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Research paper

Adoption of switchgrass cultivation for biofuel under uncertainty: A discrete-time modeling approach

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ABSTRACT

Production of biofuels from cellulosic sources, such as switchgrass, is being encouraged through mandates, incentives, and subsidies. However, uncertainty in future prices coupled with large establishment costs often inhibit their cultivation. Owing to their inability to incorporate uncertainty and dynamic decision-making, standard discounted cash flow techniques are ineffective for analyzing such investments. We formulate a discrete-time binomial framework to model output prices, allowing us to incorporate price uncertainty, stand age, and variable crop yields into the analytical framework. We analyze the feasibility of investments in switchgrass cultivation under varying price transition paths, evaluate the relationship between risk and profitability, and estimate the value of flexible decision-making options wherein the farmer can alter cultivation choices. We find that switchgrass cultivation is only 32% likely to be profitable in the base model and infer that on-farm management could play an important role in entry and exit decisions. We also find that subsidies are important for project viability and policymakers could consider incorporating payments for ecosystem services to encourage adoption.

1. Introduction

The continued consumption of fossil fuels is considered to be unsustainable owing to the non-renewable nature of the resource and the environmental consequences associated with fossil fuel use. As a result, biofuels have emerged as a favored alternative in several countries because they can enhance a country's energy security by displacing imported fuels with domestically produced alternatives, provide support to domestic agricultural markets, and possibly reduce environmental impacts through greenhouse gas (GHG) emission reductions [1]. In addition, it is believed that the physical and chemical properties of liquid biofuels require relatively limited modifications to engine technology and fueling infrastructure [2]. However, first generation biofuels, such as grain-based ethanol, could lead to an increase in food prices and competition for prime land between food crops and biofuel crops [3]. In addition, whether biofuels can result in carbon savings depends on how they are produced [4,5]. As a result, second-generation biofuels could make a substantial contribution to the energy supply mix in the future [6].

A variety of materials ranging from wood and forest residues to energy crops and grasses can be used to produce second-generation biofuels. Potential feedstocks include short-rotation woody sources such as poplar and loblolly pine, agricultural residues including straw and corn stover as well as grasses such as miscanthus, switchgrass and reed canary, among others [7,8]. In the U.S., Switchgrass (*Panicum virgatum*), a native perennial warm-season grass has been identified as a high-potential energy crop following a series of screening trials and assessments [9]. These trials and assessments were carried out across several crop species, soil types, and geographic locations because agricultural productivity and crop growth are highly dependent on such factors. Although most evaluations of switchgrass are focused primarily on its use in the production of cellulosic biofuels, it has been widely recommended for soil and wildlife conservation, summer grazing in pasture systems for beef cattle, and co-firing with coal to produce

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electricity [10]. Under favorable conditions, switchgrass can reach heights of up to 3 meters and its deep-root system that produces substantial below-ground biomass also helps in lowering soil erosion. Switchgrass is known to adapt well in nutrient-deficient systems and does not require an extensive use of fertilizers and pesticides. Studies also suggest that switchgrass cultivation results in a significant level of carbon sequestration and improves soil productivity and nutrient cycling [11–13].

In the U.S., the initial volumetric production targets set under 2007 Energy Independence and Security Act (EISA) and the renewable fuel standards (RFS) have been lowered on many occasions owing to lower fuel consumption for vehicles resulting in lower demand, and slower than expected development of cellulosic biofuel production, among other factors [14]. Along with technological advancement in the feedstock-to-fuel conversion process, a competitive, year-round supply of biomass feedstock is a major constraint in the commercial deployment of advanced biofuel production [15]. Supply-side aspects, such as feedstock cultivation intended for biofuel production and the decision making process of a landowner with regards to the cultivation of a dedicated bioenergy feedstock are critical [16].

An important aspect for feedstock cultivation relates to its profitability and opportunity costs. It is worth noting that land devoted to switchgrass cultivation could come out of land already being used for row crops, forage crops, or land that is considered marginal and considered not suitable for row crop production. However, in order to compare the economic viability of a long-duration crop such as switchgrass, the time horizon needs to be selected carefully. The establishment period for switchgrass ranges between 2 and 3 years after which the crop reaches full production levels. However, once established it is recommended that switchgrass crop be replanted after 10–15 years to maintain productivity levels [17].

Meanwhile, uncertain future crop yields and prices, coupled with relatively large upfront establishment costs, are characteristics of perennial crop production [18]. Allocating land for switchgrass cultivation requires a long-term commitment from the farmer and is often characterized with substantial entry and exit costs. Coupled with low yields in the early stages, there is limited revenues from agricultural activity, at least in the initial years. On the other hand, converting the land back to its traditional use might necessitate some exit costs associated with completely removing switchgrass root-stocks and limiting competition for subsequent crops. Thus, a financial analysis of investments in switchgrass cultivation is, like other long-term investments, fraught with various types of uncertainties. Along with the biological uncertainty associated with growing crops, factors such as climate change, an evolving policy environment, and volatile input costs, add to the complexity of analyzing economic attractiveness of switchgrass cultivation. While standard discounted cash flow techniques such as the net present value (NPV) have been commonly used to evaluate investment decisions, they are relatively rigid and do not incorporate uncertainty and dynamic decision making [19,20]. In their general framework examining entry and exit decisions of a firm, Dixit and Pindyck [21] assumed that output prices are uncertain and follow a geometric Brownian motion. In this paper, we extend the theoretical framework developed by Dixit [22], and focus on a discrete time version of the model while accounting for the option to reverse the decision and convert the land back to its original use.

