

**SWITCHGRASS CAPACITY PROCUREMENT CONTRACT
AND TONNAGE CONTRACT PRICING**

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Tianpeng Zhou
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DEDICATION

I dedicate this thesis to my parents, Xianfeng Zhou and Aifang Zhang, for the unselfish love they give to me.

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ABSTRACT

The on-farm production of switchgrass has been given considerable attention by farmers, policymakers and others. However, because the switchgrass market is not developed yet, most of the research only focuses on the switchgrass breakeven cost. The appropriate price combining interests of both the biorefinery and the farmers, or the contract price, has not been given enough attention.

Two types of contractual relationships are discussed in this thesis: Capacity Procurement Contract (CPC, per acre contract) and Tonnage Contract (TC, per ton contract). The contract prices of switchgrass under these two types of contracts are estimated in this analysis. Because the land quality and soil type also affect the yield and average cost of switchgrass production and corn production, the type of landscape also affects the contract price of switchgrass. Using west Tennessee as a case study, contract prices under four types of landscapes are analyzed: (i) a well-drained level upland (WDLU), (ii) a well- to moderately well-drained floodplain (WDFP), (iii) a moderate to somewhat poorly drained eroded sloping upland (MDSU), (iv) a poorly drained floodplain (PDFP). This research suggests that the MDSU land is the top choice for the biorefinery. Under the capacity procurement contract, the switchgrass contract price on MDSU land is \$474 per acre. Under the tonnage contract, the switchgrass contract price on MDSU land is estimated to be \$77 per ton. Compared to the capacity procurement contract, a tonnage contract is preferred by the biorefinery because the tonnage contract has more post contract risk advantage than the capacity procurement contract with regard to the unexpected change in switchgrass yield.

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CHAPTER I

INTRODUCTION

Biofuel has been in use in many countries around the world. For example, a high blend of ethanol and gasoline has been in use in Brazil for more than 30 years. Bioethanol was broadly introduced in Sweden in 2005 (Pacini and Silveira 2010). In the United States (US), concerns about the high dependency on imported oil and the environmental costs of fossil fuels are the main drivers of research on bioenergy (McLaughlin et al. 1999).

Farmers, policymakers and others have shown great interest in the on-farm production of biomass for ethanol production (English et al. 2006). The Energy Independence and Security Act of 2007 requires that 36 billion gallons of biofuel be produced from renewable sources within the US by 2022. About 6% of US corn is used to produce approximately 1 billion gallons of ethanol each year. However, this raises the ethical question with regard to the world shortage of food. Moreover, considering the continuously increasing price of corn, it is unlikely that corn can supply more than 2 billion to 2.5 billion gallons of ethanol annually in the future (McLaughlin et al. 1999).

Switchgrass has been identified as the model biomass feedstock for the biofuel industry to produce cellulosic ethanol based on the extensive research by the Bioenergy Feedstock Development Program at the Oak Ridge National Laboratory (McLaughlin et al. 1999; Fuentes and Taliaferro 2002; Epplin et al. 2007). It is a warm season, perennial grass that can grow to more than 2.75 meters in height and its rooting system can extend up to 3 meters in depth (Jensen et al. 2007). Switchgrass has a yield of 13.5-17.9 Mg per hectare or 6-8 short tons per acre in the southeastern US (Bouton 2002; Maposse et al. 1995). It can be planted in May

through early June and harvested annually using regular hay equipment (Jensen et al. 2007). Switchgrass has the greatest potential for being grown in the US among all biomass alternatives. Perlack et al. (2005) reported that 55 million acres of cropland, idle cropland, and cropland pasture could be seeded to produce switchgrass. English et al. (2006) also concluded that switchgrass could be planted on more than 100 million US acres with some incentives. The production costs of growing switchgrass in specific regions in the US are lower than those of other herbaceous crops (Khanna et al. 2008). Compared to traditional food crops such as corn and soybeans, switchgrass has many advantages. It grows on many soil types, including marginal lands not economically viable to grow traditional crops (Fewell et al. 2011), and only requires moderate inputs. For example, it is well adapted to grow on a large portion of the US land with low fertilizer applications and high resistance to naturally occurring pests and diseases (Bransby 1998). Switchgrass also helps to improve water quality and wildlife habitat (Duffy and Nanhon 2001), and protects soil from being eroded.

However, the market for switchgrass is not well developed yet (Fewell et al. 2011). Risk and uncertainty in switchgrass production and marketing are the major concerns for farmers when deciding whether to grow switchgrass. A contractual relationship with biorefineries specifying price, harvest timing, storage, and other requirements in contract clauses is welcome by farmers (Fewell et al. 2011). Meanwhile, a long-term production and harvest contract with an individual farmer can also be used by the biorefinery to reduce the switchgrass procurement risk (Epplin et al. 2007). Moreover, the high cost of constructing a production facility encourages the biorefinery to use contracts to induce farmers to supply sufficient feedstocks that will keep the plant operating at capacity (Larson et al. 2008).

Figure 1 gives a basic description of determining the switchgrass contract price between the biorefinery and the farmers. The biorefinery represents the demand side for the switchgrass, while the farmers represent the supply side of the switchgrass. The biorefinery's profit is mainly from producing and selling ethanol¹. Therefore, the revenue from ethanol sales is directly related to the ethanol market price and total ethanol output level. On the other hand, the costs of producing ethanol center on four main components: switchgrass procurement costs, switchgrass transportation cost, switchgrass storage cost, and biorefinery plant operating and maintenance cost. The conversion rate which is the amount (e.g. gallons) of ethanol produced from each ton of switchgrass measures the production efficiency in ethanol production.

The farmers can select whether to use their land to produce switchgrass or use the land as perhaps pasture for beef cattle or a traditional food crop, such as corn. If they decide to sign a contract and produce switchgrass, their profit will be determined by the switchgrass contract price, switchgrass yield, and the production costs. To attract farmers to grow switchgrass, the biorefinery must pay farmers enough to cover the explicit switchgrass production cost such as seed cost and fertilizer cost, and be high enough to cover the farmer's opportunity cost of producing switchgrass, or the expected profit from alternative land use. However, the biorefinery, a profit-maximizer itself, will try to keep the purchasing price, which is an input cost to the biorefinery, as low as possible.

¹ Under the Renewable Fuel Standard (RFS) each biorefinery has a quota for ethanol use. Biorefineries unable to meet their quota can purchase RINs (renewable identification numbers) from others who exceed their quota. A RIN is a 38-character code attached to a gallon of ethanol. Therefore, the biorefinery may also obtain profit from trading the RINs. The profit from trading RINs is not considered in this study.

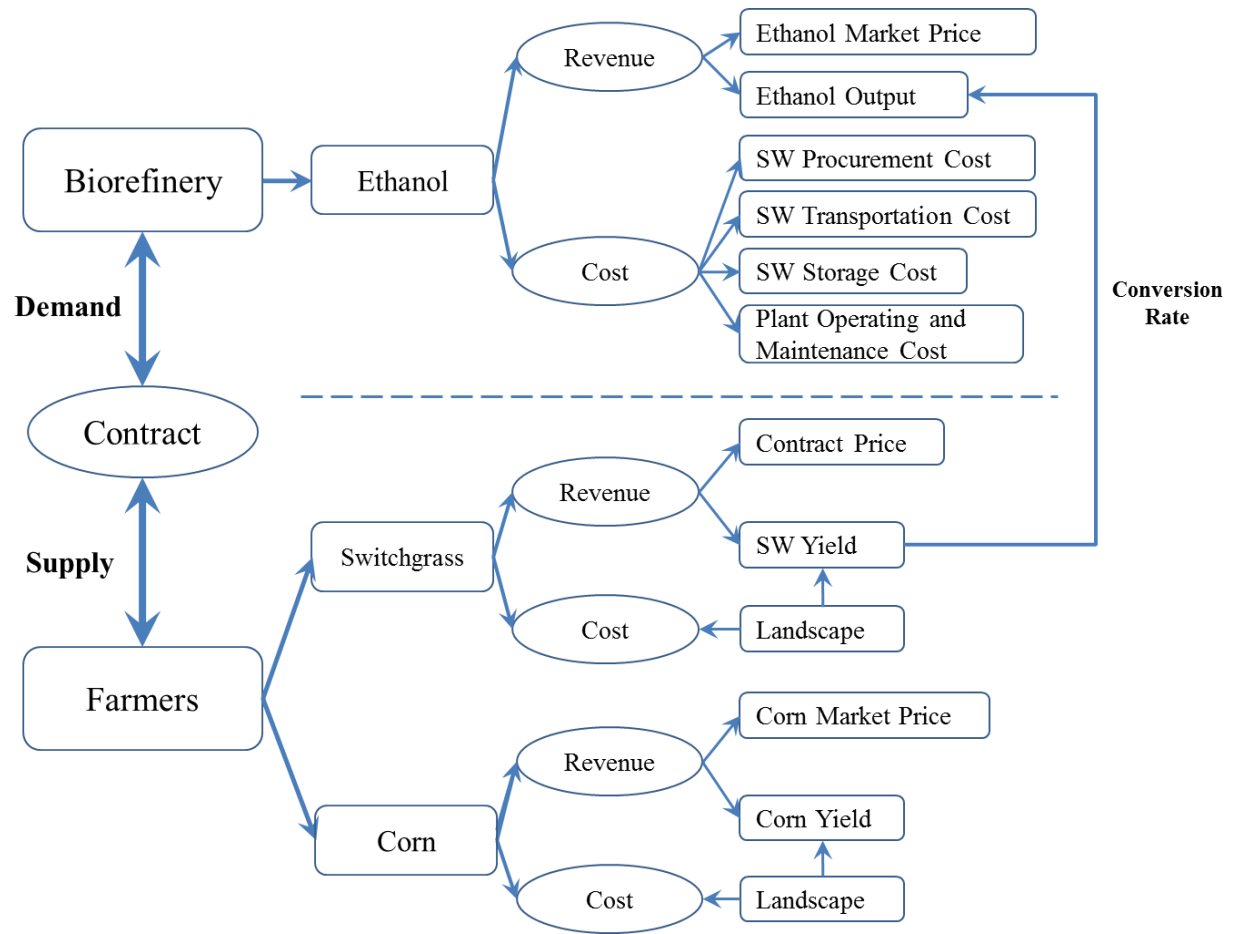


Figure 1 Switchgrass Supply/Demand Contract

Research Objectives

Using west Tennessee as a case study, the research objectives are:

1. Determine the contract price paid to the farmer under a Capacity Procurement Contract (CPC)² where the biorefinery pays a price for each acre of land allocated to switchgrass production.
2. Determine the contract price paid to the farmer under a Tonnage Contract (TC) where the biorefinery pays a price for each ton of switchgrass harvested.

² Capacity Procurement Contract is often referred to as Acreage Contract.

3. Determine the impact of land type on the contract price for both contract options.
4. Analyze the biorefinery's profit under each contract and different land types.
5. Conduct a sensitivity analysis on pre contract prices and on profits post contract.
6. Analyze contracts to determine the type contract that would be preferred by the biorefinery.

CHAPTER II

LITERATURE REVIEW

The literature review reflects the major components of Figure 1: ethanol production, switchgrass production, and contracts.

2.1 Ethanol Production

2.1.1 Ethanol Production Process

Switchgrass is classified as a lignocellulosic crop because it is primarily the cell walls that are digested to form sugars which can subsequently be fermented to produce liquid fuels (Wyman 1993; McLaughlin et al. 1999). Three major components of switchgrass are: cellulose (30-50%), hemicellulose (15-35%), and lignin (10-30%) (Carolan et al. 2007). Cellulose is a polymer of glucose, and hemicellulose is a polymer of five and six carbon sugars, mostly xylose. Both cellulose and hemicellulose can be converted to produce ethanol. Lignin cannot contribute to ethanol production. The high content of cellulose and hemicellulose (70%-90% in total) makes switchgrass the most promising feedstock for producing ethanol.

A thermo-chemical process and a biochemical process are the two ways used to convert biomass into biofuels. The thermo-chemical process is mainly used for the production of Fischer-Tropsch diesel fuel and hydrogen; biochemical processing, in contrast, is considered to be the most suitable method for converting biomass into ethanol (Carolan et al. 2007). In biochemical processing, pretreatment of switchgrass is needed to increase the surface area and make it more accessible to enzyme hydrolysis. Pretreated biomass then undergoes a hydrolysis

process to depolymerize the cellulose and hemicellulose into sugars. Next, enzymes are used to convert the sugars into ethanol through fermentation (Sun and Cheng 2002). Finally, the ethanol product is obtained through a recovery process (Carolan et al. 2007).

2.1.2 Conversion Rate

Conversion rate is usually used to determine the efficiency of producing ethanol using switchgrass as the feedstock. A higher conversion rate means that the biorefinery can produce more ethanol with a fixed amount of switchgrass or it needs less switchgrass to produce a certain amount of ethanol. Conversion rate is restricted by the technology employed by the biorefinery. For example, the conversion rate will be different between a thermo-chemical and a biochemical process. Various conversion rates are assumed in current literature. Three conversion rates, 60, 80, and 100 gallons of ethanol per ton of switchgrass, are assumed in Haque and Epplin (2012) with regard to a small, medium and large plant size biorefinery accordingly. The conversion rate was assumed to be 82.69 gallons per ton in Schmer et al. (2008). Humbird et al. (2011) reported the conversion rate to be 79.09 gallons per ton which is close to the conversion rate of a medium sized biorefinery (80.05 gallons per ton) used in Haque and Epplin (2012). Sendich et al (2008) and Wu et al. (2010) estimated the conversion rate to be 69.99 gallons per ton. Eggeman and Elander (2005) reported the conversion rate to be 64.95 gallons of ethanol out of one ton of switchgrass.

2.1.3 Ethanol Production Cost and Breakeven Price

Because the biomass market has not been well developed yet, the analysis of market price for ethanol produced from biomass is limited. Most research on ethanol price has focused on the

estimation of the biorefinery production cost, or ethanol breakeven price. Plant operation and maintenance cost includes labor cost, utilities expenses, chemical cost, taxes, repair cost, and investments. The plant operation and maintenance cost is assumed to be \$0.75 per gallon (Haque and Epplin 2012).

The estimated total cost to produce cellulosic ethanol ranges from \$0.79 to \$4.73 per gallon (Haque and Epplin 2012). The average cost estimations differ due to the assumptions of ethanol conversion rate, biorefinery investment cost, switchgrass cost as the feedstock, the commercial scale of operation, and whether storage and transportation costs were considered to be costs to the biorefinery.

Wyman (2007) indicated that total production cost per gallon of ethanol varied from \$0.52 to \$0.64, and the \$0.12 variability was due entirely to changes in ethanol yield per ton of switchgrass. The US Department of Energy estimated that the cost of producing ethanol would be \$1.02 per gallon (Aden et al. 2002; Goldemberg 2007; Tyner 2008). The study by Goldemberg (2007) showed the total ethanol production cost was \$1.07 per gallon. Tyner (2008) estimated the total cost of ethanol would be \$1.12 per gallon. The highest ethanol breakeven price was estimated by Haque and Epplin (2012) ranging from \$0.44 to \$0.72 per liter (\$1.67-\$2.73 per gallon) conditioned on different biorefinery plant sizes and ethanol conversion rate assumptions. The main difference in these estimations depended on whether storage and transportation costs were considered to be costs to the biorefinery.

Based on a sample of 4,825 monthly reports from 232 fueling stations in Minnesota between October 1997 and November 2006, the retail ethanol price ranged from \$0.74 to \$2.96 per gallon, with mean \$1.74 per gallon and standard deviation \$0.35 per gallon, while the range of the wholesale ethanol price was larger: ranging from \$0.45 to \$3.03 per gallon, with a lower

mean \$1.27 and higher standard deviation \$0.56 in 2006 dollars (Anderson 2010). Both the retail and wholesale average price of ethanol are slightly higher than the estimated breakeven prices, indicating there is only a little profit margin for biorefineries. The biorefinery may be faced with a perfectly competitive ethanol market.

2.1.4 Ethanol Futures Pricing

One of the main difficulties in an empirical study of ethanol price is that the spot market price is quite uncertain. The daily or weekly spot price is not only hard to observe directly, but also varies among different geographic regions, which makes the spot price report of ethanol unreliable. In contrast, the futures contracts are better organized and standardized, and traded actively in the exchanges. Therefore, the futures prices of ethanol provide the guidelines for the ethanol price evaluation. In fact, the corresponding prices of ethanol futures contracts closest to maturity are often used as a proxy for the spot price (Schwartz 1997). Brennan and Schwartz (1985) derived a mathematical relationship between the futures prices and spot prices using a stochastic model to describe the movement of commodity spot prices. Moreover, Gibson and Schwartz (1990) built a similar model considering both the spot price movement and the benefits from holding a futures contract, or instantaneous convenient yield, to derive the functional relationship between the futures price and the spot price. These futures pricing formulas provided the theoretical basis for applying empirical analysis to estimate and to project commodity spot prices. Applying the Kalman filter method, Schwartz (1997) found that simply modeling the commodity spot price movement without considering the instantaneous convenience yield could not describe the commodity futures price movement very well. Moreover, Schwartz and Smith (2000) described a model by splitting the spot price into two

components: a short-term price deviation component and a long-term equilibrium price component. The Kalman filter was also used in Schwartz and Smith (2000) to estimate and to forecast the unobservable commodity spot prices. The detailed futures pricing techniques can be found in Schreve (2004) and Duffie (2001). A summary of the Kalman filter method is demonstrated in Appendix A.3³.

2.2 Switchgrass Production

2.2.1 Switchgrass Yield

The planting dates of switchgrass range from late-April to mid-June. In the first year, about 25% of switchgrass will not survive the winter of that year. In the second year, the switchgrass that failed to survive will be replaced or reseeded (Khanna et al. 2008). As a perennial crop, switchgrass can be harvested annually. About 67% of the maximum yield of switchgrass will be harvested in the second year (Khanna et al. 2008). From the third year onwards, the yields remain constant through the remaining life of the crop. Mooney et al. (2009) also reported the first and second-year switchgrass yields would be 14% and 60% of third-year yields on average. Moreover, switchgrass can be harvested as a one- or two-cut system (Garland 2008). There would be an 8% increase in the yield with two-cut management for switchgrass (Alamo) compared to the one-cut management (Fike et al. 2007). When cut twice a year, the first cutting would occur when switchgrass is in late boot to very early seedhead emergence in

³ More formal and complete discussions on Kalman filter were demonstrated in Harvey (1989) (Chapter 3), Hamilton (1994) (Chapter 13), Brockwell and Davis (2002) (Chapter 8), Durbin and Koopman (2012) (Chapter 2 and 4), and West and Harrison (1997).

late-June or early-July; the second cutting would be in November or the first killing frost, whichever comes earlier (Garland 2008).

The yield of switchgrass production also varies among different production environments. The southeastern United States is considered a likely region to produce switchgrass because growing seasons are longer and the yield for traditional crops is lower compared to other regions (Boyer et al. 2012; Dicks et al. 2009; English et al. 2006; Mooney et al. 2009). Estimated across the lifespan of switchgrass, the yield per acre in the southern US is considered to be greater than that in the northern states (McLaughlin and Kszos 2005). Walsh et al. (2003) estimated that on the land currently planting traditional crops, the average yield of switchgrass in the southeast US was 5.49 tons per acre with a range from 3.40 to 6.47 tons per acre; however, the average yield was 3.48 tons per acre in the northern Plains ranging from 2.01 to 5.49 tons per acre. Duffy (2007) calculated the average yield level of switchgrass was 4 tons per acre in Iowa. Khanna et al. (2008) estimated the yield of switchgrass in Illinois was 4.20 tons per acre. In contrast, the switchgrass estimations in southern states were higher. Fike et al. (2006) reported an average yield of 5.45 tons per acre in West Tennessee. McLaughlin and Kszos (2005) reported the average yield in Tennessee was 6.16 tons per acre with the best one-year yield at 12.22 tons per acre. Muir et al. (2001) reported an average yield of 5.97 tons per acre in Texas. Epplin et al. (2007) reported that the average annual yield of switchgrass in Oklahoma was 6.06 tons per acre.

Mooney et al. (2009) reported that the yield of switchgrass was affected by the land quality. Based on a 3-year multilocation experiment at Milan, TN, they estimated the well-drained upland location suitable for row crops had the highest yield of 7.89 tons per acre and the poorly drained flood plain location had the lowest yield of 3.79 tons per acre. Similar to Mooney

et al. (2009), research in west Tennessee during a seven-year period (2005-2011) was conducted by Boyer et al. (2012) on four landscapes: (i) a well-drained level upland (WDLU), (ii) a well- to moderately well-drained floodplain (WDFP), (iii) a moderate to somewhat poorly drained eroded sloping upland (MDSU), (iv) a poorly drained floodplain (PDFP). The WDLU and WDFP landscapes were well suited for row crop production in Tennessee, while the MDSU and PDFP landscapes represented the marginal land for crop production in Tennessee (Boyer et al. 2012). During this longer time period compared to Mooney et al (2009), the average yields of switchgrass calculated by Boyer et al. (2012) across these seven years from these four types of landscapes (WDLU, WDFP, MDSU, and PDFP) were 7.19, 7.57, 7.86, and 7.17 tons per acre respectively.

