2009

Research in biomass production and utilization: systems simulation and analysis

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Recommended Citation

Bennett, Albert S., "Research in biomass production and utilization: systems simulation and analysis" (2009). *Graduate Theses and Dissertations*. 10562.
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Research in biomass production and utilization: systems simulation and analysis

by

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A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Co-majors: Agricultural Engineering; Biorenewable Resources and Technology

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2009

To My
Wife
and
Daughters

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ABSTRACT

There is considerable public interest in developing a sustainable biobased economy that favors support of family farms and rural communities and also promotes the development of biorenewable energy resources. This study focuses on a number of questions related to the development and exploration of new pathways that can potentially move us toward a more sustainable biobased economy. These include issues related to biomass fuels for drying grain, economies-of-scale, new biomass harvest systems, sugar-to-ethanol crop alternatives for the Upper Midwest U.S., biomass transportation, post-harvest biomass processing and double cropping production scenarios designed to maximize biomass feedstock production. For each question of interest, specific examples were identified and detailed models developed in MS Excel ®. Techno-economic analysis and Monte Carlo simulation techniques were used to challenge each model and evaluate viability.

The first section of this study considers post-harvest drying of shelled corn grain both at farm-scale and at larger community-scaled installations. Currently, drying of shelled corn requires large amounts of fossil fuel energy. To address future energy concerns, this study evaluates the potential use of combined heat and power systems that use the combustion of corn stover to produce steam for drying and to generate electricity for fans, augers, and control components. Techno-economic analysis suggests that there are significant economies of scale with community-based dryers, e.g. grain elevators, which show a much faster return on investment over farm-scaled systems. Because of the large capital requirements for solid fuel boilers and steam turbines/engines, both farm-scale and larger grain elevator-scaled systems benefit by sharing boiler and power infrastructure with other processes.

The second and third sections evaluate sweet sorghum as a possible “sugarcane-like” crop that can be grown in the Upper Midwest. Various harvest systems are considered including a prototype mobile juice harvester, a hypothetical one-pass unit that separates grain heads from chopped stalks and traditional forage/silage harvesters. Also evaluated were post-harvest transportation, storage and processing costs and their influence on the possible use of sweet sorghum as a supplemental feedstock for existing dry-grind ethanol plants located in the Upper Midwest. Results show that the concept of a mobile juice harvester is not economically viable due to low sugar recovery. However, traditional forage/silage harvest systems provide an economically viable harvest solution as long as chopped forage can be quickly processed in a nearby, centralized facility. The transportation of low bulk density, fresh harvested or ensiled sweet sorghum was found to significantly contribute to overall costs. However, at the scales evaluated in this study, those costs did not adversely affect the viability of sweet sorghum as a supplemental feed for existing dry-grind ethanol plant. The addition of front-end stalk processing/pressing equipment into existing ethanol facilities was also found to be economically viable when combined with the plants' use of residuals as a natural gas fuel replacement. Because of high loss of fermentable carbohydrates during ensilage, storage of sweet sorghum in bunkers was not found to be economically viable.

The forth section looks at double cropping winter triticale with late-planted summer corn and compares these scenarios to traditional single cropped corn. Double cropping systems show particular promise for co-production of grain and biomass feedstocks and potentially can allow for greater utilization of grain crop residues. However, additional costs and risks associated with producing two crops instead of one could make biomass-double crops less attractive for producers despite productivity advantages. Detailed evaluation and comparisons show double cropped triticale-corn to be at a significant economic disadvantage relative to single crop corn. The cost benefits associated with using less equipment combined with availability of risk mitigating crop insurance and government subsidies will likely limit farmer interest and clearly indicate that traditional single-crop corn will provide greater financial returns to management.

To evaluate the various sweet sorghum, single crop corn and double cropped triticale-corn production scenarios, a detailed but generic model was developed. The primary goal of this generic approach was to develop a modeling foundation that can be rapidly adapted, by an experienced user, to describe new and existing biomass and crop

production scenarios that may be of interest to researchers. To facilitate ease-of-use, the techno-economic model was developed in MS Excel®. It also incorporates the Excel add-on, Crystal Ball®, which provides Monte Carlo simulation and sensitivity analysis capabilities. The foundation model allows input of management practices, crop production characteristics and utilizes standardized machinery performance and cost information, including farm-owned machinery and implements, and machinery and farm production operations provided by custom operators. Several of the studies reported in this dissertation take advantage of the flexibility of the foundation model. Many specific models of unique production scenarios (in excess of 100) were developed and tested. Twenty of these models are actually presented in this work. More important to the success and value of this modeling approach is the now readily available Monte Carlo simulation tools, which allows researchers to describe uncertainty around key model variable in a more realistic manner. It is opinion of the author that all future crop related techno-economic studies should incorporate Monte Carlo simulations as standard practice.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

Personal interest and the desire to contribute to the search for ways to strengthen the family farm and develop a sustainable biobased economy have been the framework and impetus behind this study. Political and social pressures are now more favorable for the application of biomass as locally grown, renewable energy resources that can play a substantial role in a diverse and sustainable energy future. There are significant challenges and unanswered questions, however, regarding the use of biomass as a replacement for a very mature and well-developed petroleum-based economy. Some of these challenges and questions include:

- Are there ways to overcome the general trends toward very large economies of scale typical to petrochemical and power industries, i.e. can reliable and economically viable systems be engineered for farm- or community-scale biomass conversion projects? The benefit of a local approach and reduced scales would go a long way toward promoting rural development and off-setting transportation costs associated with highly dispersed, low bulk density biomass.
- More efficient systems capable of harvesting biomass will be essential to improving overall energy balance around biomass feedstocks and their ultimate conversion into liquid fuels, commodity chemicals, electricity, process heat, etc. Modeling the potential economic and logistical benefits of alternative biomass harvest systems will help focus limited research and development efforts and resources.
- The Brazilian sugarcane-ethanol industry has proven to be a very successful and currently utilizes far less fossil fuel than the corn based ethanol industry. Is there a similar crop-to-ethanol model that can be developed for U.S. agriculture? Is there a feedstock storage option that can be used to overcome the short harvest seasons that an alternative sugarcane-like crop would likely experience in the Upper Midwest?

- The relative attractiveness of lignocellulosic and carbohydrate-based transportation fuels has generated much interest in the research and policy communities and among the public in general. Transportation of lignocellulosic materials as well as other carbohydrate rich plant materials will have very substantial impact on the economic viability of any new biomass conversion technology. Detailed economic modeling related to biomass transportation will be essential for guiding research efforts and identifying promising system configurations and scales.
- The need for large quantities of biomass will be essential for the development of a biobased economy. Dedicated energy crops are one potential path toward supplying a portion of this biomass, however, there is a concern that dedicated energy crops may compete with food and feed crops. Are their new and alternative production scenarios that may address these concerns? Double cropping winter biomass and summer feed crops may be one possible solution. However, will these alternative production systems be able to compete with traditional single crop rotations on an economic basis and provide farmers adequate revenues to justify additional work related to more equipment intensive double cropping scenarios?

The focus of this dissertation is to consider these questions, conceptualize and/or identify new representative systems of interest and develop detailed models describing these systems. These models, in turn, will provide a platform to challenge these concepts with the ultimate goal of determining whether these new and alternative systems merit further development.

Techno-economic and sensitivity analyses are valuable research tools frequently utilized by researchers to evaluate competing and parallel paths related to biomass utilization (Bridgwater et al., 2002; Hamelinck et al., 2003; Hamelinck et al., 2005; Mitchell et al., 1995). This study includes the use of these tools to explore new concepts that potentially can benefit family farms and promote sustainable use of biomass. To evaluate the effects of uncertainty and parameter variation, Monte Carlo simulation techniques are also incorporated in the models developed in this study. Monte Carlo simulation techniques are used to describe variables of interest, not by just a single point or by low and high values typically used to test sensitivities, but by probability distributions (Metropolis and Ulam, 1949; Savvides, 1994). This methodology allows researchers to develop models that can more realistically represent uncertainties and evaluate probabilistic results that better describe a range of expected outcomes of biorenewable energy technologies.

Dissertation Organization

This dissertation follows the alternative dissertation format and is comprised of three published research papers and one paper in preparation for publication. The first explores the utilization of biomass as a fuel to dry corn grain utilizing existing grain drying technology integrated into a combined heat and power (CHP) configuration that utilizes corn stover fuel. The yearly cost of drying the U.S. shelled corn crop can easily exceed a billion dollars in fossil-based fuels (Bennett et al., 2007). This paper utilizes models that incorporate techno-economic and sensitivity analyses, and compares farm-scale and larger community-scale systems. Its primary goal is to evaluate the viability of small- to medium-scaled drying alternatives for shelled corn and consider it as one possible utilization opportunity that can promote local use of biomass. By avoiding excessive transportation costs associated with large, centralized conversion facilities these smaller systems can ultimately play a small part in helping reverse past trends toward large centralized economies of scale and reduced employment opportunities for rural communities.

The second and third papers consider sweet sorghum as an alternative sugarcane-like feedstock for ethanol production in the Upper Midwest region of the United States. The research presented in both papers address important questions related to alternative harvest systems, feedstock storage, transportation and post-harvest processing.

Other than cultural practices, sweet sorghum has been identified as a crop that in many ways is very similar to sugarcane (Bennett and Anex, 2008; Bennett and Anex, 2009). For example, post-harvest processing equipment can utilize the same mature and highly efficient technology utilized by the sugarcane industry to extract fermentable carbohydrates (FC). Sweet sorghum's FC content is similar to sugarcane and can be converted to ethanol using much of the same fermentation/distillation infrastructure currently employed by both Brazilian sugarcane and US corn ethanol industries. Post process residuals are similar to sugarcane bagasse, which can be utilized as a source of fuel for processing ethanol and co-generation of heat and electrical power.

Some of the questions and challenges that must be addressed before sweet sorghum can be established as a viable feedstock for ethanol production in the US include:

1. Are the economics of sweet sorghum as an energy crop favorable enough to entice US farmers to add it to their crop rotation?
2. There has been considerable interest in an alternative harvest system that promotes on-farm extraction of FC-rich juice and its on-farm fermentation into ethanol (McClune, 2004). The premise being that the farmer can directly benefit from adding value processing the energy crop into ethanol. Is this approach economically viable?
3. Are there existing harvest systems that can be readily adapted to sweet sorghum?
4. How important are transportation, storage and post-harvest processing costs to establishing a sweet sorghum-to-ethanol industry?

The second paper presented in this dissertation explores the viability of alternative sweet sorghum harvest systems including a mobile on-farm, juice harvester and more traditional forage/silage harvesters. It also estimates the impact of utilizing sweet sorghum process residuals as a fuel co-product. The models developed utilize techno-economic and Monte Carlo simulation tools to compare FC costs at farm-gate. The third paper explores the effects of transportation, and post-harvest storage and processing costs. Techno-economic methods and Monte Carlo simulations are also used to model various sweet sorghum production, storage and transportation scenarios and their effect on the cost of FC delivered to an ethanol production facility.

The forth paper presented is currently in preparation for publication. It explores the economic viability of double-cropped winter triticale with late-planted, summer corn as it compares to single crop corn grown on high productivity Upper Midwest cropland.

The utility and value of the combined use of both traditional techno-economic analyses with Monte Carlo simulation methods has proven to be a powerful tool for evaluating new biomass production and conversion processes.

To further exemplify the flexibility and value of this analysis technique, additional information regarding model structure is provided. As shown in Appendix A, all models used to describe sweet sorghum and double cropping scenarios are based in MS Excel ® and utilize Crystal Ball ® as an Excel Add-on. Each model is comprised of multiple worksheets that allow input of crop production characteristics, preharvest machinery and materials, harvest machinery, and for models that consider post-harvest analysis of sweet sorghum, allow inputs that describe off-farm transportation and processing. Each model also includes reference tables that describe machinery performance and cost parameters.

References

Bennett, A.S., Bern, C.J., Richard, T.L. and R.P. Anex. 2007. Corn grain drying using corn stover combustion and CHP systems. *Transactions of the ASABE* 50(6): 2161-2170.