Our paper contributes to the existing literature in multiple ways. We utilize a discrete-time model which allows us to incorporate the biological aspects of switchgrass cultivation whereby we accommodate for switchgrass age and corresponding yields over the life of the project. Furthermore, we vary our cost assumptions to account for higher upfront establishment costs and lower operational costs in subsequent time-periods. While Song *et al.* [19] highlight the importance of switchgrass age and establishment costs, their continuous-time model does not account for these factors. Our analysis is an improvement over results obtained from purely deterministic analyses as we incorporate uncertainty into the price transition for switchgrass. We evaluate the potential price transitions and associated cash flows and compute corresponding probabilities for return on investment in a dynamic setting. We use a recent time series for ethanol prices to estimate the parameters of the model, making our work both relevant and timely against the backdrop of recent declines in global gasoline prices. We introduce flexible decision making at the farm level wherein the farmer has the option to increase area under switchgrass cultivation or exit the investment during the project life after observing the corresponding output price, following the principle of adaptive management. By allowing for reversibility of land-use, our model highlights some of the conditions under which a farmer could alter his/her cultivation choices and underscores the importance of active on-farm management decisions. From a policy perspective, these insights could be used to design a program that can provide incentives and accommodate for the uncertainty associated with entering the market for advanced bioenergy. Finally, this framework can be utilized to evaluate investment decisions for other bioenergy feedstocks in different parts of the world.

2. Model framework

2.1. Binomial model and analysis of net present value

Under the framework of a binomial model, the per tonne price of switchgrass is assumed to evolve as a multiplicative binomial distribution in discrete time. Fig. 1 depicts a binomial tree that extends across two time periods. The model adopted in this paper is based on a similar binomial tree that extends across ten time periods, spanning the productive age for a switchgrass stand. At time $t = 0$, the per tonne price of switchgrass is assumed to be P. In time period $t = 1$, the price either moves up by a multiplicative factor u with probability q to reach P_u or moves down by a factor d with probability $(1 - q)$ to P_d. The binomial tree is referred to as a recombining tree because an up-move followed by a down-move yields the same value as a down-move followed by an up-move. Thus, at time $t = 2$, the price is given by one of three potential values: P_{uu}, P_{dd}, or $P_{ud} = P_{du}$.

In this framework, we assume that the volatility in prices σ is known and remains constant. The risk-neutral probabilities, i.e. the probabilities of future outcomes adjusted for risk, q and $(1 - q)$ are also known. Based on these assumptions and the general framework developed under the Cox-Ross-Rubenstein Binomial Option Pricing Model [23], the respective values for q, u, and d can be given by

$$q = \frac{e^{(r\Delta t)} - d}{u - d}, \tag{1}$$

$$u = e^{\sigma\sqrt{\Delta t}}, \tag{2}$$

$$d = \frac{1}{u}, \tag{3}$$

where Δt is the step size and r is the risk-free rate of interest. As $\Delta t \rightarrow 0$, the multiplicative binomial process described above converges to the geometric Brownian motion (GBM) [20] and the evolution of P can be described by

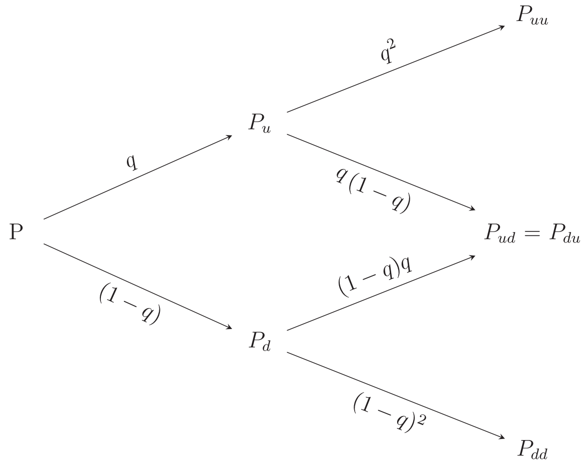

Fig. 1. A two-period recombining binomial tree depicting potential price paths and associated probabilities.

$$dP = \mu P dt + \sigma P dW, \tag{4}$$

where μ is the drift, σ is the volatility and dW is the increment of a standard Wiener process. The continuous approximation of the GBM is used to estimate the parameters in Eqs. (1)–(3). Subsequently, the parameters can be utilized to model the evolution of price in the discrete version of the model.