2.2.2 Switchgrass Production Costs and Breakeven Price

Much of the analysis of the economic potential for switchgrass has focused on estimating switchgrass production costs (Jensen et al. 2007). Mooney et al. (2009) analyzed the production costs based on the University of Tennessee Extension switchgrass production budget including the costs involved in establishment, maintenance and harvest stages. Maintenance cost included capital recovery cost, machinery repair and maintenance cost, fuel and lube cost, taxes, insurance expenses and housing cost, assuming the use of 150-hp tractors to power farm implements, labor at \$8.50 per hour, a diesel fuel price of \$2.12 per gallon, and a nominal interest rate of 8%. Establishment cost was limited to the first year of production and included machinery and labor time, seed, herbicide, fertilizer, and interest on operating costs. Seed price was \$20 per pound of pure live seed, while 98.8 pounds of P_2O_5 and 197.8 pounds of K_2O were used as nutrients per acre at a price of \$0.32 and \$0.22 per pound accordingly (Garland 2008). Harvest cost was

calculated as a function of yield for switchgrass harvested in large round bales (1500 pounds per bale) and included machinery and labor costs, bale twine cost and interest on variable operating cost. The total harvest cost varied depending on the yield of the switchgrass. Moreover, total switchgrass production cost in the first year differed from costs in subsequent years, because the cost of land preparation and planting to establish the crop occurred in the first year. In the second year, reseeding or replanting costs would occur from replacing plants that did not survive the first winter (Khanna et al. 2008). In the subsequent years, the maintenance cost and harvest cost were assumed to be constant through the remaining lifespan of switchgrass.

Breakeven price is commonly analyzed in evaluating the economic potential of switchgrass. The farm-gate breakeven price is the price per ton of switchgrass needed to offset all costs of production incurred over the lifetime of the crop discounted to current prices divided by the discounted value of successive yields (Khanna et al. 2008). Farm-gate price does not consider any other costs beyond harvest and storage of switchgrass bales at field edge. Due to the different weather and land conditions and different assumptions made on bale types and storage methods, the average cost of producing switchgrass varies among different regions, and therefore the breakeven price differs accordingly. Generally speaking, the production of switchgrass in the Southeastern US has an advantage compared to the northern US latitudes. Duffy (2007) calculated the breakeven price for switchgrass to be \$82.23 per ton in Iowa by assuming the rectangular bales and indoor storage. Khanna et al. (2008) estimated a farm-gate breakeven price for switchgrass to be \$88.90 per ton in Illinois. Perrin et al (2008) estimated the average of farm-gate breakeven prices in central Plains at \$53.52 per ton. In contrast, the breakeven price for switchgrass ranged from \$42.90 to \$62.23 per ton in the southeastern US depending on the land conditions (Mooney et al. 2009). Epplin et al. (2007) reported a unit

production cost of switchgrass for the southern states to be \$50.80 per ton without considering the costs beyond harvest. Based on the net present value (NPV) approach, Walsh et al. (2003) used the POLYSYS⁴ model to estimate the farm-gate price of bioenergy crops based on the competition with alternative usage of croplands. Through the modeling of the switchgrass supply schedule and the demand schedule, the farm-gate price of switchgrass was estimated to be \$49.91 per dry ton.

Contrary to the popular belief, few farmland acres are not used in productive activities. Therefore, switchgrass production will require some shift in traditional cropland use to “biofuel feedstocks” (Dicks et al. 2009). The competition of bioenergy crops with high-value crops in land usage determines the opportunity cost of alternative land uses (Walsh et al. 2003; Mooney et al. 2009), that is, the profits foregone from the most profitable alternative use of the land that is converted to a perennial grass (Khanna et al. 2008). A survey conducted by Jensen et al. (2007) revealed that farmers with higher net farm incomes per acre were willing to convert smaller shares of their farmland to switchgrass. Those with higher off-farm incomes were willing to convert more acres. The research done in Illinois assumed that corn and soybean were the two dominant row crops grown in rotation with each other as the alternative for switchgrass (Khanna et al. 2008). The breakeven price of switchgrass was calculated to be \$90 per dry ton after including the opportunity cost of land compared to \$65 per ton without including the opportunity cost of land (Khanna et al. 2008).

⁴ POLYSYS is an agricultural policy simulation model of the U.S. agricultural sector. It includes national demand, regional supply, livestock and aggregate income modules. POLYSYS model is used to simulate impacts to the U.S. agricultural sector resulting from changes in policy, economics, or resource conditions (Walsh et al. 2003).

2.2.3 Switchgrass Transportation and Storage

After being harvested, the feedstocks, e.g. switchgrass, need to be transported to the biorefinery and stored. Whether the storage and transportation cost should be shouldered by the biorefinery or by the farmers depends on the specification of their contracts. But due to the equipment-intensive enterprise nature of transportation and storage, it is usually assumed to be the biorefinery which shoulders the transportation and storage tasks (Cundiff and Marsh 1996). The transportation cost includes loading cost, labor cost, fuel cost, and machinery cost. The cost of hauling switchgrass can be minimized through maximizing the dry matter in every truckload (Cundiff and Grisso 2008). Larson et al. (2005) indicated that the cost of transportation was \$10 per dry ton. Perrin et al. (2008) reported that the average cost of transporting round bales to a refinery was about \$13 per ton. Other research maintained that the average transportation cost was affected by the distance shipped from the farm to the biorefinery. Walsh et al. (1998) estimated the transportation cost ranged from \$5 per dry ton to \$8 per dry ton within a 25 mile transport distance. Duffy and Nanhou (2001) claimed that the estimated transportation costs were about \$0.10 per dry ton per mile for hauling distances of less than 50 miles and the typical transportation costs were expected to be between \$5 and \$10 per dry ton for a distance less than 75 miles. Duffy (2007) estimated that the transportation cost was \$6.10 per ton within a 5-mile trip, and the transportation cost increased to \$8.65 per ton within a 30-mile trip.

The exposure of switchgrass bales to rain, ultraviolet rays and humidity result in the dry matter loss of switchgrass during the storage process (Sanderson et al. 1997). The cost of storing includes not only the cost for the facilities used, but also the dry matter loss associated with various storage methods (Duffy 2007). The storage cost also varies with regard to bale types. Rectangular bales have the cost advantage in transportation and saving space in storage

compared to round bales, but the dry matter loss is greater using square bales than using covered round bales (English et al. 2008). Large round bales have the advantage of shedding water which is especially needed in the southern U.S. due to the year-round precipitation (Larson et al. 2005). Cundiff and Marsh (1996) estimated the cost for storing round switchgrass bales without a tarp was \$3.20 per dry ton. Wang et al. (2009) determined that the cost of storage for a round bale was \$3.83 per dry ton. The difference was whether the round bales were wrapped with plastic tarp or not. Duffy (2007) estimated that the storage cost per ton for square bales ($3 \times 4 \times 8$ feet, with a weight of 950 pounds) was \$16.67 if stored in an enclosed building.

2.3 Contracts

An extensive literature examines the reason why an agricultural producer might prefer a marketing or production contract to a spot market. Asset specificity, which is the degree of an asset can be used to other purposes, and uncertainty are the key motivators for contract application (Jensen et al. 2007). The ownership of a highly specialized asset can leave a party vulnerable in negotiations which may cause the owner prefer a contract to reduce the risks involved (Jensen et al. 2011). Moreover, a greater uncertainty in price implies a greater risk from opportunistic behavior. Thus, a contract will limit the exposure to environmental (e.g. supply, demand, and price) uncertainty (Franken et al. 2009).

Contracts are widely used in traditional agricultural sectors to reduce the risk and uncertainty in production and marketing. With the level of vertical integration in agricultural markets growing over the last decade, production contracts have been more prevalent in

livestock and specialty grains markets because of the risk in production and procurement in spot markets (Goodhue 2000; Ginder et al. 2000). Principal-agent⁵ theory was used in Goodhue (2000) to model production contracts in the broiler industry. The study found that contracts outlining different compensation schemes were optimal responses to risk aversion. A transaction cost approach, used to examine specialty crop contracts in Canada, found that market power on the buyers' side led to reduced competition in the contract's compensation terms (Weleschuk and Kerr 1995). The standard marketing contract (or bushel contract) and the acreage contract in specialty grain production were also analyzed in Paulson and Babcock (2007). By modeling the production uncertainty in switchgrass and corn, the result indicated that bushel contract structure Pareto dominated the optimal acreage contract (Paulson and Babcock 2007).

Various studies have found farm characteristics and farmer demographics have an impact on farmers' choice on whether or not to use a contract. For example, a larger farm size has a positive impact on contracting (Jensen et al. 2011; Dong et al. 2008; Edleman 2006). The diversification of the farm is negatively related with contracting (Davis and Gillespie 2007; Dong et al. 2008) due to the reason that diversification can reduce the risk. Jensen et al. (2011) gave the detailed description in current literature with regard to the farm characteristic and farmer demographic impacts on the selection of contracting.

Because the market for switchgrass has not been well-developed, the risks of producing and procuring switchgrass also play a major role for farmers and the biorefinery respectively. Given the high cost of constructing a production facility, the biorefinery will have an incentive to provide the farmers a contract to guarantee a sufficient feedstock to keep the plant operating at capacity (Larson et al. 2008). Jensen et al. (2011) suggested that the farmers are willing to grow

⁵ The principal-agent problem concerns the difficulties in motivating one party (the 'agent') to act on behalf of another (the 'principal') due to information imperfection.

switchgrass under a contract. This willingness was greater among the farmers who farmed more lands, had facilities in which they could store switchgrass and had substantial off-farm income. The contract can also reduce the risk and uncertainty faced by the farmers in switchgrass marketing. Yang et al. (2012) revealed that for a given level of risk aversion, farmers with low land quality were more willing to sign contracts with a biorefinery to produce bioenergy crops due to the cost of foregoing row crop production. The higher the risk level of the farmers, the more likely they will contract with biorefineries (Yang et al. 2012). Therefore, a contractual arrangement is beneficial to both farmers and the biorefinery. A guaranteed price at which the switchgrass is sold to the biorefinery needs to be specified in the contract (Covert and English 2012). From the biorefinery's perspective, the guaranteed price facilitates the biorefinery making future predictions and calculations regarding the price of ethanol produced. From a farmer's perspective, a contract minimizes the risk and uncertainty in switchgrass production and marketing, especially when the switchgrass market is under development. Yang et al. (2012) also suggested that farmers' land allocation decisions are dependent on both their individual land quality and risk preferences. A farmer with low land quality and high degree of risk aversion will choose to lease their land for biomass production. A farmer with low land quality and low risk aversion will choose to grow the energy crop under a profit sharing contract instead of a fixed price contract.

A contract also needs to specify the lifespan of the contract for farmers and the biorefinery. A ten-year production lifespan is usually used in literature (Duffy 2007; Khanna et al. 2008). Perrin et al. (2008) maintained that the average cost of switchgrass production over ten years (\$53.61 per ton) was lower than the average cost over five years (\$59.75 per ton) based on their experience in North Dakota, South Dakota and Nebraska. Mooney et al. (2009) reported

the yield and breakeven prices of switchgrass for both a 5-year and 10-year contract lifespan and concluded that the breakeven price for a 5-year contract is higher than for a 10-year contract. The contract beyond five years may be subject to more production risk and uncertainty in future price fluctuations and does not take full consideration of the possibility of switchgrass seed improvement.

A detailed study on biomass contract structures with regard to the potential of a West Tennessee grain farm to supply lignocellulosic biomass to a biorefinery was conducted by Larson et al. (2008). Four potential types of contracts offering different levels of biomass price, yield, and production risk-sharing between farmers and biorefineries were analyzed: the spot market contract, the standard marketing contract, the acreage contract, and the gross revenue contract (Larson et al. 2008). Their research evaluated the ability and willingness of farmers to provide lignocellulosic biomass feedstocks under risk given the farmers' on-farm situation and potential contractual arrangements with user facilities (Larson et al. 2008). In a spot market contract, biomass was priced yearly on its current energy equivalent value as a substitute for gasoline. Farmers bore all the output price, yield, and production risk from biomass production in this contract. In a standard marketing contract, biomass was sold at the equivalent spot market price with a penalty for underage or excess production. Larson et al. (2005) analyzed the risk management benefits of a standard marketing contract. It was shown in Larson et al (2008) that a portion of risk was shifted from farmers to the biorefinery. An acreage contract guaranteed a fixed annual price for the actual biomass produced on the contracted acreages, and the biorefinery had to buy all the yield of the switchgrass annually. All price risks were born by the biorefinery while farmers still incurred all yield and production cost risks. In contrast, guaranteed annual gross revenue per acre over the life of the contract was provided in a gross

revenue contract (Larson et al. 2008). Larson et al. (2008) pointed out that the acreage and gross revenue contracts were more effective at inducing maximum farm biomass production at lower contract prices than the standard contract for a risk neutral decision maker.

CHAPTER III

CONCEPTUAL FRAMEWORK

3.1 The Biorefinery

3.1.1 Ethanol Production

The production function of ethanol is subject to the technology a biorefinery owns to produce ethanol using switchgrass as a feedstock. More specifically, assume the conversion rate from switchgrass to ethanol is ω , which means the biorefinery will produce ω units (e.g. gallons) of ethanol using one unit (e.g. ton) of switchgrass as feedstock; then the production function of the biorefinery is a linear function to the amount of switchgrass used as input, that is,

$$(1) \quad Y = \omega Q_t(L)$$

where Y is the quantity of ethanol produced, and $Q_t(L)$ the amount of switchgrass produced with L units (e.g. acres) of land used as the feedstock in year t . The marginal production in equation (1) is constant which is different from the usual assumption of diminishing marginal returns.

However, the conversion rate ω in equation (1) can be explained as the average conversion rate when the biorefinery uses switchgrass to produce ethanol. It represents the average production efficiency in a biorefinery's production process.

3.1.2 Biorefinery's Profit

Considering the heterogeneity among farmers, e.g. farmers locate in different counties or have different land fertility levels (Jensen et al. 2007), the biorefinery can try to sign a contract with each farmer willing to grow switchgrass. In each contract, switchgrass price is specified

clearly with other contract clauses. Through a price discrimination strategy, the biorefinery can take advantage of the heterogeneity among farmers, and achieve the greatest profit level.

All costs apart from the costs of purchasing, storing and transporting switchgrass, such as labor cost, biorefinery maintenance cost, and monitoring cost, are assumed to be at a fixed level held by the biorefinery. The biorefinery has the capacity to process all the switchgrass. Assume the total expenditure on switchgrass procurement is SW . Dry matter loss is not considered; the amount of switchgrass stored and delivered should be equal to the amount of switchgrass harvested. The total cost of producing ethanol from switchgrass is the summation of switchgrass procurement cost SW , storage cost, transportation cost, and the operating and maintenance cost. When the ethanol spot market is perfectly competitive, or the biorefinery is a price-taker in ethanol market, the revenue of selling ethanol in spot market equals the ethanol spot price $S(t)$ multiplied by ethanol output level Y , which is $S(t)Y$. So the biorefinery's profit at time t can be determined by subtracting total costs of ethanol production from the total revenue of ethanol sales, that is,

$$(2) \quad \pi_t = S(t)Y - SW - OMC \times Y - s \times Q_t(L) - m \times Q_t(L)$$

where OMC is the average plant operating and maintenance cost, s is the storage cost per ton of switchgrass stored/harvested and m is the transportation cost per ton of switchgrass transported/harvested. By substituting equation (1) into equation (2), the profit equation can be rewritten as:

$$(3) \quad \pi_t = (S(t) - OMC) \omega Q_t(L) - SW - s \times Q_t(L) - m \times Q_t(L)$$

The biorefinery should determine the contract price based on the maximization of the expected value of the future's discounted profit within the full contract lifespan. The reason that the expected value needs to be considered by the biorefinery is that though the biorefinery's

production condition may not have significant changes during the contract lifespan (therefore the costs may stay constant), the ethanol spot price will not be the same as the price when the contract is signed. Therefore the biorefinery's profit in the future is subject to the future ethanol spot market conditions, which makes it necessary to project the future profit level when it tries to enter a contract specifying the input procurement in the future. Assuming the contract lasts T years and the switchgrass is harvested once a year, by continuously discounting all the future net cash inflow/profit back into the initial time $t = 0$, the continuous-time present value is:

$$(4) \quad E \int_0^T \pi_t e^{-rt} dt = E \int_0^T [(\omega(S(t) - OMC) - s - m)Q_t(L) - SW] e^{-rt} dt$$

where r is the discount factor. Equation (4) gives the overall discounted profit level the biorefinery can achieve during a contract lifespan of T by signing a switchgrass procurement contract with a farmer.

3.1.3 Ethanol Price

3.1.3.1 Ethanol Valuation Model

Often, the daily or weekly spot prices of ethanol are hard to obtain, especially when one tries to collect the historical data. The spot market price also varies among different counties and states which makes it very uncertain. The same commodity's futures contract price is often chosen to be the proxy for the spot price. A standard model built in Schwartz (1997) described the functional relationship between the futures price and the spot price of different commodities. The model in Schwartz (1997) and its empirical application can be found in Appendix A.1.

Compared to the model described in Schwartz (1997), Schwartz and Smith (2000) developed a simpler and more intuitive model by splitting the spot price into two components:

the long-run equilibrium price component and the short-run price deviation component. The long-run equilibrium price components describe the “fair value” of the commodity based on the current demand and supply conditions. However, the spot price is usually not equal to the equilibrium price. There is a difference between the spot price and the equilibrium price in most cases, which is the short-run price deviation component. Moreover, it has been shown that the model in Schwartz and Smith (2000) is equivalent to the model described in Schwartz (1997), but the parameters to be estimated are fewer in Schwartz and Smith (2000) model. In this thesis, the Schwartz and Smith (2000) model is used to describe the price movement of ethanol due to its parsimonious property in parameter estimation.

In this model, the Efficient Market Hypothesis is adopted, which means that the futures market efficiently incorporates all public information. All the information obtained by the public, including individual investors and researchers, has already been incorporated in the futures price. For example, if an oil shortage has been expected by the public, the futures price of ethanol will increase based on the expectation of high ethanol demand in the future.

Let S_t denote the spot price of ethanol at time t . Assume that the spot price of ethanol can be decomposed into two components: the long-run equilibrium price component ξ_t and the short-term deviation component δ_t , which is,

$$(5) \quad \log(S_t) = \delta_t + \xi_t$$

Moreover, the short-term deviation is assumed to follow an Ornstein-Uhlenbeck process⁶ with mean reverting towards zero, which can be shown in a total derivative function:

$$(6) \quad d\delta_t = -\kappa\delta_t dt + \sigma_1 dz_1$$

and the equilibrium price level is assumed to follow a Brownian motion process

⁶ In an Ornstein–Uhlenbeck process, X , satisfies the following stochastic differential equation: $dX = \kappa(\tau - X)dt + \sigma dz$, where dz denotes the Wiener process (or Brownian motion).

$$(7) \quad d\xi_t = \mu dt + \sigma_2 dz_2$$

where dz_1 and dz_2 are the increments of a standard Brownian motion process⁷. Assume that the short-term deviation and equilibrium price are correlated with

$$(8) \quad dz_1 dz_2 = \rho dt$$

Equation (6) shows a negative relationship between the change in deviation and the deviation level. It means that when the short-term deviation is increasing, the speed of the deviation change will decrease until the deviation disappears. This inverse relationship is the “mean-reverting” property. In other words, the mean-reverting property in equation (6) shows that there is an inner force that will pull the spot price towards the equilibrium price level, though they seldom will be the same. The increment dz_1 describes the unexpected change in the price deviation which is subject to some unforeseeable random events. Sometimes some events will push the spot price away from the equilibrium level while some events will pull the spot price closer to the equilibrium level. Parameter κ in equation (6) describes the rate at which the short-term deviations are expected to disappear. Different from equation (6), equation (7) assumes that there is a trend in the equilibrium price movement with a rate μ though the equilibrium price is still subject to the random change dz_2 . Variables σ_1 and σ_2 describe the volatility of the random effects in both the short-run deviation and long-run equilibrium respectively, and the random effects are correlated with a coefficient ρ .

Under the assumptions mentioned in equations (5), (6), (7), and (8), it can be shown that

δ_t and ξ_t are jointly normally distributed with the mean vector (Appendix A.2):

⁷ Let $(\Omega, \mathcal{F}, p)$ be a probability space. For each $\omega \in \Omega$, Brownian motion is a continuous function $z(t)$ depending on ω that satisfies: (1) $z(0) = 0$; (2) for all $0 = t_0 < t_1 < \dots < t_n = T$, the increments $z(t_1) - z(t_0), z(t_2) - z(t_1), \dots, z(t_n) - z(t_{n-1})$ are independent, and (3) each of these increments is normally distributed with $E(z(t_{i+1}) - z(t_i)) = 0, \text{Var}(z(t_{i+1}) - z(t_i)) = t_{i+1} - t_i$ (Shreve 2004).

$$(9) \quad E[\delta_t \quad \xi_t'] = [e^{-\kappa t} \delta_0 \quad \xi_0 + \mu t']$$

which means that the expected value of the short-run price deviation component, δ_t , is $e^{-\kappa t} \delta_0$ and the expected value of long-run equilibrium price component, ξ_t , is $\xi_0 + \mu t$. Parameters δ_0 and ξ_0 stand for the current short-run price deviation component level and long-run equilibrium price component level. As can be seen from equation (9), the expectation of short-run price deviation follows an exponential path with respect to time, which is faster than the change in the expectation of long-run equilibrium price which follows a linear path along with time.

