Y\, k$) or the daily marginal revenue net of *yield* driven changes in P and K removal equal to attendant changes in cost resulting from daily opportunity cost associated with delayed cash receipt net of savings associated with avoided post-harvest storage losses ($-\, c\; s\; Y_{max}$) and *daily* P and K removal changes ($\partial PR/\partial D\; p + \partial KR/\partial D\; k$—both γ_2 and δ_2 are expected to have negative coefficients). N removal is not considered because its level of use is determined by the yield response equation. It is assumed 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 $D_{max} = \alpha_3^{\,2}/(4\alpha_2^{\,2})$ where $\partial Y/\partial D = 0$ (Debertin, 1986).

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

$$(9) \qquad N^* = (n - \alpha_4\, s)/(2\alpha_5\, s)$$

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

$$(10) \qquad L^* = \widehat{PR}/26.2, \text{ if } p_L < p; \text{ and}$$
$$L^* = 0, \text{ if } p_L \geq p,$$

because litter contains 26.2 lbs of P per ton of litter.

The profit-maximizing harvest day (D^*) occurs when solving for D in equations (6) and (7) and leads to:

$$(11) \qquad D^* = [\alpha_3^2(\gamma_3\, p + \delta_3 k - s)^2]/[4\{\alpha_2(\gamma_3\, p + \delta_3 k - s) + (i - c)s\, Y_{max} + \gamma_2 p + \delta_2\, k\}^2],$$

which solves for the tradeoff between the marginal cost of harvest date changes as driven by daily post-harvest storage loss savings and opportunity cost, daily change in P and K removed, and the marginal cost of yield changes with harvest date changes as a function of switchgrass price and the yield effect on P and K removed. In equation (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 \$76.33 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 previously determined D^*, N^*, and L^*, the partial profit (π) equation is:

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

where Y^* is the profit-maximizing, estimated yield on harvest day D^* using N^* and L^*, whereas $\widehat{PR}$ 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 $p_L < p$.

Although L^* and l are not in the equation directly, p_L takes litter cost into consideration. Hence, 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.

Cost Changes for Non-Optimal Harvest Dates in Switchgrass Price Equivalents

We solve for the price the producer needs to receive for switchgrass (s_a) so that profitability is not affected by a modified harvest date (D_a) as follows:

$$s_a = (\pi^* + N_a n + \widehat{PRa}_{p_L} + \widehat{KRa}_k) / (Y_a - [D_a - D_{max}](i - c) Y_{opp}) \qquad (13)$$

where Y_a is the yield estimate as a function of D_a, N_a, and L_a, whereas N_a and L_a are the profit-maximizing urea and litter application levels using s_a as opposed to s, respectively. The $\widehat{PRa}$ and $\widehat{KRa}$ 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. Furthermore, 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^* are used in equation (13).

Results

Yield, Yield Curve, and Nutrient Removal

Analysis of the estimated coefficients of the yield response function, described in equation (1) and shown in Table 5, reveals significant effects for the location, harvest date, N, and litter (L) application rates. The coefficient estimates on D support a yield curve consistent with field observations (increasing yields until early October and steady declines resulting from increased leaf shedding later in the season as shown in Figure 2). 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 $\alpha_4 + 2\alpha_5 N$ to α_6). This result is not surprising because lesser N efficiency of poultry litter compared with 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. Yields in 2010 and 2011 at both locations were greater than in 2009 (Figure 2) for Fayetteville yield data, similar trends at Haskell) despite much higher rainfall during the May to September growing season of 2009 (Table 3). The increase in yield after 2009 was probably the result of maturity of the stand from Year One to Year Three after establishment (McLaughlin and Kszos, 2005). Similar to Ashworth (2010), statistically significant coefficients on D resulted in an estimable yield curve. Haskell yields were 1.4 ton/acre higher, on average, than at Fayetteville (see α_1 in Table 5) and occurred with Haskell receiving a mean of 4.2 inches more cumulative precipitation over the April to September growing seasons and slightly higher mean temperatures (Table 3).