Bennett, A.S. and R.P. Anex. 2008. Farm-gate production costs of sweet sorghum as a bioethanol feedstock. *Transactions of the ASABE* 51(2): 603-613:

Bennett, A.S. and R.P. Anex. 2009. Corn grain drying using corn stover combustion and CHP systems. *Bioresource Technology* 100 (2009), pp. 1595-1607.

Bridgwater, A.V., Toft, A.J. and J.G. Brammer. 2002. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. *Renewable and Sustainable Energy Reviews* 6 (2002) 181-248.

Hamelinck, C.N., Van Hooijdonk, G. and A.P.C. Faaij. 2003. Prospects for ethanol from lignocellulosic biomass: techno-economic performance as development progresses. *Copernicus Institute, Science Technology Society,* Report NWS-E-2003-55.

Hamelinck, C.N., Van Hooijdonk, G. and A.P.C. Faaij. 2005. Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term. *Biomass and Bioenergy* 28 (2005) 384-410.

McClune, L. 2004. Personal communication: On-farm juice fermentation/juice storage systems and prototype 1-row tractor-pulled mobile juice harvester development and testing.

Metropolis, N. and S. Ulam. 1949. The Monte Carlo Method. *Journal of the American Statistical Association.* Vol. 44, Number 247, September 1949.

Mitchell, C.P., Bridgwater, A.V., Stevens, D.J., Toft, T.J. and M.P. Waters. 1995. Technoeconomic assessment of biomass to energy. *Biomass and Bioenergy* 9 (1995) 205-226.

Savvides, S.C. 1994. Risk analysis in investment appraisal. *Project Appraisal Journal*, Vol. 9, Number 1, Pages 3-18, March 1994.

CHAPTER 2. CORN GRAIN DRYING USING CORN STOVER COMBUSTION AND CHP SYSTEMS

Modified from a paper published in the *Transactions of the ASABE* [1]

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Abstract

Post-harvest drying of shelled corn grain requires large amounts of fossil fuel energy. In 2004, it was estimated that the upper Midwest consumed more than $1.4 billion of fossil fuels to dry $19.7 billion of corn grain. Over the long term, drying corn with fossil fuels may become cost prohibitive due to limited fuel reserves. To address future energy concerns for grain dryers, this study evaluated the potential use of combined heat and power (CHP) systems that use the combustion of corn stover both to produce heat for drying and to generate electricity for fans, augers, and control components. Net present value (NPV) cost estimates were determined for two continuous-flow dryers: a relatively small on-farm dryer (8.9 Mg h^{-1}), and a larger dryer more common to grain elevators (73 Mg h^{-1}). For each dryer, three levels of assumed stover price were used: $15, $25, and $35 per dry Mg for the small dryer, and $30, $45, and $60 per dry Mg for the larger dryer (includes payments to farmer and off-farm transport costs). Compared to equivalently sized fossil fuel-fired dryers, both the small and large CHP dryers were found to be more economical over the long term. Twenty-year NPV cost savings and breakeven points were estimated to be $63,523 and 14.3 years for the small CHP dryer ($25 Mg^{-1} stover) and $1,804,482 and 7.5 years for the large dryer ($45 Mg^{-1} stover). Sharing CHP infrastructure with other processes requiring heat that extend seasonal use can reduce payback periods significantly and provide broader efficiency benefits. Sensitivity analysis

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[1] Reprinted with permission of *Transactions of the ASABE*, v50 (6) pages 2161-2170.
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found cost savings to be most sensitive to fluctuations in fossil fuel costs, followed by annual use of dryer equipment.

Introduction

For many corn producers, post-harvest drying of shelled corn grain provides considerable flexibility in harvesting schedules and conditions. Compared to natural in-field drying, benefits of heated-air drying include earlier harvest, a larger harvest window, reduced field losses, reduced harvest damage, and less labor. The benefits associated with post-harvest drying, however, require significant energy input, of which the majority comes from fossil fuels. Due to ever increasing demands on limited natural gas and petroleum reserves, drying costs are likely to increase significantly.

Between 1992 and 1995, approximately 87% of the 38.8 × 106 Mg (1.52×10^9 bu) of the Iowa shelled corn crop (15 wt% moisture) was artificially dried (Bern, 1998). The energy consumption for drying was estimated to be 15.8×10^6 GJ (15.0×10^6 MMBtu), with energy from fossil fuel combustion, largely propane, providing approximately 80%. The remaining 20% came from electricity generated mostly by centralized fossil fuel-fired power stations (Bern, 1998).

By assuming the same 80/20 relationship, commercial electrical power cost of \$18.9 GJ^{-1} (\$0.068 kWh^{-1}), and propane valued at \$11.9 GJ^{-1} (\$1.15 gal^{-1}), it can be estimated that \$300 million in fossil fuel-derived energy was required in 2004 to dry Iowa's 57.0×10^6 Mg (2.24×10^9 bu) corn grain production (EIA, 2006; EIA, 2007b; USDA-NASS, 2005). Even more significant is the estimated \$1.4 billion drying cost for the entire upper Midwest corn belt (Illinois, Iowa, Indiana, Kansas, Michigan, Minnesota, Montana, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin), which in 2004 was reported to produce a combined 263×10^6 Mg (10.4×10^9 bu) of corn grain valued at \$19.7 billion (USDA-NASS, 2005).

Sustainable and Renewable Alternative Energy Sources

There is a growing global awareness that the sustainability and long-term success of society depend on reducing our reliance on fossil fuels as a primary energy source. As concerns for the environment, national security, and fossil fuel costs continue to grow, biorenewable energy resources, including dedicated energy crops and agricultural residues, are increasingly viewed as attractive options and essential components for the future conversion to more sustainable, bio-based economies. Significant constraints, however, currently limit the practical application of these alternative biorenewable energy resources. Most power generation facilities in the developed world are large-scale centralized power stations, which rely on energy-dense and/or easily transported fossil fuels such as coal, petroleum, and natural gas. In contrast, biomass-based fuel sources are generally highly dispersed in nature and have relatively high moisture contents, low bulk densities, and low heating values. Because of these constraints, it is economically prohibitive and inefficient (both in time and energy), in most cases, to transport large quantities of low-density biomass to large centralized power stations.

Apart from the operational and construction benefits associated with economies of scale, there are also limitations to the maximum efficiencies attainable by large-scale, fossil fuel-fired power generating facilities, which typically operate at energy efficiencies that range from 35% to 45%. Greater efficiencies are possible. For example, very large-scale, combined-cycle power stations are the trend in U.S. power generation research efforts and are projected to achieve up to 60% efficiencies (Brown, 2003). The most advanced systems under consideration are combinations of gas turbines, fuel cells, and steam turbines. Existing large-scale, combined-cycle systems typically employ high-temperature gas turbines followed by lower-temperature steam turbines and operate at efficiencies approaching 47% (Brown, 2003). Further increases in energy efficiencies, however, will be much more difficult to attain. This is because large, centralized systems are not able to economically utilize the vast quantities of low-grade waste heat that they generate. In addition, the nominal operating efficiencies of fossil fuel-dependent power stations do not reflect the energy consumed in fossil fuel exploration, extraction, processing, transport, power transmission, and grid maintenance, nor do they reflect the negative environmental impacts associated with fossil fuel-fired power plants.

Small-Scale, Localized Power Generation

In contrast to large-scale power generation, smaller decentralized power stations located in agricultural communities can take advantage of their close proximity to highly dispersed biomass resources. More importantly, they can incorporate multi-process designs that are able to recover and utilize the low-grade heat energy that is otherwise typically wasted, leading to greater energy use efficiencies. There are currently combined heat and power (CHP) plants operating in Europe that are able to achieve energy efficiencies greater than 85% (Nikolaisen et al., 1998). Some of the processes that can be incorporated into these alternative decentralized power plants include systems for distillation, food processing, electrical energy generation, absorption-based refrigeration, and hot water and space heating for buildings, greenhouses, and aquaculture.

One of the possible areas where decentralized CHP scenarios can be applied is in continuous-flow corn grain drying applications. Instead of natural gas or propane, these CHP systems use corn stover to fuel a steam boiler to power a steam engine or turbine and electrical generator. These engines in turn drive a grain dryer's fan motors, auger motors, and electronic controls. Low-pressure steam engine exhaust can also be readily condensed to provide part of the process heat required by the dryers. Additional high-pressure steam can be used to provide the remaining process heat required to dry corn grain. In addition to the costs associated with the purchase and operation of a boiler, steam engine, and generator, only minor modifications to the actual grain drying equipment would be necessary. These include the installation of steam condensers inside the dryer to replace gas burners and fuel systems.

Corn stover, comprised of corn stalks, leaves, and cobs, represents an ideal biomass feedstock for decentralized CHP drying applications. It is widely available across the Midwestern U.S., and a recent study conducted by the USDA and DOE (Perlack et al.,

2005) estimates that over 68 million dry Mg (75 million tons) can be sustainably harvested each year in the U.S.

Study Objective

Currently, grain driers are heated by the direct use of relatively "clean" combustion products from natural gas or propane. Due to stover's relatively high chlorine and ash content, combustion products from biomass, such as corn stover, would preferably be used indirectly; for this study, indirect use is accomplished with a steam condenser (Brown, 2003). When used directly in a grain dryer, these materials are corrosive and can lead to the deposition of unwanted or harmful particulates in the grain. In addition, a direct-fired, fossil fuel-heated grain dryer is not nearly as capital intensive as a hypothetical grain dryer with an additional steam boiler, engine/turbine, generator, and condenser.

Since the annual cost of drying U.S. corn grain production using fossil fuel-heated dryers is significant, the objective of this study was to evaluate the economic feasibility and sensitivities of drying corn with corn stover as a possible fuel alternative in both small (8.9 Mg h^{-1}) and large (73 Mg h^{-1}) capacity continuous-flow grain dryers. Potential benefits to converting to CHP stover-fired dryers include more environmentally friendly systems that may ultimately promote greater energy independence for rural communities.

Economic feasibility was determined by comparing the difference in the net present value (NPV) in operating costs of traditional fossil fuel-fired dryers and CHP-configured stover-fired dryers over a 20-year period. Sensitivities were tested by varying likely values for annual dryer use, CHP capital investments, labor wages, interest rates, and fossil fuel costs.

Methods

Corn Stover Collection Costs, Transport Costs and Pricing Assumptions

From 2000 to 2005, the average U.S. corn grain yield (dry weight) was reported to be 220 million Mg year^{-1}, which averages to be approximately 7.56 Mg ha^{-1} year^{-1} (USDA-NASS, 2005). According to Perlack et al. (2005), it is reasonable to assume a 1:1 dry grain to dry stover ratio; therefore, the U.S. also likely produced an average of 220 million Mg year^{-1} of dry corn stover during the same period. However, although a very large mass of corn stover is produced annually, soil conservation concerns limit how much of it can be removed for bio-energy related applications. Recommendations for sustainable collection rates of stover depend on the type of soil, topography, crop rotation, tillage practices, and other environmental constraints. Some stover residues should be left in the field, and a minimum of 30% surface coverage by residue is required to comply with USDA guidelines for erosion protection (Glassner et al., 1999). Residue removal has the greatest potential on mildly sloping, no-till fields, with recommended collection values of up to 58% (Wayman and Parekh, 1990). Hasche et al. (2003) estimated the impact of stover removal on soil erosion for various combinations of corn and soybean rotations. Their study indicated that soil erosion is largely dependent on tillage practices and slope, with biomass removal of secondary importance and soil type having a relatively minor effect. No biomass removal was recommended for land slopes greater than 11.5% or when intensive tillage practices (fall moldboard plowing) are employed on slopes greater than 2.5%. In comparison, 40% removal rates are possible when no-till practices are used on rapidly regenerating soils with slopes up to 7%, or when no-till is used on slowly regenerating soils with slopes below 2.5%.