Moreover, the variance-covariance matrix of δ_t and ξ_t can be written as

$$(10) \quad \text{vcov}[\delta_t, \xi_t] = \begin{bmatrix} (1 - e^{-2\kappa t}) \frac{\sigma_1^2}{2\kappa} & (1 - e^{-\kappa t}) \frac{\rho \sigma_1 \sigma_2}{\kappa} \\ (1 - e^{-\kappa t}) \frac{\rho \sigma_1 \sigma_2}{\kappa} & \sigma_2^2 t \end{bmatrix}$$

which means that the variances of the short-run price deviation component, δ_t , and the long-run equilibrium price component, ξ_t , are $(1 - e^{-2\kappa t}) \frac{\sigma_1^2}{2\kappa}$ and $\sigma_2^2 t$. Therefore, the variance of long-run equilibrium price increases with time which shows that the forecasted price will be less accurate in the future. The covariance of short-run price deviation component and the long-run equilibrium price component is $(1 - e^{-\kappa t}) \frac{\rho \sigma_1 \sigma_2}{\kappa}$.

Given the current level of short-run price deviation and long-run equilibrium price components, though they are hypothetical values, δ_0 and ξ_0 , the log of the ethanol spot price is then normally distributed with the mean and variance:

$$(11) \quad E(\log(S_t)) = e^{-\kappa t} \delta_0 + \xi_0 + \mu t$$

and

$$(12) \quad \text{var}(\log(S_t)) = (1 - e^{-2\kappa t}) \frac{\sigma_1^2}{2\kappa} + \sigma_2^2 t + 2(1 - e^{-\kappa t}) \frac{\rho\sigma_1\sigma_2}{\kappa}$$

Equations (11) and (12) can be derived directly from equation (5) in which $\log(S_t)$ is defined to be the summation of short-run price deviation component δ_t and long-run equilibrium price component ξ_t . The ethanol spot price is therefore log-normally distributed with the expected price given by

$$(13) \quad E(S_t) = \exp(E(\log(S_t)) + \frac{1}{2} \text{var}(\log(S_t)))$$

or

$$(14) \quad \log(E(S_t)) = e^{-\kappa t} \delta_0 + \xi_0 + \mu t + \frac{1}{2} \left((1 - e^{-2\kappa t}) \frac{\sigma_1^2}{2\kappa} + \sigma_2^2 t + 2(1 - e^{-\kappa t}) \frac{\rho\sigma_1\sigma_2}{\kappa} \right)$$

If the forecast horizon increases ($t \rightarrow \infty$) and κ is positive, the log of the expected spot price can be simplified as

$$(15) \quad \log(E(S_t)) = (\xi_0 + \frac{\sigma_1^2}{4\kappa} + \frac{\rho\sigma_1\sigma_2}{\kappa}) + \left(\mu + \frac{1}{2} \sigma_2^2 \right) t$$

which means that the expected future ethanol spot price follows an exponential time path.

Under the risk-neutral valuation paradigm, the risk-neutral stochastic process is needed to describe the dynamics of the spot ethanol prices, and discounts all cash flows at a risk-free rate (Schwartz and Smith 2000). By introducing two market price of risks, λ_1 and λ_2 , for short-run price deviation component and long-run equilibrium price component accordingly to specify the reductions in the drifts for each process, under an equivalent martingale measure⁸, the risk-neutral stochastic processes can be rewritten as

⁸ Equivalent martingale measure assumption rules out the possibility of arbitrage. The detailed description on equivalent martingale measure can be found in Shreve (2004) (Chapter 5), Duffie (2001) (Chapter 6), Elliott and Kopp (2005) (Chapter 2).

$$(16) \quad d\delta_t = -(\kappa\delta_t - \lambda_1)dt + \sigma_1 dz_1^*$$

$$(17) \quad d\xi_t = (\mu^* - \lambda_2)dt + \sigma_2 dz_2^*$$

where dz_1^* and dz_2^* are increments of standard Brownian motion processes with

$$(18) \quad dz_1^* dz_2^* = \rho dt$$

λ_1 and λ_2 reduce the adjustment speed for both the short-run price deviation component and the long-run equilibrium price component. Different from equation (6), under risk-neutral situation, the short-term deviation tends to revert back to κ/λ_1 instead of zero and the drift of equilibrium price is μ^* (defined to be $\mu - \lambda_2$) instead of μ . Using similar reasoning for equations (9)-(15), under this risk-neutral process, the expected value and variance of the log of spot price, $\log(S_t)$, are

$$(19) \quad E^*(\log(S_t)) = e^{-\kappa t} \delta_0 + \xi_0 - (1 - e^{-\kappa t}) \lambda_1 / \kappa + \mu^* t$$

and

$$(20) \quad \text{var}(\log(S_t)) = (1 - e^{-2\kappa t}) \frac{\sigma_1^2}{2\kappa} + \sigma_2^2 t + 2(1 - e^{-\kappa t}) \frac{\rho \sigma_1 \sigma_2}{\kappa}$$

Equations (19) and (20) provide the basic information needed to derive the futures pricing formula.

Let F_T denote the current ethanol futures market price with time T from now until maturity. Under the risk neutral assumption, the futures contract price is equal to the forward contract price assuming the interest rate is fixed, which means the futures contract price equals to the expected spot price, that is,

$$(21) \quad \log(F_T) = \log(E^*(S_t)) = E^*(\log(S_t)) + \frac{1}{2} \text{var}^*(\log(S_t)) = e^{-\kappa t} \delta_0 + \xi_0 + A(T)$$

where

$$A(T) = -\frac{(1-e^{-\kappa T})\lambda_1}{\kappa} + \mu^*T + \frac{1}{2}\left[(1-e^{-2\kappa T})\frac{\sigma_1^2}{2\kappa} + \sigma_2^2T + 2(1-e^{-\kappa T})\frac{\rho\sigma_1\sigma_2}{\kappa}\right]$$

Equation (21) represents the functional relationship between the futures contract price and the current short-run price deviation component level and the long-run equilibrium price component level. The time to maturity also affects the price of the futures contract through $A(T)$. All the other unknowns are parameters which can be calculated through empirical estimation.

3.1.3.2 Empirical Model

The price of ethanol futures contracts can be obtained by transforming the valuation model into an empirical model. However, the ethanol spot price is hard to determine, because it differs between different geographic locations across the country. Moreover, it is also hard to detect the short-run price deviation component and the long-run equilibrium price component that make up the spot prices as in equation (5). Therefore, they can only be treated as unobservable variables. Then, equation (21) cannot be estimated directly using time series methods. Instead, the spot price of ethanol and the forecasted price movement of ethanol in the future can be estimated and projected using ethanol futures price data through the Kalman filter method.

Kalman filter is an algorithm for sequentially updating a linear projection for the system each time a new observation is brought in (Hamilton 1994). Once the recursive relationships between the observable variable and the prediction of unobservable variables are built, the unknown parameters can be estimated using Maximum-Likelihood Estimation with the data obtained. The basics on the Kalman filter method are demonstrated in Appendix A.3.

If we consider contracts with different days to maturity, $T_1, T_2, \dots, T_n$, equation (21) can be rewritten as a discrete form:

$$(22) \quad y_t = Z_t [\delta_t \quad \xi_t]' + d_t + \varepsilon_t$$

where

$y_t = [\log(F_{T_1}) \quad \dots \quad \log(F_{T_n})]'$, $n \times 1$ vector of observed futures prices with time maturities $T_1, T_2, \dots, T_n$;

$$Z_t = \begin{bmatrix} e^{-\kappa T_1} & 1 \\ \vdots & \vdots \\ e^{-\kappa T_n} & 1 \end{bmatrix} \quad n \times 2 \text{ matrix};$$

$$d_t = [A(T_1) \quad \dots \quad A(T_n)]' \quad n \times 1 \text{ vector.}$$

ε_t denotes the measurement error and follows a serially uncorrelated normal distribution with the expected value and variance to be

$$E(\varepsilon_t) = 0 \quad \text{var}(\varepsilon_t) = H = \begin{bmatrix} s_1^2 & & \\ & \ddots & \\ & & s_n^2 \end{bmatrix}$$

Once the data on the futures prices are obtained, the futures prices $F_{T_1}, F_{T_2}, \dots, F_{T_n}$ are obtained.

The time left to maturity $T_1, T_2, \dots, T_n$ can also be obtained. Therefore, the short-run price

deviation component δ_t and long-run equilibrium price component ξ_t are the only unknown

variables in equation (22). Without knowing the value of δ_t and ξ_t , the parameters in equation

(22) are impossible to be estimated. To estimate the parameters, more assumptions on δ_t and ξ_t

need to be imposed. From equations (6) and (7), the state equation can be written in discrete

time steps as

$$(23) \quad [\delta_t \quad \xi_t]' = T[\delta_{t-1} \quad \xi_{t-1}]' + c + \omega_t$$

where

$$T = \begin{bmatrix} e^{-\kappa\Delta t} & 0 \\ 0 & 1 \end{bmatrix}, \quad 2 \times 2 \text{ matrix};$$

$$c = [0 \ \dots \ \mu\Delta t]', \quad 2 \times 1 \text{ vector}.$$

and where Δt represents the minimum time unit used in measuring time left to maturity.

Moreover, ω_t is the random error and follows a serially uncorrelated normal distribution with

$$E(\omega_t) = 0 \quad \text{var}(\omega_t) = \begin{bmatrix} (1 - e^{-2\kappa\Delta t}) \frac{\sigma_1^2}{2\kappa} & (1 - e^{-\kappa\Delta t}) \frac{\rho\sigma_1\sigma_2}{\kappa} \\ (1 - e^{-\kappa\Delta t}) \frac{\rho\sigma_1\sigma_2}{\kappa} & \sigma_2^2\Delta t \end{bmatrix}$$

ε_t and ω_t are uncorrelated with all lags, that is,

$$E(\varepsilon_t \omega_t) = 0, \quad t = 1, 2, \dots, T \text{ and } s = 1, 2, \dots, T$$

Combining equations (22) and (23), the parameters κ , σ_1 , σ_2 , μ , μ^* , λ_1 , ρ and H can be estimated. Intuitively, the long-maturity futures contract price will give information on the equilibrium price and the difference between near- and long-term futures prices gives information about the short-term deviations (Schwartz and Smith 2000). Mathematically, from equation (5), it can be presented as,

$$(24) \quad F_{T_1} = \exp(\delta_0 + \xi_0) \text{ and } F_{T_n} = \exp(\xi_0)$$

Therefore, if the current futures prices are known, the initial (or current) equilibrium price component and the price deviation component can be obtained through equation (24).

3.2 Farmers

Faced with the contract price of switchgrass proposed by the biorefinery, the farmers choose either to accept or to reject the offer. If the offer is accepted, the farmer signs a T -year contract with the biorefinery agreeing to supply switchgrass each year to the biorefinery, and is paid annually at the contracted price. If the offer is rejected, the farmer grows an alternative crop instead. Corn is used as the alternative crop in this analysis. Therefore, the farmer's decision is based on whether the profit from signing a contract and growing switchgrass is high enough to cover the profit earned from growing alternative crops, such as corn. In other words, the profit from growing corn can be viewed as the reservation value considered by the farmer as to whether to grow switchgrass or corn.

3.2.1 Switchgrass

3.2.1.1 Switchgrass Yields

The annual output level of switchgrass is determined by the inputs and other factors, such as weather. To simplify the analysis, only the land acreage is used as the single input in this model. Therefore, the switchgrass production function can be written as

$$Q_{sw}(L) = f_1(t, L)\tilde{\varepsilon}$$

where $f_1(t, L)$ is the total output capacity of growing switchgrass on L acres of land in year t , and $\tilde{\varepsilon}$ is a positive random factor switchgrass output is subject to. Output capacity function $f_1(t, L)$ is assumed to be independent the random factors. $\tilde{\varepsilon}$ has the probability density function $g(\cdot)$, cumulative density function $G(\cdot)$, support $[\underline{\varepsilon}, \bar{\varepsilon}]$, finite mean ε_0 and variance σ_ε^2 . The multiplication of switchgrass output capacity and the random factor means that the effect of a

yield random factor is to amplify or to narrow the output capacity to some yield level. For example, when the weather is abnormal in some year, e.g. a serious drought hits the region, $\tilde{\varepsilon}$ will be small, which makes the multiplication of $f_1(t, L)$ and $\tilde{\varepsilon}$ be small. So the actual switchgrass output level is low in that particular year, and the weather condition of that year will not affect the switchgrass production in the next year.

However, by assuming the average yield of switchgrass from one acre of land is γ_1 across years significantly simplifies the analysis on switchgrass production. The expected switchgrass production from L acres of land can then be written as a linear function of land acreages, that is,

$$(25) \quad E(Q_t(L)) = \alpha_t \gamma_1 L$$

where α_t is the percentage of switchgrass harvested in year t compared to the maximum annual yield during the lifespan of switchgrass. More specifically, Mooney et al. (2009) reported that the maximum switchgrass yield occurred from the third year after planting, while the yield in the first year is only 14% of the maximum yield, and the yield in the second year is 60% of the maximum. Therefore, $\alpha_1 = 14\%$, $\alpha_2 = 60\%$, $\alpha_3 = 100\%$, $\alpha_4 = 100\%$, $\dots$. γ_1 represents the productivity of switchgrass out of each acre of land, and therefore it varies among different types of landscapes. For example, the yield of switchgrass on fertile land is greater than the less fertile land.

3.2.1.2 Switchgrass Production Cost

Assuming the average switchgrass production cost is c_1 per ton, the total cost of producing switchgrass on L acres of land can be written as,

$$(26) \quad C_{sw} = c_1 Q_t(L)$$

c_1 can also be viewed as the breakeven price of producing switchgrass. It incorporates all the switchgrass production costs, including establishment cost, maintenance cost, harvest cost, etc.

3.2.2 Corn

3.2.2.1 Corn Production

Similar to switchgrass production, the production function of corn can also be specified as the multiplication of corn potential production $f_2(L)$ and a random factor $\tilde{\epsilon}$:

$$Q_{corn}(L) = f_2(t, L) \tilde{\epsilon}$$

$\tilde{\epsilon}$ is the random factor indicating all the factors affecting the production level of corn, e.g. weather. Similar to $\tilde{\epsilon}$, $\tilde{\epsilon}$ has a density function $h(\cdot)$, cumulative density function $H(\cdot)$, support $[\underline{\epsilon}, \bar{\epsilon}]$, finite mean ϵ_0 and variance σ_{ϵ}^2 . The corn production capacity function $f_2(L)$ is assumed to be independent of yield distribution $H(\cdot)$.

To simplify the corn production function above, the average yield each year from one acre of land across years is assumed to be γ_2 . Therefore, the expected corn yield each year on L acres of land is

$$(27) \quad E(Q_{corn}(L)) = \gamma_2 L$$

γ_2 represents the productivity of different types of landscapes. In this analysis, only two types of landscapes, traditional crop production lands and marginal lands are considered. Expected yields on traditional crop production lands will be larger than that from the marginal lands.

Assuming the average corn production cost is c_2 per ton, the total cost of producing corn on L acres of land can be written as,

$$(28) \quad C_{corn} = c_2 Q_{corn}(L)$$

where c_2 incorporates all the corn production costs, such as fertilizer purchasing cost, labor cost, and fuel costs.

3.2.2.2 Corn Profit

The maximum expected corn profit is the opportunity cost to the farmers, when the farmers consider signing a contract with the biorefinery to grow switchgrass for a few years. During the same lifespan as the switchgrass contract, the expected discounted overall future corn profit is:

$$(29) \quad E \int_0^T [P_t Q_{corn}(L) - C_{corn}] e^{-rt} dt$$

where r is the discount factor.

Farmers will determine the optimal amount of land usage L to obtain the maximum expected profit from corn production. Substituting equation (27) and (28) into equation (29), the profit maximization problem faced by the farmers can be written as:

$$(30) \quad E\Pi_0 = \max_L \int_0^T [E(P_t) - c_2] \gamma_2 L e^{-rt} dt$$

$$s.t. \quad L \leq \bar{L}$$

where $\bar{L}$ is the amount of land owned by the farmer. Therefore, the maximum profit from growing corn is:

$$(31) \quad E\Pi_0 = \int_0^T [E(P_t) - c_2] \gamma_2 \bar{L} e^{-rt} dt$$

Because the average yield of corn varies among different landscapes, the profit of growing corn will also be different between traditional crop production lands and marginal lands. If all other factors are assumed to be equal, the profit from growing corn on marginal lands will be smaller

than that from the traditional crop production lands because the productivity (γ_2) on marginal lands is smaller than that on traditional crop lands.

3.2.2.3 Corn Price

3.2.2.3.1 Corn Valuation Model

To simplify the analysis, corn is the only alternative traditional food crop considered by the farmers to grow on the land in this model. The potential profit from corn production determines whether the farmers are willing to grow switchgrass. Farmers need to project the future corn price. However, similar to ethanol spot prices, the corn spot market price is often hard to observe directly. Therefore, the corn futures price is used as the proxy to estimate the corn spot prices. The Schwartz and Smith (2000) model is also used together with Kalman filter to get the expected price of corn.

Assume that the spot price of corn at time t , P_t , can be decomposed into two parts: the long-run equilibrium price component ξ_t' and the short-run deviation from the equilibrium component δ_t' , that is,

$$\log(P_t) = \delta_t' + \xi_t'$$

Moreover, the short-run deviation component and long-run equilibrium price component are also assumed to follow the following stochastic processes:

$$(32) \quad \begin{aligned} d\delta_t' &= -\kappa'\delta_t' dt + \sigma_1' dz_1' \\ d\xi_t' &= \mu' dt + \sigma_2' dz_2' \\ dz_1' dz_2' &= \rho' dt \end{aligned}$$

where dz_1' and dz_2' are the increments of a standard Brownian motion process. κ' describes the rate at which the short-run deviation is expected to disappear. Similar to the deductions in ethanol pricing, the expected corn price in the future can be derived as a function of spot corn price and the expected time length, that is,

$$(33) \quad E(P_t) = \exp\left(E(\log(P_t)) + \frac{1}{2} \text{var}(\log(P_t))\right)$$

or

$$(34) \quad \log(E(P_t)) = e^{-\kappa't} \delta_0' + \xi_0' + \mu't + \frac{1}{2} \left((1 - e^{-2\kappa't}) \frac{\sigma_1'^2}{2\kappa'} + \sigma_2'^2 t + 2(1 - e^{-\kappa't}) \frac{\rho' \sigma_1' \sigma_2'}{\kappa'} \right)$$

When the forecast horizon increases ($t \rightarrow \infty$), the log of the expected spot price will be close to

$$(35) \quad \log(E(P_t)) = \left(\xi_0' + \frac{\sigma_1'^2}{4\kappa'} + \frac{\rho' \sigma_1' \sigma_2'}{\kappa'} \right) + \left(\mu' + \frac{1}{2} \sigma_2'^2 \right) t$$

Under risk-neutral assumption, the equations (30) (31) and (32) can be revised by introducing martingale measurement and two prices of market risks, that is,

$$(36) \quad d\delta_t' = -(\kappa'\delta_t' - \lambda_1')dt + \sigma_1' dz_1^{*'}$$

$$(37) \quad d\xi_t' = (\mu^{*'} - \lambda_2')dt + \sigma_2' dz_2^{*'}$$

$$(38) \quad dz_1^{*'} dz_2^{*'} = \rho' dt$$

where $\mu^{*'} = \mu' - \lambda_2'$, $dz_1^{*'}$ and $dz_2^{*'}$ are the increments of standard Brownian motion processes under martingale measurement, and λ_1' and λ_2' are the market price of risks for the short-run price deviation component and the long-run equilibrium price component. Let F_T' denote the current corn futures market price with time T from now until maturity. The futures price can be derived as

$$(39) \quad \log(F_t') = \log(E^*(P_t)) = e^{-\kappa t} \delta_0' + \xi_0' + B(T)$$

where

$$B(T) = -\frac{(1-e^{-\kappa T})\lambda_1'}{\kappa'} + \mu^* T + \frac{1}{2} \left[(1-e^{-2\kappa T}) \frac{\sigma_1'^2}{2\kappa'} + \sigma_2'^2 T + 2(1-e^{-\kappa T}) \frac{\rho' \sigma_1' \sigma_2'}{\kappa'} \right]$$

3.2.2.3.2 Empirical Model

Similar to the ethanol pricing, the parameters are estimated by applying Kalman filter method. Considering the contracts with n different days to maturity $T_1, T_2, \dots, T_n$, equation (39) can be rewritten as a discrete form, that is

$$(40) \quad y_t' = F_t \begin{bmatrix} \delta_t' & \xi_t' \end{bmatrix}' + d_t' + \varepsilon_t'$$

where

$$y_t' = \begin{bmatrix} \log(F_{T_1}') & \dots & \log(F_{T_n}') \end{bmatrix}', \quad n \times 1 \text{ vector of observed futures prices with days}$$

to maturity $T_1, T_2, \dots, T_n$;

$$F_t = \begin{bmatrix} e^{-\kappa T_1} & 1 \\ \vdots & \vdots \\ e^{-\kappa T_n} & 1 \end{bmatrix}, \quad n \times 2 \text{ matrix};$$

$$d_t = \begin{bmatrix} B(T_1) & \dots & B(T_n) \end{bmatrix}', \quad n \times 1 \text{ vector.}$$

ε_t' denotes the measurement error and follows a serially uncorrelated normal distribution with

$$E(\varepsilon_t') = 0 \quad \text{var}(\varepsilon_t') = H = \begin{bmatrix} s_1'^2 & & \\ & \ddots & \\ & & s_n'^2 \end{bmatrix}$$

From equations (30) and (31), the state equation written in discrete time steps is

$$(41) \quad \begin{bmatrix} \delta_t' & \xi_t' \end{bmatrix}' = G \begin{bmatrix} \delta_{t-1}' & \xi_{t-1}' \end{bmatrix}' + c' + \omega_t'$$

where

$$G = \begin{bmatrix} e^{-\kappa'\Delta t} & 0 \\ 0 & 1 \end{bmatrix}, \quad 2 \times 2 \text{ matrix};$$

$$c' = [0 \quad \dots \quad \mu'\Delta t]', \quad 2 \times 1 \text{ vector}.$$

ω_t' is the random error and follows a serially uncorrelated normal distribution with

$$E(\omega_t') = 0 \quad \text{var}(\omega_t') = \begin{bmatrix} (1 - e^{-2\kappa'\Delta t}) \frac{\sigma_1'^2}{2\kappa'} & (1 - e^{-\kappa'\Delta t}) \frac{\rho'\sigma_1'\sigma_2'}{\kappa'} \\ (1 - e^{-\kappa'\Delta t}) \frac{\rho'\sigma_1'\sigma_2'}{\kappa'} & \sigma_2'^2 \Delta t \end{bmatrix}$$

ε_t' and ω_t' are uncorrelated with all lags, that is,

$$E(\varepsilon_t' \omega_t') = 0, \quad t = 1, 2, \dots, T \text{ and } s = 1, 2, \dots, T$$

The long-run equilibrium price component and short-run deviation component at current time can be calculated from the following equations based on the near- and long-term futures (Schwartz and Smith 2000):

$$(42) \quad F_{T_1}' = \exp(\delta_0' + \xi_0') \text{ and } F_{T_n}' = \exp(\xi_0')$$

The parameters needed to be calculated are κ' , σ_1' , σ_2' , μ' , μ^* , λ_1' , ρ' and H' . The projected price movement trend can be obtained by substituting the estimated parameters into the equations (34) and (35).