The net present value (NPV) of a project is the sum of discounted cash flows associated with a project. Mathematically it can be described as:

$$NPV = -CF_0 + \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t}, \tag{5}$$

where CF_0 is the initial investment at time $t = 0$ and CF_t represents the net cash flow (inflows - outflow) at time t. The inflows/revenues at each time-step are the value of agricultural output computed using the estimated per tonne market price of switchgrass P_t times the quantity of output or yield per hectare Y_t. Similarly, the outflows/expenditures represent the costs C_t associated with harvesting the produce and other on-farm/off-farm activities. Therefore, the CF_t term in Eq. (5) can be expressed as $CF_t = P_t Y_t - C_t$. Finally, r is the interest rate used to discount future cash flows to their present value. A positive NPV indicates that the present value of inflows exceeds the value of outflows over the life of the project thereby yielding a positive return on investment.

2.2. Analysis of profitability

For a 10-period binomial tree, there are $2^{10} = 1024$ possible price transition paths that can yield different NPVs. We use a combination of probability and matrix algebra to delineate all the potential price paths and associated NPVs using tools in R [24,25]. We consider a matrix $\mathbf{U}_{1024\times10}$ that represents the magnitude of all the possible permutations of an up-move u and a down-move d over the life of the project. Multiplying $\mathbf{U}$ by a scalar P, the inital price, allows us to capture the transition of switchgrass prices over the 10-year period. Similarly, we consider a matrix of yearly yields $\mathbf{Y}_{10\times10}$ which incorporates varying yields during the project life, i.e. lower yields in the early years until the switchgrass stand is established and optimal/full potential yields during the latter years of the project. Finally we consider a non-stochastic matrix of costs $\mathbf{C}_{1024\times10}$. Although the costs vary based on the year of operation, we assume that the costs are known prior to initiation of the project. The above matrices are used to compute year-on-year net revenues over the project life. Finally, discounting yearly net revenues to year 0, aggregating net revenues over the project life, and subtracting initial establishment costs CF_0 incurred in time-period $t = 0$, gives us the NPV under each price transition scenario.

3. Data and parameter estimates

In order to estimate the returns to a farmer, we construct a hypothetical time series of switchgrass prices. Using the Nebraska Energy Office database (http://www.neo.ne.gov/statshtml/66.html), we obtained a month-on-month time series of ethanol prices from December 2006 to December 2015. We chose this database due to the availability of recent data on ethanol prices. In addition, our cost and yield estimates for switchgrass pertain to the U.S. Midwest region, and ethanol prices in Nebraska can be considered representative for this region. The time period for the data series spans a period of 9 years and includes the twelve months prior to the passage of the 2007 EISA, which came into effect in December 2007. To arrive at the farmgate price of switchgrass, we adapt the methodology described in Song *et al.* [19]. We begin with historical ethanol prices and assume three levels of conversion efficiency (liters per tonne of ethanol) to estimate dollar prices per tonne of switchgrass. We subtract conversion costs and transportation costs to estimate the ethanol producers' willingness to pay for the feedstock. The ethanol producers' willingness to pay for the feedstock along with government subsidies determine the farmgate price.

Our assumptions pertaining to conversion costs are informed by previously published literature and a site visit to a cellulosic biofuel pilot plant operated by the University of Florida, Gainesville at their facility in Perry, Florida. Haque and Epplin (2012) collate cellulosic ethanol production costs reported by other studies ranging from 0.21 $ per liter to 0.89 $ per liter [26]. Differences in conversion costs arise from a variety of factors ranging from type of feedstock, pre-treatment, type of enzyme, yield as well as other economic assumptions. As a result, conversion costs exhibit large variations across different studies. Based on a recent study conducted by the University of Florida, we assume the conversion cost is 0.43 $ per liter [27]. Although the primary feedstock used in their study was sugarcane bagasse, discussions with the research team at the Perry plant suggested that the input requirements and the conversion process for ethanol produced using switchgrass would be similar [personal communication with Dr. L. Ingram at the University of Florida, Gainesville on 11/12/2015]. Additionally, the conversion cost assumed in this article lies within the range obtained from the meta-analysis conducted in Haque and Epplin (2012). We have not made specific assumptions on feedstock quality, or storage. However, transportation costs are assumed at 8.82 $ per tonne [28], which is comparable with transportation costs for a 48 kilometer radius [29].

The United States Department of Agriculture (USDA) provides financial assistance to farmers and landowners for growing, maintaining and harvesting biomass used for energy and bioproducts under the Biomass Crop Assistance Program (BCAP). The support usually comes in the form of establishment payments for growing new biomass crops, annual maintenance payments and matching payments towards collection, harvesting, transportation and storage costs [30]. In August 2015, the USDA revised the cost-share match to an equivalent of 22.05 $ per dry tonne of feedstock [31]. In our computations, we assume the government subsidy is $22.05 to compute our farm gate price. However, previously the USDA provided matching payments equivalent to 49.60 $ per dry tonne under the BCAP program, which we assume as the level of subsidy in our modified scenario [32]. We estimate parameters under both scenarios and compare our analysis under varying subsidy regimes. This helps to highlight the importance of government subsidies to make switchgrass cultivation economically competitive.