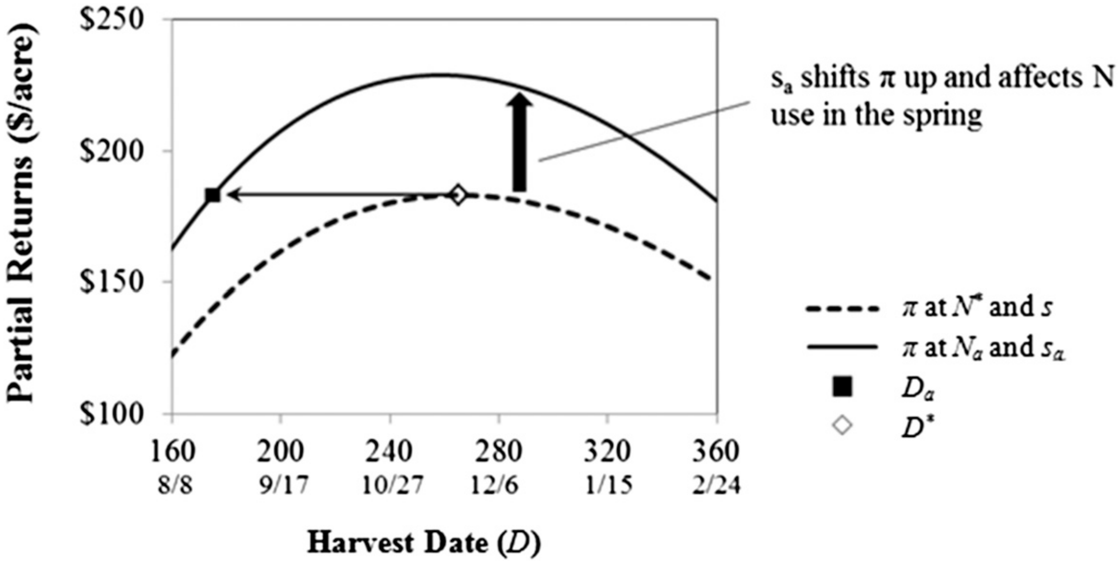

Figure 1. Producer Cost-Driven Changes in Switchgrass Price at a Nonprofit-Maximizing Harvest Date Along with Effects on Nitrogen Application and Partial Returns at Fayetteville, AR, 2009, Given an Initial Nitrogen (N) Fertilizer Price n = $0.63/lb of N, Phosphorus (P) Fertilizer Price p = $1.59/lb of P, Potassium (K) Fertilizer Price k = $0.59/lb of K, Operating Interest Rate i = 4% p.a., and Storage Losses c = 10% over Six Months at Initial s = $50/ton and N^* = 65 lb/ac and Alternative Harvest Date Switchgrass Price s_a = $58.41/ton and N_a = 71 lb/ac. Litter Is Not Applied in This Example

This suggests that the deeper soil at Haskell conferred greater water storage and availability than at Fayetteville.

Table 6 summarizes the nutrient removal equations. Amounts of N, P, and K removed per acre decreased significantly with delayed harvest,

Table 5. Generalized Least Squares Estimates for Yield Response to Location, Harvest Date, Commercial Fertilizer, and Poultry Litter, 2009–2011 for Fayetteville, AR, and Haskell, OK, with Year Treated as a Random Effect

Dependent Variable[a]		Yield (Y)	Mean = 5.43
Independent Variable		Coefficient[b]	Standard Error
Constant	α_0	–23.62***	3.10
LOC	α_1	1.42***	0.34
D	α_2	–0.1288***	0.0169
$D^{0.5}$	α_3	3.8269***	0.4529
N	α_4	0.0323**	0.0097
N^2	α_5	–0.000152*	0.000078
L	α_6	0.0053**	0.0019
R^2		0.72	
Adjusted R^2		0.70	
Number of observations		71	

[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. *LOC* is a zero/one variable set to zero except for *LOC* = 1 for Haskell. Base calculations are for Fayetteville. Random year effect was statistically superior to a fixed-effects specification using the Hausman test.
[b] *, **, and *** indicate significance at p = 0.05, 0.01 and <0.01, respectively. Standard errors were calculated using the Wallace Hussain estimators of component variances.

