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Optimal *N* Application Rates on Switchgrass for Producers and a Biorefinery

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Abstract: This study analyzes the effects of *N* fertilizer application rates on profitability of growing switchgrass and using the feedstock in a pyrolysis biorefinery facility to create a source of sustainable aviation fuel (SAF) supply in Tennessee. Switchgrass (*Panicum virgatum* L.) is a perennial bunchgrass native to North America with traits suitable for biofuel and co-product production. Previous chemical analysis has shown that ash content in switchgrass is related to the amount of nitrogen applied to the field, while at the biorefinery level, the percentage ash content reduces the biorefinery fuel output. To obtain optimal nitrogen (*N*) application rates for the switchgrass producers and the biorefinery, a two-part analysis is employed. First, a partial budgeting profitability analysis is conducted for this cropping enterprise at the farm-gate level without considering downstream implications of biomass quality, i.e., ash content. Second, the effects of higher ash content as a percentage of the feedstock on biorefinery output are analyzed. Results show farm-gate profit is maximized when *N* fertilizer is applied at 111 kg/ha, while as a result of increased production levels and decreased percentage ash content, biorefinery profit is maximized when *N* is applied at 157 kg/ha. Lower ash could lead to premium prices paid to switchgrass producers if higher quality feedstock were to be demanded as part of an integrated biofuel industry.

Keywords: switchgrass; ash content; optimal nitrogen; farmer; biorefinery

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1. Introduction

1.1. Background and Purpose

"The Clean Air Act (CAA) defines 'cellulosic biofuel' as 'renewable fuel derived from any cellulose, hemicellulose, or lignin that is derived from renewable biomass and has lifecycle greenhouse gas emissions, as determined by the Administrator, that are at least 60% less than the baseline lifecycle greenhouse gas emissions' "[1]. To achieve this cellulosic biofuel classification, the Environmental Protection Agency (EPA) examines a company's proposed pathway from feedstock to fuel and evaluates the impact that fuel will have on greenhouse gas emissions. There are several pathways that have been approved that produce cellulosic biofuel as an end product.

Sustained growth of the cellulosic biofuels industry in the United States and other regions will rely, in part, on feedstock development that is both profitable for growers but also economically and technologically viable for conversion to biofuels and co-products. Switchgrass (*Panicum virgatum* L.) is a bunchgrass native to the United States that has been the subject of considerable research, partly because it is a biofuel feedstock that does not have direct competition as a food crop [2–5]. Agronomically, switchgrass is a hearty perennial grass with erect stems and a rooting depth of up to 3.5 m deep [6] and can be grown on marginal lands such as lands used in the Conservation Reserve Program (CRP) [7]; a program that for a yearly rental payment removed environmentally sensitive land from agricultural production by planting species that provided environmental services [8]. Switchgrass yields can be increased with nitrogen (*N*) application [7,9,10].

However, the ash content in harvested switchgrass is impacted by the quantity of nitrogen applied. Since ash content is inversely correlated with biofuel conversion efficiency, lower ash content switchgrass translates into higher quality feedstock and, potentially, a higher price paid per unit of harvested switchgrass [11]. Practically all biorefineries with a thermochemical platform have experienced a problem with ash, especially those that utilize a catalyst in the process. For a pyrolysis-based biorefinery (from this point on referred to as biorefinery), it has been shown that a higher ash content decreases biofuel yield [12]. At the grower/conversion interface of the supply chain, to determine optimal application of *N*, both the beneficial effects on yields to switchgrass growers and the negative effect increased ash content (i.e., quality) has on the conversion process should be considered. While this tradeoff may exist, sufficient research has not evaluated the effects of this price-yield tradeoff on farmer returns from growing switchgrass, nor the optimal levels of *N* for the supply chain.

Assuming that nitrogen impacts both crop yield and biorefinery efficiency, two objectives surface: the farmer wishes to apply nitrogen at a level that optimizes his/her return, and the biorefinery wishes to purchase feedstock that provide a level of efficiency. Two entities with somewhat different objectives. Does the biorefinery ask the farmer to increase N so that ash is reduced, or does the biorefinery accept the feedstock produced at the optimal farmers N rate and see a decrease in the biorefinery's efficiency?