We compute farmgate prices under three conversion scenarios with conversion rates of 250, 292, and 334 liters of ethanol per tonne of switchgrass. These three conversion rates are referred to as the Low, Medium, and High scenarios in the remainder of the paper. Unless specified otherwise, all the results are presented for the Medium scenario. Furthermore, in order to estimate the parameters of the model, prices and costs are deflated using a monthly series of the Personal Consumption Expenditures Price Index obtained from the St. Louis Federal Reserve (available at https://fred.stlouisfed.org/series/CPIAUCSL#0). The base year is 2009 [CPI; 2009 = 100] which indicates that all prices and costs have been scaled to represent equivalent dollar values in 2009. In order to estimate the drift μ and the volatility σ parameters for the price process, we use a discrete version of the GBM. If P_t follows a GBM,

$$\ln P_t - \ln P_{t-1} = \left(\alpha - \frac{1}{2}\sigma^2\right) + \sigma\varepsilon \tag{6}$$

where $\varepsilon \sim N(0,1)$ [19]. The maximum likelihood estimates of α and σ are $\widehat{\alpha} = m + \frac{1}{2}s^2$ and $\widehat{\sigma} = s$ where m and s are the sample mean and standard deviation of the $\ln P_t - \ln P_{t-1}$ series [19,21]. Our analysis confirms that the transformed time-series for the data is stationary, allowing us to arrive at reliable estimates for our parameters. For the NPV analysis, we made informed assumptions pertaining to the per hectare yield, potential yield in the early years prior to stand establishment, stand life, establishment costs, operational costs and interest rates, which are outlined in Table 1.

Table 1
Summary of assumptions for the NPV analysis.

Variable	Assumption	Source
Duration	10 years	[37]
Plot size	1 hectare	
Establishment costs ($t = 0$)	$1006.72	[38]*; deflated to 2009 prices
Operational Costs (years 1 and 2)	$632.99 and $655.38	[38]*; deflated to 2009 prices
Operational Costs (years 3–10)	$600.30 per year	[38]*; deflated to 2009 prices
Yield per hectare	13.44 tonnes	[37,38]*
Yield (years 1 and 2)	30% and 70%	[37]
Yield (years 3–10)	100%	[37]
Interest rate r	4.6%	[39]

*values represented in SI units.

4. Results and discussion

Fig. 2 shows the estimated monthly per tonne price of switchgrass for the Medium conversion scenario where a tonne of switchgrass yields 292 liters of ethanol. This time-series was utilized to derive the parameters of the model. Our estimates for the average price P_{avg}, drift α and volatility σ in the three scenarios for the entire data-set under lower subsidy regime are given in Table 2.

Since the parameters were estimated using monthly data, it is important to use the appropriate time-step in order to compute the magnitude of the up-move u and the down-move d. The adjusted magnitudes, shown in Table 3, are computed using Eqns. (2)–(3) with a $\Delta t = 1/12$.

4.1. NPV computations

We set the initial per tonne price for switchgrass at $55.29, which is the average per tonne price estimated using historical ethanol prices, conversion and transportation costs, and a $22.05 subsidy as described earlier. Beginning with this initial price, we construct a binomial tree that extends in time for ten periods. To compute the NPV of an investment in switchgrass cultivation we consider one price realization at each time period. The revenues from the cultivation activity are computed using these prices whereas the costs, yield, and interest rate assumptions are identical to those stated previously. We evaluate a subset of these potential price paths and compare the NPVs under these scenarios. These computations help us highlight the sensitivity of the NPV to favorable and unfavorable price transitions. Tables 4 and 5 provide a summary of the price scenarios and the NPVs.

Out of the 7 scenarios described in Table 4, the NPV was positive only in two scenarios; (i) when prices increased in all periods, and (ii) when prices rose in the initial 5 periods and fell thereafter. These results are not particularly surprising because under the NPV framework revenues and costs arising in the early years after project inception are valued more whereas revenues/costs in the later years are heavily discounted and thus valued lower. However, a relatively wide spread in NPV among the different scenarios highlights the influence of the price transition on project NPVs with the spread between the NPVs in best and worst case scenarios, i.e. the scenario in which prices rise in all periods vis-à-vis the scenario in which prices fall in all subsequent periods, is nearly $8200.

In Table 5 we present additional price transition scenarios that help us identify critical-points in the NPV time-line wherein a switch occurs from negative to positive NPVs. The results indicate that if prices move up for the first fourth time-periods, then even if prices decline in the remaining six time-periods, the project NPV is positive. However, an up-move in prices only for the first three time-periods, followed by a decline in prices in subsequent periods, is not sufficient to cover for the project costs. On the other hand, if prices decline during the first three time-periods, an up-move in prices in the subsequent periods is insufficient to result in a positive project NPV. This also provides the farmer vital information about the potential profitability of the project much ahead of the project termination date. Under the existing binomial framework, if the per tonne price of switchgrass falls to $37.68 by the third time-period, the prospects for the project are unfavorable. Meanwhile, if the per tonne price rises to $90.15 by the fourth time-period the project outcome will always be favorable for the farmer given the assumptions of this model.