Potential feedstock costs delivered to the plant (adjusted to 2007 dollars) for agricultural residues were reported to range from $18.10 per dry Mg for low-cost sources up to $66.50 per dry Mg for high-cost sources (Lynd, 1996). Recently, more detailed cost estimates have been developed specifically for the collection of corn stover. Sokhansanj and Turhollow (2002) estimated baling costs associated with the more common large round bales (0.580 dry Mg bale^{-1}) and compared them with large rectangular baling systems (0.770 dry Mg bale $^{-1}$). In their study, stover was assumed to be collected after completion of the grain harvest and delivered to an intermediate storage facility. Stover harvest rates were assumed to be 3.8 dry Mg ha^{-1} (42% of available residues). Cost estimates, adjusted to 2007 dollars, for both options were similar at $25.00 per dry Mg for round bales and $27.30 per dry Mg for rectangular bales. These estimates provide no payments to farmers for stover or storage. They are also impractically low for centralized processing facilities because they do not include costs related to reloading and delivery of bales from intermediate storage areas.

For very large farming operations and grain elevators, transportation will play a more significant role in determining final stover collection costs. Transportation costs for distances greater than 8 km were considered by Perlack and Turhollow (2002) and included cost estimates for corn stover collection and delivery to hypothetical ethanol processing facilities using large 580 kg round bales and large 590 kg rectangular bales. Collection procedures were very similar to those described by Sokhansanj and Turhollow (2002). Results from Perlack and Turhollow (2002) (adjusted to 2007 dollars) indicated that round bale collection and delivery costs (dry basis) to an intermediate storage area ranged from $30.20 Mg^{-1} for small ethanol processing facilities (450 Mg d^{-1}) to $31.60 Mg^{-1} for large facilities (3,630 Mg d^{-1}). Large rectangular bales were slightly more expensive, with costs ranging from $30.60 Mg^{-1} to $32.90 Mg^{-1}. Hauling distances from intermediate storage to processing facilities ranged from 35 km for small facilities to close to 100 km for very large facilities and typically added another $11.80 Mg^{-1} to $16.40 Mg^{-1} for large round and rectangular baling systems. When combining baling and off-farm transport, the total costs of large baling systems were found to range from $42.00 to $49.40.

There are other possible options for the collection and transport of stover based on one-pass, whole-plant harvest schemes. These alternative harvest systems have the potential to be much more economical than current baling systems (Quick, 2000; Shinners et al., 2003; Tuetken, 2002).

In this study, potential variability of on-farm stover collection costs, off-farm transportation costs, demand for alternative biofuels, and payments to farmers were simulated by using three price scenarios for small on-farm dryers and a second set of price scenarios for a large dryer typical of what an independent grain elevator might use. The dry basis stover price scenarios are \$15, \$25, and \$35 Mg^{-1} for the smaller on-farm dryer and \$30, \$45, and \$60 Mg^{-1} for the large dryer. Price scenarios for the large dryer are higher to account for off-farm transportation costs and payments made to farmers for purchasing stover.

Corn Stover as an Alternative Energy Source

An annual sustainable production of 68 million dry Mg of corn stover (Perlack et al., 2005) represents a very significant source of biomass. If that same biomass is completely converted to thermal energy (e.g., as steam) with a process efficiency of 80% and lower heating value of 16.5 MJ kg^{-1} (Morey et al., 2006), then the U.S. would be able to annually generate an additional 0.90 EJ (0.85 quadrillion Btu) of energy. In comparison, the U.S. currently uses more than 100 EJ of energy per year throughout its entire economy (Brown, 2003). Although 0.90 EJ is slightly less than 0.9% of the U.S. energy economy, it still represents a significant economic resource. For example, approximately 35 × 109 L of propane worth \$13 billion is required to generate 0.90 EJ of heat energy. There are significant challenges to utilizing low energy dense, highly dispersed biomass resources such as corn stover. However, when compared to current prices for propane and natural gas, the potential for economic savings is considerable. This is clearly indicated by the values shown in table 2.1, which compare this study's simulated costs of stover energy, on a per GJ basis, to U.S. commercial market prices for both natural gas and propane between August 2005 and July 2007 (EIA, 2007a, 2007b). The values shown for costs of stover energy do not include capital costs associated with stover-to-energy conversion equipment.

Limited Direct Application of Corn Stover Combustion Products

One of the primary limiting factors in utilizing corn stover as an energy source for drying grain is its relatively high concentration of chlorine. Chlorine becomes highly corrosive, forming hydrochloric acid, when allowed to condense on metal surfaces. Fortunately, this corrosion problem can be readily overcome by indirect firing or by using stover combustion gases to generate steam instead of sending them directly into a grain dryer. Unfortunately, a significant efficiency penalty is associated with the indirect application of condensing steam to provide process heat for grain drying. Part of this penalty can be compensated by the low cost of corn stover, and by incorporating CHP generation schemes into the grain drying system.

Table 2.1. Comparative energy costs for stover, natural gas and propane

Corn Stover Combustion	**Units**	**Small Dryer**				**Large Dryer**		
Stover Feedstock Cost (d.b.)	$ Mg^{-1}	15.0	25.0	35.0		30.0	45.0	60.0
Stover Lower Heating Value	GJ Mg^{-1}	16.5	16.5	16.5		16.5	16.5	16.5
Combustion efficiency	%	80%	80%	80%		80%	80%	80%
Stover Energy Cost	**$ GJ^{-1}**	**1.14**	**1.89**	**2.65**		**2.27**	**3.41**	**4.55**
Natural Gas Combustion				NG not available on most farms				
Natural Gas Cost	$ GJ^{-1}			9.01	10.82	13.57		
	$ MMBtu^{-1}			9.50	11.40	14.30		
Combustion efficiency	%			97%	97%	97%		
Natural Gas Energy Cost	**$ GJ^{-1}**			**9.78**	**11.74**	**13.69**		
Propane Combustion								
Propane Cost	$ m^{-3}			383	423	462		
	$ gal^{-1}			1.45	1.60	1.75		
Combustion efficiency	%			97%	97%	97%		
Propane Energy Cost [a]	**$ GJ^{-1}**			**15.43**	**17.02**	**18.62**		

[a] Propane energy content: 25.6 GJ m^{-3} (92,000 BTU gal^{-1}).

In steam-fired power plants, high chlorine concentrations in combustion products can also cause significant boiler tube corrosion problems for high-pressure steam (>6.0 MPa) at temperatures greater than 450°C (Nikolaisen et al., 1998; Bryers, 1996). Fortunately, in grain drying applications, less expensive boilers that operate at lower pressures (<2.3 MPa) and below 220°C can be used, with which the very high temperature corrosion of boiler tubes from chlorine is not considered to be a significant problem. Other maintenance issues associated with tube fouling from ash and particle depositions are assumed to be important, but manageable. This is especially true for corn grain drying applications, which are typically operated for only a few months each year. As a result, considerable downtime is available for maintaining boiler tubes.

Fossil Fuel Fired Continuous-Flow Grain Dryers

Performance data for two continuous-flow grain dryers fabricated by Delux Manufacturing Company (Delux, 2005) located in Kearney, Nebraska, provided the basis for the analytical comparisons. Both units considered for this study are modified, cross-flow designs that improve drying efficiencies by using heat recovery from the grain cooling section to preheat air entering the heated section. According to the manufacturer, heat recovered from the cooling section can increase the air temperature from 17°C to 28°C (30°F to 50°F). This study assumes the minimum 17°C. The first unit considered is a relatively small continuous dryer typical of what a moderate to large (e.g., 300 to 600 ha) family farming operation might use and where propane would be the fuel of choice. The second dryer is much larger and represents what a typical grain elevator might use, and where natural gas or propane might be the fuel of choice. Table 2.2 shows dryer capacities, electrical loads, and heating loads applied in this study. Boiler sizing is based on estimated heat load requirements for an ambient air temperature of 4.4°C. Heat loads at 20°C are based on the manufacturer's performance data (Delux, 2005).

Table 2.2. Continuous dryer capacity, and electrical and heating loads

Dryer Size	Dryer Capacity		Electrical Load [a]		Ambient Temp.		Heating Load [b]	
	$Mg\ h^{-1}$	$bu\ h^{-1}$	kW	HP	ºC	ºF	$GJ\ h^{-1}$	$BTU\ h^{-1}$
Small	8.9	350	16.4	22	21	70	2.2	$2.1x10^{6}$
					4.4	40	2.8	$2.7x10^{6}$
Large	73	2880	160	214	21	70	19.9	$18.9x10^{6}$
					4.4	40	25.5	$24.2x10^{6}$

[a] Electrical loads include fan(s), auger(s) and control systems.

[b] Heating loads for a 5% moisture removal (20% to 15%, wet basis).

Components and Capital Investments for CHP Modified Continuous-Flow Grain Dryers

To convert from a traditional fossil fuel, direct-fired, continuous-flow grain dryer to a system capable of using corn stover as its primary fuel, the addition of a stover-fired steam boiler, steam engine or turbine with a generator, and steam condensers, which replace a natural gas or propane burner, is necessary. Table 2.3 shows component sizing and capital cost estimates for the small and large dryer CHP systems.

Prices for the grain dryers were obtained from Delux Manufacturing Company (Delux, 2005). Costs for stover-fired steam boilers were obtained from Hurst Boiler and Welding Co. (Zebley, 2005). It was calculated that the smaller dryer would require slightly less than 735 kW (2.5 MMBtu h^{-1}). Due to limited availability of solid fuel-fired systems under 980 kW (3.3 MMBtu h^{-1}), the sizing and cost protocol described by Ulrich and Vasudevan (2004) was used to the estimate the cost for the 735 kW system. The basic formula for this sizing and cost protocol relation is as follows:

$$C_v = C_u \bullet (v/u)^{a} \tag{1}$$

where C_v is the estimated equipment purchase cost

v is the capacity associated with estimated purchase cost

C_u is a known equipment cost

u is the capacity associated with known equipment cost

a is the sizing exponent.

The larger dryer was calculated to require a maximum of 6870 kW (23.0 MMBtu h^{-1}). The larger boiler system also includes costs associated with federally mandated pollution control systems. Installation costs along with additional equipment for material handling and buildings structures are included in estimates for both the small and larger dryer CHP systems. Based on manufacturer price quotes (Zebley, 2005), the sizing exponent used to estimate the cost of the 735 kW solid-fuel boiler was calculated to be approximately 0.65.

Table 2.3. Component sizing and capital investments

		Small Dryer Installation			Large Dryer Installation		
Concept	**Unit**	**Size**	**Standard**	**Stover**	**Size**	**Standard**	**Stover**
Continuous Dryer	Mg h^{-1}	8.9	35,000	35,000	73	175,000	175,000
Propane Tanks		-	4,000	-	-	-	-
Steam Engine	kW	24	-	13,050	-	-	-
Steam Turbine	kW	-	-	-	239	-	65,000
Generator	kW	19	-	5,000	185	-	235,000
Boiler System	kW (MPa)	735(1.0)	-	232,000	6870 (1.7)	-	1,250,000
Condenser	m^2	17.7	-	43,520	162	-	139,350
Stover Storage	m^2	153	-	12,000	3860	-	302,000
Utility Tractor		-	-	-	56	-	34,000
Total Capital			39,000	340,570		175,000	2,200,350

Because of difficulties in obtaining small-scale steam turbines (less than 100 kW), this study assumed the use of a steam engine coupled to a commercially available PTO-driven generator for the small dryer CHP system. A steam engine performance model was used to estimate power output and steam requirements. The model was developed using methods and actual engine performance data (Stumpf, 1912). Small engine and generator costs were estimated from similarly sized components available from internet sources (Brown, 2005; Grainger, 2005) and by employing sizing protocols, described in equation 1, and installation factors (Ulrich and Vasudevan, 2004). A more traditional steam turbine and generator was assumed for the large dryer CHP system, with prices obtained from a manufacturer (Nick, 2005). To minimize capital investments and take advantage of steam engine designs, which typically operate at these lower pressures, a maximum operating pressure of 1.0 MPa (150 psig) was assumed for the small dryer CHP boiler system. The large dryer CHP system was assumed to use a boiler operating at a pressure of 1.7 MPa (250 psig). This will better accommodate commercial steam turbines that are capable of operating at relatively low pressures.