1.2. Studies of Feedstock Ash Content and Effects on Conversion

Numerous studies have evaluated the impact of ash on biorefinery efficiency when using a thermochemical platform. Ou et al. [12] analyzed the impacts of feedstock properties such as ash, moisture, and carbon content on fast-pyrolysis biorefinery fuel conversion. The process fuel conversion model used in their study was based on previous research by Jones et al. [13]. The ash content in the study ranged from 1% to 7% and had a significant negative correlation with biorefinery output yield. A reduction in bio-oil and hydrocarbon yields occur as the feedstock's ash content increases. In Ou et al. [12], the biorefinery facility was assumed to have a capacity of 2000 metric tons of feedstock per day. The study sequentially held ash, moisture, and carbon constant to estimate the impact of each variable on biofuel yield. They found at a 1% ash content and constant moisture and carbon contents that biofuel yield was 114.3 liters per metric ton of feedstock input; whereas, at 5% ash content with the same assumptions, biofuel yield decreased to 98.4 liters per metric ton of feedstock input. Based on the analysis they conducted, it was found that it is important to use dry feedstocks with low ash content for the success of a fast pyrolysis facility, and that this should be an objective of supply-chain optimization for fast pyrolysis facilities.

Additional studies record similar results. Yildiz et al. [14] found that 3% ash content had a direct impact on yield and the composition of the desired products formed in a catalytic fast pyrolysis conversion process. Li et al. [15] examined the impacts of biomass ash content of 0.3–7.7% and reported that under pyrolysis, biofuel yields decreased by more than half, while biochar increased slightly as ash content increased. Kenney et al. [16] explored the impacts of higher ash content in pyrolysis conversions and found less than 1% ash to be preferred due to the impairment on catalysts and slag formation during the combustion process. Additionally, the study revealed that switchgrass with higher ash content creates excess conversion cost and maintenance requirements in thermochemical refinement. Edmunds et al. [17] conducted a biomass feedstock characterization for switchgrass and pine residues and found that switchgrass had a relatively higher ash content (1.3%) than loblolly pine (0.76 to 1.13%). However, the results of their study did not show a strong correlation between ash content and pyrolysis product yields, which could be due to the low ash materials used in their study. Furthermore, Gonzalez et al. [18] and Li et al. [15] both reported that higher ash content decreases the net present value (NPV) of bio-refineries in a break-even analysis.

In addition to a reduction in efficiency because of ash, pretreatments to reduce impurities will result in increases in expenses. Strategies to remove ash from harvested biomass to reduce the additional risk of wear on biomass processing equipment are being developed. The minerals either need to be removed or equipment constructed in a manner that reduces wear and tear [19]. Liu et al. [20] suggest that hot water extraction could be used to reduce the inorganic impurities present in biomass which are problematic when gasification is used.

While the aforementioned research has provided important information about how switchgrass yield responds to N application and also how ash content may lower conversion facility efficiency, none of these studies have examined the potential price–yield tradeoff that might be created. Findings from such research could be helpful in feedstock pricing, farm planning, and developing contractual arrangements and bioenergy policy instruments. The findings could also be used in further analysis using multi-objective programming models, such as those used by [21–27].

2. Methods

2.1. Conceptual Framework

This study uses a partial budgeting framework to maximize the return to fertilizer costs subject to other costs held constant both at the grower and refiner levels. Other aspects required to grow the feedstock remain unchanged and therefore will not affect decisions surrounding input application. A similar assumption is made for the biorefinery, except transportation costs and feedstock quality are also considered.

The farmer is assumed to maximize net returns from switchgrass production. The partial net returns for the farm (NR_{Farm}) can be expressed as follows in Equation (1):

$$NR_{Farm} = P(N_a) * S(N_a) - C(N_a) - OC_{Farm} \tag{1}$$

where P is price received for switchgrass feedstock per metric ton, S is switchgrass yield per hectare with $P * S$ equaling gross revenues per hectare, C represents the variable application costs of nitrogen, and OC_{Farm} are other costs per hectare. P, S, and C could be in the case of P and are in the case of S and C functions of the quantity of applied nitrogen (N_a). If the marketplace incorporates the effects of N on ash content and ultimately conversion efficiency, then price of switchgrass, P, could be discounted according to the amount of N applied. The costs of applying N_a are not impacted by the rate since applying some N is required, and therefore it is included in OC_{Farm}.

As with the farmer, the bio-refinery is assumed to maximize net returns, $NR_{Refinery}$, and can be characterized using Equation (2):

$$NR_{Refinery} = FP * FY(S(N_a),\ Ash\ (N_a)) * Q - FC - OC_{Refinery} + RIN{*}FY(S(N_a),\ Ash\ (N_a)) * Q \tag{2}$$

where FP is the expected price received for the biofuel product in \$/liter; FY is the per metric ton conversion rate of feedstock to fuel which is impacted by switchgrass quantity (S) as previously defined and ash content (Ash), which are, in turn, both functions of N_a application; Q is the annual quantity of biomass converted to fuel (metric tons); FC are the delivered feedstock costs; and OC are other conversion facility costs. The renewable identification numbers (RIN) are a second output of the facility and are attached to the fuel output. RINs are credits that the US EPA uses to track and enforce renewable fuels mandate compliance in the US. RINs are attached to renewable fuels as they are produced and detached when the renewable fuel is mixed with fossil fuels. Essentially, RINs are records of individual batches of renewable fuel being blended into the US gasoline, aviation and diesel fuels, and take on a value as companies supplying fossil fuels attempt to meet compliance requirements. Pathways are approved by the EPA. A cellulosic pathway (Pathway L) using switchgrass as a feedstock receives a D code of 7. The non-ester renewable fuels with a heating value of at least 123,500 has an equivalence value (EV) of 1.7 [28].