3.3 Contracts

Some assumptions need to be specified in advance to build the proposed switchgrass pricing model. First, the contract arrangement is assumed to be under a forced compliance regime, which means that the biorefinery monitors the action of the farmers to guarantee the full employment of the technology and resources owned by farmers (Cachon and Lariviere 2001). The biorefinery monitoring activity is so intense that the farmers are forced to do their best to produce the switchgrass. Farmers have no chance to “shirk” under a given contract structure. Second, both the biorefinery and the farmers are risk neutral. Therefore, they are assumed to pursue the maximum profit in the contract structure: a monopsonistic biorefinery would try to suppress the contract price paid to the farmers; however, the farmers could switch to corn if the switchgrass contract price is too low. Also, the ethanol output of the biorefinery is assumed to be less than the market demand upper bound⁹, which means that no ethanol has to be put into storage. Two different switchgrass contract types are modeled: the capacity procurement contract and the tonnage contract.

⁹ The “blend wall” is created by current regulation requiring the ethanol blended into gasoline be no more than 10% ethanol. This is the biggest barrier faced by the ethanol industry in the US, and which may cause the demand for ethanol to be less than the supply.

3.3.1 Capacity Procurement Contract (CPC)

3.3.1.1 Farmers' Choice in a Capacity Procurement Contract

3.3.1.1.1 Switchgrass Profit from a Capacity Procurement Contract

In a capacity procurement contract, the biorefinery will pay a price for each unit of land allocated toward switchgrass production. When accepting the biorefinery's price offer, farmers will receive ρ_{CPC} ¹⁰ per acre of land for all the switchgrass harvested to the biorefinery each year within the contract lifespan. Therefore, a farmer's gross revenue in each year from the land is

$$(43) \quad SW = \rho_{CPC} L$$

where L represents the total acreage of land contracted in producing switchgrass.

The profit of producing switchgrass under a capacity procurement contract at time t can be written by subtracting total cost C_{sw} from total contract revenue SW :

$$(44) \quad \pi_1(t) = SW - C_{sw}$$

Because of the assumption that the contract price, land usage and total cost are independent of time, farmers' profit from growing switchgrass is also independent of time, that is,

$$(45) \quad \pi_1 = \rho_{CPC} L - c_1 Q_t(L)$$

The expected net present value of growing switchgrass is achieved by discounting all of the future profit back to the initial time $t = 0$. The expected present value can be written as:

$$(46) \quad E \int_0^T \pi_1(t) e^{-rt} dt = E \int_0^T [\rho_{CPC} - \alpha_t c_1 \gamma_1] L e^{-rt} dt$$

where r is the discount factor. Faced with the proposed contract price ρ_{CPC} from the biorefinery, an own-welfare maximizing farmer would choose the optimal level of land usage by maximizing the expected present value from growing switchgrass with the land constraint:

¹⁰ The unit of capacity procurement contract price is dollars per acre.

$$(47) \quad E\Pi_1 = \max_L \int_0^T [\rho_{CPC} - \alpha_t c_1 \gamma_1] L e^{-rt} dt$$

$$s.t. \quad L \leq \bar{L}$$

where $\bar{L}$ is the total land owned by the farmer. Therefore, the optimal level of profit is,

$$(48) \quad E\Pi_1 = \int_0^T [\rho_{CPC} - \alpha_t c_1 \gamma_1] \bar{L} e^{-rt} dt$$

by using all the land $\bar{L}$ in switchgrass production.

3.3.1.1.2 Choice between Switchgrass and Corn

Farmers are willing to accept the contract price offer and supply switchgrass to the biorefinery each year thereafter only when the expected profit from growing switchgrass $E\Pi_1$ is no less than the expected profit from growing corn $E\Pi_0$, that is,

$$(49) \quad E\Pi_1 \geq E\Pi_0$$

Or,

$$(50) \quad \int_0^T [\rho_{CPC} - \alpha_t c_1 \gamma_1] \bar{L} e^{-rt} dt \geq \int_0^T [E(P_t) - c_2] \gamma_2 \bar{L} e^{-rt} dt$$

In other words, $E\Pi_0$ is the minimum expected profit that the farmers require to grow switchgrass. When the expected profit from producing switchgrass is less than that of producing corn, the farmers will not turn to switchgrass production. They will still continue producing traditional crops like corn. That means, the contract price of switchgrass should be high enough to cover the profit foregone from corn production and the cost of switchgrass production. For example, when the corn yield γ_2 is high, which means it would probably be profitable producing corn, the switchgrass profit should also be high. Therefore, the profit from producing corn is the opportunity cost for the farmers to enter into a contract. When the expected net revenue from

switchgrass production is less than the corn opportunity cost, farmers would not switch from corn production.

3.3.1.2 Capacity Procurement Contract Structure

As a first-mover, the biorefinery would always propose the switchgrass contract price based on its expectation of the farmer's optimal land usage. The biorefinery would own all the bargaining power as a monopsonistic participant in switchgrass production. The biorefinery would try to maximize its expected profit level while still giving the farmers enough incentive to participate in growing switchgrass. Therefore, the capacity procurement contract structure can be written as

$$\max_{\rho_{CPC}} E \int_0^T \pi_t e^{-rt} dt \quad s.t. \quad E\Pi_1 \geq E\Pi_0$$

The biorefinery is faced with the trade-off between obtaining high profit and providing enough incentive to the farmers. To maximize its profit, the biorefinery needs to keep the contract price level as low as possible, because paying money to purchase switchgrass is a main cost to the biorefinery. However, the switchgrass contract price cannot be too low, because then the farmers will not produce switchgrass and will produce corn instead. More specifically, the switchgrass capacity procurement contract pricing problem can be rewritten as

$$(51) \quad \begin{aligned} \max_{\rho_{CPC}} \quad & \int_0^T [(\omega(E(S(t)) - OMC) - s - m)\alpha_t \gamma_1 \bar{L} - \rho_{CPC} \bar{L}] e^{-rt} dt \\ s.t. \quad & \int_0^T [\rho_{CPC} - \alpha_t c_1 \gamma_1] \bar{L} e^{-rt} dt \geq \int_0^T [E(P_t) - c_2] \gamma_2 \bar{L} e^{-rt} dt \end{aligned}$$

Therefore, the optimal switchgrass contract price is

$$(52) \quad \rho_{CPC}^* = \frac{c_1 \gamma_1 \int_0^T \alpha_t e^{-rt} dt + \int_0^T [E(P_t) - c_2] \gamma_2 e^{-rt} dt}{\int_0^T e^{-rt} dt}$$

At this contract price level, the constraint in equation (51) is binding, which means that the contract price should be set in such a way that the expected profit from a switchgrass contract is the same as the expected profit from corn production for each farmer. The switchgrass contract price is subject to the farmer's expectation of future corn price, switchgrass and corn yields and production costs. Substituting the expected corn price equation (35) into switchgrass price equation (52), the switchgrass price can be written as

$$(53) \quad \rho_{CPC}^* = \frac{c_1 \gamma_1 \int_0^T \alpha_t e^{-rt} dt}{\int_0^T e^{-rt} dt} - c_2 \gamma_2 + \gamma_2 e^{(\xi_0' + \frac{\sigma_1'^2}{4\kappa'} + \frac{\rho' \sigma_1' \sigma_2'}{\kappa'})} \frac{\int_0^T e^{(\mu' + \frac{1}{2} \sigma_2'^2 - r)t} dt}{\int_0^T e^{-rt} dt}$$

or,

$$(54) \quad \rho_{CPC}^* = \frac{c_1 \gamma_1 \int_0^T \alpha_t e^{-rt} dt}{\int_0^T e^{-rt} dt} - c_2 \gamma_2 + \frac{\gamma_2}{1 - e^{-rT}} \frac{1}{\mu' + \frac{1}{2} \sigma_2'^2 - r} e^{(\xi_0' + \frac{\sigma_1'^2}{4\kappa'} + \frac{\rho' \sigma_1' \sigma_2'}{\kappa'})} \left[e^{(\mu' + \frac{1}{2} \sigma_2'^2 - r)T} - 1 \right]$$

The proof to equation (54) has been shown in the Appendix A.4. When the contract lifespan increases ($T \rightarrow \infty$), the switchgrass price will increase from equation (54) if the discount rate is large enough ($r > \mu' + \frac{1}{2} \sigma_2'^2$). Moreover, the contracted switchgrass price will converge to a fixed level given a high discount rate as the contract lifespan increases accordingly, that is,

$$(55) \quad \rho_{CPC}^* \rightarrow \frac{c_1 \gamma_1 \int_0^T \alpha_t e^{-rt} dt}{\int_0^T e^{-rt} dt} - c_2 \gamma_2 + \frac{r \gamma_2}{r - \mu' - \frac{1}{2} \sigma_2'^2} e^{(\xi_0' + \frac{\sigma_1'^2}{4\kappa'} + \frac{\rho' \sigma_1' \sigma_2'}{\kappa'})} \text{ as } T \rightarrow \infty.$$

The biorefinery's profit can then be calculated by substituting the switchgrass contract price into the biorefinery's expected profit in equation (51). Moreover, from equation (55), the following two results can be obtained theoretically:

- a) a current high equilibrium corn price component (ξ_0') will put the switchgrass contract price high. For example, during the year that a drought causes the corn equilibrium price level to be high, the contract entered by the farmers in that year will specify a higher price than the regular years;
- b) if the corn price fluctuation is large, either from short-run impact (σ_1') or the long-run impact (σ_2'), the switchgrass contract price will tend to be higher compared to the price of contracts entered in a year when the corn price is more stable.

3.3.2 Tonnage Contract (TC)

3.3.2.1 Farmers' Choice in a Tonnage Contract

3.3.2.1.1 Switchgrass Profit from a Tonnage Contract

Different from the capacity procurement contract, the tonnage contract specifies the switchgrass contract price according to the actual switchgrass yield instead of total acreage of land used in switchgrass production. Under the tonnage contract, the switchgrass is paid by the biorefinery for each unit (e.g. ton) of switchgrass harvested. Farmers need to provide the entire switchgrass yield to the biorefinery. Therefore, the biorefinery's total switchgrass procurement cost will be:

$$(56) \quad SW' = \rho_{TC} Q_t(L)$$

where ρ_{TC} ¹¹ represents the switchgrass contract price under a tonnage contract. And the farmers' profit of producing switchgrass at time t is:

$$\pi_1'(t) = SW' - C_{sw}$$

¹¹ The unit of tonnage contract is dollars per ton.

which can be written as

$$(57) \quad \pi_1' = \rho_{TC} Q_t(L) - c_1 Q_t(L)$$

The expected net present value of growing switchgrass is achieved by discounting all of the future profit back to the initial time $t = 0$. The expected present value can be written as:

$$(58) \quad E \int_0^T \pi_1' e^{-rt} dt = \int_0^T [\rho_{TC} - c_1] \alpha_t \gamma_1 L e^{-rt} dt$$

where r is the discount factor.

Similar to the farmers' decision under the capacity procurement contract, farmers' land allocation in switchgrass can be obtained by maximizing the expected profit level under the land constraint:

$$(59) \quad E\Pi_1' = \max_L \int_0^T [\rho_{TC} - c_1] \alpha_t \gamma_1 L e^{-rt} dt$$

$$s.t. \quad L \leq \bar{L}$$

The optimal profit level is,

$$(60) \quad \int_0^T [\rho_{TC} - c_1] \alpha_t \gamma_1 \bar{L} e^{-rt} dt$$

3.3.2.1.2 Choice between Switchgrass and Corn

The biorefinery needs to provide enough revenue to the farmers to guarantee that the farmers have enough incentive to produce switchgrass instead of corn, that is,

$$(61) \quad E\Pi_1' \geq E\Pi_0$$

or,

$$(62) \quad \int_0^T [\rho_{TC} - c_1] \alpha_t \gamma_1 \bar{L} e^{-rt} dt \geq \int_0^T [E(P_t) - c_2] \gamma_2 \bar{L} e^{-rt} dt$$

which means the farmer will be willing to produce switchgrass only when there will be higher expected profit level than that from producing corn.

3.3.2.2 Tonnage Contract Structure

In the tonnage contract, the biorefinery will try to maximize its own profit while providing the farmers enough incentive to produce switchgrass. The tonnage contract structure can be written as:

$$(63) \quad \max_{\rho_{TC}} E \int_0^T \pi_t e^{-rt} dt$$

$$s.t. \quad E\Pi_1' \geq E\Pi_0$$

Substituting equations (58) into (63), the switchgrass tonnage contract structure can be rewritten as

$$(64) \quad \max_{\rho_{TC}} \int_0^T [(\omega(E(S(t)) - OMC) - s - m)\alpha_t \gamma_1 \bar{L} - \rho_{TC} \alpha_t \gamma_1 \bar{L}] e^{-rt} dt$$

$$s.t. \quad \int_0^T [\rho_{TC} - c_1] \alpha_t \gamma_1 \bar{L} e^{-rt} dt \geq \int_0^T [E(P_t) - c_2] \gamma_2 \bar{L} e^{-rt} dt$$

Therefore, the optimal switchgrass contract price under a tonnage contract is:

$$(65) \quad \rho_{TC}^* = c_1 + \frac{\gamma_2 \int_0^T [E(P_t) - c_2] e^{-rt} dt}{\int_0^T \alpha_t e^{-rt} dt}$$

At this price level, the constraint in equation (64) is also binding which means that the expected profit from switchgrass contract is the same as the profit from growing corn during the contract lifespan. Moreover, substituting the corn price expectation equation (35) into the equation (65) above, the switchgrass contract price can be written as

$$(66) \quad \rho_{TC}^* = c_1 - \frac{c_2 \gamma_2}{\gamma_1} \frac{\int_0^T e^{-rt} dt}{\int_0^T \alpha_t e^{-rt} dt} + \frac{\gamma_2}{\gamma_1} e^{(\xi_0' + \frac{\sigma_1'^2}{4\kappa'} + \frac{\rho' \sigma_1' \sigma_2'}{\kappa'})} \frac{r}{r - \mu' - \frac{1}{2} \sigma_2'^2} \frac{1 - e^{(\mu' + \frac{1}{2} \sigma_2'^2 - r)T}}{1 - e^{-rT}}$$

When the contract lifespan increases, if the discount rate is high enough, $r > \mu' + \frac{1}{2} \sigma_2'^2$, the contract price under tonnage contract will increase to a fixed level:

$$(67) \quad \rho_{TC}^* \rightarrow c_1 - \frac{c_2 \gamma_2}{\gamma_1} \frac{\int_0^T e^{-rt} dt}{\int_0^T \alpha_t e^{-rt} dt} + \frac{\gamma_2}{\gamma_1} e^{(\xi_0' + \frac{\sigma_1'^2}{4\kappa'} + \frac{\rho' \sigma_1' \sigma_2'}{\kappa'})} \frac{r}{r - \mu' - \frac{1}{2} \sigma_2'^2}$$

The biorefinery's profit level can then be estimated by substituting the switchgrass tonnage contract price into the biorefinery's expected profit function in equation (64).

Therefore, the following results can be obtained from equation (67):

- a) the higher the equilibrium corn price level, the higher the switchgrass contract price will be;
- b) during the years with high corn price fluctuations σ_1' and σ_2' , the switchgrass contract price will tend to be higher than the contract price with more stable price changes.

3.4 Summary

In summary, when the biorefinery is a monopsonistic buyer, the biorefinery will propose to each individual farmer a contract in which a contract price is specified. The contract can either be a capacity procurement contract in which the price is specified for each acre of land allocated towards switchgrass production or be a tonnage contract in which the switchgrass procurement price is specified for each ton of switchgrass purchased from this farmer. The contract price level is given in equation (52) under a capacity procurement contract and in

equation (65) under a tonnage contract. It can be seen from these contract pricing formulas that the CPC or TC prices will be affected by the land productivity for both the switchgrass and the corn, which means that the prices will be different for farmers owning different lands.

Therefore, the biorefinery can specify different contract prices based on each farmer's land type.

The monopsonistic biorefinery will gain the largest possible profit through the price discrimination process by providing the individual farmer with specific contract price.

CHAPTER IV

DATA

4.1 Ethanol Futures Price Data

Ethanol futures contracts have been traded on the Chicago Mercantile Exchange (CME) for only a few years. The CME launched corn-based ethanol contracts on March 23, 2005, with floor-based trading. Ethanol futures can be delivered every month of every year. The price of ethanol futures contract price is quoted on the CME by dollar per gallon. One ethanol contract is standardized to contain 29,000 gallons of ethanol. To guarantee the sample size is large enough for empirical tests, the data used to test the ethanol empirical valuation model consist of daily observations of ethanol futures prices from August 29, 2009 to August 31, 2012. For each date, prices for the futures contracts maturing in 1, 3, 5, 7 and 9 months were used. Table 1 describes the characteristics, mean value and standard deviation, of the ethanol futures price data collected for each type of contract. With longer maturities, the futures contract price is lower, and the price standard deviation is also lower. Moreover, the range of the ethanol futures price for the contracts maturing in one month during this period is \$1.40 - \$4.23 per gallon, compared to the price range for the contracts maturing in 3 months (\$1.40 - \$3.16 per gallon), 5 months (\$1.45 - \$2.92 per gallon), 7 months (\$1.46 - \$2.90 per gallon) and 9 months (\$1.47 - \$2.88 per gallon).

Table 1 Ethanol Futures Contract Data

Contract Maturity	Mean Price (\$ per gallon)	Price Standard Deviation (\$ per gallon)
1 month	2.14	0.4265
3 months	2.08	0.3740
5 months	2.05	0.3459
7 months	2.02	0.3244
9 months	2.01	0.3091

* From August 29, 2009 to August 31, 2012: 1767 Daily Observations

4.2 Corn Futures Price Data

Corn futures contracts are among the earliest contracts traded on the CME. The maturities of corn futures are in March, May, July, September, and December of each year. The corn futures contracts are standardized to be 5,000 bushels per contract and the corn futures price is quoted in cents per bushel on the CME. In this analysis weekly observations of corn futures prices are used to test the corn empirical valuation model from January 6, 1997 to December 29, 2011. For each date, prices for the futures contracts with maturity 1, 5, 9, 13 and 17 months were used. The corn futures price data characteristics, mean value and standard deviation, for each type of contract are described in Table 2. Moreover, the range of the corn futures price for the contracts maturing in one month during this period is \$1.86 - \$7.87 per bushel, compared to the price range for the contracts maturing in 5 month (\$2.80 - \$7.88 per bushel), 9 months (\$2.18 - \$8.05), 13 months (\$2.34- \$8.16) and 17 months (\$2.38 - \$7.00).

Table 2 Corn Futures Contract Data

Contract Maturity	Mean Price (\$ per bushel)	Price Standard Deviation (\$ per bushel)
1 month	3.15	1.43
5 months	3.23	1.45
9 months	3.30	1.37
13 months	3.35	1.32
17 months	3.37	1.25

* From January 6, 1997 to December 29, 2011: 756 Weekly Observations

4.3 Ethanol Production Data

Four parameters are involved in the ethanol production process: the biorefinery's operation and maintenance cost, transportation cost, storage cost, and conversion rate. The estimations of these parameters vary in the current literature. Using west Tennessee as the basis in this analysis, the plant operation and maintenance cost is assumed to be \$0.75 per gallon (Haque and Epplin 2012). The variability of transportation cost is demonstrated in Table 3. It ranges from \$6.48 per ton to \$13.86 per ton. The base value in this analysis is \$10 per ton within a 25 mile distance. The storage cost is assumed to be \$3.83 per dry ton for round bales and \$17.84 per dry ton for square bales (Wang et al. 2009).