4.2. Profitability and risk

Evaluating the entire set of potential price paths, associated revenues, and costs allows us to closely study the distribution of NPVs. Fig. 3 provides a histogram of project NPVs indicating a positive skew to the distribution. While the spread of NPVs is quite wide, it is important to highlight that the probability of achieving a positive NPV is approximately 0.32 while the odds of making a loss are approximately 0.68. In other words, the project will yield a positive return approximately only 32% of the time.

In addition, an analysis of the odds of making profits or incurring losses with the passage of time reveals some interesting results. From an a priori probability of a positive return on investment at 0.32 at time $t = 0$, if the per tonne price of switchgrass moves up during period $t = 1$, the odds of making a profit on the investment increase to 50%. Moreover, if the price moves up in periods 1 and 2, the odds of a positive NPV increase to 72%. If prices continue to transition upwards in periods 3 and 4 the probability of attaining a

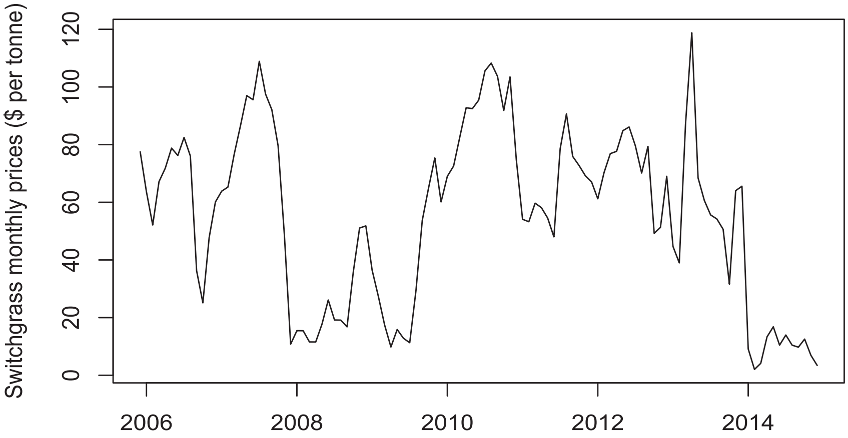

Fig. 2. Switchgrass prices for Medium conversion efficiency - estimated using historical ethanol prices under the low-subsidy scenario.

Table 2
Average prices and parameters with Low, Medium, and High conversion under the low subsidy scenario.

Low	Medium	High
$P_{avg} = 49.17$	$P_{avg} = 55.29$	$P_{avg} = 61.41$
$\alpha_l = 0.05$	$\alpha_m = 0.06$	$\alpha_h = 0.11$
$\sigma_l = 0.38$	$\sigma_m = 0.43$	$\sigma_h = 0.54$

Table 3
Magnitude of up-move and down-move under Low, Medium, and High scenarios.

Low	Medium	High
$u_l = 1.11$	$u_m = 1.13$	$u_h = 1.17$
$d_l = 0.89$	$d_m = 0.88$	$d_h = 0.86$

Table 4
Price Transition scenarios and corresponding NPVs.

Price Transition	Net Present Value
$P_t\uparrow$ (price moves up in every subsequent period)	$NPV_{HIGH} = \$5009.16$
$P_t\nearrow\searrow$ (price moves up first 5 periods, and then down 5 periods)	$NPV_{HL} = \$1428.68$
$P_t\nearrow\searrow$ (price moves up-down in alternate periods)	$NPV_{UD} = \$-418.75$
$P_t = P_0$ (Price constant at $55.29)	$NPV = \$-664.98$
$P_t\searrow\nearrow$ (price moves down-up in alternate periods)	$NPV_{DU} = \$-1034.67$
$P_t\searrow\nearrow$ (price moves down first 5 periods, and then up 5 periods)	$NPV_{LH} = \$-2145.31$
$P_t\downarrow$ (price moves down in every subsequent period)	$NPV_{LOW} = \$-3170.87$

Table 5
Additional price transition scenarios and corresponding NPVs.

Price Transition	Net Present Value
$P_t\nearrow\searrow$ (price moves up first 3 periods, and then down 7 periods)	$NPV_{U3D7} = \$-545.20$
$P_t\nearrow\searrow$ (price moves up first 4 periods, and then down 6 periods)	$NPV_{U4D6} = \$444.87$
$P_t\searrow\nearrow$ (price moves down first 3 periods, and then up 7 periods)	$NPV_{D3U7} = \$-547.58$
$P_t\searrow\nearrow$ (price moves down first 2 periods, and then up 8 periods)	$NPV_{D2U8} = \$790.99$

positive NPV on the project are 93% and 100% respectively as also noted in Table 6.

On the other hand, Table 7 shows that the probability of incurring losses increases if the per ton price of switchgrass declines with time. From an a priori probability of loss at 0.68, if the price falls at time $t = 1$, the probability of incurring a loss increases to 87%.A decline in prices for the 3 consecutive periods results in a probability of loss at 100%, i.e. the NPV will always be negative irrespective of favorable future price movements.