In Ou et al. [12], the analysis is concerned with the total ash, moisture, and carbon content of switchgrass. For the purpose of this study, moisture and carbon are held constant as these variables are not believed to be impacted by applied *N*. Ash content was allowed to vary as ash content was identified as having significant impact on conversion yield.

2.1.1. Switchgrass Yield and Nitrogen Application

For purposes of model specification selection for switchgrass yield as a function of *N*, four different yield functions are estimated and tested against each other including a quadratic response function (QRF), a mixed quadratic response function (MQRF), a linear response plateau (LRP), and a mixed linear response plateau (MLRP). As in Boyer et al. [16], techniques such as the log likelihood ratio (LLR) test, as well as the Akaike information criterion (AIC), adjusted AIC (AICC), and Bayesian information criterion (BIC) fit statistics are used in model specification selection and testing. Using these aforementioned model fit testing criteria, the mixed quadratic response function (MQRF) is selected to further explain the relationship between switchgrass yield and *N* application. As in [16], the MQRF displayed in Equation (3) shows the relationship between *N* fertilizer application and switchgrass yield as:

$$S(N) = \beta_0 + \beta_1 N_a + \beta_2 {N_a}^2 + v + \varepsilon \tag{3}$$

where β_0 , β_1, and β_2 are the yield response parameters estimated using observed yields; ε is the random error term accounting for variation in yields from unexplained factors; v is included to capture the yield variability from year-to-year due to changes in weather, harvest timing, and other situational effects which are assumed to be unrelated to the independent variables and independent of the error term; N_a is *N*-fertilizer application rate in kilograms per hectare; ${N_a}^2$ represents a quadratic *N* term; and all other variables have been previously defined. The results of the yield response function provide an estimated quantity of switchgrass at the farm-gate level in dry metric tons per hectare for a given fertilization rate.

2.1.2. Ash Content and *N* Fertilizer Application

Similar to the switchgrass yield response function, an MQRF is estimated for the effect of *N* fertilizer application on ash content in switchgrass. Chemical composition and yield variability from year-to-year result from changes in weather, harvest timing, and other situational effects justifies including random effects in the function which are assumed to be independent of the error term. The ash content as a function of *N* is written in Equation (4):

$$Ash(N_a) = \delta_0 + \delta_1 N_a + \delta_2 {N_a}^2 + v + \varepsilon \tag{4}$$

where δ_0 , δ_1, and δ_2 are the percent ash response parameters estimated using observed applied nitrogen levels; ε is the random error term accounting for variation in ash from unexplained factors; v is included to capture the ash variability from year-to-year due to changes in weather, harvest timing, and other situational effects which are assumed to be unrelated to the independent variables and independent of the error term; and all variables have been previously defined.

The biorefinery assumed in this study is replicated from Ou et al. [12] for facility capacity as well as controls for ash content, moisture, and carbon. To estimate biofuel yield in liters, a quadratic response function (QRF) is used. The response function estimating biofuel yield is not a mixed model showing year random effects as there is no information on year-to-year variation. Equation (5) represents the biorefinery yield equation and is a function of feedstock characteristics:

$$FY = \phi_0 + \phi_1 Ash + \phi_2 Ash^2 + \phi_3 Moist + \phi_4 Moist^2 + \phi_5 Carbon + \phi_6 Carbon^2 \tag{5}$$

where *FY* represents the fuel yield in gasoline equivalent liters per dry metric ton; ϕ_i represents the six parameter estimates; and *Ash, Moist*, and *Carbon* are components of switchgrass used as a feedstock to produce fuel expressed in percentage terms.

As in Ou et al. [12], a feedstock capacity of 2000 metric tons of feedstock per day is used for this analysis. Assuming the facility runs at 90% efficiency, the total feedstock processing capacity is 656,000 metric tons per year. In this study, both moisture and carbon content are held constant at 35% and 46%, respectively, when predicting biofuel yield. When varying ash content from zero to five percent, biofuel yield ranges from 137.78 to 108.32 liters per dry metric ton. The fuel price paid to the biorefinery for their final output is assumed to be $0.71 per liter [29].