The condenser installation was assumed to be comprised of two stages: a lower-pressure condenser that receives low-pressure exhaust from the steam engine or turbine, followed by a higher-pressure condenser that applies most of the heat energy needed to raise temperatures in the grain dryer to just under 95°C. Figure 2.1 shows a schematic of the small (8.9 Mg h^{-1}) and large (73 Mg h^{-1}) dryer systems, including hypothetical condenser placement, airflow rates, and general dimensions. Condenser capacity was determined using the maximum heat and air temperature requirements for each dryer and the following formula (Ulrich and Vasudevan, 2004):

$$A = Q / (U \bullet \Delta T_m) \qquad (2)$$

where A is the exterior bare tube exchanger surface area, excluding fins (m^2),

Q is the heat transfer rate (W),

U is the overall heat transfer coefficient ($J\ m^{-2}\ s^{-1}\ K^{-1}$), and

ΔT_m is the log-mean of hot- and cold-end “approach” temperatures (K).

Typical overall heat transfer coefficient (U) values for condensing steam in air-cooled (fin-fan) heat exchangers range from 790 to 850 $J\ m^{-2}\ s^{-1}\ K^{-1}$, where fin area is approximately 15 to 20 times that of the bare tube area (Ulrich and Vasudevan, 2004). For this study, a more conservative value of 500 $J\ m^{-2}\ s^{-1}\ K^{-1}$ was used to calculate heat exchanger bare tube area. Condenser capital costs were also estimated (Milligan, 2005). Installation costs were estimated by applying multipliers typically used by the chemical processing industry (Ulrich and Vasudevan, 2004).

Although not necessary in many regions, stover storage costs, assuming the use of a totally enclosed hay barn, are also included (House and Stone, 1988; Taylor, 1995). The purchase cost of a dedicated utility tractor for transporting stover bales between storage and materials processing is included in capital cost estimates for the large dryer system.

Financial Analysis

A 20-year financial analysis was used to predict the potential for cost savings generated by converting from traditional fossil fuel-fired grain dryers to stover-fired CHP grain dryer systems. The analysis included initial capital costs, equipment and structures depreciation, and operational costs associated with the additional labor needed to handle stover.

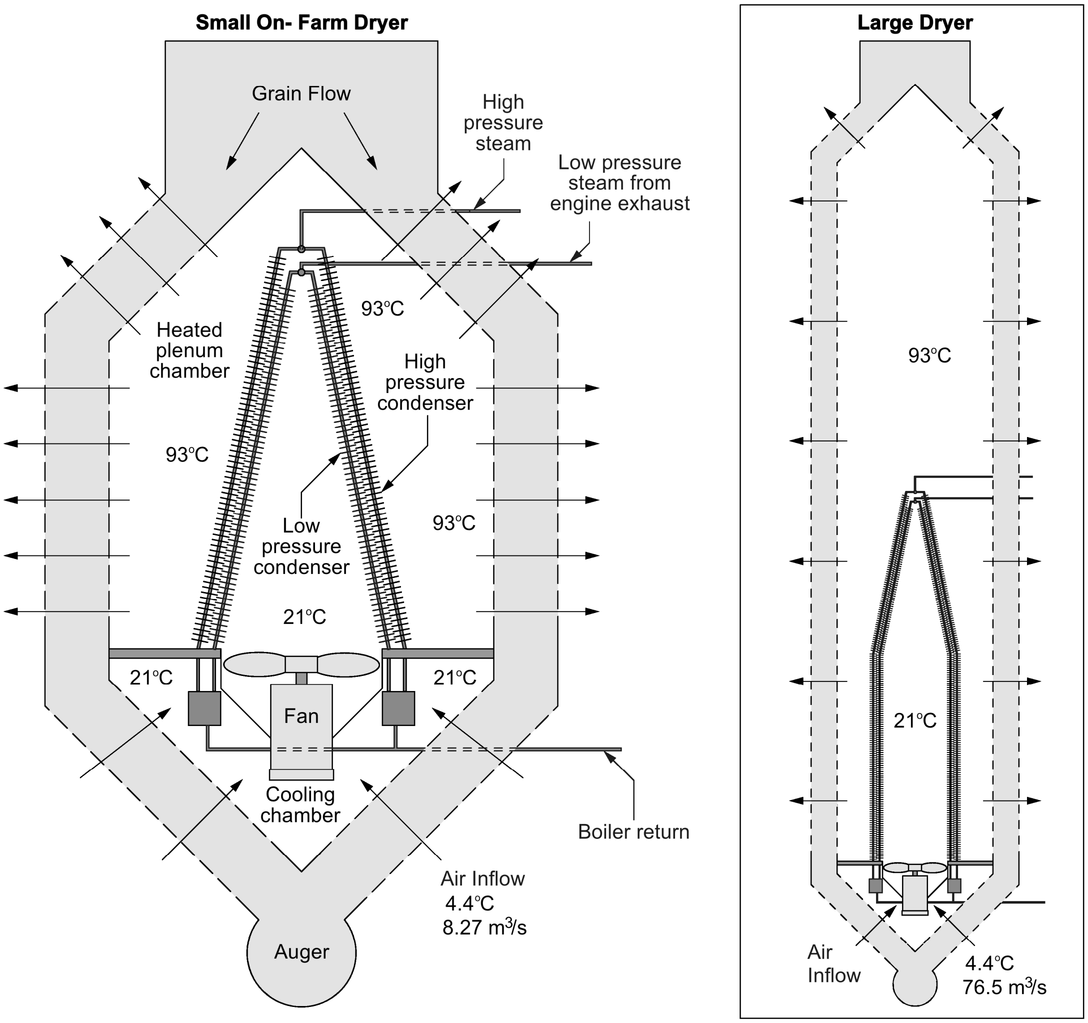

Figure 2.1. Modified, continuous CHP crossflow grain dryers

Depreciation was assumed to follow a 20-year straight-line relation for capital investments. Annual interest and inflation rates were assumed to be 7% and 1%, respectively, and were combined to establish a discount rate (i) of 5.94%. The following formula was used to calculate the discount rate:

$$i = [\,(\text{interest rate} + 1) / (\text{inflation rate} + 1)\,] - 1 \tag{3}$$

Discounted annual cash flow (DACF) was calculated by the following formula:

$$\text{DACF} = \text{ACF} / (1 + i)^{n} \tag{4}$$

where ACF is the annual cash flow, which included the sum of energy and equipment costs minus depreciation, and

n is the year.

For each analysis, the net present value (NPV) cost was subsequently calculated by summing the discounted annual cash flow. Differences between the NPV of operational costs for stover and fossil fuel systems were subsequently used to compare and evaluate the potential for medium- to long-term cost savings of stover-fired CHP systems. Operational costs for both fossil fuel and stover-fired CHP systems include fuel costs, depreciation, and an annual maintenance cost equal to 2% of the initial capital invested (Brown, 2003). Financial costs for each system assume 60% financing of initial capital using a 7-year loan compounded monthly. While fossil fuel systems include electrical power costs, stover-fired CHP systems include additional stover handling and labor costs.

The small dryer is assumed to operate 6 weeks per year and 14 h per day, while the large dryer system is assumed to operate 10 weeks per year and 24 h per day. Labor to move stover between the bale storage building and processing equipment is assumed to be \$12 h^{-1}. This value is based on actual surveys conducted by Iowa State University Extension Service and Occupational Employment Statistics, which reported farm machinery operators earning approximately \$10 h^{-1}; an additional 20% is included to account for benefits and other employer expenses (BLS, 2007; Edwards and Smith, 2006). It is also assumed that approximately 10% of the labor is associated with operating a tractor to move bales. The cost to operate the small utility tractor (labor excluded) is taken to be \$21 h^{-1} (Edwards, 2007).

Fossil Fuel and Electricity Cost Assumptions

According to the U.S. Energy Information Administration (EIA), between January 2005 and December 2006, the average U.S. commercial prices for natural gas and propane were approximately \$10.10 GJ^{-1} (\$10.65 $MMBtu^{-1}$) and \$16.50 GJ^{-1} (\$1.60 gal^{-1}), respectively (EIA, 2007a, 2007b). These same values are used for comparisons. The cost of electrical energy is assumed to be \$18.9 GJ^{-1} (\$0.068 kWh^{-1}) (EIA, 2006).

Results and Discussion

Twenty-Year Cost Comparisons

The potential cost savings resulting from the use of stover CHP dryer systems are shown in figures 2.2 and 2.3. Savings for both the large and small dryer systems are represented as net present values (NPV). Details regarding each of the six scenarios shown in figure 2.2 and 2.3 are provided in table 2.4, including three scenarios where 100% of the CHP-related capital investments and financial costs are charged to the dryer systems and three scenarios where only 25% of the capital and financial costs associated with the solid-fuel boiler, steam turbine/engine, and generator are charged to the dryer analysis. Included are values used for annual dryer use, capital investments, depreciation, fossil fuel cost, stover cost, each scenario's accumulated DACF at year 20, and savings breakeven point (i.e., where accumulated DACF values for CHP systems are equal to fossil fuel-fired systems). The large capital investments associated with a CHP dryer systems and the limited operation time (1 to 3 months) support the rationale for sharing capital and financial expenses; for example, the CHP unit can supply winter heat to a greenhouse structure.

During the early years of the investment, fossil fuel-fired dryers are less expensive to operate due to the CHP stover system's high capital investment requirements. With time, however, all of the modeled alternative CHP systems become the more economical investment, as is clearly indicated in figures 2.2 and 2.3. This especially true for shared CHP configurations.

Other processes that might share a CHP system include winter greenhouses, aquaculture operations, and residential heat and electricity. Low-cost locally grown biomass fuels could make these types of enterprises attractive for many farming communities, which are now searching for means of improving farm profitability and promoting rural development. In addition, it is not uncommon to find grain elevators near the center of small rural towns in the Midwest corn belt. This would allow a large CHP dryer system to sell waste heat to nearby residents during winter months, and selling electrical power to a local grid may be an attractive and profitable option for reducing fossil fuel dependence.

The potential savings in fossil fuel use can be significant when converting to a CHP dryer configuration. For example, the small 8.9 Mg h^{-1} (350 bu h^{-1}) dryer modeled in this study could save 33,000 GJ in fossil fuel use, which for propane valued at \$16.5 GJ^{-1} (\$1.60 gal^{-1}) is worth approximately \$545,000. In comparison, over 20 years, a single large stover-fired 73 Mg h^{-1} (2880 bu h^{-1}) dryer can avoid the use of approximately 855,000 GJ of propane worth \$14.1 million.

Sensitivity Analysis

Model sensitivities were tested and compared to the corresponding base case scenarios L-2, L-5, S-2, and S-5 (table 2.4) by varying annual dryer use, CHP capital investments, labor wages, interest rates, and fossil fuel costs by ±10%. For each of the tested variables, table 2.5 shows the 20-year saving, corresponding percent difference from base case conditions, and breakeven point. The models show the greatest sensitivity to changes in fossil fuel costs, followed by annual dryer use.