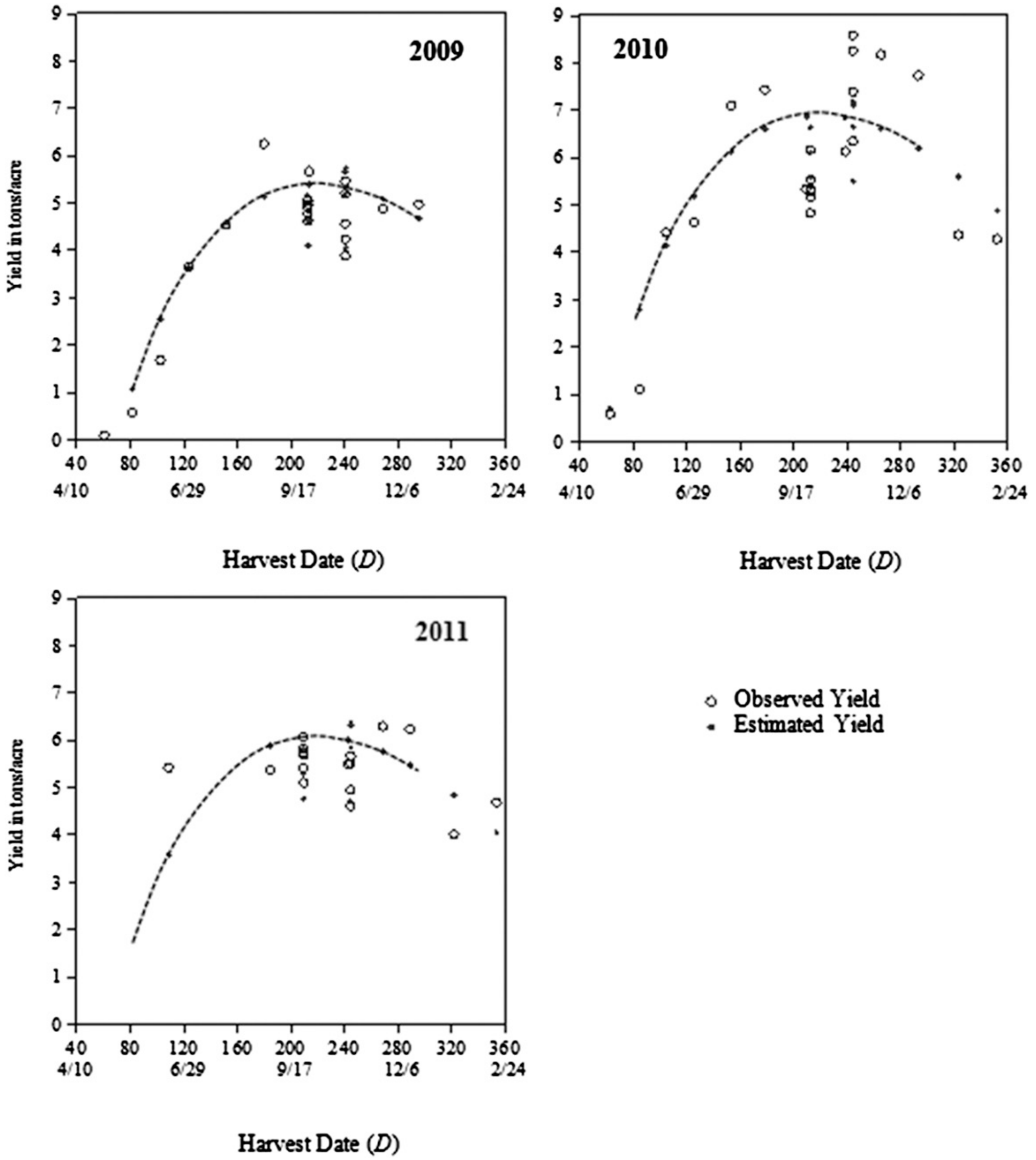

Figure 2. Estimated versus Observed Harvest Date Effects for Fayetteville, AR, under Varying Urea Fertilizer Application Rates (2009–2011). The Dashed Line is the Estimated Yield at the Same Nitrogen (N) Fertilizer Level by Harvest Date in 2009. Its Shape Was Superimposed on 2010 and 2011 (shifting up and down only) to Showcase Estimation Procedure as Scatterplots Are Drawn to the Same Scale. Black solid Dots Off the Curve Are Estimates at Different N Fertilizer Levels That Would Also Shift the Curve

which is consistent with nutrient translocation to the root system late in the production season (Parrish and Fike, 2005). Note that delayed harvest does not always lead to a statistically significant reduction in N concentration in the literature (Gouzaye et al., 2014; Guretzky et al., 2011). Haskell results, where only poultry litter was applied, showed lower N and K removal

Table 6. Generalized Least Squares Estimates for N, P, and K Removal Rates, 2009–2011, for Fayetteville, AR, and Haskell, OK, with Year Treated as a Random Effect

Dependent Variable[a]	Independent Variable		Coefficient Estimate[b]	Standard Error	R^2 (adjusted R^2)
Nitrogen removed (*NR*)	*Constant*	β_0	69.82***	12.79	0.75 (0.73)
Mean = 62	*LOC*	β_1	–14.26**	4.83	
	D	β_2	–0.29***	0.04	
	Y	β_3	10.53***	1.49	
Phosphorus removed (*PR*)	*Constant*	γ_0	27.62***	4.50	0.48 (0.44)
Mean = 14	*LOC*	γ_1	5.45**	1.86	
	D	γ_2	–0.07***	0.01	
	Y	γ_3	0.01	0.02	
Potassium removed (*KR*)	*Constant*	δ_0	66.26**	22.92	0.66 (0.63)
Mean = 76	*LOC*	δ_1	–37.37***	9.47	
	D	δ_2	–0.38***	0.07	
	Y	δ_3	17.88***	2.83	

[a] NR, PR, and KR are the nutrient removal rates in lbs/acre at day of harvest (*D*) for the observed yield (*Y*). *LOC* is a zero/one variable set to zero except for *LOC* = 1 for Haskell. Base calculations are for Fayetteville. Random year effect was statistically superior to a fixed year effects specification using the Hausman test. Number of observations was 38 for each equation.
[b] *, **, and *** indicate significance at the p = 0.05, 0.01 and <0.01, respectively. Standard errors were calculated using the Wallace Hussain estimators of component variances.
N, nitrogen; P, phosphorus, K, potassium.

compared with Fayetteville. This supports the contention of uncertain timing of N release stated previously. Yield was a major determinant of N and K removal, but not of P removal. As yield increased, the amount of N and K removal increased with no significant increase in the amount of P removed. This lack of significance 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, nutrient replacement, 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, 2009. Other locations and production years are not shown because the yield curves as shown in the figures would only shift up or down and hence not alter the marginal changes in performance resulting from changes in s and n. As expected, profitability increased as s increased and decreased as n increased. The optimal harvest date (D^*) moves toward the maximum yield Day 221, or October 7, 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 because poultry litter is a cheaper source of P than commercial P. It also led to earlier profit-maximizing harvest dates because the cost of nutrient removal in the harvested biomass took on a lesser role.

Figure 3 captures this relationship by showing estimated *Y*, *NR*, *PR*, *KR*, and partial profit (π) for the baseline of Fayetteville, 2009. Note that although the *D* coefficients on *NR*, *PR*, and *KR* are all linear in equations (2–4), *NR*, *PR*, and *KR* in Figure 3 are curvilinear because 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 six months, maximum yield (D_{max}) occurs in early October. Profit-maximizing

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

		n (adjusted to $/ton of urea fertilizer)				
s ($/dry ton)	Variable[a]	$400	$500	$575	$700	$800
	D^*	December 6	December 5	December 5	December 5	December 4
	N^*	71	62	55	44	35
	Y^*	5.23	5.13	5.03	4.85	4.67
$40	π^*	$141	$135	$131	$126	$124
	$\widehat{NR}$	37	36	35	33	32
	$\widehat{PR}$	9	9	10	10	10
	$\widehat{KR}$	47	46	44	41	38
	D^*	November 22	November 21	November 21	November 21	November 21
	N^*	78	71	65	56	49
	Y^*	5.48	5.42	5.35	5.23	5.12
$50	π^*	$195	$188	$183	$176	$171
	$\widehat{NR}$	44	43	42	41	40
	$\widehat{PR}$	10	10	10	10	10
	$\widehat{KR}$	57	56	55	53	51
	D^*	November 14	November 14	November 14	November 13	November 13
	N^*	83	77	72	65	59
	Y^*	5.60	5.56	5.51	5.43	5.35
$60	π^*	$252	$243	$238	$229	$223
	$\widehat{NR}$	47	47	46	46	45
	$\widehat{PR}$	11	11	11	11	11
	$\widehat{KR}$	62	62	61	59	58

Notes: $p = \$1.59$/lb, $k = \$0.59$/lb, $i = 4\%$ p.a., and $c = 10\%$ over six months. Maximum yield day of harvest is October 7. 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 date are calculated using equations (9) and (11). The estimated yield, Y^*, is calculated using equation (1) for Fayetteville in 2009 using the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield, fertilizer use, and nutrient removal rates using equation (12) with N^*, $\widehat{PR}(Y^*, D^*)$ and $\widehat{KR}(Y^*, D^*)$. $\widehat{NR}(Y^*, D^*)$ rates are shown to demonstrate difference in fertilizer application versus nutrient removal.