Table 3 Transportation Cost Rate Data

Source	Transportation Cost Rate (\$ per dry ton)
Walsh et al. (1998)	5 to 8 *
Duffy (2007)	6.10 **
Duffy and Nanhou (2001)	5 to 10 ***
Larson et al. (2005)	10 (Base Value)
Perrin et al. (2008)	13

* Within a 25 mile distance

** Within a 30-mile trip

*** Within a 75 mile distance

The conversion rate is shown in Table 4. The conversion rate of switchgrass into ethanol ranges from 59.92 gallons per ton to 99.95 gallons per ton with regard to different firm size and technology used. The base rate of 80.05 gallons per ton for medium-sized biorefinery firms is used from Haque and Epplin (2012).

Table 4 Estimation of Switchgrass Conversion Rate (Haque and Epplin 2012)

Source	Conversion Rate (gallons per ton)
Haque and Epplin (2012)	99.95
Aden et al. (2002)	90.12
Schmer et al. (2008)	82.69
Haque and Epplin (2012)	80.05 (Base Value)
Humbird et al. (2011)	79.09
Sendich et al. (2008)	77.90
Wingren et al. (2003)	76.94
Wingren et al. (2004)	73.10
Sendich et al. (2008)	69.99
Wu et al. (2010)	69.99
Kazi et al. (2010)	69.03
Wingren et al. (2003)	67.11
Eggeman and Elander (2005)	64.95
Haque and Epplin (2012)	59.92

* Variation in conversion rate assumptions reflects the difference in ethanol production technology with regard to different firm size.

4.4 Switchgrass Production Data

4.4.1 Switchgrass Yields

According to Mooney et al. (2009), the first- and second- year switchgrass yields are 14% and 60% respectively of the third-year yield which can be considered as the maximum yield (Griffith et al. 2012). The switchgrass maximum yield varies in the current literature. Table 5 is a summary of the switchgrass yield estimations. The estimation ranges from 3.79 tons per acre to 7.89 tons per acre. Generally speaking, the yields in northern states are less than those in southern states because of the variation between upland and lowland.

Land in West Tennessee is divided into four different landscapes (Mooney et al. 2009; Boyer et al. 2012): (i) a well-drained level upland (WDLU), (ii) a well- to moderately well-drained floodplain (WDFP), (iii) a moderate to somewhat poorly drained eroded sloping upland (MDSU), (iv) a poorly drained floodplain (PDFP). The relative position of these four landscapes is demonstrated in Figure 2. The average switchgrass yield between 2006 and 2011 from each landscape is shown in Table 6 (Boyer et al. 2012).

Table 5 Switchgrass Yield Estimation Data

Source	Switchgrass Yields (tons per acre)
Walsh et al. (2003)	5.49
Duffy (2007)	4.00
Khanna et al. (2008)	4.20
Pimentel and Patzek (2005)	4.91
Fike et al. (2006)	5.45
McLaughlin and Kszos (2005)	6.16
Muir et al. (2001)	5.97
Epplin et al. (2007)	6.06

* Variation reflects differences in location and land type

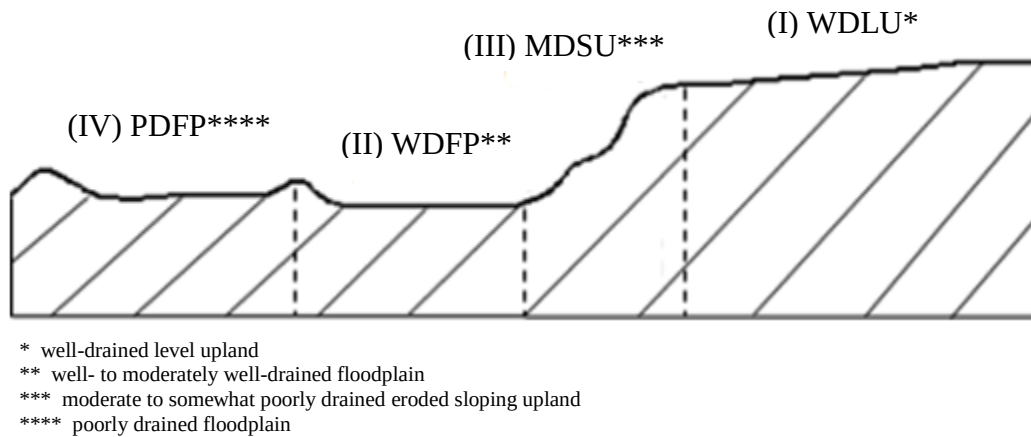


Figure 2 Four Landscapes in Tennessee

Table 6 Switchgrass Yield from Four Landscapes in Tennessee (Boyer et al. 2012)

Landscape	Yield (tons per acre)
WDLU *	7.65
WDFP **	8.33
MDSU ***	8.64
PDFP ****	6.62

* well-drained level upland

** well- to moderately well-drained floodplain

*** moderate to somewhat poorly drained eroded sloping upland

**** poorly drained floodplain

4.4.2 *Switchgrass Breakeven Price*

The estimated average production cost, or farm-gate breakeven price, of switchgrass also varies in the literature. Table 7 shows breakeven price estimations done by researchers in different states and range from \$45.91 per dry ton to \$94.80 per dry ton and reflects differences in farm-gate price or price delivered to biorefineries. Based on the research done by Mooney et al. (2009) and Boyer et al. (2012), the breakeven price of producing switchgrass on four types of landscapes in west Tennessee is shown in Table 8.

Table 7 Switchgrass Breakeven Price Estimations

Source	Breakeven Price Estimation (\$ per dry ton)
Duffy (2007)	91.05
Khanna et al. (2008)	88.9
Perrin et al. (2008)	53.52
Mooney et al. (2009)	\$42.90 to \$62.23
Epplin et al. (2007)	50.80
Walsh et al. (2003)	49.91

* Variation in method of storage, payment of transportation, and storage costs.

Table 8 Switchgrass Breakeven Price for Four Landscapes in Tennessee
(Mooney et al. 2012; Boyer et al. 2012)

Landscape	Breakeven Price (\$ per ton)
WDLU *	53.10
WDFP **	48.31
MDSU ***	49.76
PDFP ****	58.14

* well-drained level upland

** well- to moderately well-drained floodplain

*** moderate to somewhat poorly drained eroded sloping upland

**** poorly drained floodplain

4.5 Corn Production Data

Based on the tests done on corn grain yield in Tennessee by Allen et al. from 2007 to 2012 for 17 early-season corn hybrids and the field crop budget made by the University of Tennessee Extension, the average yield of corn was assumed to be 150 bushels per acre for traditional croplands. The corn yield on marginal lands is much lower than that grown on traditional croplands. Varvel et al. (2008) reported that the average yield of corn on marginal land is roughly 97 bushels per acre based on different levels of nitrogen application. The average cost of growing corn is estimated to be \$450.52 per acre according to the field crop budgets for 2013 made by the University of Tennessee Extension (McKinley and Gerloff 2013).

Table 9 Corn Yield from Four Landscapes in Tennessee

Landscape		Yield (bushels per acre)
Traditional Crop Production Land	WDLU *	150
	WDFP **	
Marginal Land	MDSU ***	97
	PDFP ****	

* well-drained level upland

** well- to moderately well-drained floodplain

*** moderate to somewhat poorly drained eroded sloping upland

**** poorly drained floodplain

4.6 Summary of Production Parameters

Table 10 indicates the production parameters used in this analysis to represent a case situation in west Tennessee. The first column displays the symbols used in Chapter III. The second column describes the symbols in the first column. The third column shows the value of the parameters in this analysis.

Table 10 Summary of Production Parameters for the West Tennessee Case Study

Symbol	Description	Base Value
ω	Conversion Rate (gallons per ton)	80
s	Storage Cost (\$ per ton)	3.83
m	Transportation Cost (\$ per ton)	10
OMC	Plant and Maintenance Average Cost (\$ per gallon)	0.75
r	Discount Rate	8%
$\bar{L}$	Land Endowment (acres)	133 *
γ_1	Average Yield of Switchgrass (tons per acre)	WDFP 7.65
		WDLU 8.33
		MDSU 8.64
		PDFP 6.62
c_1	Average Cost of Switchgrass (\$ per ton)	WDFP 53.10
		WDLU 48.31
		MDSU 49.76
		PDFP 58.14
γ_2	Average Yield of Corn (bushels per acre)	WDFP 150
		WDLU 150
		MDSU 97
		PDFP 97
$\bar{c}_2^{**}$	Average Cost of Corn (\$ per acre)	450.52

*Land endowment is assumed to be the average farm acreage in Tennessee (Jensen et al. 2007).

** $\bar{c}_2 = c_2\gamma_2$

CHAPTER V

RESULTS

5.1 Expected Ethanol Price

The Kalman filtering process is used to estimate the ethanol spot price and the expectation of ethanol price in the future based on the historical data of the ethanol futures prices. The parameters in the state space model, equations (18) and (19) in Chapter III, can be calculated efficiently through the maximum likelihood estimation shown in Appendix A.3. By varying the parameters and rerunning the Kalman filter for each initial group of parameters, the parameters that maximize the log-likelihood function can be identified (Schwartz and Smith 2000). Under the five contracts with five different maturity lengths, the parameters to be estimated are κ , σ_1 , σ_2 , μ , μ^* , λ_1 , ρ and H , plus the variance-covariance matrix of measurement error $H(s_1, s_2, s_3, s_4 \text{ and } s_5)$. To guarantee that the parameters obtained are the global maximum estimator, different initial values are used to solve the optimization problem. Using the ethanol futures data from August 29, 2005 to August 31, 2012, the maximum likelihood estimators are shown in Table 11.

All the estimated parameters are significant at the 1% level (Table 11). The estimated values of measurement error standard deviation are small, which indicates that the ethanol futures pricing equation (17) describes the futures pricing mechanism well. Furthermore, using the average 1-month and 5-month ethanol futures prices from May 5, 2005 to December 31, 2012, \$2.13 and \$2.00 per gallon, the current short-run price deviation component δ_0 and the long-run equilibrium price component ξ_0 can be estimated:

$$\exp(\delta_0 + \xi_0) = 2.13 \text{ and } \exp(\xi_0) = 2.00$$

Therefore, $\delta_0 = 0.06$ and $\xi_0 = 0.69$.

Table 11 Maximum-Likelihood Parameter Estimates (Ethanol)

Parameter	Description		Estimate	Standard Error
κ	Short-term Mean reverting rate		0.80	0.0850
σ_1	Short-term volatility		0.58	0.0431
σ_2	Equilibrium volatility		0.40	0.0353
μ	Equilibrium drift rate		0.02	0.1226
μ^*	Risk-neutral equilibrium drift rate		0.15	0.0302
λ_1	Short-term market price of risks		0.46	0.0394
ρ	Correlation in increments		-0.74	0.0506
		Contract Maturity		
s_1	Standard deviation for measurement error	1 month	0.044	0.0008
s_2	Standard deviation for measurement error	2 months	0.004	0.0005
s_3	Standard deviation for measurement error	3 months	0.019	0.0003
s_4	Standard deviation for measurement error	4 months	0.018	0.0003
s_5	Standard deviation for measurement error	5 months	0.007	0.0004

The estimated spot market price of ethanol, subject to the maximum-likelihood parameters, is shown in Figure 3, and in relation to the futures price with the closest maturity (1 month). The ethanol spot price and the 1-month-to-maturity futures contract price coincide (Figure 3) which is consistent with the theory that the futures price and spot price are converging to each other as the futures contract approaches maturity.

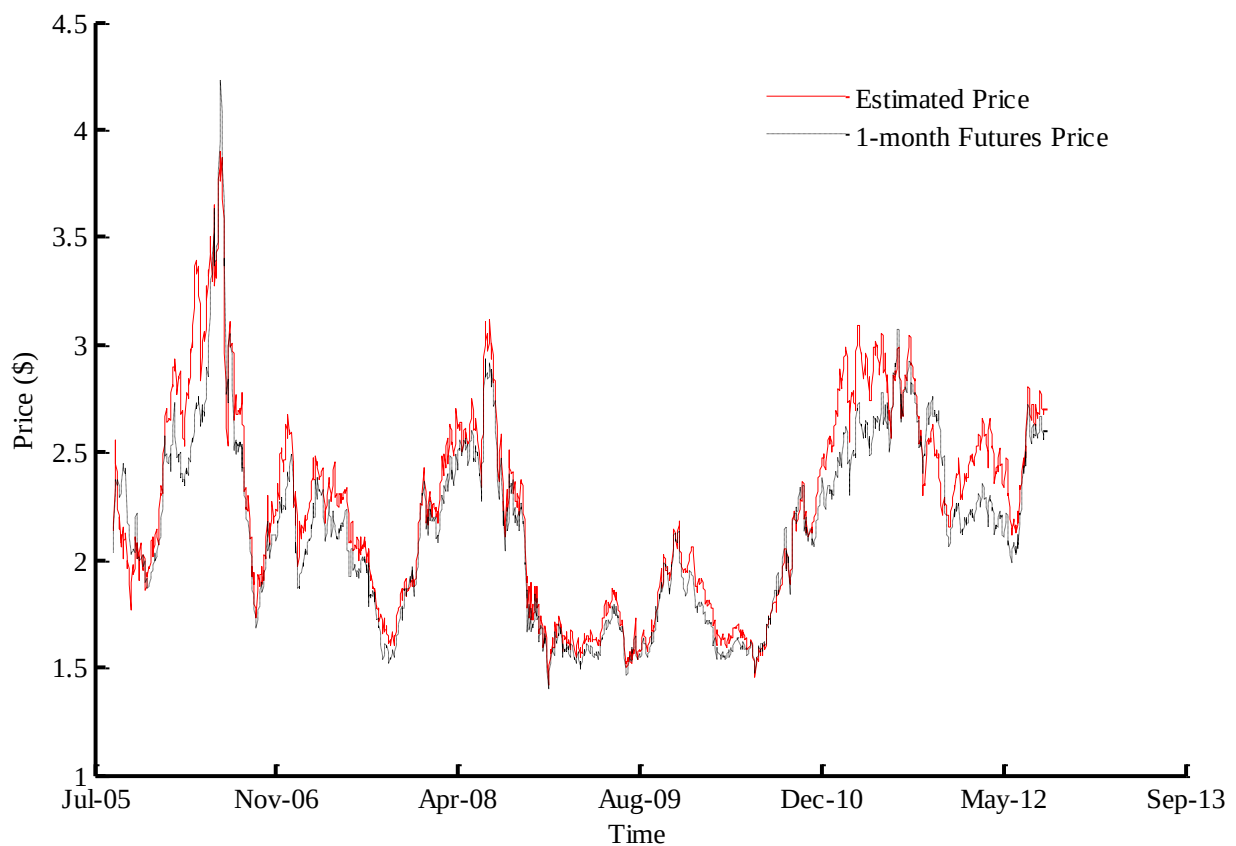


Figure 3 Estimated Ethanol Spot Market Price and One-Month Ethanol Futures Price

With the estimated parameters in Table 11, the expected ethanol price movement can be calculated from equation (14) in Chapter III. The projected ethanol prices in the following five years (2014-2018) are displayed in Table 12. The ethanol price will be between \$2.10 and \$2.18

per gallon. This is very close to the ethanol effective retail price forecasted by the Food and Agricultural Policy Research Institute (FAPRI) at the University of Missouri (\$2.00-2.06 per bushel from 2014 to 2018) (FAPRI-MU 2013). The projected ethanol price will first decrease and then increase after 2015.

Table 12 The Ethanol Price* Forecast (2014-2018)

Years	2014	2015	2016	2017	2018
Price (\$ per gallon)	2.11	2.10	2.11	2.14	2.18

* in 2013 dollars

5.2 Expected Corn Price

Similar to section 5.1, the maximum-likelihood corn price estimators can also be obtained through Kalman filter process. The parameters to be estimated are: κ' , σ_1' , σ_2' , μ' , μ^* , λ_1' , ρ' and H' , plus the variance-covariance matrix of measurement error H' (s_1' , s_2' , s_3' , s_4' and s_5'). Table 13 presents the maximum-likelihood estimators in the corn pricing process.

Different initial parameter values have also been tried to guarantee that the log-likelihood value is the largest. The data used are the corn futures prices with 1-month, 5-month, 9-month, 13-month, and 17-month left to maturity from January 6, 1997 to December 29, 2011.

All the estimated parameters are significant at the 1% level, which means that the Kalman filter has used the historical data efficiently and the corn pricing model describes the

corn price movement. Furthermore, using the average September and October price of 1-month and 17-month corn futures contracts from 2007 to 2012, \$5.19 and \$5.37 per bushel accordingly, the current short-run price deviation component and the long-run equilibrium price component δ'_0 and ξ'_0 can be estimated:

$$\exp(\delta'_0 + \xi'_0) = 5.19 \text{ and } \exp(\xi'_0) = 5.37$$

Therefore, $\delta'_0 = -0.03$ and $\xi'_0 = 1.68$.

Table 13 Maximum-Likelihood Parameter Estimates (Corn)

Parameter	Description		Estimate	Standard Error
κ'	Short-term Mean reverting rate		0.51	0.0661
σ_1'	Short-term volatility		0.32	0.0257
σ_2'	Equilibrium volatility		0.19	0.0153
μ'	Equilibrium drift rate		0.02	0.0481
$\mu^{*'} $	Risk-neutral equilibrium drift rate		-0.17	0.0214
λ_1'	Short-term market price of risks		-0.09	0.0340
ρ'	Correlation in increments		-0.33	0.1182
		Contract Maturity		
s_1'	Standard deviation for measurement error	1 month	0.008	0.0020
s_2'	Standard deviation for measurement error	5 months	-0.016	0.0010
s_3'	Standard deviation for measurement error	9 months	0.019	0.0006
s_4'	Standard deviation for measurement error	13 months	-0.012	0.0017
s_5'	Standard deviation for measurement error	17 months	-0.023	0.0020

Figure 4 displays the spot market price of corn estimated under the maximum-likelihood parameters in Table 2. The current futures prices with 1-month left to maturity are also depicted in Figure 4. The corn spot price and the 1-month futures price coincide which is consistent with the theory that the futures price converges to the spot price as the contract gets closer to expiration (Hull 2009).

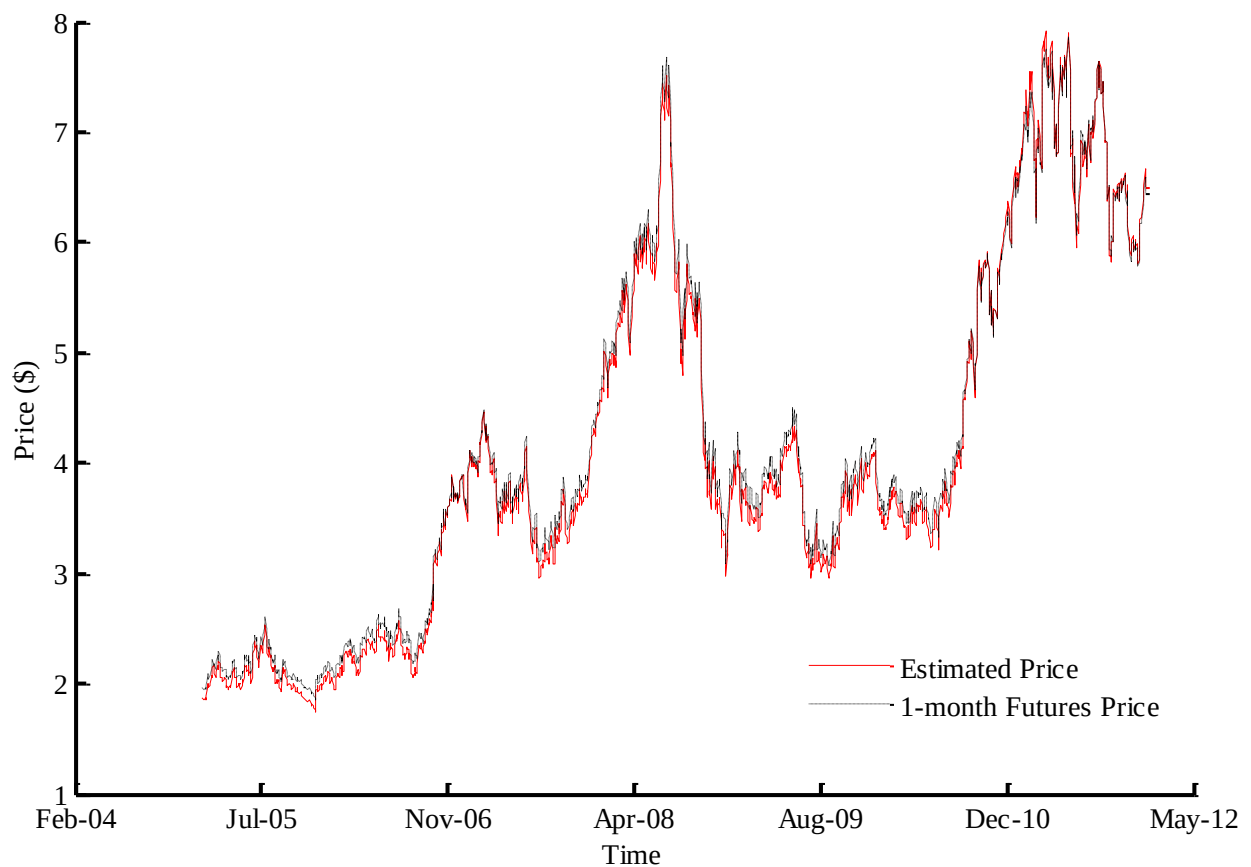


Figure 4 Estimated Corn Spot Market Price and One-Month Corn Futures Price

Using the estimated parameters in Table 13, the expected corn price path in the future can be estimated from equation (34) in Chapter III. The estimated prices in the following five years

are shown in Table 14. The projected price is also close to the corn farm price projected by FAPRI between 2014 and 2018, \$5.18-4.83 per bushel (FAPRI 2013). The corn price projection shows a trend of decreasing in next a few years.