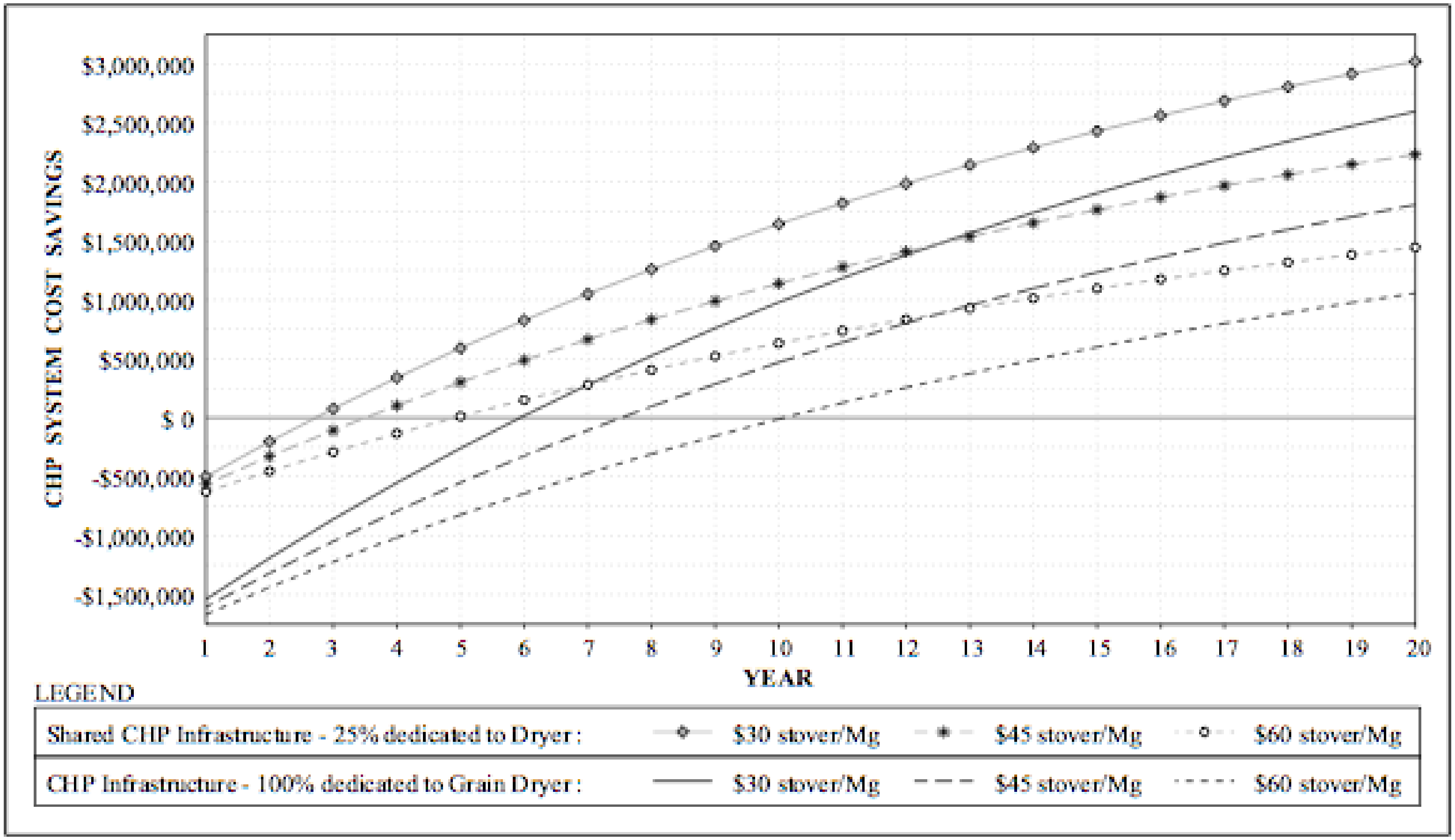

Figure 2.2. Large dryer (73 Mg/h): net present value cost of stover-fired combined heat and power dryer "minus" net present value cost of the natural gas-fired dryer.

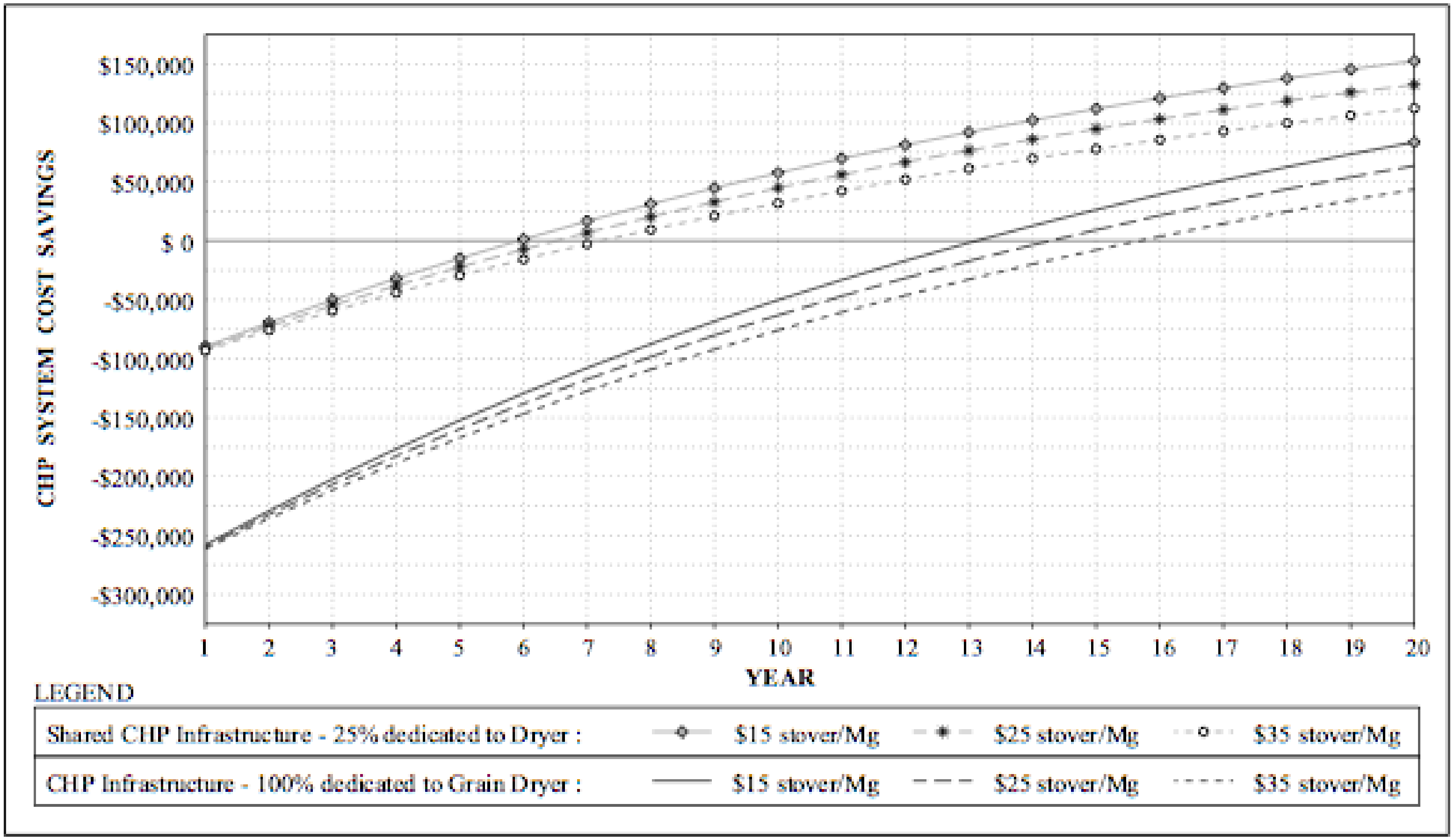

Figure 2.3. Small dryer (8.9 Mg/h): net present value cost of stover-fired combined heat and power dryer "minus" net present value cost of propane-fired dryer.

Table 2.4. Modeled scenarios corresponding to figures 2.2 and 2.3

		Fossil Fuel-Fired Dryer[a]			Stover-Fired CHP Dryer[b]				CHP Savings	
Scenario	Annual Dryer Use (h)	Fuel Cost ($ GJ^{-1})	Dryer Capital ($)	Annual Deprec. ($)	Stover Cost ($ Mg^{-1})	CHP Capital ($)	CHP Equipment Use	Annual Deprec. ($)	20-Year Accumulated Savings ($)[c]	Breakeven Point (years)
Large dryer (fig. 2.2)										
L-1	1680	10.10	175,000	-8,750	30	2,200,350	Dedicated	-110,018	2,593,296	5.9
L-2	1680	10.10	175,000	-8,750	45	2,200,350	Dedicated	-110,018	1,804,482	7.5
L-3	1680	10.10	175,000	-8,750	60	2,200,350	Dedicated	-110,018	1,015,668	10.3
L-4	1680	10.10	175,000	-8,750	30	1,037,850	Shared	-51,893	3,020,693	2.7
L-5	1680	10.10	175,000	-8,750	45	1,037,850	Shared	-51,893	2,231,879	3.5
L-6	1680	10.10	175,000	-8,750	60	1,037,850	Shared	-51,893	1,443,065	4.9
Small dryer (fig. 2.3)										
S-1	588	16.50	39,000	-1,750	15	374,570	Dedicated	-17,029	83,616	13.1
S-2	588	16.50	39,000	-1,750	25	374,570	Dedicated	-17,029	63,523	14.3
S-3	588	16.50	39,000	-1,750	35	374,570	Dedicated	-17,029	43,430	15.7
S-4	588	16.50	39,000	-1,750	15	187,033	Shared	-7,652	152,565	5.9
S-5	588	16.50	39,000	-1,750	25	187,033	Shared	-7,652	132,472	6.5
S-6	588	16.50	39,000	-1,750	35	187,033	Shared	-7,652	112,379	7.2

[a] Electrical power: \$0.068 kWh^{-1}.

[b] Labor to handle stover: \$12 h^{-1}.

[c] 7% interest rate.

Conclusions

This study illustrates that corn stover can provide an economically viable fuel for grain drying systems for both small and large CHP systems. Sensitivity analysis indicates that the economics of CHP-driven grain dryers resist significant variation in capital, fuel, and labor costs; interest rates; and annual use of CHP equipment. However, some significant challenges must be met before CHP dryers can be considered practical for commercial applications. Prominent constraints include the high cost of relatively small turbine and generator systems, and the unavailability of large steam engines (or small turbines) and commercial dryers fitted with steam condensers. The capital investments required for boiler systems capable of handling agricultural residues are also significant (nearly ten times the cost of package fossil fuel boilers). High boiler and CHP equipment costs, however, can be mitigated by sharing the CHP infrastructure with other heat-requiring processes and, with time, can benefit from competition and wider applications of biomass-based CHP systems. This cost reduction is especially important for small to medium-sized farming operations, where the high initial capital investments and longer payback, combined with additional labor and maintenance requirements, will limit the practical application of farm-scale CHP systems.

Table 2.5. Sensitivity analysis: 20-year CHP savings for dedicated and shared CHP infrastructure

Variable	Unit	Base Value	Adjusted Value		Accumulated Savings ($)		% Difference		Breakeven (years)	
			-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%
Large Dryer										
Dedicated CHP - Base case (scenario L-2)										
Annual dryer use	h	1,680	1,512	1,848	1,549,571	2,059,393	-14.1	14.1	8.2	6.9
CHP capital[a]	$	1,689,350	1,520,415	1,858,285	1,878,945	1,730,020	4.1	-4.1	6.9	8.2
Hourly wages	$\$\,h^{-1}$	12.0	10.8	13.2	1,827,718	1,781,247	1.3	-1.3	7.5	7.6
Interest rate	%	7.0	6.3	7.7	2,010,931	1,616,039	11.4	-10.4	7.4	7.7
Fossil fuel costs	$\$\,GJ^{-1}$	10.10	9.09	11.11	1,306,692	2,302,272	-27.6	27.6	9.0	6.5
Shared CHP - Base case (scenario L-5)										
Annual dryer use	h	1,680	1,512	1,848	1,976,968	2,486,790	-11.4	11.4	3.9	3.2
CHP capital[a]	$	422,338	380,104	464,571	2,263,602	2,200,156	1.4	-1.4	3.2	3.8
Hourly wages	$\$\,h^{-1}$	12	10.8	13.2	2,255,114	2,208,644	1.0	-1.0	3.5	3.5
Interest rate	%	7	6.3	7.7	2,406,069	2,072,514	7.8	-7.1	3.5	3.5
Fossil fuel costs	$\$\,GJ^{-1}$	10.10	9.09	11.11	1,734,089	2,729,669	-22.3	22.3	4.3	3.0
Small Dryer										
Dedicated CHP - Base case (scenario S-2)										
Annual dryer use	h	588	529	647	45,936	81,110	-27.7	27.7	15.5	13.3
CHP capital[a]	$	293,570	264,213	322,927	74,757	52,289	17.7	-17.7	13.1	15.4
Hourly wages	$\$\,h^{-1}$	12.0	10.8	13.2	71,655	55,391	12.8	-12.8	13.8	14.8
Interest rate	%	7.0	6.3	7.7	82,368	46,374	29.7	-27.0	13.5	15.2
Fossil fuel costs	$\$\,GJ^{-1}$	16.50	14.85	18.15	32,113	94,933	-49.4	49.4	16.6	12.6
Shared CHP - Base case (scenario S-5)										
Annual dryer use	h	588	529	647	114,885	150,058	-13.3	13.3	7.1	6.0
CHP capital[a]	$	73,393	66,053	80,732	136,811	128,132	3.3	-3.3	5.9	7.1
Hourly wages	$\$\,h^{-1}$	12.0	10.8	13.2	140,604	124,339	6.1	-6.1	6.3	6.8
Interest rate	%	7.0	6.3	7.7	146,113	120,014	10.3	-9.4	6.4	6.6
Fossil fuel costs	$\$\,GJ^{-1}$	16.50	14.85	18.15	101,062	163,881	-23.7	23.7	7.7	5.6

[a] Includes CHP steam turbine/engine, generator, solid-fuel boiler, and condenser.