N, nitrogen; P, phosphorus, K, potassium.

N fertilizer application was at $N^* = 65$ lb/ac. This finding is similar to that reported by Haque, Taliaferro, and Epplin (2009) and Reynolds, Walker, and Kirchner (2000). Partial profit-maximizing harvest date (D^*) occurs later than point D_{max} because nutrient savings with delayed harvest are possible.

To assess the relative importance of the cost of N applied (n) versus the impact of switchgrass price (s), calculated elasticities of s on $\pi^* \left(\frac{\Delta\pi}{\Delta s} \cdot \frac{\bar{s}}{\bar{\pi}} = 1.44 \text{ at } n = 0.63\text{/lb and } s \text{ varying from \$40 to \$60 per ton}\right)$ in comparison with the elasticity of n on $\pi^* \left(\frac{\Delta\pi}{\Delta n} \cdot \frac{\bar{n}}{\bar{\pi}} = -0.20 \text{ at } s = \$50 \text{ per ton and } n \text{ varying from \$400 to \$800 per ton}\right)$ showed that changes in s had a larger effect on profitability than changes induced by modifying n.

Similar to Tables 7 and 8, Table 9 illustrates the impact of the cost of K or k on partial profitability. Compared with changes in s that drive N^* and hence harvest date as reported in Tables 7 and 8, k cost changes had a larger effect on harvest date as KR is replaced by potash fertilizer with post-harvest information available and because large D and Y effects on nutrient removal were estimated (Table 6). Depending on k and s price, harvest date occurred from October 30 to December 5. This suggests that although 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

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

		n (adjusted to $/ton of urea fertilizer)				
s ($/dry ton)	Variable[a]	$400	$500	$575	$700	$800
	D^*	November 19	November 19	November 18	November 17	November 16
	N^*	71	62	55	44	35
	L^*	0.40	0.40	0.40	0.41	0.41
	(N_L, K_L)	(3.4, 20.0)	(3.5, 20.0)	(3.5, 20.1)	(3.6, 20.2)	(3.7, 20.3)
$40	Y^*	5.43	5.33	5.24	5.05	4.88
	π^*	$156	$151	$147	$143	$141
	$\widehat{NR}$	43.7	42.8	42.0	40.3	38.8
	$\widehat{PR}$	10.5	10.5	10.6	10.6	10.7
	$\widehat{KR}$	57.0	55.4	54.0	51.1	48.3
	D^*	November 10	November 10	November 9	November 9	November 8
	N^*	78	71	65	56	49
	L^*	0.42	0.43	0.43	0.43	0.43
	(N_L, K_L)	(3.5, 21.1)	(3.6, 21.2)	(3.7, 21.2)	(3.7, 21.3)	(3.8, 21.4)
$50	Y^*	5.59	5.53	5.47	5.35	5.24
	π^*	$212	$205	$200	$194	$190
	$\widehat{NR}$	48.1	47.5	47.0	45.9	44.9
	$\widehat{PR}$	11.1	11.1	11.2	11.2	11.2
	$\widehat{KR}$	63.4	62.4	61.4	59.5	57.8
	D^*	November 5	November 5	November 4	November 4	November 3
	N^*	83	77	72	65	59
	L^*	0.44	0.44	0.44	0.44	0.44
	(N_L, K_L)	(3.6, 21.8)	(3.7, 21.8)	(3.7, 21.9)	(3.8, 21.9)	(3.8, 22.0)
$60	Y^*	5.68	5.63	5.59	5.51	5.43
	π^*	$269	$261	$255	$248	$242
	$\widehat{NR}$	50.5	50.1	49.8	49.0	48.3
	$\widehat{PR}$	11.5	11.5	11.5	11.5	11.5
	$\widehat{KR}$	66.9	66.2	65.5	64.2	62.9

Notes: k = \$0.59/lb, l = \$35/ton, i = 4% p.a., and c = 10% over six months. p_L ranges from \$0.08/lb when N and K are at their maxima with s = \$60/ton and n = \$0.43/lb to –\$0.09/lb when N and K are at their minima at s = \$40/ton and n = \$0.86/lb. Maximum yield day of harvest is October 7. 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 equations (9) and (11). L^* is based on phosphorus replacement and hence is limited to $\widehat{PR}(Y^*, D^*)$. The estimated yield, Y^*, is calculated using equation (1) for Fayetteville in 2009 using the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield, fertilizer use, and nutrient removal rates using equation (12) with N^*, $\widehat{PR}(Y^*, D^*)$ and $\widehat{KR}(Y^*, D^*)$. N_L and K_L are N and K supplied through litter application. $\widehat{NR}(Y^*, D^*)$ rates are shown to demonstrate difference in nutrient application versus nutrient removal.
N, nitrogen; P, phosphorus, K, potassium.