Several model specifications were tested including the quadratic response function (QRF), MQRF, linear response plateau (LRP), and the mixed linear response plateau (MLRP). As in [30], techniques such as the log likelihood ratio (LLR) test, as well as the Akaike information criterion (AIC), adjusted AIC (AICC), and Bayesian information criterion (BIC) fit statistics, are used in model specification selection and testing. The MQRF was selected for both Equations (3) and (4), and the QRF was selected for Equation (5). The results indicated that the mixed effect models were stronger when considering year random effects. With respect to biofuel yield, however, no year random effects are present. Thus, only the LRP and QRF models were estimated. Based on the results of AIC, BIC, and LLR testing, the QRF function proved to be the best fit at predicting biofuel yield.

2.1.3. Optimizing *N* Fertilizer for Farms and Refinery

The base case of the switchgrass farmer in this analysis is considered "naïve" toward the effects of ash content. In the base case, the producer does not receive a higher price for quality-considered product. Therefore, to maximize net returns, the optimal *N* fertilizer application is only a function of quantity or yield (S). Expanding the NR function given in Equation (1), substituting in the deterministic portion of Equation (3), the equation for the farmer can be written as follows:

$$NR_{Farm} = P_S * \left(\beta_0 + \beta_1 N_a + \beta_2 {N_a}^2\right) - P_N * N_a - OC_{Farm} \tag{6}$$

where the price paid to producers (P_S) is frequently referred to as the farmgate feedstock price or just feedstock price and is multiplied by Equation (3), showing the impact of *N* fertilizer on switchgrass yield (S), and is less than both the fertilizer price (P_N) multiplied by the fertilizer quantity (N_a) and the farm's other costs in growing switchgrass (OC_{Farm}). In this calculation it is assumed that yield will not impact OC_{Farm}. This equation provides the net returns level associated with a variable quantity of *N* fertilizer application.

The optimal farm *N* rate (N_a^*) is obtained by equating the first order condition of Equation (6) to 0 and solving for N_a^* [31]:

$$N_a^* = -\frac{\beta_1 P_S - P_N}{2\beta_2 P_S} \tag{7}$$

The result of the first order condition indicates the global maximum on the net returns curve estimated in Equation (6) and determines the optimal N_a application rate for the farmer.

With respect to the biorefinery, net returns will be maximized when ash is minimized. The nitrogen level where ash is minimized is determined by taking the first order derivative of Equation (4) with respect to nitrogen, setting it equal to 0, and solving for nitrogen (Equation (8)).

$$N_{min}^{**} = \delta_1 / (2 * \delta_2) \tag{8}$$

where N_{min}^{**} is the nitrogen level that minimizes ash in the biomass feedstock, and the δ_i are parameter estimates previously defined in Equation (4) [31]. At this level of nitrogen, ash will be minimized and the biorefinery rate of conversion of biomass will be maximized with respect to ash content. The biorefinery's profit function is dependent on the conversion of biomass to fuel and takes the form:

$$NR_{Refinery} = \left(FP_f * FY_f * Q\right) + \left(RIN_{D7} * EV_f * FY_f * Q\right) - FC - OC_{Refinery} \tag{9}$$

where $NR_{Refinery}$ is the net returns of the biorefinery, FP_f is the biorefinery fuel price in \$/liter for fuel type f, *RIN* is the value of the renewable identification number provided by the EPA in \$.liter, FC are the delivered feedstock costs in \$, $OC_{Refinery}$ is the biorefinery's other costs of production in \$, FY_f is the biorefinery fuel yield in liters per dry metric ton of switchgrass for fuel type *f*, EV_f is the equivalence value for fuel type *f*, and *Q* is the annual quantity of switchgrass purchased for conversion in metric tons.

2.2. Data

Three equations are estimated in this analysis and measure the impact nitrogen has on yield and ash content of the feedstock, as well as the impact of ash content on the biorefinery yield. Once a year, harvest was conducted and samples drawn. The harvest occurred post senescence and the collected samples were tested for moisture content in a forced air oven. They were then placed in storage. The switchgrass yield data and its quality information resulted from experiments that were conducted at the University of Tennessee's Research and Education Center in Milan, Tennessee (35°56/N, 88°43/W) on Alamo switchgrass from 2004–2014 [30]. Yield estimates were determined from this experiment. The experiment was conducted on three different landscapes, with four nitrogen application rates, and five initial seeding rates.