Farm-based and local micro-, small-, and medium-scale CHP facilities offer considerable potential. With the right focus, these CHP systems will be able to take advantage of the large supplies of local, carbon dioxide neutral, agricultural and forestry residues, and dedicated energy crops, which will ultimately provide greater national security, and an environmentally friendly and more sustainable energy base.

Acknowledgements

The assistance and advice from Mr. Steve Shultz at Delux Manufacturing Company, regarding continuous-flow grain dryers, and from Mr. Gene Zebley at Hurst Boiler and Welding Company, regarding the use of solid fuel boilers, is greatly appreciated.

References

Bern, C. J. 1998. Preserving the Iowa corn crop: Energy use and CO_2 release. *Applied Eng. in Agric.* 14(3): 293-299.

BLS. 2007. Occupational employment statistics: Agricultural equipment operators. Washington, D.C.: U.S. Department of Labor, Bureau of Labor Statistics. Available at: www.bls.gov/oes/current/oes452091.htm#(3). Accessed October 2007.

Brown, M. 2005. Prices for 3 hp and 20 hp two-cylinder, single-stage steam engines. Available at: www.mikebrownsolutions.com. Accessed November 2005.

Brown, R. C. 2003. *Biorenewable Resources: Engineering New Products from Agriculture.* Ames, Iowa: Iowa State University Press.

Bryers, R. W. 1996. Fireside slagging, fouling, and high-temperature corrosion of heat-transfer surface due to impurities in steam-raising fuels. *Prog. Energy Combustion Sci.* 22: 29-120.

Delux. 2005. Delux continuous-flow grain dryers. Kearney, Neb.: Delux Manufacturing Co. Available at: www.deluxmfg.com. Accessed December 2005.

Edwards, W. 2007. Personal communication and unpublished 2007 machinery cost spreadsheet. Ames, Iowa: Iowa State University Extension Service.

Edwards, W., and D. Smith. 2006. 2006 Iowa farm custom rate survey. Publication FM 1698. Ames, Iowa: Iowa State University Extension Service.

EIA. 2006. 2004 Iowa commercial electric price. Washington, D.C.: U.S. Government Energy Information Administration. Available at: www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html. Accessed February 2006.

EIA. 2007a. Commercial natural gas prices. Washington, D.C.: U.S. Government Energy Information Administration. Available at: tonto.eia.doe.gov/dnav/ng/ng_pri_sum_a_EPG0_PCS_DMcf_m.htm. Accessed October 2007.

EIA. 2007b. Commercial propane prices for PAD district II. Washington, D.C.: U.S. Government Energy Information Administration. Available at: tonto.eia.doe.gov/dnav/pet/hist/d900200002m.htm. Accessed October 2007.

Glassner, D., J. Hettenhaus, and T. Schechinger. 1999. Corn stover potential: Recasting the corn sweetener industry. In *Perspectives on New Crops and New Uses*, 74-82. J. Janick, ed. Alexandria, Va.: ASHS Press.

Grainger. 2005. Prices for 15 kW and 40 kW PTO generators. Lake Forest, Ill.: W. W. Grainger, Inc. Available at: www.grainger.com. Accessed November 2005.

Hasche, A., T. L. Richard, and J. M. Laflen. 2003. Estimating the impact of biomass harvest on soil erosion using the WEPP model. ASAE Paper No. 036078. St. Joseph, Mich.: ASAE.

House, H. K., and R. P. Stone. 1988. Barn hay drying. Guelph, Ontario: Ontario Ministry of Agriculture, Food, and Rural Affairs. Agdex No. 120/736. Available at: www.omafra.gov.on.ca/english/engineer/facts/88-110.htm. Accessed November 2005.

Lynd, L. R. 1996. Overview and evaluation of fuel ethanol from cellulosic biomass: Technology, economics, the environment, and policy. *Ann. Rev. Energy Environ.* 21: 403-465.

Milligan, D. A. 2005. Matches web site: Providing process and cost engineering services to the chemical, energy, manufacturing, and metallurgical industries. Edmond, Okla.: Matches. Available at: www.matche.com. Accessed November 2005.

Morey, R. V., D. G. Tiffany, and D. L. Hatfield. 2006. Biomass for electricity and process heat at ethanol plants. *Applied Eng. in Agric.* 22(5): 723-728.

Nick, T. 2005. Personal communication. Dresser-Rand/Coppus division steam turbines. Chicago, Ill.: Somes-Nick and Co.

Nikolaisen, L., C. Nielsen, M. G. Larsen, V. Nielsen, U. Zielke, J. K. Kristensen, and B. Holm-Christensen. 1998. Straw for energy production: Technology - environment - economy. Søborg, Denmark: The Centre for Biomass Technology and The Danish Energy Agency. Available at: www.videncenter.dk/uk/index.htm. Accessed July 2005.

Perlack, R. D., and A. F. Turhollow. 2002. Assessment of options for the collection, handling, and transport of corn stover. Publication No. ORNL/TM-2002/44. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Perlack, R. D., L. L. Wright, A. F. Turhollow, R. L. Graham, B. J. Stokes and D. C. Erbach. 2005. Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. Publication No. DOE/GO-102995-

2135, ORNL/TM-2005/66. Oak Ridge, Tenn.: Oak Ridge National Laboratory. Available at: http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf. Accessed April 2006.

Quick, G. R. 2000. Handling and densification for commercial processing of biomass feedstock. In *Proc. Colloquium: Corn Stover Harvesting, Handling, and Densification for Commercial Processing of Biomass Feedstock*. Ames, Iowa: Iowa State University.

Shinners, K. J., B. N. Binversie, and S. Philippe. 2003. Whole-plant corn harvesting for biomass: Comparison of single-pass and multiple-pass harvest systems. ASAE Paper No. 036089. St. Joseph, Mich.: ASAE.

Sokhansanj, S., and A. F. Turhollow. 2002. Baseline cost for corn stover collection. *Applied Eng. in Agric.* 18(5): 525-530.

Stumpf, J. 1912. *The Una-Flow Steam-Engine.* New York, N.Y.: D. van Nosttrand Co.

Taylor, R. 1995. Large round bale hay storage. Publication No. MF-1066. Manhattan, Kans.: Kansas State University Agricultural Experiment Station and Cooperative Extension Service.

Tuetken, T. J. 2002. Development of corn stover harvesting and densification systems. MS thesis. Ames, Iowa: Iowa State University, Department of Agricultural and Biosystems Engineering.

Ulrich, G. D., and P. T. Vasudevan. 2004. *Chemical Engineering Process Design and Economics: A Practical Guide.* 2nd ed. Durham, N.H.: Process Publishing.

USDA-NASS. 2005. U.S. grain production data. Washington, D.C.: USDA National Agricultural Statistics Service. Available at: www.nass.usda.gov:81/ipedb/. Accessed December 2005.

Wayman, M., and S. Parekh. 1990. *Biotechnology of Biomass Conversion: Fuels and Chemicals from Renewable Resources.* Philadelphia, Pa.: Open University Press.

Zebley. G. 2005. Personal communication. Coolidge, Ga.: Hurst Boiler and Welding Co., Inc.

CHAPTER 3. FARM-GATE PRODUCTION COSTS OF SWEET SORGHUM AS A BIOETHANOL FEEDSTOCK

Modified from a paper published in the *Transactions of the ASABE* [5]

Albert S. Bennett[6,3], Robert P. Anex[7]

Abstract

Sweet sorghum has been identified as a possible ethanol feedstock because of its high biomass yield, sugar content, and potential for grain co-production. Extracted fermentable carbohydrates (FC) can be easily fermented to ethanol. Residuals contain sufficient energy to power ethanol processing facilities. Sweet sorghum, however, has found limited use because of poor post-harvest storage characteristics and short harvest window in cooler climates. To help determine the practicality of sweet sorghum as an ethanol feedstock in the Midwest, production costs are estimated for different harvest scenarios including self-propelled (SP) and tractor-pulled juice, forage, and hypothetical whole-plant-grain (WPG) harvesters. Production cost estimates are generated using preharvest and harvest cost models in combinations representing current best practice and promising near-term solutions. Estimated net costs included income from co-products: residuals for fuel, ensilage, and grain. The most financially attractive scenario is the SP forage harvester. Depending on harvest conditions, and assuming combustion of co-produced residuals valued at \$6 GJ^{-1}, the expected net farm-gate FC costs are predicted to be \$6.9 to \$24 Mg^{-1}. These values are considerably less than comparable net farm-gate FC costs for corn grain production. When sweet sorghum feedstocks are located in close proximity to processing facilities, lower FC costs will be sufficient to offset increased transportation costs associated with moving wet biomass. Further study, however, is required to evaluate the associated capital and logistical requirements for integrating seasonal sweet sorghum, or sorghum wet-stored via ensilage, into existing and future bioethanol processing facilities.

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[1] Reprinted with permission of *Transactions of the ASABE*, v51 (2) pages 603-613.

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Introduction

Cellulosic materials are generally thought to be the most likely feedstock for large-scale ethanol production from biomass in the long-term, due to their potentially larger supply and lower price compared to other carbohydrate sources (Perlack et al., 2005). However, low cost, plentiful supply, and ease of conversion have made carbohydrates the preferred feedstocks for bioethanol production. Starch-rich materials, such as grains, have the advantage of established feedstock and processing infrastructure, and a more homogenous and reactive form of carbohydrate than that found in cellulosic materials. An advantage of both starch and sugar-rich materials over cellulosic materials is that they can be processed to sugar streams of sufficient purity to accommodate production of high-value products such as food, pharmaceuticals, and fiber-grade polymers. Plant materials high in soluble sugars yield the most readily converted form of carbohydrate, requiring lower inputs of chemicals and energy for processing, and the technology for the extraction of sugars is fully mature and highly efficient, reducing processing costs. Sugar is the preferred carbohydrate feedstock for many high-value products and is also used to produce around half of the world's ethanol, the largest biocommodity (Murray, 2005).

One of the most adaptable and highly productive sugar-rich plants is sorghum. Both sweet and grain varieties of sorghum are of interest as agricultural energy crops due to high yields, drought tolerance, relatively low input requirements, and ability to produce high yields under a wide range of environmental conditions (Buxton et al., 1999; Grassi et al., 2004; Hunter, 1994; Hunter and Anderson, 1997; Miller and McBee, 1993). Sweet sorghum is of particular interest because of the large volume of readily fermentable juice that can be expressed. Hunter and Anderson (1997) indicated that the sugar produced in sweet sorghum has a potential ethanol yield up to 8,000 L ha^{-1}, or about twice the ethanol yield potential of maize grain, In addition to producing large amounts of sugar-rich biomass, hybrids can be developed from crosses between grain-type seed parents and sweet-type pollen parents (Hunter and Anderson, 1997). The product of these crosses typically increase biomass yields and sugar content when compared to the original grain-type seed parents. Such hybrids can co-produce grain at levels approaching the yields of the grain-type seed parent (Miller and McBee, 1993).