a change in the switchgrass price (s) relative to the baseline. Similar to findings in Table 9, storage losses had a large effect on D^*. As expected, the smaller the post-harvest storage loss rate, the earlier the harvest date. Likewise, the greater the post-harvest storage loss rate, the greater the harvest delay, because standing crop yield losses were smaller than post-harvest storage losses. Earlier harvest also leads to a decrease in expected partial returns because greater nutrient removal with earlier harvest as well as reduced storage loss savings, relative to the yield-maximizing harvest date, ultimately leads 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 because they are calculated relative to the yield-maximizing harvest date. However, actual post-harvest storage losses borne by the

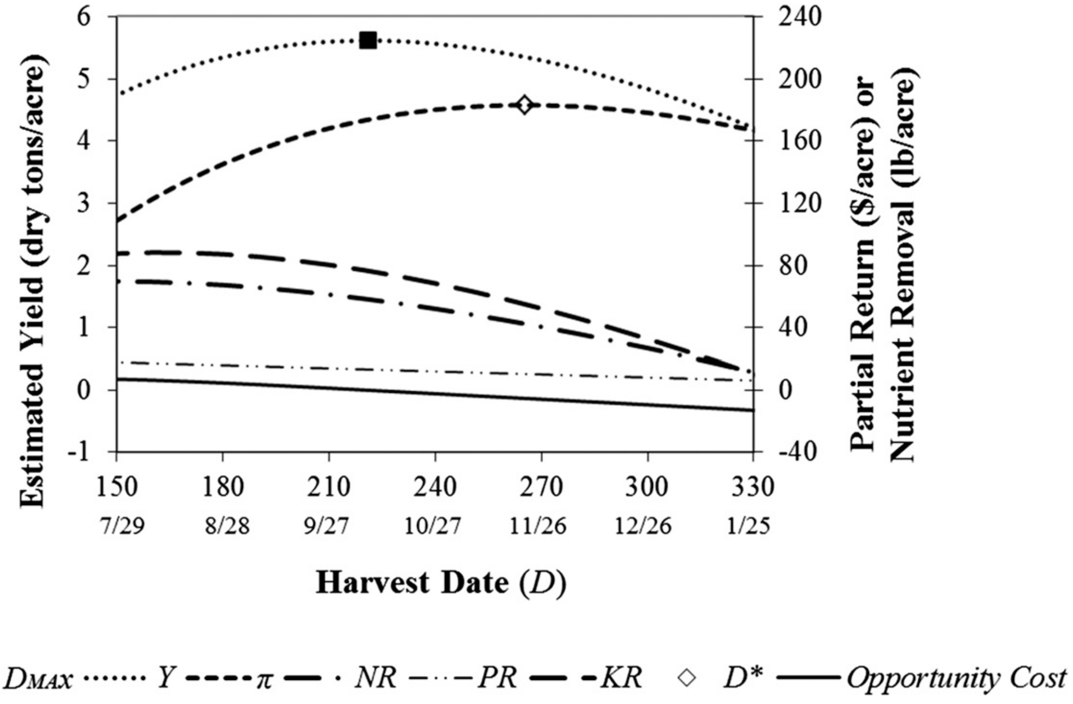

Figure 3. Relationship among Estimated Yield (*Y*), Nutrient Removal (*NR, PR, KR*), and Resultant Partial Returns (π) for Fayetteville, AR, 2009, at Switchgrass Price s = \$50/ton, Nitrogen (N) Fertilizer Price n = \$0.63/lb of N, optimal N Fertilizer Application Rate of N^* = 65 lb/ac, Phosphorus (P) Fertilizer Price p = \$1.59/lb of P, Potassium (P) Fertilizer Price k = \$0.59/lb of K, Operating Interest Rate i = 4% p.a., and Storage Losses c = 10% over Six Months. Day of Maximum Yield, D_{MAX}, Occurs before the Partial Profit-Maximizing Harvest Date, D^*. Litter Is Not Applied in This Example

biorefinery are not considered in the partial return equation of the producer in this analysis. Nonetheless, Table 10 provides 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 c, a price change in p_L leads to lesser harvest date ramifications because N_L and K_L play a relatively minor role at low $\widehat{PR}$.

Cost Changes for Alternate Harvest Dates in Switchgrass Price Equivalents

Because partial returns are mainly a function of s and because s significantly affects the optimal harvest date as well as initial N fertilizer application rate, price premia were calculated to inform producers about cost implications of alternative harvest dates (Table 12). Suppose a biorefinery has a multi-year contract with a target price of s = \$50/ton and sets their annual delivery schedule in advance. Furthermore, assume they would like to custom harvest producer x's fields on Day 175 as opposed to the producer's economic optimum of Day 265. Table 12 shows that a producer would be indifferent between the optimum harvest day of 265 at s = \$50/ton and Day 175 at s_a= \$56.73/ton, or a premium of \$6.73 per ton for switchgrass to cover the loss associated with lower yield and higher nutrient removal. Knowing this potential premium ahead of time, producer x also adjusts the N application rate (from 65 lbs/acre to 70 lbs/acre) to obtain a higher yield on harvest Day 175 (5.33 tons/acre)