4.3. Computation of option values

The results from Table 5 and section 4.2 provide interesting insights, and present an opportunity to evaluate the influence of dynamic management pertaining to on-farm cultivation decisions. Given individual specific risk tolerance, a farmer has the option to expand the area of land under cultivation if the odds of making a profit on the investment or the magnitude of the NPV are beyond his/her preferred threshold or exit the investment if the price transitions appear to be unfavorable. We consider two management options: (1) the option to expand, and (2) the option to abandon.

4.3.1. Option to expand cultivation

Under this management option, we assume that the farmer has the ability to scale-up his operation by doubling the area under switchgrass cultivation from one hectare to two hectares. The costs associated with pre-establishment activities and year-on-year cultivation are assumed to remain the same as those stated earlier. In other words, we do not assume any inflation in costs and also do not account for any economies of scale in production activity. In addition, the yields on the additional hectare follow the same assumptions, i.e. 30% and 70% of potential in years 1 and 2 and 100% of potential beginning in year 3. However, we assume that the project ends at the end of the 10th year, at the same time as the completion of the first project. For example, if the farmer decides to expand cultivation in the second year, the revenues from the cultivation begin from the following year. Thus the end of life of project for the new investment is not exactly in line with the potential duration of the switchgrass stand.

Typically, after observing the prevailing per tonne market price for switchgrass at the end of a particular time period, a farmer could decide to expand operations. Establishment costs will be incurred immediately in order to prepare the land for switchgrass cultivation. However, the stream of revenues will only accrue one period later. We compute the NPV of the new investment under varying price scenarios to evaluate whether the option to expand switchgrass production yields an additional value to the farmer. Assuming that the per tonne price of switchgrass rises in all periods prior to exercising the option to expand cultivation, we evaluate the

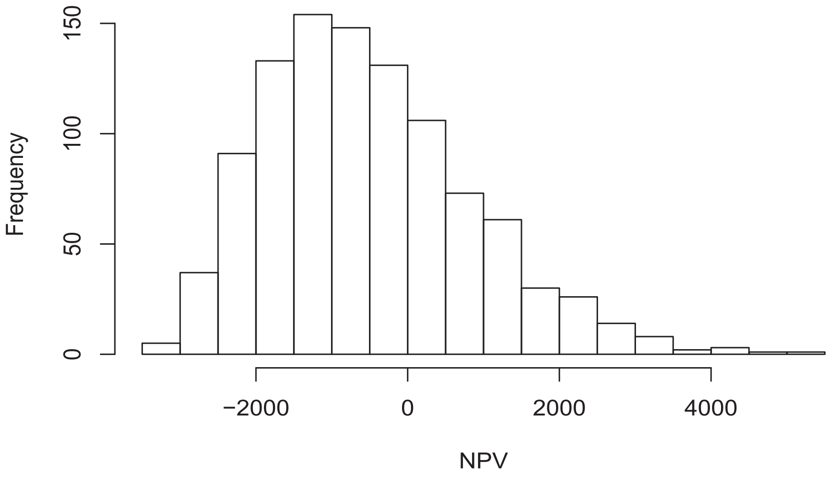

Fig. 3. Histogram of net present values for the medium scenario.

Table 6
Case 1 - Comparison of project profitability and NPVs wherein prices rise in all preceding periods.

	$t = 0$	$t = 1$	$t = 2$	$t = 3$	$t = 4$
Profit Odds	0.32	0.50	0.72	0.93	1.0
Loss Odds	0.68	0.50	0.28	0.07	0.0
	$t = 0$	$t = 1$	$t = 2$	$t = 3$	$t = 4$
Minimum NPV	$-3170.87	$-2419.56	$-1523.49	$-545.20	$444.87
Expected NPV	$-644.98	$4.74	$729.79	$1470.37	$2185.45
Maximum NPV	$5009.16	$5009.16	$5009.16	$5009.16	$5009.16

Table 7
Case 2 - Comparison of project profitability and NPVs wherein prices fall in all preceding periods.

	$t = 0$	$t = 1$	$t = 2$	$t = 3$
Profit Odds	0.32	0.13	0.03	0.0
Loss Odds	0.68	0.87	0.97	1.0
	$t = 0$	$t = 1$	$t = 2$	$t = 3$
Minimum NPV	$-3170.87	$-3170.87	$-3170.87	$-3170.87
Expected NPV	$-644.98	$-1283.47	$-1804.93	$-2218.93
Maximum NPV	$5009.16	$ 2613.52	$789.98	$-547.58

odds of the project being feasible/infeasible based on entry decisions at time periods 1 through 5 and their corresponding NPVs.