One of the primary disadvantages of sorghum and other plants rich in soluble sugars is that they are only seasonally available and storage is expensive, making it difficult to use infrastructure efficiently and to schedule labor. To avoid spoilage, conversion must be initiated quickly after harvest, and in temperate climates, such as the Midwest U.S., the harvest window is limited by freezing weather. If not handled properly, both delayed fermentation and freezing weather can lead to "souring" of juices, loss of sugar content, reduced ethanol yield, or failed fermentation (Cundiff and Parrish, 1983; Eiland et al., 1983; Eiland and Clayton, 1984; Monroe and Sumner, 1983; Parrish and Cundiff, 1985). Despite these limitations, sorghum remains attractive due to its high yield on less-productive lands and high sugar content. Sorghum can potentially provide a secondary, low-cost feedstock for corn dry milling ethanol facilities. It can possibly be stored wet via ensilage or partially processed to a storable syrup and converted in dedicated conversion facilities. It could also be the seasonally low-priced feedstock for integrated biorefineries that will produce high-value products from a high-quality hexose feedstream as well as a biocommodity such as ethanol from cellulose-derived sugars (Bohlmann, 2005).

The practicality and economic viability of sorghum as an industrial feedstock depends on many factors, including sorghum production cost, infrastructure costs, complexity of operation, transportation and market location, and co-product value. For biocommodities, feedstocks have a large and often dominant impact on process economics, siting of facilities, environmental impacts, and process development (Lynd et al., 1999). Biorefineries that could utilize sorghum are expected to have cost structures similar to those of other modern refinery examples, such as petroleum refining and corn wet milling, in which the cost of feedstock represents a majority (60% to 70%) of the total product value (Lynd et al., 2005; Wyman, 1999).

The objective of the present work is to estimate the cost of producing sorghum feedstocks and co-products in the North-Central U.S., including the use of Monte Carlo simulation techniques and sensitivity analysis. The representative location considered is Story County, Iowa; however, parameters are evaluated over ranges representative of the entire region. An engineering-economic cost methodology is used incorporating Monte Carlo simulation to develop ranges of likely costs. Sweet sorghum pre-harvest and harvest costs and their probable ranges are modeled for production and harvest scenarios representing current best practice and promising near-term future scenarios. While we make these costs estimates for sorghum to be used as an ethanol feedstock, the sorghum could also be used for other purposes. The costs form a benchmark to gauge improvements in sorghum harvest systems designed to provide feedstock for bioproduction rather than food and feed uses.

Methods

Sweet sorghum production cost models are formulated in Microsoft Excel spreadsheets. Crystal Ball software (Decisioneering, Inc., 2007) is used to evaluate uncertainty through Monte Carlo simulation, perform sensitivity analysis, and generate distributions that describe likely fermentable carbohydrate (FC) production costs. Figure 3.1 is a graphical representation of the general flow and key variables incorporated into each Excel-based production cost model, including variables tested by Monte Carlo simulation and sensitivity analysis using Crystal Ball add-on software.

Monte Carlo Simulations

In this study, Monte Carlo simulations are used to determine the expected value and likely range of fermentable carbohydrate costs for each of the harvest systems considered. Monte Carlo simulation is a stochastic method that generates a distribution of results from which likely values can be inferred and where each simulation utilizes a large number of iterations (10,000 for this study) to generate a result distribution (Decisioneering, Inc., 2007). For each iteration, a randomly generated value is assigned to parameters of interest, which are related to crop yields, machinery performance, and processing. Values for each parameter or variable of interest are generated according to a defined probability function that describes the likely distribution of parameter values within the Monte Carlo simulations. As described by Decisioneering, Inc. (2007), there are numerous types of continuous and discrete probability distributions that can be applied to Monte Carlo parameters, including normal, triangular, uniform, Poisson, lognormal, exponential, gamma, Pareto, logistic, and Weibull. This study utilizes triangular distributions to describe the likely range of values for machinery, yield, and processing related parameters. When data are limited, which is the case in this study, a simple triangular distribution can be used because only three defining points are required to generate a representative probability distribution, including a minimum, maximum, and most likely value.

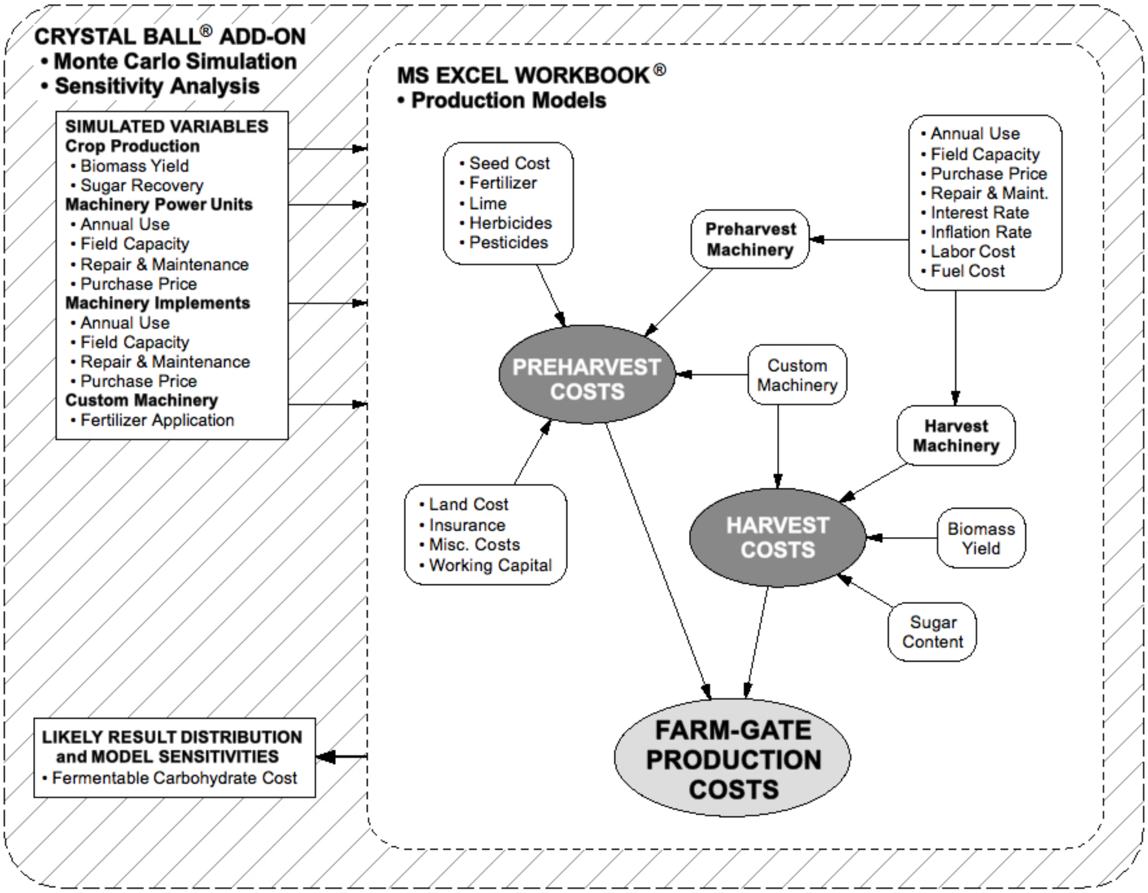

Figure 3.1. Flow diagram: MS Excel-based production model and Crystal Ball Monte Carlo simulation and sensitivity analysis

Model Uncertainties and Parameters

There are many uncertainties associated with estimating the cost to produce fermentable carbohydrates from sweet sorghum. Variations in individual farms: their size, management practices, crop rotations, percent of rented versus owned farmland, land rental costs, available machinery, soil types and fertility, topography, microclimates, rainfall and temperature, and levels of crop insurance (if available) can all affect production costs. Machinery operational costs also strongly affect production costs and are dependent on many factors, including farming conditions, operator experience, actual machinery capital costs, interest and inflation rates, machinery life, annual use, repairs and maintenance, depreciation, field capacities, fuel costs, and labor costs. All of these uncertainties add to the variability in the likely production costs.

This study focuses on the uncertainties associated with crop yields, machinery operations, and process efficiency. Other farm-specific, harvest-system invariant uncertainties such as herbicide, fertilizer and seed costs, land rent, percent land rented, labor hourly rate, interest and inflation rates, and fuel costs can also significantly affect the overall FC production costs. However, in all of the models developed for this study, these uncertainties are considered identical and therefore will not change the relative conclusions that we can draw from the resultant probability distributions developed by each model and how they compare between different harvest systems.

Preharvest and harvest machinery cost and performance parameters are incorporated into each sweet sorghum production model and include uncertainty in likely machinery list and purchase prices, annual use, field capacity, and repairs and maintenance. List prices for machinery are based on values available through the Iowa State University (ISU) Extension Service (Edwards, 2007). Actual list prices of machinery can vary significantly, especially when considering that power units with the same horsepower can come with many different options and add-ons, not to mention the large number of independent manufactures of implements. An informal internet survey of machinery list prices found that values easily vary by ±10% from the values used by the ISU Extension Service. In this study, uncertainty in machinery list price is assumed to follow a triangular distribution using these same values. The actual purchase price of machinery is assumed to have a 15% discount from the manufacture's list price, and discounts up to 20% are not uncommon (Edwards, 2007; Shinners, 2007). This study simulates purchase price uncertainty with a triangular distribution based on a 15% ±5% discount on manufacturer's list price.

Estimating the annual use (hours) of machinery is important in determining operational costs, and any deviations from average annual use can significantly change operational costs. The uncertainty associated with annual equipment use on a given farm is dependent on many factors, including crops grown, the size and condition of both farm and equipment, and operator experience. Likely annual hourly use values for power units and implements are available from the ISU Extension Service (Edwards, 2007). Uncertainty estimates (approx. ±40%) are based on ASABE and ISU published variations in field efficiencies and field speed, and the resulting range in times required to complete typical farm operations (Edwards, 2007; ASABE Standards, 2003b). The cost of repair and maintenance is dependent on many factors. Uncertainties related to machinery repair and maintenance are taken from ASABE Standards, which provide formulas to calculate likely costs and stipulate that under normal conditions estimates will vary ±25% (ASABE Standards, 2003a). Harvest rates for the 4-row self-propelled (SP) harvesters are assumed to be 45.4 Mg h^{-1} ±20% while the 2-row tractor-pulled (TP) units are taken to operate at 16.3 Mg h^{-1} ±20% (Hanna, 2002, 2006). The self-propelled juice and whole-plant-grain harvesters are assumed to respectively cost $35,000 and $65,000 more than traditional self-propelled forage harvesters.

Sorghum Cultural Practices

The cultural practices appropriate for sorghum grown as a biomass feedstock are assumed to be approximately the same as those for sorghum produced for food and feed purposes (Buxton et al., 1999; Hunter, 1994; Hunter and Anderson, 1997; Kuepper, 1992;

Lueschen et al., 1991; Undersander et al., 1990; Wiedenfeld, 1984). Sorghum cultural practices and pre-harvest cost assumptions used here are based on ISU Extension publications, the experience of local sorghum producers, and USDA-ERS census data (Duffy and Smith, 2007; Edwards, 2007; Edwards et al., 2001; Edwards and Smith, 2006a, 2006b; Maasdam Syrup Mill, 2004; USDA-ERS, 2007). Estimated pre-harvest costs are shown in Table 3.1.