For chemical composition, there were 160 samples tested from a subsample of the experiment for chemical composition. A subset of the data utilized in this analysis was analyzed for switchgrass chemical composition including waste minerals or ash content as a percentage of switchgrass feedstock. Samples from harvests in 2006, 2008, 2010, 2012, and 2013 were used in the analysis. Other years of data were available, but because of resource availability, quality data measurements were conducted for these select years. The initial two years were not chosen as switchgrass maturity is not reached until the third growing season. The plots utilized for the study are abbreviated by field N21 and 212. Field 212 is characterized with a well-drained Grenada silt loam soil type, with no slope in an upland position of site. Field N21 has a well-drained Vicksburg silt loam soil type and no slope, and positioned in a flood plain. Both fields were planted in switchgrass with plots identified within the field. Nitrogen fertilizer was applied to sub plots with rates of application of 0, 67, 134, and 201 kg/ha. The source of the *N* was ammonium nitrate (NH_4NO_3). Each of these treatments was applied annually. According to Mooney et al. [32], switchgrass requires very little P and K; however, 89 kilograms of P_2O_5 and K_2O were applied per hectare annually to ensure that nutrients removed from the fields during harvest were replaced.

Samples were ground up using a Thomas Scientific (Swedesboro, NJ, USA) Model 4 Wiley mill using a 40 mesh (0.425 mm) screen. Since ground biomass's moisture content can rapidly change when exposed to air, the ground samples sat for three weeks at ambient conditions (approximately 23 °C, 63% relative humidity). Total solids measurements were completed using a sub-sample dried in a 105 °C convection oven for a minimum of 4 h to determine the percent of total solid prior to compositional analyses. Each sample was first combusted at 575 °C for 24 h and weighed for measurement of total ash content. A total of eight primary components were quantified as a mass percentage of the oven dried biomass (on % dry basis): extractives, cellulose, hemicellulose (combined values for xylan, galactan, arabinan, and mannan), lignin, and total ash. For further details on the process used to conduct chemical composition analysis, see [29].

3. Results

The descriptive statistics including mean, standard deviation, minimum and maximum for switchgrass yield and ash content are shown in Table 1. Mean annual switchgrass yield over the four fertilizer application rates, two locations, and five production years range from 12.8 to 17.1 dry mt per ha. Having no *N* applied results in 2.56% ash composition, while applying 134 kg per ha results in an ash content of 2.11%. In each time period, as nitrogen applied increased, % ash decreased.

Table 1. Descriptive statistics for Alamo switchgrass yield and ash content when varying nitrogen fertilizer application.

N Fertilizer Rate	Mean	Std. Dev	Minimum	Maximum
(kg/ha)	**Yields (Dry Metric Tons/ha)**			
0	12.8	4.6	3.2	25.4
67	15.1	5.3	5.9	34.5
134	17.1	5.1	6.4	32.7
201	15.3	6.8	0.2	32.1
	Ash Content (% biomass)			
0	2.56	0.58	0.63	4.41
67	2.21	0.59	0.47	4.01
134	2.11	0.46	1.08	3.58
201	2.11	0.61	0.80	3.76

To estimate the biorefinery annual yield as a function of ash, moisture, and carbon content (Equation (5)), the 64 observations from Ou et al.'s [12] supplemental data were used. Yield of gasoline and diesel were converted to gasoline equivalents by dividing the diesel volume by 0.88 and summing the volumes of production.

Supplementing the data described above are two spreadsheet models that provide cost information on growing switchgrass and producing fuel through assuming a pyrolysis pathway. Ou et al. [12] used a technical economic assessment tool created at North Carolina State University to estimate $OC_{Refinery}$ and provide a fuel price (FP_f). English et al. [33] developed a switchgrass decision tool that contains the cost of production for switchgrass and to estimate FOC and the price of nitrogen (P_N). The RIN price is based on the 2020 average D3 price of $0.47 per liter, which assumes a 60% reduction in greenhouse gas emissions (GHG) (Table 2).

Table 2. Average maximum, minimum, and standard deviation of renewable identification number (RIN) prices in 2020 for D3, D4, D5, and D6 products ($/liter).

Statistic	D3	D4	D5	D6
Average	$0.47	$0.20	$0.19	$0.16
Maximum	$0.86	$0.54	$0.53	$0.47
Minimum	$0.25	$0.10	$0.09	$0.04
Standard Deviation	$0.16	$0.10	$0.09	$0.10
Estimated from Source: [34]				

3.1. Switchgrass N Fertilizer and Ash Content

The mean switchgrass yield when varying *N* fertilizer applications of 0, 67, 134, and 201 kg/ha are 12.84, 15.07, 17.13, and 15.34 metric tons per hectare, respectively (see Table 1). Using a one-way ANOVA test, these statistically significant values suggest a positive relationship between switchgrass yield and *N* fertilizer application (Table 3). Building upon the previous literature's connection between the "quantity" aspect of switchgrass production, additional inspection revealed the "quality" aspect, as well. The mean switchgrass ash content (% ash) when varying *N* fertilizer in 67 kg per hectare increments shows that the % ash means decrease from 2.56, 2.21, 2.11, and 2.11 for the selected *N* application rates (see Table 1). These results suggested a negative relationship between % ash content and *N* fertilizer application rate.