Table 14 The Corn Price* Forecast (2014-2018)

Years	2014	2015	2016	2017	2018
Price (\$ per bushel)	5.45	5.29	5.10	4.89	4.69

* in 2013 dollars

5.3 Switchgrass Capacity Procurement Contract

5.3.1 Switchgrass CPC Price and the Biorefinery's Profitability

In this analysis, a five-year contract lifespan assumption is adopted. Based on the capacity procurement contract structure (equation (51)) and the assumption that the first year's and the second year's harvest are only 14% and 60% of the third, fourth, and fifth year's harvest, which means that $\alpha_1 = 14\%$, $\alpha_2 = 60\%$, and $\alpha_3 = \alpha_4 = \alpha_5 = 100\%$ (Mooney et al. 2009), the switchgrass contract price under the capacity procurement contract can be estimated from equation (52). Besides the projections of the corn price and ethanol price in the following 5 years (2014-2018), the information in Table 10 is also used. Moreover, the contract price will be affected by the land quality on which the switchgrass is grown. The west Tennessee per acre

contract prices for four types of landscapes (WDFP, WDLU, MDSU, and PDFP) under a five-year capacity procurement contract are shown in Table 15.

Table 15 CPC Price and the Biorefinery's Profit Estimation

Landscapes		Contract Price (dollars per acre)	Biorefinery's Profit* (in thousand dollars)
Traditional Cropland	WDFP	795	13.5
	WDLU	792	53.7
Marginal Land	MDSU	474	240.1
	PDFP	442	142.2

* Discounted five-year profit from a contract on 133 acres of land

The per acre contract prices on traditional croplands (WDFP and WDLU) are much higher than per acre prices on the marginal lands (MDSU and PDFP) (\$795 and \$792 per acre compared to \$474 and \$442 per acre). The price of switchgrass grown on a well- to moderately well-drained floodplain (WDFP) is the highest (\$795/acre) while the price of switchgrass grown on a poorly drained floodplain (PDFP) is the lowest (\$442/acre). The reason for the large price difference shown in Table 15 is due to the large difference in corn yields grown on traditional croplands and marginal lands. The yield of corn on traditional croplands is much larger than that on marginal land (150 bushels per acre compared to 97 bushels per acre). Considering that the corn price is relatively high since 2007 compared to the price level in the 1990s and early 2000s, the corn farmers will have a relatively high profit level from traditional croplands. Therefore, the biorefinery will have to propose a high switchgrass contract price to encourage the farmers to switch to growing switchgrass instead of growing corn. However, because the corn yields on marginal lands are relatively low, though the corn price is relatively high, the total corn profit

level will still be much lower than that from traditional croplands. Therefore, a lower contract price will be a suitable proposal by the biorefinery to those farmers on marginal lands.

Consequently, the farmers' expected profit, total switchgrass revenue minus explicit switchgrass production cost, from each contract (5 years, 133 acres) can also be calculated. On WDFP and WDLU lands, the expected profit from each contract is \$267.9 thousand, and on MDSU and PDFP lands, the expected profit from each contract is \$88.7 thousand.

Because the capacity procurement contract prices proposed on different landscapes are different, the biorefinery's profits also vary based on different land types (Table 15). The projected profits from the contracts in turn affect the biorefinery's selection of the farmer with whom to sign a contract. From the biorefinery's profit function in equation (51), the switchgrass contract prices that make the biorefinery breakeven under four landscapes (WDFP, WDLU, MDSU, and PDFP) can be estimated, which are \$820, 893, 927, and 710 per acre with regard to the contracts signed with farmers on WDFP, WDLU, MDSU, and PDFP lands. The estimated contract prices are all lower than these prices. That indicates the biorefinery will have positive profit from each contract regardless of the type of land the farmer owns. Moreover, the expected profit the biorefinery can get from each contract on each type of landscape is shown in Table 15. There is a significant profit difference between the contract on traditional croplands and marginal lands. The estimated biorefinery profits from traditional croplands are much lower than that from marginal lands (\$13.5 thousand and \$53.7 thousand compared to \$240.1 thousand and \$142.2 thousand). Therefore, the biorefinery will not choose to sign capacity procurement contracts with farmers on traditional croplands (WDFP and WDLU) if they can sign contracts with farmers on marginal lands (MDSU and PDFP). Moreover, the profit from MDSU land is notably higher than the profit from PDFP land (\$240.1 thousand compared to \$142.2 thousand

per contract) though the contract prices are close to each other (\$474 per acre compared to \$442 per acre). The reason is that the average yield of switchgrass on MDSU is higher than that on PDFP (8.64 tons per acre compared to 6.62 tons per acre), and the average cost of switchgrass production on MDSU is lower than that on PDFP (\$49.76 per ton compared to \$58.14 per ton). Therefore, the biorefinery can not only purchase the switchgrass at a lower price, but also have a larger average supply from farmers on MDSU lands.

The expected ethanol price level also limits the biorefinery's profit prediction. The current technology limits the ability of making ethanol out of switchgrass, that is, the conversion rate limits the biorefinery's profitability. With the advance of technology in converting switchgrass into ethanol, the conversion rate will be higher. Then the biorefinery will have the ability to produce more ethanol out of a fixed amount of switchgrass, which will increase its revenue and promote profitability. In all, at current circumstances, the biorefinery will prefer to sign capacity procurement contracts with farmers on marginal lands, especially with farmers on the MDSU lands.

As indicated above, the switchgrass CPC price is composed of two parts: the switchgrass production cost and corn profit. The switchgrass CPC price not only needs to cover the switchgrass production cost, but also needs to cover the potential profit from alternative land usage, such as producing corn. Figure 5 shows the percentages in switchgrass capacity procurement contract prices from these two components under the four landscapes. For example, on the WDFP land, 36.5% of the CPC price (\$290 out of \$795 per acre) is to cover the switchgrass production cost, while 63.5% of the CPC price (\$505 out of \$795 per acre) is to cover the opportunity cost from the potential to produce corn. In contrast, on the MDSU land, 64.8% of the CPC price (\$307 out of \$474 per acre) is to cover the switchgrass production cost,

while 35.2% of the CPC price (\$167 out of \$474 per acre) is to cover the corn potential profit. Therefore, on traditional croplands (WDFP and WDLU), the potential gain from producing corn has a larger share in switchgrass CPC price determination than the switchgrass production cost. However, on marginal lands (MDSU and PDFP), the switchgrass production cost is the key determinant and has a larger share in switchgrass CPC price determination than corn profit. Therefore, when corn price increases, the CPC price for switchgrass on traditional croplands will react to a larger extent than that of switchgrass grown on marginal lands; however, the advance in switchgrass production technology which lowers the switchgrass production cost will affect the CPC price on marginal lands to a larger extent.

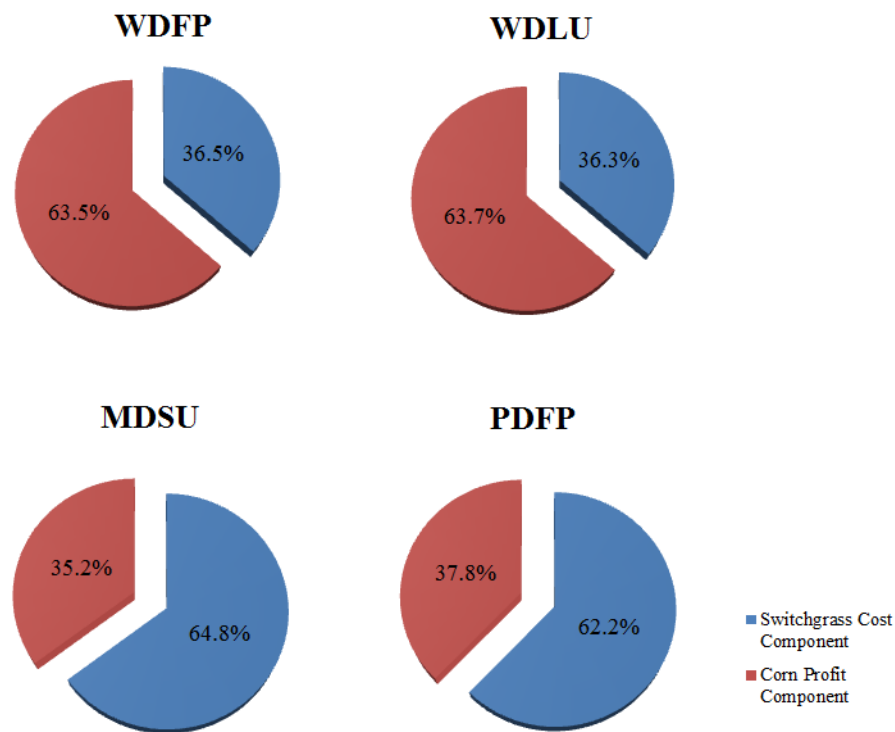


Figure 5 Percentages in CPC Price from Switchgrass Cost and Corn Profit

5.3.2 Sensitivity Analysis

Four key factors play important roles in switchgrass pricing: corn price forecast, switchgrass average yield, corn average yield, and discount rate. The corn price has been forecast in Section 5.2, and the switchgrass average yield, corn yield, and the discount rate are based on the estimations in current literature. The estimated switchgrass CPC price has been given in Table 15. Through sensitivity analysis, the impacts of the change in these factors on switchgrass CPC price can be analyzed.

If the corn price projection decreases by 10%, the projected corn prices will be \$4.91, \$4.76, \$4.59, \$4.40, and \$4.22 per bushel in each year from 2014 to 2018. Table 16 shows the new switchgrass price estimation and percentage change after revising the corn price forecast. The contract price then will be \$699 per acre for switchgrass grown on WDFP and \$697 per acre for switchgrass on WDLU compared to \$413 per acre and \$380 per acre for MDSU and PDFP respectively. The decrease in switchgrass contract price is relatively the same among these four types of lands, ranging from 11.9% to 14.1% following the 10% decrease in corn price forecast. Therefore, the elasticities of corn price projection on CPC contract price are approximately 1.21, 1.19, 1.29, and 1.41 for switchgrass grown on WDFP, WDLU, MSDU, and PDFP lands accordingly. That indicates that the switchgrass CPC price is sensitive to the corn price projection, and the switchgrass CPC price decrease on marginal lands is slightly larger than the price decrease on traditional croplands. The switchgrass contract price needs to be adjusted by a higher percentage than the corresponding change in corn price projection. Accordingly, the biorefinery's profit will increase if the CPC price decreases (Table 16). Contracts on MDSU land continues to bring the highest profits for the biorefinery among these four landscapes.

Table 16 Impact of 10% Decrease in Corn Price Forecast on Switchgrass CPC Price and the Biorefinery's Profit

Landscapes	New Switchgrass Price (dollars per acre)	% Decrease in Switchgrass Price	Biorefinery's Profit* (in thousand dollars)
WDFP	699	12.1	64.3
WDLU	697	11.9	104.4
MDSU	413	12.9	\$272.9
PDFP	380	14.1	\$175.0

* Discounted five-year profit from a contract on 133 acres of land

When the switchgrass yields increase by 10%, the new switchgrass yield levels will be 8.41, 9.16, 9.50, and 7.28 tons per acre for WDFP, WDLU, MDSU, and PDFP respectively. Table 17 reports the impact on switchgrass CPC prices if the switchgrass yields increase by 10%. The switchgrass CPC price increases following the increase in switchgrass yield. The switchgrass price on MDSU and PDFP is more sensitive to the switchgrass yields (6.5% and 6.3%) compared to the WDFP and WDLU lands (3.7% and 3.7%). Therefore, the elasticities of switchgrass yield on switchgrass CPC price are 0.37, 0.37, 0.65, and 0.63 for switchgrass grown on WDFP, WDLU, MDSU, and PDFP accordingly. For all four landscapes, the switchgrass yield does not have a very strong impact on switchgrass price: the switchgrass CPC price increases by a lesser percentage than the increase in switchgrass yield. Moreover, the CPC price adjustments on marginal lands (MDSU and PDFP) are much higher (almost doubled) than that on traditional croplands (WDFP and WDLU), which indicates on less-fertile lands, the yield of switchgrass is more critical in switchgrass CPC price determination than that on more fertile

lands. The biorefinery's profit will increase, but will not change the fact that the biorefinery will prefer to sign contracts with farmers on marginal lands.

Table 17 Impact of 10% Increase in Switchgrass Yield on Switchgrass CPC Price and the Biorefinery's Profit

Landscapes	New Switchgrass Price (dollars per acre)	% Increase in Switchgrass Price	Biorefinery's Profit* (in thousand dollars)
WDFP	824	3.7	41.5
WDLU	821	3.7	85.8
MDSU	505	6.5	272.9
PDFP	470	6.3	165.2

* Discounted five-year profit from a contract on 133 acres of land

If the corn yields decrease by 10%, the new corn yields levels will be 135 bushels per acre and 87 bushels per acre for traditional croplands and marginal lands accordingly. Table 18 shows the impact of corn yield changes on switchgrass CPC Prices. The switchgrass price will decrease following the decrease in corn yields. For a 10% decrease in corn yields, the CPC prices decrease by 12.1%, 11.9%, 13.3%, and 14.3% for switchgrass grown on WDPF, WDLU, MDSU, and PDFP accordingly. Therefore, the elasticities of corn yields on switchgrass CPC price are approximately 1.21, 1.19, 1.33, and 1.43 for each of these four types of land. The corn yields have a large impact on the switchgrass CPC price: the CPC price decreases by a larger percentage than the decrease in corn yields. The biorefinery's profit increases when the corn

yields decreases, but still, the biorefinery will prefer to sign contracts with farmers on marginal lands.

Table 18 Impact of 10% Decrease in Corn Yield on Switchgrass CPC Price and the Biorefinery's Profit

Landscapes	New Switchgrass Price (dollars per acre)	% Decrease in Switchgrass Price	Biorefinery's Profit* (in thousand dollars)
WDFP	699	12.1	64.3
WDLU	697	11.9	104.2
MDSU	411	13.3	273.8
PDFP	379	14.3	175.7

* Discounted five-year profit from a contract on 133 acres of land

If farmers perceive switchgrass production to be more risky compared to corn production, the discount rate considered by the farmers for switchgrass production will be higher. Therefore, a 10% discount rate is assumed for switchgrass production while keeping the discount rate for ethanol production and corn production at 8%. The switchgrass CPC price and the biorefinery's profit can be re-estimated. Table 19 shows the switchgrass CPC price and the biorefinery's profit level on four landscapes under the 10% switchgrass production discount rate. The biorefinery needs to raise the contract price when the farmers believe that the switchgrass production contract contains higher risks. Consequently, the biorefinery's profit will decrease following the increase in the switchgrass capacity procurement contract prices.

Table 19 Switchgrass CPC Price and the Biorefinery's Profit under 10% Discount Rate

Landscapes	Switchgrass Price (dollars per acre)	% Increase in Switchgrass Price	Biorefinery's Profit* (in thousand dollars)
WDFP	818	3.0	1.1
WDLU	816	3.0	41.2
MDSU	480	1.2	237.3
PDFP	448	1.3	139.1

* Discounted five-year profit from a contract on 133 acres of land

5.4 Switchgrass Tonnage Contract

5.4.1 Switchgrass TC Price and the Biorefinery's Profitability

Similar to the capacity procurement contract, a five-year stand switchgrass tonnage contract is assumed to be the contract lifespan for both the biorefinery and farmers. Based on the tonnage contract pricing equation (64) and the assumption that the first year's and second year's harvest is only 14% and 60% of the yield in the third, fourth and fifth year ($\alpha_1 = 14\%$, $\alpha_2 = 60\%$, and $\alpha_3 = \alpha_4 = \alpha_5 = 100\%$) (Mooney et al. 2009), the switchgrass contract prices under the tonnage contract are shown in Table 20. The switchgrass TC prices are also affected by the type of landscape on which the switchgrass is grown. Using west Tennessee as a case study, Table 20 shows the contract price for each of the four typical landscapes (WDFP, WDLU, MDSU, and PDFP) under a five-year stand (2014-2018) switchgrass tonnage contract.

Table 20 TC Price and the Biorefinery's Profit Estimation

Landscape		Contract Price (dollars per ton)	Biorefinery's Profit* (in thousand dollars)
Traditional Cropland	WDFP	145	13.6
	WDLU	133	53.7
Marginal Land	MDSU	77	240.1
	PDFP	93	142.2

* Discounted five-year profit from a contract on 133 acres of land

Similar to the CPC price, the tonnage contract prices on traditional croplands (WDFP and WDLU) are much higher than the prices on the marginal lands (MDSU and PDFP). The per ton price of switchgrass grown on a well- to moderately well-drained floodplain (WDFP) is the highest (\$145/ton) while the per ton price of switchgrass grown on a moderate-to-somewhat-poorly-drained eroded sloping upland (MDSU) is the lowest (\$77/ton). The TC price on WDLU land (\$133 per ton) is similar to the price on WDFP land, and the TC price on PDFP land (\$93 per ton) is similar to the price on MDSU land. The price difference between switchgrass on traditional croplands and switchgrass on marginal lands is due to the large difference in corn yields grown on traditional croplands and marginal lands (150 bushels per acre compared to 97 bushels per acre). With the corn price prediction in the following five years, a relatively high corn profit level can be expected on traditional croplands. Therefore, the biorefinery needs to propose a high enough switchgrass TC price level to give the farmers incentive to grow switchgrass. In contrast, because the corn yields on marginal lands are relatively low, though the corn price can be expected to be high, the total profit level will still be much lower than that from

traditional croplands. Therefore, a low contract price can be proposed by the biorefinery to those farmers on marginal lands.

Compared to the estimated breakeven prices in current literature (Table 7), the tonnage contract price on traditional land is much higher than estimated breakeven prices. One reason is that most breakeven estimates do not take the opportunity cost from alternative land usage into account. Therefore, during the recent years when the corn price is high, the contract price in this analysis also needs to be high to compensate the farmers' potential loss on corn production. This is especially the case on traditional croplands. Moreover, the tonnage contract price estimated in this analysis on the marginal lands is only slightly higher than the breakeven prices estimated in other research, such as Mooney et al. (2009). This suggests that the opportunity cost to grow switchgrass on marginal lands is much lower compared to the traditional croplands.

Table 20 also shows the biorefinery's profit level. The biorefinery will prefer to buy the switchgrass from the farmers planting on marginal lands. Farmers on MDSU lands will be the first choice for the biorefinery to offer a switchgrass tonnage contract. Similar to the capacity procurement contract, besides switchgrass contract price difference, the low ethanol price forecast and limitation in current conversion rate are also the main factors restricting the biorefinery's profitability.

For each landscape, the switchgrass TC price is also determined by the switchgrass production cost and corn profit. On WDFP land, 36.5% of the TC price (\$52.9 out of \$145 per ton) is to cover the switchgrass production cost, while 63.5% of the TC price (\$92.1 out of \$145 per ton) is to cover the potential corn profit. In contrast, 64.8% of the TC price (\$49.9 out of \$77 per ton) on MDSU land is to cover the switchgrass production cost, while 35.2% of the TC price (\$27.1 out of \$77 per ton) is to compensate for the corn profit. On traditional croplands (WDFP

and WDLU), the potential gain from producing corn is more important than the switchgrass production cost in switchgrass tonnage contract price determination. However, on marginal lands (MDSU and PDFP), the switchgrass production cost is the key determinant.

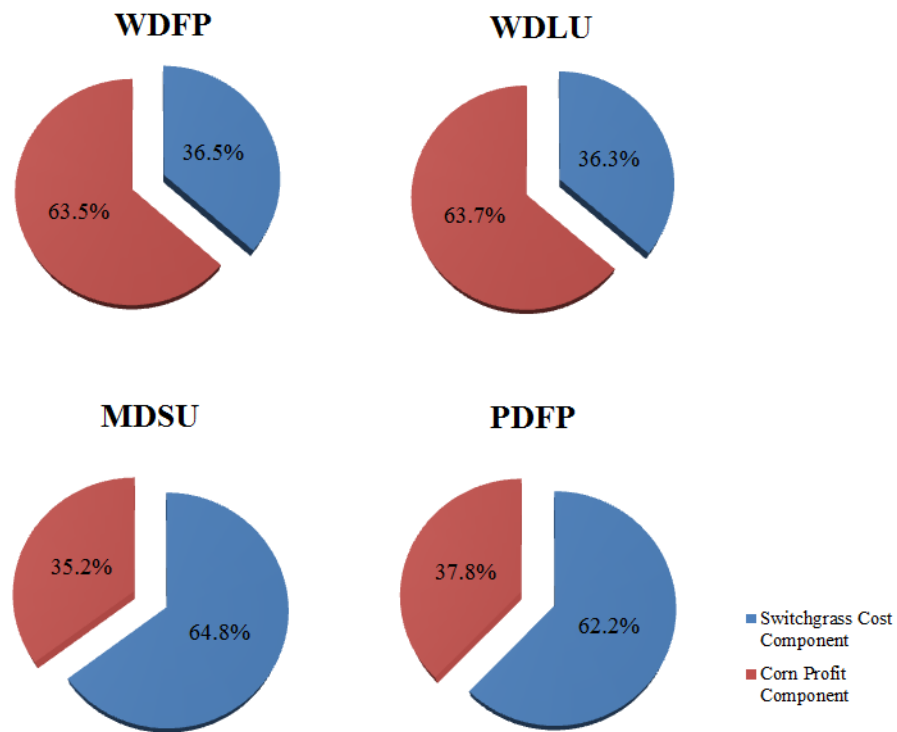


Figure 6 Percentages in TC Price from Switchgrass Cost and Corn Profit

5.4.2 Sensitivity Analysis

In this section, the impacts of the key factors, corn price forecast, switchgrass yield, corn yield and discount rate, on tonnage contracts are analyzed through sensitivity analysis.