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

		k (adjusted to $/ton of potash fertilizer)				
s ($/dry ton)	Variable[a]	$400	$500	$590	$700	$800
	D^*	November 7	November 13	November 18	November 26	December 5
	N^*	55	55	55	55	55
	L^*	0.43	0.42	0.40	0.38	0.36
	(N_L, K_L)	(3.8, 21.5)	(3.7, 20.8)	(3.5, 20.1)	(3.4, 19.1)	(3.2, 18.0)
$40	Y^*	5.34	5.29	5.24	5.14	5.02
	π^*	$154	$150	$147	$144	$141
	$\widehat{NR}$	46.3	44.2	42.0	38.6	34.8
	$\widehat{PR}$	11.3	10.9	10.6	10.0	9.5
	$\widehat{KR}$	60.0	57.1	54.0	49.2	43.7
	D^*	November 2	November 6	November 9	November 15	November 20
	N^*	65	65	65	65	65
	L^*	0.44	0.44	0.43	0.41	0.40
	(N_L, K_L)	(3.8, 22.1)	(3.7, 21.7)	(3.7, 21.2)	(3.5, 20.6)	(3.4, 19.9)
$50	Y^*	5.53	5.50	5.47	5.42	5.37
	π^*	$208	$204	$200	$196	$192
	$\widehat{NR}$	49.8	48.4	47.0	45.0	42.8
	$\widehat{PR}$	11.6	11.4	11.2	10.8	10.5
	$\widehat{KR}$	65.3	63.4	61.4	58.6	55.6
	D^*	October 30	November 2	November 4	November 8	November 12
	N^*	72	72	72	72	72
	L^*	0.45	0.45	0.44	0.43	0.42
	(N_L, K_L)	(3.8, 22.5)	(3.8, 22.2)	(3.7, 21.9)	(3.6, 21.4)	(3.6, 20.9)
$60	Y^*	5.63	5.61	5.59	5.56	5.53
	π^*	$264	$259	$255	$251	$247
	$\widehat{NR}$	51.8	50.8	49.8	48.4	46.9
	$\widehat{PR}$	11.9	11.7	11.5	11.2	11.0
	$\widehat{KR}$	68.3	66.9	65.5	63.6	61.6

Notes: l = $35/ton, i = 4% p.a., n = $0.63/lb, and c = 10% over six months. p_L ranges from $0.37/lb when N and K are at their maxima with s = $60/ton and k = $0.40/lb to –$0.39/lb when N and K are at their minima at s = $40/ton and k = $0.80/lb. Maximum yield day of harvest is October 7. 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^* and D^*, the profit-maximizing N fertilizer application rates in lb/acre and harvest in days after March 1, are calculated using equations (9) and (11). L^* is based on phosphorus replacement and hence is limited to $\widehat{PR}$ (Y^*, D^*). The estimated yield, Y^*, is calculated using equation (1) for Fayetteville in 2009 using the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield, fertilizer use, and nutrient removal rates using equation (12) with N^*, $\widehat{PR}$ (Y^*, D^*), and $\widehat{KR}$ (Y^*, D^*). N_L and K_L are N and K supplied through litter application. $\widehat{NR}$ (Y^*, D^*) rates are shown to demonstrate difference in nutrient application versus nutrient removal.
N, nitrogen; P, phosphorus, K, potassium.

than what would have occurred with a switchgrass price expectation of $50/ton and 65 lbs of N (5.27 tons/acre with data not shown in Table 12). Given the yield response to harvest date, the price premia needed to compensate for cost changes, and estimated yields, optimal N application rates (N^*) deviate more or less symmetrically from the optimal harvest date. Figure 1 depicts this scenario graphically. To maintain the partial return before 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 yields with higher N application. Alternatively, a biorefinery may want to alter the harvest date after N has already been applied. Our analysis suggests little change in price premia and hence results are not reported but are available from the author on request.

Nonetheless, nutrient removal of P and K declines with harvest delays, and hence lesser

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

		Storage Losses, c (adjusted to daily loss rate)				
s ($/dry ton)	Variable[a]	5%	7.5%	10%	12.5%	15%
	D^*	November 10	November 14	November 18	November 22	November 27
	N^*	55	55	55	55	55
	L^*	0.42	0.41	0.40	0.39	0.38
	(N_L, K_L)	(3.7, 21.1)	(3.6, 20.6)	(3.5, 20.1)	(3.5, 19.6)	(3.4, 19.1)
$40	Y^*	5.32	5.28	5.24	5.19	5.14
	π^*	$145	$146	$147	$148	$150
	$\widehat{NR}$	45.3	43.6	42.0	40.3	38.5
	$\widehat{PR}$	11.1	10.8	10.6	10.3	10.0
	$\widehat{KR}$	58.6	56.3	54.0	51.5	49.1
	D^*	November 2	November 6	November 9	November 13	November 17
	N^*	65	65	65	65	65
	L^*	0.44	0.44	0.43	0.42	0.41
	(N_L, K_L)	(3.8, 22.2)	(3.7, 21.7)	(3.7, 21.2)	(3.6, 20.7)	(3.5, 20.3)
$50	Y^*	5.53	5.50	5.47	5.43	5.40
	π^*	$198	$199	$200	$201	$203
	$\widehat{NR}$	49.8	48.4	47.0	45.5	44.0
	$\widehat{PR}$	11.6	11.4	11.2	10.9	10.7
	$\widehat{KR}$	65.4	63.4	61.4	59.4	57.3
	D^*	October 28	November 1	November 4	November 8	November 11
	N^*	72	72	72	72	72
	L^*	0.46	0.45	0.44	0.43	0.42
	(N_L, K_L)	(3.9, 22.7)	(3.8, 22.3)	(3.7, 21.9)	(3.6, 21.4)	(3.6, 21.0)
$60	Y^*	5.64	5.61	5.59	5.56	5.53
	π^*	$253	$254	$255	$257	$258
	$\widehat{NR}$	52.3	51.1	49.8	48.4	47.0
	$\widehat{PR}$	12.0	11.7	11.5	11.3	11.0
	$\widehat{KR}$	69.1	67.3	65.5	63.7	61.7

Notes: k = $0.59/lb, l = $35/ton, i = 4% p.a., and n = $0.63/lb. p_L ranges from $0.005/lb when N and K are at their minima with s = $40/ton to $0.012/lb when N and K are at their maxima at s = $60/ton. Maximum yield day of harvest is October 7. 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^* and D^*, the profit-maximizing N fertilizer application rates in lb/acre and harvest in days after March 1, are calculated using equations (9) and (11). L^* is based on phosphorus replacement and hence is limited to $\widehat{PR}(Y^*, D^*)$. The estimated yield, Y^*, is calculated using equation (1) for Fayetteville in 2009 using the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield, fertilizer use, and nutrient removal rates using equation (12) with N^*, $\widehat{PR}(Y^*, D^*)$, and $\widehat{KR}(Y^*, D^*)$. N_L and K_L are N and K supplied through litter application. $\widehat{NR}(Y^*, D^*)$ rates are shown to demonstrate difference in nutrient application versus nutrient removal.