Table 3. Parameter estimates and significance for the ANOVA of ash content (% of biomass) of Alamo switchgrass and ANOVA of switchgrass yield when varying nitrogen fertilizer (N) application rates (kg/hectare).

	Ash Dependent Variable (% Biomass)		**Yield Dependent Variable (000 kg/Hectare)**	
Test Variables	**Parameter Estimate**	**Significance Level**	**Parameter Estimate**	**Significance Level**
Intercept	2.5568	<0.0001	12.8346	<0.0001
67	−0.3465	<0.0001	2.2358	0.0018
134	−0.4434	<0.0001	4.2947	<0.0001
201	−0.4481	<0.0001	2.5014	0.0005

Building upon the relationship between N and switchgrass yield, an MQRF was estimated to represent both the yield potential of the crop and the ash content of the biomass. As shown in Table 4, the MQRF model for yield has an intercept value of 14.18 dry metric tons per hectare which represents the yield when 0 kg of N fertilizer are applied. The effect of N applied is 0.066 and N^2 is -0.00025. The statistical maximum derived from the response function shows a yield of 18.6 dry metric tons per hectare when 134 kg of N per hectare is applied. The curve fitting the non-linear relationship for ash content and N is also estimated and has an intercept value of 2.549% ash when no N fertilizer is applied. The β_1 value is -0.0060 and the β_2 value is 0.000019. Given these results, a "U-shaped" curve was derived showing the marginal decrease in ash content when N fertilizer application increases. The estimated quadratic function results in a functional form that contains a minimum value between 134 and 201 kg/ha. The mean ash content values for 0 and 67 N application rates are greater than those for 134 and 201. Given the functional form selected and the switchgrass quality data generated for switchgrass, the minimum ash content for the switchgrass quality function should fall between the 134 and 201 kg/ha. This reduction continues until a minimum ash content of 2.08% occurs when N is applied at a rate of 157 kg per hectare.

Table 4. MQRF parameter estimates or yield and ash models in Alamo switchgrass.

	Yield Parameter Estimates (β_j) Equation (3)	***p*-Value**	**Ash Content Parameter Estimates (δ_j) Equation (4)**	***p*-Value**
	(Dry Metric tons/ha)		**(% Ash Content)**	
Intercept	14.18	0.0006	2.549	0.0001
N	0.066	0.0001	−0.006	0.0001
N^2	−0.00025	0.0001	0.000019	0.0006
R^2	0.92		0.99	
R^2adj	0.78		0.97	

The results of the quadratic response function estimating biofuel yield (FY) (liters) at the biorefinery in liters per metric ton considering ash, moisture, and carbon content of switchgrass had an intercept value of 243.85 (Table 5). The ϕ_1 value representing the coefficient associated with the variable ash content had a statistically significant result of -15.318. The quadratic ash term also showed significant results term with a value of 1.200. Contrary to the ash content findings, neither the moisture nor carbon content proved to have statistically significant results on biofuel yield. The means for both moisture (35%) and carbon content (46%) are held constant in this analysis.

3.2. Farm-Gate Profitability

The optimal N application derived from Equation (7) is 111 kg/ha assuming an $80 per ton price for the biomass delivered to the plant and a price for nitrogen of $0.85/kg (Table 6). Nitrogen fertilizer costs at this rate are equal to $94 per hectare. The switchgrass yield (S) is estimated to be 18.47 dry metric tons per hectare. Additionally, the ash content of the feedstock is estimated to be 2.12%. As shown in Table 6, as expected, if fertilizer price (P_N) increases, the optimum *N* application-level decreases for the producer, and as feedstock price increases (P_S), the optimum fertilizer level increases. A producer would not exceed 134 kg per ha *N* application as application levels beyond that point results in decreased yield. Ash content will not decrease to 2.08% of biomass without incentives to achieve that level. Furthermore, the biorefinery output ranges from 193.2 mm liters of gasoline equivalents per year when the price is $40 per MT, to 193.8 mm liters per year at $120 per MT. At the base case of $80 per MT and a fertilizer price of $0.85 per kg, the farmer will see a net return of $744 per hectare if switchgrass production cost is estimated at $723 per hectare, including a cost of *N* fertilizer applied at a rate of 67 kg/ha [33].

Table 5. Parameter estimates for quadratic response function for biofuel yield (liters) considering ash, moisture, and carbon content in Alamo switchgrass (n = 64) (Equation (5)).

	Parameter Estimates (Φ_i)	***p*-Value**
Intercept	243.85	0.008
Ash	−15.318	0.000
Ash^2	1.200	0.000
Moisture	−0.0015	0.988
$Moisture^2$	0.000023	0.989
Carbon	−0.566	0.882
$Carbon^2$	0.0014	0.973
R^2	0.992	
R^2adj	0.991	

Data were generated from a modelling simulation exercise by Ou et al. [12].