If the corn price decreases by 10%, the corn prices will be \$4.91, \$4.76, \$4.59, \$4.40, and \$4.22 per bushel in each year from 2014 to 2018. Table 21 shows the new switchgrass price estimation and percentage change after revising the corn price forecast. For all four types of

landscapes, the switchgrass price decreases following the decrease in forecasted corn price. On traditional croplands, the switchgrass contract prices decrease to \$128 and \$117 per ton for WDFP and WDLU or by 11.7% and 12.0% respectively. The elasticities of corn price prediction on switchgrass TC price are 1.17 and 1.20 accordingly for WDFP and WDLU. In contrast, the prices decrease to \$67 and \$80 per ton on MDSU and PDFP or by 13.0% and 14.0% respectively. The elasticities of corn price prediction on MDSU and PDFP on the switchgrass TC prices are 1.30 and 1.40 accordingly. All the elasticities are greater than 1 which indicates the percentage change in switchgrass TC price will be larger than the percentage change in predicted corn prices. Moreover, the percentage changes on marginal lands are more than that on traditional croplands, though they are similar. The biorefinery still prefers to sign contracts to purchase switchgrass from farmers on marginal lands, especially on MDSU lands, though the profits have increased for each type of landscapes.

Table 21 Impact of 10% Decrease in Corn Price Forecast on Switchgrass TC Price and the Biorefinery's Profit

Landscapes	New Switchgrass Price (dollars per ton)	% Decrease in Switchgrass Price	Biorefinery's Profit* (in thousand dollars)
WDFP	128	11.7	64.3
WDLU	117	12.0	104.4
MDSU	67	13.0	\$272.9
PDFP	80	14.0	\$175.0

* Discounted five-year profit from a contract on 133 acres of land

When the switchgrass yield increases by 10%, the new switchgrass yield levels will be 8.41, 9.16, 9.50, and 7.28 tons per acre for WDFP, WDLU, MDSU, and PDFP respectively. Table 22 reports the impact of switchgrass yield increase on switchgrass TC prices. The switchgrass price will decrease following the increase in switchgrass yield. When the switchgrass yield increases by 10% on each type of land, the switchgrass price will decrease by 5.5%, 6.0%, 3.9% and 3.2% with respect to WDFP, WDLU, MDSU, and PDFP accordingly. The elasticities of switchgrass yield on switchgrass TC price will be 0.55, 0.60, 0.39, and 0.32 for WDFP, WDLU, MDSU, and PDFP accordingly. Compared to the switchgrass yield elasticities for capacity procurement contract, the impact of switchgrass yield on switchgrass tonnage contract price on MDSU and PDFP is much smaller. The biorefinery's profit will increase, but will not change the preference to contract with farmers on marginal lands.

Table 22 Impact of 10% Increase in Switchgrass Yield on Switchgrass TC Price and the Biorefinery's Profit

Landscapes	New Switchgrass Price (dollars per ton)	% Decrease in Switchgrass Price	Biorefinery's Profit* (in thousand dollars)
WDFP	137	5.5	41.5
WDLU	125	6.0	85.8
MDSU	74	3.9	272.9
PDFP	90	3.2	165.2

* Discounted five-year profit from a contract on 133 acres of land

If the corn yield decreases by 10%, the new corn yields levels will be 135 bushels per acre and 87 bushels per acre for traditional croplands and marginal lands accordingly. Table 23

reports the switchgrass price change following the corn yield decrease. On WDFP land, the switchgrass TC price will decrease from \$145 to \$128 per ton or 11.7%. On WDLU land, the switchgrass price will decrease from \$133 to \$117 per ton or 12.0%. On MDSU land, the switchgrass price will decrease from \$77 to \$67 per ton or 13.0%, while on PDFP land the switchgrass price will decrease from \$93 to \$80 per ton or 14.0%. Therefore, the elasticities of corn yield on switchgrass tonnage contract will be 1.17, 1.20, 1.30, and 1.40. All the corn yield elasticities are higher than 1 which means that the switchgrass TC price will decrease by a larger percentage than the decrease in corn yields. The biorefinery will still prefer to choose to build a contractual relationship with farmers planting on MDSU and PDFP lands.

Table 23 Impact of 10% Decrease in Corn Yield on Switchgrass TC Price and the Biorefinery's Profit

Landscapes	New Switchgrass Price (dollars per ton)	% Decrease in Switchgrass Price	Biorefinery's Profit* (in thousand dollars)
WDFP	128	11.7	64.3
WDLU	117	12.0	104.2
MDSU	67	13.0	273.8
PDFP	80	14.0	175.7

* Discounted five-year profit from a contract on 133 acres of land

If the farmers believe that producing switchgrass is more risky than producing corn, the discount rate for switchgrass production will be higher than that for corn production. Assuming the discount rate for the farmers to produce switchgrass is 10% while the discount rate for the

ethanol and corn production is still 8%, the new switchgrass tonnage contract can be re-estimated. Table 24 shows the switchgrass TC price and the biorefinery's profit level on four landscapes under the 10% switchgrass production discount rate. The switchgrass tonnage contract price will increase slightly following the increase in the switchgrass production discount rate. Consequently, the biorefinery's profit will decrease following the increase in the switchgrass tonnage contract price. The biorefinery will still prefer to sign contracts with farmers on marginal lands. Moreover, under 10% discount rate for switchgrass production, the biorefinery will not offer a contract with the farmers on WDFP land because the biorefinery will expect a negative profit from each contract.

Table 24 Switchgrass TC Price and the Biorefinery's Profit under 10% Discount Rate

Landscapes	Switchgrass Price (dollars per ton)	% Increase in Switchgrass Price	Biorefinery's Profit* (in thousand dollars)
WDFP	151	4.1	-3.9
WDLU	139	4.2	36.2
MDSU	79	2.3	234.3
PDFP	96	2.5	136.4

* Discounted five-year profit from a contract on 133 acres of land

5.5 Post Contract Risk Analysis

5.5.1 Switchgrass Yield Risk under the Capacity Procurement Contract

After the farmers accept the switchgrass procurement contract, both the farmers and the biorefinery go into the post contract stage, in which the farmers will grow switchgrass and

provide the harvested switchgrass to the biorefinery for ethanol production. Assuming the CPC price to be $\bar{\rho}_{CPC}$, the biorefinery's profit from each contract can be derived from the equation (51), which is,

$$(68) \quad \int_0^T \left[(\omega(E(S(t)) - OMC) - s - m) \alpha_t \gamma_1 \bar{L} - \bar{\rho}_{CPC} \bar{L} \right] e^{-rt} dt$$

And the farmer's overall profit during the contract lifespan can also be calculated to be

$$(69) \quad \int_0^T [\bar{\rho}_{CPC} - \alpha_t c_1 \gamma_1] \bar{L} e^{-rt} dt$$

After the contract has been signed, neither the farmers nor the biorefinery can alter the switchgrass contract price under either the capacity procurement contract or the acreage contract. If the switchgrass yield γ_1 were to decrease, under a capacity procurement contract, the biorefinery's profit will decrease because the biorefinery will have less feedstock supply to produce ethanol (equation (68)). The biorefinery's total revenue decreases while costs remain relatively constant. The farmers' profit, however, will increase following the switchgrass yield decrease (equation (69)). The switchgrass capacity procurement contract has locked the price paid to the farmers on the farmers' entire land. When the switchgrass yield decreases unexpectedly during the contract lifespan, the farmer's cost on switchgrass production will decrease accordingly. Therefore, the farmer's switchgrass production profit will increase. The impact of a 10% unexpected decrease in switchgrass yield on the biorefinery's profit and farmer's profit during the CPC lifespan is shown in Table 25. On the other hand, when the switchgrass yield is unexpectedly high during the switchgrass CPC lifespan, the biorefinery's profit will increase accordingly from equation (68) because the biorefinery then has more feedstock supply and therefore more ethanol production. However, the farmers' profit will suffer a decrease due to the fact that the switchgrass selling price has been locked at a low level

and the total production cost increases. In both cases the biorefinery and the farmers' profit will be affected by the unexpected switchgrass yield change under a capacity procurement contract but the biorefinery will be affected to a larger extent (Table 25).

Table 25 Impact of 10% Decrease in Switchgrass Yield on the Biorefinery's and the Farmer's Profit at Post CPC Contract Stage

Landscapes		Contract Price (dollars per acre)	% Decrease in Biorefinery's Profit*	% Increase in Farmer's Profit
Traditional Cropland	WDFP	795	320.8	5.8
	WDLU	792	88.3	5.7
Marginal Land	MDSU	474	20.5	18.4
	PDFP	442	26.5	16.5

* Discounted five-year profit from a contract on 133 acres of land

5.5.2 Switchgrass Yield Risk under the Tonnage Contract

If the TC price is assumed to be $\bar{\rho}_{TC}$, the biorefinery's profit from each contract can be derived from the equation (64), which is,

$$(70) \quad \int_0^T [(\omega(E(S(t)) - OMC) - s - m)\alpha_t \gamma_1 \bar{L} - \bar{\rho}_{TC} \alpha_t \gamma_1 \bar{L}] e^{-rt} dt$$

And the farmer's overall profit without taking the opportunity cost on corn production during the contract lifespan can also be calculated to be

$$(71) \quad \int_0^T [\bar{\rho}_{TC} - c_1] \alpha_t \gamma_1 \bar{L} e^{-rt} dt$$

Faced with the given tonnage contract price, both the farmer's and the biorefinery's profit will be affected by the unexpected switchgrass yield change. For example, when the switchgrass yield decreases unexpectedly during the contract lifespan, the biorefinery's profit will decrease accordingly (equation (70)), and the farmers' profit will also decrease following the decrease in switchgrass yield. The biorefinery's profit decreases because the revenue decrease from ethanol production is larger than the switchgrass procurement cost decrease. The farmers' profit will decrease because the contract price only guarantees a per unit price of switchgrass; therefore, when the switchgrass yield decreases, the total revenue will also decrease. Table 26 shows the percentage decreases in both the farmers' and the biorefinery's profits following the unexpected decrease in switchgrass yield during the contract lifespan. The biorefinery's profit change and the farmers' profit percentage change will be the same as the switchgrass yield's percentage change. And the biorefinery's profit will change in a smaller percentage under the tonnage contract compared the percentage change in the biorefinery's profit change under the capacity procurement contract (Table 25 and Table 26). This reveals that the biorefinery will be more willing to use the tonnage contract compared to the capacity procurement contract considering the post contract risks. In most landscapes (WDFP, MDSU, and PDFP), the farmers' profit risk with regard to the switchgrass yield change will also be smaller under the tonnage contract. However, the effects of the switchgrass yield change on farmers' profit change are opposite between the capacity procurement contract and the tonnage contract. When the switchgrass yield increases, both the biorefinery's and the farmers' profits will increase accordingly.

When the contractual relationship has been built between the biorefinery and the farmers, a potential risk also comes from the alternative land usage. If the corn price or the corn yield increases unexpectedly, the farmer has to give up more to produce switchgrass. However, from

equation (68) and (70), the biorefinery's profit will not be affected by the corn production once the contract price has been specified under both the capacity procurement contract and the tonnage contract. Therefore, only the farmers are faced with the risks from corn production returns.

Table 26 Impact of 10% Decrease in Switchgrass Yield on the Biorefinery's and the Farmer's Profit at Post TC Contract Stage

Landscapes		Contract Price (dollars per ton)	% Decrease in Biorefinery's Profit*	% Decrease in Farmer's Profit
Traditional Cropland	WDFP	145	10	10
	WDLU	133	10	10
Marginal Land	MDSU	77	10	10
	PDFP	93	10	10

* Discounted five-year profit from a contract on 133 acres of land

Comparing Table 25 and Table 26, the biorefinery will be more willing to use a tonnage contract compared to a capacity procurement contract. For example, on MDSU land, the biorefinery's profit from each contract under a tonnage contract is the same as the estimated profit under a capacity procurement contract. However, the biorefinery is subject to a higher risk with regard to the switchgrass yield under the capacity procurement contract. Under the capacity procurement contract, the biorefinery pays the farmers a fixed amount of money based on the acres farmers used for planting switchgrass no matter how much switchgrass can be harvested that year. On MDSU lands, the biorefinery pays each farmer \$474 for each acre of land planted

to switchgrass. However, in the first year, the yield of switchgrass will only be 14% of the maximum yield level. Therefore, in the first year, the biorefinery may very well lose money from ethanol production because the supply of the switchgrass is too low. In contrast, under the tonnage contract, the switchgrass is paid by each ton of switchgrass harvested. Therefore, in the first year, when the switchgrass yield is low, the biorefinery's expenditure on switchgrass in the first year is also low, which means that the biorefinery can adjust the procurement cost based on the switchgrass harvest condition. And the biorefinery therefore is not necessarily losing money in the first year. The overall risk faced by the biorefinery within the contract lifespan will thus be higher under the capacity procurement contract compared to the tonnage contract.

CHAPTER VI

CONCLUSION

The on-farm production of biomass for ethanol production has been given more and more attention from farmers, policymakers and others. Switchgrass has been identified as one of the most promising biomass feedstocks to be used to produce cellulosic ethanol. Compared to traditional crops, switchgrass can be grown on various landscapes, including marginal lands. Much research has been done with regard to the economic feasibility of producing switchgrass. Most of the research focuses on the estimation of production costs or the breakeven prices. The breakeven prices of switchgrass range from \$46 to \$94 per ton based on different environments where it is grown. However, because the biomass market is not developed yet, the market price of switchgrass has not been given much attention.

In this thesis, a model is built combining both the biorefinery and the farmers in a contractual relationship. Two procurement contract types have been discussed: the capacity procurement contract and the tonnage contract. In a capacity procurement contract, the biorefinery pays the farmers a fixed price for each acre of land allocated towards switchgrass production. In a tonnage contract, the biorefinery pays the farmer a price for each ton of switchgrass harvested. Both the supply side and the demand side for switchgrass are considered. Corn is considered as an alternative crop for the farmers. Because the switchgrass procurement contract covers the expectation of the biorefinery and the farmers for the next five years, the expected ethanol price and corn price for years 2014 through 2018 have been estimated using historical futures prices.

Land quality and soil types also affect the yields and average costs of switchgrass production and corn production. Therefore, the types of landscapes also affect the contract price of switchgrass. Using west Tennessee as a case study, the contract prices under four types of landscapes are investigated based on Boyer et al. (2012): (i) a well-drained level upland (WDLU), (ii) a well- to moderately well-drained floodplain (WDFP), (iii) a moderate to somewhat poorly drained eroded sloping upland (MDSU), (iv) a poorly drained floodplain (PDFP).

For the capacity procurement contract, the farm-gate switchgrass contract prices are \$795, \$792, \$474, and \$442 per acre for the switchgrass grown on WDLU, WDFP, MDSU and PDFP lands respectively. Under the tonnage contract, the prices are \$145, \$133, \$77, and \$93 per ton for the switchgrass grown on WDLU, WDFP, MDSU, and PDFP respectively. The large price differences between the switchgrass grown on traditional croplands (WDLU and WDFP) and marginal lands (MDSU and PDFP) are largely due to the high yields and high recent market price of corn as an alternative crop that could be grown in place of switchgrass. To maximize the profit, the biorefinery will prefer to sign contracts with the farmers growing switchgrass on marginal lands. MDSU land is their top choice.

Sensitivity analysis is conducted on the capacity procurement contract prices and the tonnage contract prices on four aspects: corn price prediction, switchgrass yield prediction, corn yield prediction, and farmers' discount rate. The result reveals that a lower corn price and a lower corn yield will cause the CPC and TC prices to be lower, because the farmers' corn profit will be lower following the decrease in corn price and yield prediction. A higher farmers' discount rate will cause the CPC and TC prices to be higher, because the farmers will require more compensation following the higher risk perception in the switchgrass production contract.

Under the capacity procurement contract, a higher switchgrass yield will cause the per acre contract price to be higher, because the switchgrass production costs will be higher. On the other hand, under the tonnage contract, the per ton contract price will be lower when the switchgrass yield is higher because the farmers do not need as much profit per ton to keep the switchgrass profit equal to that from corn production. In total, corn price and corn yield predictions have a higher impact on switchgrass contract prices compared to impact from switchgrass yield and farmers' discount rate.

Post contract sensitivity analysis with regard to a change in switchgrass yield or a change in corn price is also conducted in this study. It reveals that a tonnage contract is preferred by the biorefinery compared to the capacity procurement contract. The tonnage contract has more post contract risk advantage than the capacity procurement contract with regard to the unexpected change in switchgrass yield.

It is hard to project the corn price and ethanol price for a long time range, such as 10 years. A 5-year contract is discussed in this thesis. The impact of economies of scale for both the farmers and the biorefinery can be considered in future studies. Changes in technology will also affect the profitability of the biorefinery. Transportation costs could be used as variable based on distance. In this study, switchgrass dry matter losses in transportation and storage were not considered as a function of either type of switchgrass bale or type of storage used. Future research can also incorporate other alternative land uses besides corn production. Soybeans, cotton, hay, and livestock can be considered as the alternative choices for the farmers. It will refine the farmers' decision process if more alternatives are considered.

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APPENDIX

A.1 Schwartz (1997) Two-Factor Model

Based on the Efficient Market theory proposed by Fama (1965), the commodity price can be assumed having incorporated all the available information by that time. Assume the commodity spot price of commodity $S(t)$ follows the stochastic process (Gibson and Schwartz 1990; Schwartz 1997):

$$(A.1.1) \quad dS = (\mu - \delta)Sdt + \sigma_1 Sdz_1$$

where μ denotes the long run log price, σ_1 is the volatility term, and dz_1 describes a Brownian motion. δ denotes the instantaneous convenience yield (cost-of-carry) which can be interpreted as the flow of services accruing to the holder of the commodity sellers but not to the holder of a futures contract. Fabozzi et al. (2009) explained the convenience yield as:

“... It is in the futures market that investors send a collective message about how any new information is expected to impact the cash market. ... the futures price and the cash market are tied together by the cost of carry. If the futures price deviates from the cash market price by more than the cost of carry, arbitrageurs ... would pursue a strategy to bring them back into line. Arbitrage is the mechanism that assures that the cash market price will reflect the information that has been collected in the futures market.” (Fabozzi et al. 2009)

The convenience yield is defined to be “the flow of services which accrue to the owner of a physical inventory but not to the owner of a contract for future delivery” by Brennan (1991). It is also assumed to follow a stochastic process:

$$(A.1.2) \quad d\delta = \kappa(\alpha - \delta)dt + \sigma_2 dz_2$$

where κ denotes the speed of mean reversion to the long run mean log price α , σ_2 is the volatility term, and dz_2 describes a Brownian motion. Furthermore, assume

$$(A.1.3) \quad dz_1 dz_2 = \rho dt$$

The change in commodity convenience yield $d\delta$ has two components: a systematic change $\kappa(\alpha - \delta)dt$ and a random change $\sigma_2 dz_2$. The systematic percentage change in commodity price is the change that can be predicted from the current commodity price which is negatively related to the current commodity price. This inverse relationship between the future price expectation and current price level is the “mean-reverting” property. The second term in equations (A.1.1) and (A.1.2) represents the random change in commodity price. The Brownian motion accounts for all the unavailable information and unknown factors in commodity futures price determination. The randomness comes from Brownian motion’s property that unexpected change in future commodity price and convenience yield is independent of the price change at any earlier time.

Defining $X = \log(S)$, and applying Itô’s lemma¹²,

$$\begin{aligned} dX &= \frac{\partial X}{\partial t} dt + \frac{\partial X}{\partial S} dS + \frac{\partial^2 X}{\partial S^2} dS dS \\ &= \frac{1}{S} dS - \frac{1}{2} \times \frac{1}{S^2} dS dS \\ &= \frac{1}{S} ((\mu - S)S dt + \sigma_1 S dz_1) - \frac{1}{2} \frac{1}{S^2} \sigma_1^2 S^2 dt \\ &= (\mu - \delta) dt + \sigma_1 dz_1 - \frac{1}{2} \sigma_1^2 dt \\ &= \left(\mu - \delta - \frac{1}{2} \sigma_1^2 \right) dt + \sigma_1 dz_1 \end{aligned}$$

¹² Itô’s lemma is used to find the differential of a time-dependent function of a stochastic process, because derivatives cannot be obtained from stochastic process. Let $f(t, x)$ be a function for which the partial derivatives $f_t(t, x)$, $f_x(t, x)$, and $f_{xx}(t, x)$ are defined and continuous, and let $z(t)$ be a Brownian motion. Then, for each $T \geq 0$, $f(T, z(T)) = f(0, z(0)) + \int_0^T f_t(t, z(t)) dt + \int_0^T f_x(t, z(t)) dz + \frac{1}{2} \int_0^T f_{xx}(t, z(t)) dz dz$. For Brownian motion $z(t)$, $dz dz = dt$, and $dz dt = 0$ (Shreve 2004).