N, nitrogen; P, phosphorus, K, potassium.

cost implications occurred for later-than-profit-maximizing harvest dates compared with earlier-than-profit-maximizing harvest dates. Optimization of harvest date given storage cost, yield, and processing cost differences at the biorefinery as a function of nutrient concentrations in the biomass is beyond the scope of this analysis.

Conclusions

The objectives of this article were to: 1) analyze the economic tradeoffs among yield, initial fertilizer application, and nutrient removal as driven by harvest date at varying input and output price levels; and 2) provide insight for biorefinery buyers about effects of changing

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

		l in \$/ton of Litter (3–3–3)				
s (\$/dry ton)	Variable[a]	\$20	\$30	\$35	\$40	\$50
	D^*	November 13	November 16	November 18	November 20	November 24
	N^*	55	55	55	55	55
	L^*	0.42	0.41	0.40	0.40	0.39
	(N_L, K_L)	(3.7, 20.8)	(3.6, 20.3)	(3.5, 20.1)	(3.5, 19.9)	(3.4, 19.4)
\$40	Y^*	5.29	5.26	5.24	5.22	5.17
	π^*	\$153	\$149	\$147	\$145	\$141
	$\widehat{NR}$	44.2	42.7	42.0	41.2	39.6
	$\widehat{PR}$	10.9	10.7	10.6	10.5	10.2
	$\widehat{KR}$	57.1	55.0	54.0	52.9	50.6
	D^*	November 5	November 8	November 9	November 11	November 13
	N^*	65	65	65	65	65
	L^*	0.44	0.43	0.43	0.42	0.42
	(N_L, K_L)	(3.7, 21.7)	(3.7, 21.4)	(3.7, 21.2)	(3.6, 21.1)	(3.6, 20.7)
\$50	Y^*	5.50	5.48	5.47	5.46	5.43
	π^*	\$207	\$202	\$200	\$198	\$194
	$\widehat{NR}$	48.5	47.5	47.0	46.5	45.4
	$\widehat{PR}$	11.4	11.2	11.2	11.1	10.9
	$\widehat{KR}$	63.5	62.1	61.4	60.7	59.2
	D^*	November 1	November 3	November 4	November 5	November 7
	N^*	72	72	72	72	72
	L^*	0.45	0.44	0.44	0.44	0.43
	(N_L, K_L)	(3.8, 22.2)	(3.7, 22.0)	(3.7, 21.9)	(3.7, 21.7)	(3.6, 21.5)
\$60	Y^*	5.61	5.60	5.59	5.58	5.56
	π^*	\$262	\$258	\$255	\$253	\$249
	$\widehat{NR}$	50.9	50.1	49.8	49.4	48.6
	$\widehat{PR}$	11.7	11.6	11.5	11.4	11.3
	$\widehat{KR}$	67.0	66.0	65.5	65.0	63.9

Notes: k = \$0.59/lb, i = 4% p.a., n = \$0.63/lb, and c = 10% over six months. p_L ranges from \$–0.57/lb when N is at its minimum and K is relatively small with s = \$60/ton and l = \$20/ton to \$0.59/lb when N is at its maximum and K is relatively large with s = \$60/ton and l = \$50/ton. Maximum yield day of harvest is October 7. Note that comparisons across switchgrass price, s, and litter cost, l, 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 equations (9) and (11). L^* is based on phosphorus replacement and hence is limited to $\widehat{PR}$ (Y^*, D^*). The estimated yield, Y^*, is calculated using equation (1) for Fayetteville in 2009 using the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield, fertilizer use, and nutrient removal rates using equation (12) with N^*, $\widehat{PR}$ (Y^*, D^*), and $\widehat{KR}$ (Y^*, D^*). N_L and K_L are N and K supplied through litter application. $\widehat{NR}$ (Y^*, D^*) rates are shown to demonstrate difference in nutrient application versus nutrient removal.

N, nitrogen; P, phosphorus, K, potassium.

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, although economically attractive, led to lower N use efficiency compared with commercial N fertilizer applications. Commercial N fertilizer provides enhanced plant-available N during the key growth period. With the P limit imposed, the use of litter also provided insufficient N and K.