Table 6. Estimates of optimum levels of biomass yield and corresponding biorefinery output as price of feedstock varies between 40 and 120 dollars per dry metric ton (P_S) and two levels of *N* price (P_N) ($0.85 and $1.46 per kg), considering ash, moisture, and carbon content in Alamo switchgrass.

P_S	**Optimum Yield [1]**	**Optimum Nitrogen Application [2]**	**Ash Content [3]**	**Farmer Net Returns [4]**	**Biorefinery Output (Gasoline Equiv.) [5]**
$/mt	**Dry mt**	**kg Per ha**	**% Biomass**	**$ Per ha**	**MM Liters**
		P_N = $0.85 per kg			
40.00	18.13	90.00	2.17	10.01	193.2
60.00	18.38	104.00	2.13	375.67	193.5
80.00 [6]	18.47	111.00	2.12	744.32	193.7
100.00	18.51	115.00	2.11	1114.17	193.7
120.00	18.53	118.00	2.11	1484.62	193.8
		P_N = $1.46 per kg			
40.00	17.23	59.00	2.26	−35.69	192.2
60.00	18.00	84.00	2.18	318.31	193.0
80.00	18.25	96.00	2.15	681.12	193.3
100.00	18.37	103.00	2.14	1047.47	193.5
120.00	18.43	108.00	2.13	1415.59	193.6
		Maximum Yield			
80.00	18.58	132.00	2.09	735.60	193.9
		Minimum Ash			
80.00	18.43	157.00	2.08	702.08	194.0

[1] Estimated with Equation (4) based on the nitrogen level estimated by Equation (7) and estimates provided in Table 2. [2] Estimated based on Equation (7) assuming the price paid per delivered metric ton of feedstock and the fertilizer price. [3] Estimated based on Equation (4) and estimates provided in Table 2 based on the nitrogen level estimated by Equation (7). [4] According to [21], switchgrass production cost is estimated at $723 per hectare including a cost of *N* fertilizer applied at a rate of 135 kg/ha valued at $0.85 per kg. [5] Estimated using the biorefinery yield Equation (5) (see Table 3). [6] Baseline optimum level.

3.3. Biorefinery Profitability

Table 6 shows that when the integrated industry biorefinery is seeking to minimize ash content of incoming switchgrass feedstock as a percentage of the biomass, the optimal *N* rate is 157 kg/ha. At the minimum ash level of *N* application, gross returns to the biorefinery are estimated at $292.9 million assuming that P_F is equal to $0.71 per liter, the fuel produced has an EV value of 1.7, and the price paid for feedstock is $80 per MT at 35% moisture or less. Based on Ou et al. [12], the average minimum fuel selling price (MFSP) required to achieve a net present value of $0 with a discount rate of 10% ranged from $1.00 with an ash percentage of 1, to $1.07 per liter with an ash percentage of 3. Therefore, the cost of producing the fuel (ROC) is assumed to be equal to MFSP times FY. Since the percentage ash level is 2.08 under the minimized ash solution, an interpolation of the two points results in the MFSP that captures the cost of production of an estimated $1.03 per liter. Net returns at the optimal point for the biorefinery is $92.96 million. However, if the biorefinery uses the feedstock that occur when farmers optimize, the ash content is 2.11% and its net returns are estimated at 92.76 million, a decrease in net returns of $0.2 million.

3.4. Potential Incentive Program

The differences between optimal *N* application rates at the farmgate and biorefinery suggest the possibility that an incentive program may encourage farmers to apply at rates that will be more beneficial to the biorefinery. Analysis suggests that a biorefinery running an assumed total of 656,000 dry metric tons of switchgrass per year would produce different quantities of biofuel depending on ash content of the feedstock. Specifically, if the ash content were to be less than 0.5% (for control purposes), the refinery could produce 220.8 million liters annually. Whereas, if the ash content were to be 5%, the refinery would produce 174.1 million liters annually; a decrease of over 45 million liters. Having a 2% ash content will result in a reduction in potential biorefinery production from a theoretical yield of 220.8 million liters to 195 million liters (Table 7).

Table 7. Estimates of annual biofuel production and value based on a 2000 metric ton facility when varying ash content in switchgrass feedstock assuming a per liter price of $0.71 and a RIN value of $0.47 per liter.