Under the assumptions described above, we observe that the odds of realizing a profit increase with the passage of time. However, the rate of change in profitability odds appear to plateau after time period $t = 4$. If an individual farmer were to make a decision primarily based on a particular threshold of the odds of making a profit, then he/she can decide to make the additional investment at a later time period. Meanwhile, from the perspective of maximizing NPV, exercising the option to expand at time period $t = 4$ compared to $t = 5$ allows the farmer to capture maximum gains from favorable price movements in the future, albeit also exposing him/her to greater downside risks (see Table 8). This computation is influenced by the end date of the project and thus the results do not account for the potential upside or downside of future price movements corresponding to the biological age of the switchgrass stand. Furthermore, the expected NPV of the additional investment is analogous to the value of the option to expand investment corresponding to each time period.

4.3.2. *Option to abandon cultivation*

Similar to the option to expand, we also evaluate the economic value of the option to abandon the current investment in switchgrass. We know that if the per tonne price for switchgrass falls to $37.68 by the third time-period, a future up-tick in prices for all subsequent periods will still yield a negative return on investment. Under this scenario, the farmer could be better off by abandoning the investment in switchgrass in order to limit his/her downside losses. We assume a scenario where prices are declining in every preceding period and that the cost of switching out of switchgrass cultivation to the alternate land use is equal to 111 $ per hectare [19]. Finally, we assume that the alternate land use is hay cultivation and the average revenue, net of costs, is 272.17 $ per hectare [33].

Based on the computations for the first three time periods, we can observe that the value of the option to exit the investment is the highest at time period $t = 3$ as shown in Table 9. The likelihood of profits is zero if prices have declined in the first three time periods and abandoning this investment while choosing an alternative with a positive revenue stream allows the farmer to limit the downside. However, exiting the investment in switchgrass during the earlier time-periods, also results in the farmer losing out on the opportunity to make profits arising from favorable price transitions if they were to occur.

The value of the alternative land use and the exit costs have a significant bearing on the eventual option value. If we assume that the alternate land use yields a per hectare net revenue is $544.34, which is twice as much compared to the scenario described above, the ensuing results suggest that the option value demonstrates a monotonic decline. Table 10 indicates that, if the magnitude of the revenues from alternate land use is high enough, the timing of the decision to exit the investment in switchgrass becomes very important.

5. Sensitivity analysis and alternate scenarios

We consider alternate scenarios and evaluate their influence on project NPVs. Based on the different conversion efficiencies, we can vary model inputs such as price, and magnitude of the up-move and the down-move to compute a range of project NPVs under the Low and High conversion scenarios as described in 2 and 3.

Similar to the analysis conducted for the Medium conversion scenario we compute project NPVs for a subset of price paths as

Table 8
Option value of expand decision under rising prices.

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
Expected NPV with expansion	\$-180.99	\$923.09	\$1929.61	\$2781.20	\$3446.47
Expected NPV status quo	\$4.74	\$729.79	\$1470.37	\$2185.45	\$2861.92
Option value	\$-185.73	\$193.30	\$459.24	\$595.75	\$584.55

Table 9
Option value of exit decision under declining prices and alternate revenue of $272.17.

	$t = 1$	$t = 2$	$t = 3$
Exit NPV	\$352.30	\$-122.68	\$-438.07
Expected NPV status quo	\$-1283.47	\$-1804.93	\$-2218.93
Option value	\$1635.77	\$1682.25	\$1780.86

Table 10
Option value of exit decision under declining prices and alternate revenue of $544.34.

	$t = 1$	$t = 2$	$t = 3$
Exit NPV	\$2235.15	\$1511.41	\$958.21
Expected NPV status quo	\$-1283.47	\$-1804.93	\$-2218.93
Option value	\$3518.62	\$3316.34	\$3177.14

Table 11
Price transition scenarios and corresponding NPVs.

Price Transition	NPV_l	NPV_h
$P_t \uparrow$ (price moves up in every subsequent period)	\$2765.83	\$9316.39
$P_t \nearrow\searrow$ (price moves up first 5 periods, and then down 5 periods)	\$244.37	\$3248.42
$P_t \nearrow\searrow$ (price moves up - down in alternate periods)	\$ − 1138.66	\$472.74
$P_t = P_0$ (Price constant $P_l = \$49.17$ and $P_h = \$\ 61.41$)	\$ − 1235.03	\$ − 94.92
$P_t \searrow\nearrow$ (price moves down-up in alternate periods)	\$ − 1613.87	\$ − 395.71
$P_t \searrow\nearrow$ (price moves down first 5 periods, and then up 5 periods)	\$ − 2496.20	\$ − 1877.94
$P_t \downarrow$ (price moves down in every subsequent period)	\$ − 3331.77	\$ − 3179.93

well as the expected odds for profit/loss of the investment. Table 11 provides a summary of the price scenarios and NPVs. The results of the NPV analysis under the Low scenarios indicate that the potential upside on the project is significantly lower than the High scenario, indicating that the starting price and volatility play a crucial role in overall project profitability. Furthermore, the NPV transitions from negative to positive occur at different time intervals in the High scenario when compared to the Low and Medium scenarios, which could result in different on-farm management practices. Table 12 shows the odds of profit and loss for the other two scenarios. It is important to note that even in the High scenario, the farmer is 48% likely to attain a negative return on investment, making investments in switchgrass an unattractive economic proposition.