Table 12. Switchgrass Price Needed to Compensate Producers for Non-Optimal Harvest Date Along with Attendant Yield, Modified N, and Litter Application Rates, and N, P, and K Removal for Fayetteville, 2009

Optimal Harvest Date Conditions[a]		Alternate Harvest Date Conditions (D_a)[b]	175 August 23	200 September 17	225 October 12	Profit-Max	275 December 1	300 December 26	325 January 20
s	$40	s_a	$46.25	$42.86	$40.96	$D^* = 263$ November 18	$40.10	$40.92	$42.70
Y^*	5.24	Y_a	5.23	5.46	5.49	$\pi^* = 147.12$	5.09	4.71	4.23
N^*	55	N_a	62	58	56		55	56	58
L^*	0.40	L_a	0.62	0.56	0.50		0.37	0.31	0.25
(N_L, K_L)	(3.5, 20.1)	(N_{La}, K_{La})	(0.6, 5.5)	(0.6, 4.9)	(0.5, 4.4)		(0.4, 3.3)	(0.3, 2.7)	(0.2, 2.2)
$\widehat{NR}$	42.0	$\widehat{NR}_a$	67.6	62.7	55.7		36.9	25.5	13.1
$\widehat{PR}$	10.6	$\widehat{PR}_a$	16.3	14.7	13.0		9.8	8.2	6.5
$\widehat{KR}$	54.0	$\widehat{KR}_a$	87.0	81.6	72.7		46.7	30.5	12.4
s	$50.00	s_a	$56.73	$52.81	$50.75	$D^* = 254$ November 9	$50.38	$51.85	$54.62
Y^*	5.47	Y_a	5.33	5.58	5.62	$\pi^* = 200.19$	5.24	4.86	4.37
N^*	65	N_a	70	67	66		66	67	69
L^*	0.43	L_a	0.62	0.56	0.50		0.37	0.31	0.25
(N_L, K_L)	(3.7, 21.2)	(N_{La}, K_{La})	(5.3, 31.0)	(4.8, 27.9)	(4.3, 24.8)		(3.2, 18.6)	(2.7, 15.5)	(2.1, 12.4)
$\widehat{NR}$	47.0	$\widehat{NR}_a$	68.6	63.9	57.1		38.4	27.0	14.6
$\widehat{PR}$	11.2	$\widehat{PR}_a$	16.3	14.7	13.0		9.8	8.2	6.5
$\widehat{KR}$	61.4	$\widehat{KR}_a$	88.8	83.7	75.1		49.4	33.1	14.9
s	$60.00	s_a	$67.38	$62.88	$60.64	$D^* = 249$ November 4	$60.70	$62.84	$66.61
Y^*	5.59	Y_a	5.39	5.64	5.70	$\pi^* = 255.45$	5.40	4.93	4.44
N^*	72	N_a	76	74	73		69	74	76
L^*	0.44	L_a	0.62	0.56	0.50		0.37	0.31	0.25
(N_L, K_L)	(3.7, 21.9)	(N_{La}, K_{La})	(5.3, 31.0)	(4.7, 27.9)	(4.2, 24.8)		(3.2, 18.6)	(2.6, 15.5)	(2.1, 12.4)
$\widehat{NR}$	49.8	$\widehat{NR}_a$	69.3	64.6	57.9		38.8	27.9	15.3
$\widehat{PR}$	11.5	$\widehat{PR}_a$	16.3	14.7	13.0		9.6	8.2	6.5
$\widehat{KR}$	65.5	$\widehat{KR}_a$	89.8	84.9	76.4		51.1	34.4	16.2

Notes: $n = \$0.63$, $k = \$0.59$/lb, $l = \$35$/ton, $i = 4\%$ p.a., and $c = 10\%$ over six months. p_L ranges from \$0.01/lb when N and K are at their maxima with $s = \$67.38$/ton and $D_a = 175$ to \$0.005/lb when N and K are at their minima at $s = \$42.70$/ton and $D_a = 325$. Maximum yield day of harvest is October 7.

[a] N^*, L^*, and D^*, are the profit-maximizing N fertilizer application rates in lb/acre and tons/acre. These values are calculated using equations (9) and (11). The estimated yield, Y^*, in dry tons/acre is calculated using equation (1) for Fayetteville in 2009 using the associated D^* and N^*. Partial returns, π^*, are calculated at estimated yield, fertilizer use and nutrient removal, storage, and opportunity cost using equation (12). D^* and π^* are reported in the middle column of alternative harvest date results that have $\pi_a = \pi^*$.

[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, L_a, where $\widehat{NRa}$, $\widehat{PRa}$, and $\widehat{KRa}$ are functions of Y_a and D_a. N_{La} and K_{La} are the nitrogen and potassium supplied by litter, respectively. Only price comparisons within the same row are appropriate.

N, nitrogen; P, phosphorus, K, potassium.

Optimal N fertilization was a function of switchgrass and fertilizer price. Optimal harvest dates varied by switchgrass price, P and K removal, storage loss, and opportunity cost of delayed sale time. Optimal day of harvest occurred later than the maximum yield date with greater delays at lower switchgrass prices, because K removal in particular took on a greater economic role than yield loss with delayed harvest. Price premia from 12% to 15% were estimated to compensate producers for harvest dates in mid-August and slightly lesser premia were obtained for harvest in mid-January. Our results are similar to those of Mooney et al. (2012), in the sense that storage costs play an important role for switchgrass logistics. Although we accounted for post-harvest storage losses, we added in-field storage as affected by the cost of nutrient replacement and initial fertilizer application rates and did not focus on baling or post-harvest storage technology. Our results are also similar to those of Gouzaye et al. (2014) in the sense that harvest delays past mid-December are costly.

Although not analyzed specifically, this article also demonstrated location and year effects on switchgrass yields for two different locations. Adding more locations to the analysis would provide insight on further location effects, particularly as they pertain to the optimal harvest date for yield and nutrient removal, because 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 compensate producers for non-optimal 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. It is not our intention to suggest that potential biorefineries provide contracts with producers that are harvest date-specific. We provide estimates of cost changes in switchgrass price equivalent form for alternative harvest dates. Depending on a biorefinery's desired harvest date range or delivery schedule, they may use the information presented to set an average price for a range of dates, for example, to minimize otherwise formidable transactions costs and compensate producers with higher cost.

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