Therefore, the log spot commodity price can be characterized as an Ornstein-Uhlenbeck stochastic process¹³:

$$(A.1.4) \quad dX = \left(\mu - \delta - \frac{1}{2} \sigma_1^2 \right) dt + \sigma_1 dz_1$$

Since convenience yield risk cannot be hedged, the risk-adjusted convenience yield process will have a market price of risk associated with it (Schwartz 1997). Under equivalent martingale measure, equations (A.1.1) and (A.1.2) can be rewritten as

$$(A.1.5) \quad dS = (r - \delta)Sdt + \sigma_1 S dz_1^*$$

$$(A.1.6) \quad d\delta = [\kappa(\alpha - \delta) - \lambda]dt + \sigma_2 dz_2^*$$

$$(A.1.7) \quad dz_1^* dz_2^* = \rho dt$$

λ is the market price of risk (assumed constant) and dz_1^* and dz_2^* are the increments to the Brownian motion under the equivalent martingale measure.

Futures prices then must satisfy the partial differential equation (Gibson and Schwartz 1990):

$$(A.1.8) \quad \frac{1}{2} \sigma_1^2 S^2 F_{SS} + \sigma_1 \sigma_2 \rho S F_{S\delta} + \frac{1}{2} \sigma_2^2 F_{\delta\delta} + (r - \delta) S F_S + (\kappa(\alpha - \delta) - \lambda) F_\delta - F_T = 0$$

subject to the terminal boundary condition $F(S, \delta, 0) = S$.

Bjerk Sund (1991) has shown that the solution to equation (A.1.8) is

$$(A.1.9) \quad F(S, T) = E(S(T)) = S \exp \left(-\delta \frac{1 - e^{-\kappa T}}{\kappa} + A(T) \right)$$

Or,

¹³ An Ornstein-Uhlenbeck process, X , satisfies the following stochastic differential equation: $dX = \kappa(\tau - X)dt + \sigma dz$, where $\theta > 0$, μ and $\sigma > 0$ are parameters and dz denotes the Wiener process (or Brownian motion).

$$(A.1.10) \quad \log F(S, T) = \log S - \delta \frac{1 - e^{-\kappa T}}{\kappa} + A(T)$$

where

$$A(T) = \left(r - \hat{\alpha} + \frac{1}{2} \frac{\sigma_2^2}{\kappa^2} - \frac{\sigma_1 \sigma_2 \rho}{\kappa} \right) T + \frac{1}{4} \sigma_2^2 \frac{1 - e^{-2\kappa T}}{\kappa^3} + \left(\hat{\alpha} \kappa + \sigma_1 \sigma_2 \rho - \frac{\sigma_2^2}{\kappa} \right) \frac{1 - e^{-\kappa T}}{\kappa^2}$$

$$\hat{\alpha} = \alpha - \frac{\lambda}{\kappa}.$$

■

A.2 Derivation of Equations (9) and (10) (Schwartz and Smith (2000))

Let $\Delta t = t / n$, then equations (6) and (7) can be written as

$$x_t = c + Qx_{t-1} + \eta_t$$

where

$$x_t = \begin{bmatrix} \delta_t & \xi_t \end{bmatrix}'$$

$$c = \begin{bmatrix} 0 & \mu \Delta t \end{bmatrix}'$$

$$Q = \begin{bmatrix} \phi & 0 \\ 0 & 1 \end{bmatrix}$$

$\phi = 1 - \kappa \Delta t$, and η_t is a vector of serially uncorrelated, normally distributed distribution matrix

with

$$E(\eta_t) = 0$$

and

$$\text{var}(\eta_t) = \begin{bmatrix} \sigma_1^2 \Delta t & \rho \sigma_1 \sigma_2 \Delta t \\ \rho \sigma_1 \sigma_2 \Delta t & \sigma_2^2 \Delta t \end{bmatrix}$$

Therefore, the n-step ahead mean vector m_n and variance-covariance matrix V_n can be given recursively as:

$$(A.2.1) \quad m_n = c + Qm_{n-1} \quad \text{and} \quad V_n = QV_{n-1}Q + \text{var}(\eta_t)$$

It can be shown that

$$(A.2.2) \quad m_n = \begin{bmatrix} \phi^n \delta_0 & \xi_0 + \mu n \Delta t \end{bmatrix}$$

and

$$V_n = \begin{bmatrix} \sigma_1^2 \Delta t \sum_{i=0}^{n-1} \phi^{2i} & \rho \sigma_1 \sigma_2 \Delta t \sum_{i=0}^{n-1} \phi^i \\ \rho \sigma_1 \sigma_2 \Delta t \sum_{i=0}^{n-1} \phi^i & n \Delta t \sigma_2^2 \end{bmatrix}$$

Because $\sum_{i=0}^{n-1} \phi^i = \frac{1-\phi^{n-1}}{1-\phi}$ and $\sum_{i=0}^{n-1} \phi^{2i} = \frac{1-\phi^{2(n-1)}}{1-\phi^2}$, when n approaches infinity, ϕ^n

approaches $e^{-\kappa t}$ and ϕ^{2n} approaches $e^{-2\kappa t}$. Then,

$$(A.2.3) \quad \Delta t \sum_{i=0}^{n-1} \phi^{2i} \rightarrow \frac{1-e^{-2\kappa t}}{2\kappa} \quad \text{and} \quad \Delta t \sum_{i=0}^{n-1} \phi^i \rightarrow \frac{1-e^{-\kappa t}}{\kappa}$$

Equations (9) and (10) can be obtained by substituting (A.2.3) into (A.2.1).

■

A.3 State Space Form and Kalman Filter

In this section, only basic theory of Kalman Filter is demonstrated. More formal and complete discussion on Kalman Filter can be found in Harvey (1989) (Chapter 3), Hamilton (1994) (Chapter 13), Brockwell and Davis (2002) (Chapter 8), Durbin and Koopman (2012) (Chapter 2 and 4), and West and Harrison (1997).

A.3.1 State Space Form

The state space form describes a dynamic estimation system. Let y_t be a multivariate time series vector containing n elements. y_t is observable and is related to a $m \times 1$ vector x_t via an observation equation:

$$(A.3.1) \quad y_t = Z_t x_t + d_t + \varepsilon_t$$

where Z_t is an $n \times m$ matrix, d_t is an $n \times 1$ vector and ε_t is an $n \times 1$ vector of serially uncorrelated disturbance with mean zero and covariance matrix H_t , that is,

$$(A.3.2) \quad E(\varepsilon_t) = 0 \quad \text{and} \quad \text{var}(\varepsilon_t) = H_t$$

To put equation (A.3.1) under the Gaussian process framework, assume ε_t is normally distributed, that is,

$$(A.3.3) \quad \varepsilon_t \sim N(0, H_t)$$

When $n = 1$, the observation equation (A.3.1) can be written as an univariate model:

$$(A.3.4) \quad y_t = Z_t' x_t + d_t + \varepsilon_t$$

where Z_t is an $m \times 1$ vector, and

$$(A.3.5) \quad \varepsilon_t \sim N(0, h_t)$$

In general, the unknown state vector x_t is assumed to be generated via a Markov process:

$$(A.3.6) \quad x_t = T_t x_{t-1} + c_t + R_t \eta_t$$

where T_t is an $m \times m$ matrix, c_t is an $m \times 1$ vector, R_t is an $m \times p$ matrix, and η_t is a $p \times 1$ vector of serially uncorrelated Gaussian disturbance, that is,

$$(A.3.7) \quad \eta_t \sim N(0, Q_t)$$

Equations (A.3.1) and (A.3.6) together construct the state space representation. Three more assumptions are needed to analyze the state space model:

$$E(\varepsilon_t \eta_s') = 0$$

$$E(\varepsilon_t x_1') = 0$$

$$E(\eta_t x_1') = 0$$

for all $s, t = 1, 2, \dots, T$. x_1 is the initial state vector. These assumptions mean that d_t provides no more information about x_{t+s} for $s = 0, 1, \dots$ besides that contained in y_{t-1} , and the initial state vector is uncorrelated with any realizations of ε_t and η_t .

A.3.2 Kalman Filter

Consider the state space model of equations (A.3.1) and (A.3.6). Let $x_{i|j}$ denote the optimal estimation of x_i based on all the information up to and including y_j , e.g.

$$x_{t|t} = E[x_t | y_t, y_{t-1}, \dots, y_1]$$

$$x_{t|t-1} = E[x_t | y_{t-1}, y_{t-2}, \dots, y_1]$$

Let $P_{i|j}$ denote the $m \times m$ covariance matrix of the estimated error based on the information set

$Y_j = \{y_j, y_{j-1}, \dots, y_1\}$, e.g.

$$P_{t|t} = E[(x_t - x_{t|t})(x_t - x_{t|t})']$$

$$P_{t|t-1} = E[(x_t - x_{t|t-1})(x_t - x_{t|t-1})']$$

When y_t is available, the estimator of x_t , $x_{t|t-1}$, can be updated:

$$(A.3.8) \quad x_{t|t} = x_{t|t-1} + P_{t|t-1} Z_t' F_t^{-1} (y_t - Z_t x_{t|t-1} + d_t)$$

$$(A.3.9) \quad P_{t|t} = P_{t|t-1} - P_{t|t-1} Z_t' F_t^{-1} Z_t P_{t|t-1}$$

where

$$(A.3.10) \quad F_t = Z_t P_{t|t-1} Z_t' + H_t$$

Substituting equation (A.3.8) into equation (A.3.6), the prediction of unobserved variable in the next stage is,

$$x_{t+1|t} = T_{t+1} x_{t|t} + c_{t+1} = T_{t+1} \left[x_{t|t-1} + P_{t|t-1} Z_t' F_t^{-1} (y_t - Z_t x_{t|t-1} + d_t) \right] + c_{t+1}$$

This equation can be simplified as

$$(A.3.11) \quad x_{t+1|t} = [T_{t+1} - K_t Z_t] x_{t|t-1} + K_t y_t + (c_{t+1} - K_t d_t)$$

where

$$(A.3.12) \quad K_t = T_{t+1} P_{t|t-1} Z_t' F_t^{-1}$$

The recursion for the covariance matrix is

$$(A.3.13) \quad P_{t+1|t} = T_{t+1} \left(P_{t|t-1} - P_{t|t-1} Z_t' F_t^{-1} Z_t P_{t|t-1} \right) T_{t+1}' + R_{t+1} Q_{t+1} R_{t+1}'$$

And the prediction for y_{t+1} at time t is

$$(A.3.14) \quad y_{t+1|t} = Z_{t+1} x_{t+1|t} + d_{t+1}$$

$y_{t+1|t}$ can be obtained by substituting equation (A.3.11) into equation (A.3.14). The Kalman filter is started with the unconditional mean and variance of x_1 (Hamilton 1994):

$$(A.3.15) \quad x_{1|0} = E(x_1)$$

$$(A.3.16) \quad P_{1|0} = E \left[(x_1 - x_{1|0})(x_1 - x_{1|0})' \right]$$

The group of equations from (A.3.8) to (A.3.16) constructs the algorithm of Kalman Filter recursion process. The Figure 7 illustrates the process more intuitively:

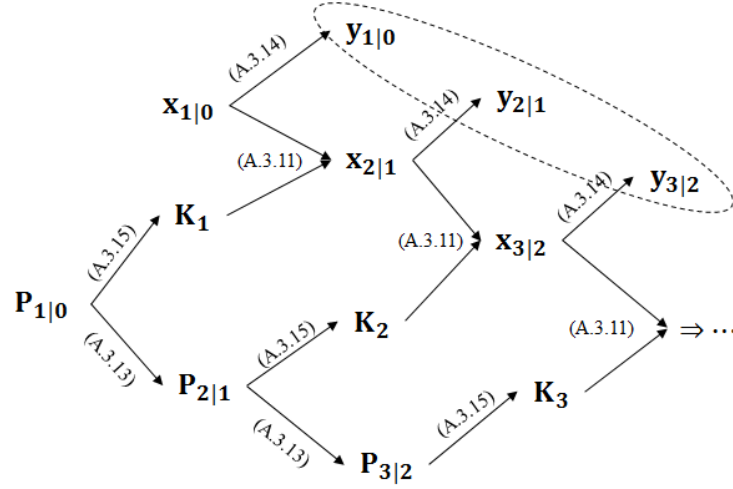


Figure 7 The Recursion Process of Kalman Filter

The formal derivation of Kalman filter can be found in Harvey (1989), page 109 - 110.

A.3.3 Maximum Likelihood Estimation

The theory of maximum likelihood estimation is based on T sets of observations, $Y_j = \{y_j, y_{j-1}, \dots, y_1\}$. The probability density function can be written as:

$$(A.3.17) \quad L(Y_t; \psi) = \prod_{t=1}^T P(y_t | Y_{t-1})$$

where ψ denotes all the unknown parameters involved in the state space model, and $P(y_t | Y_{t-1})$ denotes the probability of y_t conditional on all the information received till time $t-1, Y_{t-1}$.

Rewrite the observation equation (A.3.1) as

$$(A.3.18) \quad y_t = Z_t x_{t|t-1} + Z_t (x_t - x_{t|t-1}) + d_t + \varepsilon_t$$

The conditional expected value and variance of y_t at time $t-1$ can then be calculated from equation (A.3.18):

$$(A.3.19) \quad E_{t-1}(y_t) = y_{t|t-1} = Z_t x_{t|t-1} + d_t$$

$$(A.3.20) \quad \text{var}_{t-1}(y_t) = Z_t P_{t|t-1} Z_t' + H_t = F_t$$

Therefore, the log likelihood function can be written as

$$(A.3.21) \quad \log L = -\frac{NT}{2} \log(2\pi) - \frac{1}{2} \sum_{t=1}^T \log |F_t| - \frac{1}{2} \sum_{t=1}^T v_t' F_t^{-1} v_t$$

where $v_t = y_t - y_{t|t-1}$. Let

$$(A.3.22) \quad \ell_t = -\frac{N}{2} \log(2\pi) - \frac{1}{2} \log |F_t| - \frac{1}{2} v_t' F_t^{-1} v_t$$

Then, $\log L = \sum_{t=1}^T \ell_t$. Differentiating ℓ_t with respect to the i th element of ψ ,

$$\frac{\partial \ell_t}{\partial \psi_i} = -\frac{1}{2} \text{tr} \left(F_t^{-1} \frac{\partial F_t}{\partial \psi_i} \right) - \frac{1}{2} \left[\frac{\partial v_t'}{\partial \psi_i} F_t^{-1} v_t - v_t' F_t^{-1} \frac{\partial F_t}{\partial \psi_i} F_t^{-1} v_t + v_t' F_t^{-1} \frac{\partial v_t}{\partial \psi_i} \right]$$

It can be rewritten as

$$(A.3.23) \quad \frac{\partial \ell_t}{\partial \psi_i} = -\frac{1}{2} \text{tr} \left(\left[F_t^{-1} \frac{\partial F_t}{\partial \psi_i} \right] - \left[I - F_t^{-1} v_t v_t' \right] \right) - \frac{\partial v_t'}{\partial \psi_i} F_t^{-1} v_t$$

where I is the identity matrix. The first order derivative of the log likelihood function can be obtained:

$$(A.3.24) \quad \frac{\partial \log L}{\partial \psi_i} = -\frac{1}{2} \sum_{t=1}^T \left\{ \text{tr} \left(\left[F_t^{-1} \frac{\partial F_t}{\partial \psi_i} \right] - \left[I - F_t^{-1} v_t v_t' \right] \right) - \frac{\partial v_t'}{\partial \psi_i} F_t^{-1} v_t \right\}$$

The Maximum Likelihood Estimators can be derived while assuming $\frac{\partial \log L}{\partial \psi_i} = 0$, for all

$i = 1, 2, \dots, n$. The numerical method to evaluate the parameters can be found in Harvey (1989),

Chapter 3. The gradient vector at the maximum likelihood estimates can be presented as

$$\hat{G} = \frac{\partial \log L}{\partial \psi'} \bigg|_{\psi = \hat{\psi}}$$

The information matrix plays a very important role in calculating the covariance matrix of maximum likelihood estimators. Differentiating the equation (A.3.23), with respect to the j th element of ψ , ψ_j , gives,

$$\begin{aligned} \frac{\partial^2 \ell_t}{\partial \psi_i \partial \psi_j} = & \frac{1}{2} \text{tr} \left[\frac{\partial \left[F_t^{-1} \frac{\partial F_t}{\partial \psi_i} \right]}{\partial \psi_j} \left[I - F_t^{-1} v_t v_t' \right] \right] - \frac{1}{2} \text{tr} \left[F_t^{-1} \frac{\partial F_t}{\partial \psi_i} F_t^{-1} \frac{\partial F_t}{\partial \psi_j} F_t^{-1} v_t v_t' \right] \\ & + \frac{1}{2} \text{tr} \left[F_t^{-1} \frac{\partial F_t}{\partial \psi_i} F_t^{-1} \left[\frac{\partial v_t}{\partial \psi_j} v_t' + v_t \frac{\partial v_t'}{\partial \psi_j} \right] \right] - \frac{\partial^2 v_t'}{\partial \psi_i \partial \psi_j} F_t^{-1} v_t - \frac{\partial v_t'}{\partial \psi_i} \frac{\partial F_t^{-1}}{\partial \psi_j} v_t \\ & - \frac{\partial v_t'}{\partial \psi_i} F_t^{-1} \frac{\partial v_t}{\partial \psi_j} \end{aligned}$$

Therefore, the ij -th element of the information matrix can be written as

$$\frac{\partial^2 \log L}{\partial \psi_i \partial \psi_j} = \sum_{t=1}^T \frac{\partial^2 \ell_t}{\partial \psi_i \partial \psi_j}$$

Denoting the information matrix as H , then the information matrix at the maximum likelihood estimates can be presented as

$$\hat{H} = \frac{\partial^2 \log L}{\partial \psi \partial \psi'} \bigg|_{\psi = \hat{\psi}}$$

The covariance matrix can be calculated as:

$$\text{var}(\hat{\psi}) = -\hat{H}^{-1}$$

which is a $n \times n$ matrix. Hamilton (1994) showed that under certain conditions, quasi-maximum likelihood estimates give consistent and asymptotically normal estimates of the true value of ψ , with

$$\hat{\psi} - \psi \xrightarrow{L} N(0, \text{var}(\hat{\psi})) \quad \blacksquare$$

A.4 Derivation of Equation (54)

Substituting the expected corn price equation (35) into switchgrass price equation (52), the switchgrass price can be written as

$$\begin{aligned} \rho^* &= c_1 \gamma_1 + \frac{r}{1 - e^{-rT}} \int_0^T [E(P(t)) - c_2] \gamma_2 e^{-rt} dt \\ &= c_1 \gamma_1 + \frac{r}{1 - e^{-rT}} \int_0^T \left[e^{(\xi_0' + \frac{\sigma_1'^2}{4\kappa'} + \frac{\rho' \sigma_1' \sigma_2'}{\kappa'}) + (\mu' + \frac{1}{2} \sigma_2'^2) t} - c_2 \right] \gamma_2 e^{-rt} dt \\ &= c_1 \gamma_1 + \frac{r \gamma_2}{1 - e^{-rT}} \int_0^T \left[e^{(\xi_0' + \frac{\sigma_1'^2}{4\kappa'} + \frac{\rho' \sigma_1' \sigma_2'}{\kappa'}) + (\mu' + \frac{1}{2} \sigma_2'^2 - r) t} - c_2 e^{-rt} \right] dt \\ &= c_1 \gamma_1 - c_2 \gamma_2 + \frac{r \gamma_2}{1 - e^{-rT}} e^{(\xi_0' + \frac{\sigma_1'^2}{4\kappa'} + \frac{\rho' \sigma_1' \sigma_2'}{\kappa'})} \int_0^T e^{(\mu' + \frac{1}{2} \sigma_2'^2 - r) t} dt \\ &= c_1 \gamma_1 - c_2 \gamma_2 + \frac{r \gamma_2}{1 - e^{-rT}} \frac{e^{(\mu' + \frac{1}{2} \sigma_2'^2 - r) T} - 1}{\mu' + \frac{1}{2} \sigma_2'^2 - r} e^{(\xi_0' + \frac{\sigma_1'^2}{4\kappa'} + \frac{\rho' \sigma_1' \sigma_2'}{\kappa'})} \end{aligned}$$

which is equation (54). When $T \rightarrow \infty$, and $\mu' + \frac{1}{2} \sigma_2'^2 - r < 0$,

$$e^{-rT} \rightarrow 0 \quad \text{and} \quad e^{(\mu' + \frac{1}{2} \sigma_2'^2 - r) T} \rightarrow 0$$

Therefore, the switchgrass price will converge to

$$\rho \rightarrow c_1 \gamma_1 - c_2 \gamma_2 + \frac{r \gamma_2}{r - \mu' - \frac{1}{2} \sigma_2'^2} e^{(\xi_0' + \frac{\sigma_1'^2}{4\kappa'} + \frac{\rho' \sigma_1' \sigma_2'}{\kappa'})} \quad \blacksquare$$

VITA

Tianpeng Zhou is an international master's student at the University of Tennessee, Knoxville. Having completed his bachelor's degrees in Economics (Honor's) in China, he continued in his study at the University of Tennessee (UT) as a master's student majoring in Agricultural Economics. He enjoys the period studying and working in the Department of Agricultural and Resource Economics at UT, and he likes the people around him. He feels that he is so blessed to have these unforgettable two years at UT. He is expected to graduate in August, 2013.