Finally, we consider an alternate subsidy regime where the per tonne subsidy for switchgrass is $49.60. The parameters for the model were re-estimated while the assumptions of the model such as costs, yields and interest rate were kept unchanged. The parameters for this simulation were $P_0 = 81.88$, $u = 1.06$ and $d = 0.94$, however, the methodology used to compute the NPVs under multiple price transition paths as well as the profit/loss odds was identical to that adopted in the earlier sections of the paper. We consider only the Medium conversion efficiency scenario and found that, under the parameters of this model, the odds of making a loss on the investment came in at only 1% implying that the farmer can realize a profit in 99% of the outcomes.

Table 12
Profit/Loss odds in the Low and High Price Scenarios.

	P_l	P_h
Profit Odds	0.12	0.52
Loss Odds	0.88	0.48

6. Discussion

This study evaluates the economic value of switchgrass investments under price uncertainty. By adopting a discrete-time model, our approach is more realistic as we are able to incorporate the time-to-establishment characteristics of switchgrass cultivation as opposed to continuous time approaches. Furthermore, we account for variations in yield and operational costs during the project life-span to identify specific transition paths and the corresponding project NPVs indicating time-thresholds that result in a positive return on investment.

Federal and state policies are important factors influencing the cellulosic biofuels industry and understanding the profitability dynamics of the biofuels industry is extremely important from both private sector and policy perspectives [34]. However, the decision to invest in switchgrass will not only be guided by profitability of the investment itself, but also the profitability of the existing use of the land, among other factors. Previous studies have demonstrated that corn prices can be one of the most important factors influencing the profitability of investments in energy crops [19,35]. Our analysis considered hay as an alternate crop and demonstrated the sensitivity of investment decisions under multiple price scenarios. While our model assumed a relatively conservative yield assumption at 13.44 tonnes per hectare, it is likely that commercial cultivation of switchgrass could result in higher yields and therefore translate into higher returns on investment. The analysis can be easily modified for other varieties of switchgrass or other energy grasses with similar characteristics in the U.S. or for other energy grasses in other parts of the world. Finally, interest rates and access to finance could also influence the profitability of investments in switchgrass whereas technological advancements in conversion processes could increase overall profitability and translate into higher farmgate prices.

From an ecosystem services perspective, it is well known that perennial grasses such as switchgrass provide substantial carbon sequestration and soil nutrient retention. Moreover, they tend to require lower chemical and fertilizer inputs, and are beneficial for erosion control. Noe *et al.* [36] developed a model with payments for two ecosystem services, carbon sequestration and phosphorous retention, and found that prairie biomass production on marginal lands was 22% likely to be profitable when compensation for these services was included. However, they concluded that the profitability gap between conventional row crops and prairie cannot be bridged with payments for these two services alone. From a policy perspective, a payment that compensates for the market value of the direct and indirect ecosystem services of switchgrass cultivation could be considered. This may, on the one hand, result in higher returns to the landowner and make the investment in switchgrass more attractive while mitigating some of the consequences of on-farm activities on human and aquatic systems.

We only considered a single discount rate and we assumed no borrowing requirements for both initial capital costs and operating expenses. Future work could evaluate the impact of credit constraints and cost of capital on the feasibility of investments in switchgrass. In addition, preordained contracts between biofuel producers and farmers and insurance programs to protect the farmer from downside risks in a relatively nascent bioenergy industry could provide adequate assistance to farmers to adopt switchgrass cultivation. This framework can be adapted to compare the feasibility of investments in switchgrass and other energy crops or also for alternatives including agroforestry. Feedstock quality characteristics, timing of harvest, and storage costs could also be incorporated to extend the analysis. Finally, cultivation and processing cost estimates from other regions in the US and other parts of the world could be extremely useful to extend research in this area.

7. Conclusions

Based on the results of our model, it is evident that returns on switchgrass cultivation exhibit high volatility. This problem is accentuated by the relatively large up-front costs and long period of establishment until the crop reaches potential yield levels which are incorporated into the discrete-time model. In the medium conversion scenario with low subsidies, the likelihood of profitability of the investment is merely 32%. Furthermore, even in the high conversion scenario the farmer is likely to attain a negative return on investment in 48% of the outcomes. The relatively low profitability of switchgrass cultivation against the backdrop of price and demand uncertainties, could inhibit farmer participation. As such, subsidies could play an important role in encouraging farmer participation and our research is able demonstrate that project profitability is significantly higher in the high-subsidy assumption. For policy makers, it could be important to consider the nature of subsidies that could range from payments under existing crop assistance programs or compensation for ecosystem services provided by switchgrass.

The relationship between risk and profitability under different price transition paths and an analysis of option values highlights the relationship between the value of the option to expand or abandon the investment and the timing of the decision. We demonstrate the sensitivity of the option value, highlight the importance of active on-farm management, and validate the value of managerial flexibility in decision making. Landowners can adopt more dynamic farm management approaches to adjust their farming practices under evolving market conditions.

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