Ash Content	Annual Biofuel Yield	Annual Value of Biofuel Production	Per Ton Benefit/Cost to Biorefinery as a Result of % Ash Content
(% of Biomass)	(mm Liters/Year)	$/Facility	$/Dry MT
0.50	220.7	$170,869,111	30.49
1.00	206.6	$159,940,564	13.83
2.00	194.9	$150,869,171	0.00
3.00	185.6	$143,654,932	−11.00
4.00	178.7	$138,297,848	−19.16
5.00	174.1	$134,797,917	−24.50

The switchgrass that was harvested from the plots contained mostly physiological ash. While some samples had a maximum level of ash of up to 4.41%, the mean level of switchgrass ash content hovered between 2.11 and 2.56%. In a study conducted in the 1990s, McLaughlin et al. [35] found that switchgrass hovers around 4.5 to 5.8% ash. If switchgrass at 5% ash enters the facility, then the costs (comparing 5% ash to 2% ash) to the facility is in the vicinity of $16 million unless the feedstock can be treated to remove the ash, which would add an estimated $24.50 per dry MT.

The biorefinery may also have other cost-effective measures to reduce the ash content of feedstock. Blending switchgrass with a lower % ash feedstock such as hybrid poplar may decrease ash and hence increase yield. However, these measures will likely increase the cost of the feedstock. Weighing costs of additional mediation of ash content to the potential biofuel yield gains provided by reduced ash will provide an excellent cost–benefit analysis.

4. Conclusions

Agronomic and mechanical measures can be taken by the producer to reduce ash content. These measures occur in the maintenance, harvest, and storage supply chain segments. In this paper, an examination of the impact of ash on the economic viability of a biorefinery was explored. The type of soil and other measures that occur when harvesting and storing the feedstock may also impact ash content.

Net returns are shown to be a function of quantity, as well as quality of the feedstock produced when refined into fuel. Nitrogen fertilizer application is shown through econometric models to have a statistically significant impact on switchgrass yield as well as ash content. By varying the N application and assessing profitability at both the farm-gate and biorefinery level, the link between final fuel conversion and management practices is demonstrated. The existence of opposing goals and incentive structures give rise to the possibility for an incentive payment structure to be created to promote more optimal outcomes for both the producer and the biorefinery. As ash content moves from 1% to 5%, over $25 million dollars is lost as a result of reduced productivity. Ash content in harvested switchgrass material ranged from 0.46 to 4.41% and was dependent on the amount of nitrogen applied.

5. Limitations

This study represents a first analysis of optimal N application from a supply chain perspective. However, the study has several limitations. The analysis represents a snapshot in time. Further research may provide a different optimal N fertilizer application for both the farm and the biorefinery. Since the model biorefinery did not have a complex budget tied to production costs, it is difficult to assume that the optimal N application estimated at the refinery is accurate. An extension of this research would be to include both of these budgets and determine the optimal N application throughout the supply chain. Another continuation of this study would be to model the interaction of feedstock moisture content and biorefinery operational costs. Excess moisture in the feedstock adds cost to the biorefinery because of the duration and energy requirement of the drying process. To address this limiting factor, moisture content could be included as a secondary variable which could affect the optimal N rate, as well as the price per metric ton received by the farmer. In other words, it is another layer of complexity regarding the quality of feedstock. Another continuation is to determine an economically efficient cost-relief program for the biorefinery and work backwards to estimate the impact of that program on the farmer. Furthermore, this analysis was conducted for a single location. Costs and agronomic conditions could vary across other regions. Future analysis should likely consider a wider set of geographic locations. Finally, the switchgrass used to develop the yield and quality functions came from a ten-year study conducted at Milan, TN. The characteristics of the switchgrass regarding ash content were not as variable across nutrient levels, landscapes, or seeding rates. Harvesting plots, even though located within fields of switchgrass, may have reduced ash to the embodied levels.

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16. Abstract

This study analyzes the effects of N fertilizer application rates on profitability of growing switchgrass and using the feedstock in a pyrolysis biorefinery facility to create a source of sustainable aviation fuel (SAF) supply in Tennessee. Switchgrass (Panicum virgatum L.) is a perennial bunchgrass native to North America with traits suitable for biofuel and co-product production. Previous chemical analysis has shown that ash content in switchgrass is related to the amount of nitrogen applied to the field, while at the biorefinery level, the percentage ash content reduces the biorefinery fuel output. To obtain optimal nitrogen (N) application rates for the switchgrass producers and the biorefinery, a two-part analysis is employed. First, a partial budgeting profitability analysis is conducted for this cropping enterprise at the farm-gate level without considering downstream implications of biomass quality, i.e., ash content. Second, the effects of higher ash content as a percentage of the feedstock on biorefinery output are analyzed. Results show farm-gate profit is maximized when N fertilizer is applied at 111 kg/ha, while as a result of increased production levels and decreased percentage ash content, biorefinery profit is maximized when N is applied at 157 kg/ha. Lower ash could lead to premium prices paid to switchgrass producers if higher quality feedstock were to be demanded as part of an integrated biofuel industry.

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