Table 3.1. Preharvest costs estimates for sweet sorghum

Concept			Fixed ($ / ha)	Variable ($ / ha)	Total ($ / ha)
Preharvest Machinery (hired labor included)					
17' Tandom Disk, 105 hp tractor			$7.20	$5.34	**$12.54**
21' Field Cultivator, 105 hp tractor			$4.47	$4.58	**$9.04**
8-row Planter, 105 hp tractor			$12.01	$9.53	**$21.54**
8-row Cultivator, 105 hp tractor			$5.50	$4.84	**$10.34**
45' Sprayer (herbicide), 75 hp tractor			$1.59	$1.21	**$2.81**
Liquid Fertilizer Application				$11.12	**$11.12**
Seeds, chemicals, etc.	($ / kg)	(kg / ha)			
Seed	$13.23	2.80		$37.07	**$37.07**
Nitrogen	$0.68	44.8		$30.64	**$30.64**
Phosphate	$0.82	67.2		$54.86	**$54.86**
Potash	$0.51	67.2		$34.10	**$34.10**
Herbicide Application				$79.07	**$79.07**
Lime (yearly cost)				$17.30	**$17.30**
Crop Insurance				$17.30	**$17.30**
Miscellaneous				$24.71	**$24.71**
Interest on preharvest variable costs (at 8% for 8 months)				$17.69	**$17.69**
Land Rent					
Percent of Rented Land	55%				
Cash Rent Equivalent	$444.78		$244.63		**$244.63**
PREHARVEST COST TOTALS			$275.40	$349.35	**$624.74**

On average, Iowa farmers with total income greater than $10,000, rent approximately 55% of their total farmland (USDA-NASS, 2007). Preharvest costs for each model assume a prototypical Iowa farm with a 55% land rental rate, along with constant land rental costs of \$445 ha^{-1} (\$180 ac^{-1}) for high-yield corn-soybean cropland. Cash equivalent land rental costs are taken directly from estimates published in ISU Extension publication FM 1712 (Duffy and Smith, 2007); however, growing demand for corn ethanol will likely drive land costs higher. Interest and inflation rates (7% and 1%, respectively), diesel costs (\$0.58 L^{-1}; \$2.20 gal^{-1}), hired labor costs (\$11 h^{-1}), and percent hired labor (8%) are assumed to be constant and are based on current machinery cost calculations and production cost data provided by the ISU Extension Service (Edwards, 2007; Smith and Edwards, 2005). Fertilizer application costs are based on published custom rates (Edwards and Smith, 2006a). Fertilizer use is based on typical application rates and actual practices (Kuepper, 1992; Lueschen et al., 1991; Undersander et al., 1990; Wiedenfeld, 1984; Maasdam Syrup Mill, 2004).

Sorghum Biomass Yield

Several studies of sweet sorghum production and potential ethanol yields have been conducted in the upper Midwest (Buxton et al., 1999; Hunter, 1994; Putnam et al., 1991; Smith and Buxton, 1993). Turhollow (1994) reported several cultivars consistently producing greater than 25 Mg dm ha^{-1} year^{-1}. A comprehensive study of sweet sorghum grown in the North-Central region was conducted at Iowa State University between 1991 and 1993 (Hunter, 1994). Yields were compared among 11 cultivars grown at two Iowa locations over three consecutive years. Table 3.2 presents annual and averaged biomass and total sugar yield data for six of the study's most productive cultivars. These values are representative of high-yield management practices on Class 1 land. Based on these data, the sweet sorghum harvest scenarios examined in this study each assume a triangular yield distribution, with most likely yield of 17.3 Mg ha^{-1} and a yield range of 15.8 to 18.4 Mg ha^{-1}.

Table 3.2. Sweet sorghum yield data and ethanol potential, Iowa State University (1991 to 1993)

		Dry Matter[a] (Mg ha^{-1})				Total Sugar[a] (Mg ha^{-1})				Potential Ethanol[b] (L ha^{-1})			
Sweet Sorghum Cultivar & Source		1991 yield	1992 high	1993 low	Ave. yield	1991 yield	1992 high	1993 low	Ave. yield	1991 yield	1992 high	1993 low	Ave. yield
Keller	Weslaco[c]	14.7	24.7	13.5	17.6	6.4	13.0	5.1	8.2	3,453	7,013	2,751	4,406
Wray	Weslaco[c]	16.1	23.8	11.6	17.2	6.9	12.3	4.1	7.8	3,722	6,635	2,212	4,190
Dale	MAFES[d]	15.5	21.4	10.6	15.8	6.6	12.2	4.4	7.7	3,560	6,581	2,374	4,172
Grassl	Weslaco[c]	21.0	23.8	10.5	18.4	7.6	11.7	3.6	7.6	4,100	6,312	1,942	4,118
Theis	MAFES[d]	15.7	22.0	12.1	16.6	6.0	10.9	5.0	7.3	3,237	5,880	2,697	3,938
M81E	MAFES[d]	18.2	22.3	13.9	18.1	6.6	10.7	4.1	7.1	3,560	5,772	2,212	3,848
Average		16.9	23.0	12.0	17.3	6.7	11.8	4.4	7.6	3,605	6,366	2,365	4,112

[a] Source data: Hunter (1994)
[b] 95% extraction of sugars, 1.76 kg fermentable carbohydrates per liter of ethanol produced
[c] Weslaco Experimental Station, Weslaco, TX
[d] Mississippi Agriculture and Forestry Experimental Station, Meridian, MS

In Table 3.2, total sugar content is positively correlated with dry matter yield. This relationship is the result of good growing conditions, allowing the plant to produce both more biomass and sugar. Linear regression of the data in Table 3.2 yields the following equation:

$$TS = 0.62 \times DM - 3.17 \qquad (r2 = 0.90) \quad (1)$$

where TS is total sugar (Mg ha^{-1}),
and DM is total dry matter (Mg ha^{-1}).

Equation 1 is used in Monte Carlo simulation of sorghum production costs to generate the corresponding total sugar values. For the range of biomass production values used (15.8 to 18.4 Mg ha^{-1}), equation 1 predicts total sugar content ranging from 6.1 to 8.5 Mg ha^{-1}, and a ratio of total sugar production to total dry matter ranging from 0.41 to 0.45.

Also included in Table 3.2 are estimates of ethanol potential assuming 95% sugar extraction efficiency based on highly developed sugarcane processing technologies (Chen and Chou, 1993; Goldemberg, 1994; Hugot, 1960; Moreira and Goldemberg, 1999; Worley and Cundiff, 1992). Ethanol yield potentials assume a sugar-to-ethanol conversion rate of 1.76 kg of fermentable carbohydrates (i.e., sugar) per liter of ethanol produced (Putnam et al., 1991). However, sugar extraction efficiency from sweet sorghum biomass will depend on the harvest system employed and whether stationary, high-efficiency extraction equipment is used to separate biomass from FC.

Sweet sorghum varieties are capable of producing large amounts of sugar-rich biomass. As with maize, there is the potential with sorghum for harvesting both grain as well as sugar-rich stalks to realize considerable harvest efficiencies. Hybrids have been developed from crosses between grain-type seed parents and sweet-type pollen parents that increase biomass yields and sugar content when compared to the original grain-type seed parent (Hunter and Anderson, 1997; Miller and McBee, 1993; Rajvanshi and Nimbkar, 2004; Hong-Tu and Xiu-Ying, 1986). Hybrids can co-produce grain at levels approaching the yields of the grain-type seed parent (Hunter, 1994) and can also achieve high sugar content and total biomass yield (Hong-Tu and Xiu-Ying, 1986). The protein-rich grain represents an important co-product that may improve the overall economic potential of the crop (Hunter and Anderson, 1997; Rajvanshi and Nimbkar, 2004; Hong-Tu and Xiu-Ying, 1986). To evaluate the hypothetical hybrid sorghum variety, total biomass yield potential was taken to be the same as sweet sorghum (i.e., 15.8 to 18.4 Mg ha^{-1}). A much larger fraction of grain, however, is included in this scenario, with most likely yield of 3.3 Mg ha^{-1} and overall yield range of 2.6 to 3.9 Mg ha^{-1}. The ratio of total sugar production to total dry matter (excluding grain) is assumed to follow the same linear relation shown in equation 1 and ranges from 0.40 to 0.45.

In subsequent analyses of different harvest scenarios, harvest rate (ha h^{-1}) will be a function of the fresh weight of the crop. Moisture content (wb) is taken to be 75% in all cases. This moisture content is comparable with the data in Table 3.2, where average moisture content at harvest was 75.1% (low: 72.3%, high: 77.9%).

Sorghum Biomass Harvest Scenarios

The options for harvesting sorghum include removing the whole or chopped stalk, or pressing the sugar-rich juice in the field and removing only the juice or the juice and pressed stalk. Intact whole-stalk harvest systems have been developed (Monroe and Sumner, 1983; Rains and Cundiff, 1993; Rains et al., 1990); however, they are not considered in this analysis due to the impracticality of whole-stalk storage (Cundiff and Parrish, 1983; Eiland et al., 1983; Eiland and Clayton, 1984; Parrish and Cundiff, 1985; Worley and Cundiff, 1992).

Chopped stalks can be collected with traditional forage harvesters that are readily available and can be easily adapted to harvest sweet sorghum. The primary disadvantage of this approach includes the rapid loss of sugars in the first 24 hours after chopping. As a result of this, forage harvesters must to be tied to facilities that are capable of readily processing chopped material.

In-field juice harvesters expel the sugar-rich juice during harvest and can thus eliminate the cost of transporting stalk material. As proposed by McClune (2004), this approach may also permit the use of low-cost, on-farm fermentation as an alternative to large-scale processing/fermentation facilities. A prototype juice harvester has been successfully demonstrated with sweet sorghum varieties (McClune, 2004; Zenk, 2005).

Scenarios evaluated in this study include using a forage harvester, a mobile juice harvester, and a self-propelled, whole-plant-grain harvester that captures stripped stalks and seed heads as separate streams during a single pass. In total, five harvest systems are evaluated: (1) 4-row self-propelled forage harvester, (2) 2-row tractor-pulled forage harvester, (3) 4-row self-propelled juice and residual stalk harvester, (4) 2-row tractor-pulled juice harvester, and (5) 4-row self-propelled whole-plant-grain harvester.

Each harvest system, except the tractor-pulled mobile juice harvester (system 4), is evaluated using two different in-field transport scenarios. The first assumes that forage is directly loaded into a transport truck that travels alongside the harvester unit. The second in-field transport scenario assumes less than optimum field conditions that require a second tractor-pulled wagon to move forage to field's edge, where it is transferred to a transport truck. To facilitate transfer of harvested materials, it is assumed that each harvester is pulling and directly loading into a hi-dump wagon, which is able to rapidly dump into a second tractor-pulled hi-dump wagon.

The tractor-pulled mobile juice harvester is also evaluated for two different harvest scenarios. The first assumes that residuals are left in-field for soil enrichment, and the second considers 50% recovery of field-dried residuals using round bales. Baling and transport to the field's edge is assumed to have an average cost of \$17 Mg^{-1} (Edwards and Smith, 2006a; Jose and Brown, 1996).

Power requirements for the 4-row self-propelled forage and juice harvesters are assumed to be 216 kW (290 hp), while the hypothetical 4-row self-propelled whole-plant-grain harvester is assumed to require 256 kW (340 hp), with an additional 37 kW (50 hp) to accommodate grain head separation. The 2-row tractor-pulled harvesters are assumed to require 138 kW (185 hp). The second hi-dump wagon required for forage harvest under non-optimal field conditions requires a 78 kW (105 hp) tractor. The mobile juice harvesters are assumed to require a separate 56 kW (75 hp) tractor to pull a 7.57 m^3 (2000 gal) tanker for in-field transport of juice. The hypothetical whole-plant-grain harvester is also taken to require a second 71 kW (95 hp) tractor and wagon to transport grain heads.

It is assumed that the stalk material harvested by the forage and whole-plant-grain harvesters are pressed using technology similar to that used in sugarcane processing facilities that achieve an average extraction efficiency of 95% (Goldemberg, 1994; Worley and Cundiff, 1992). The most advanced sugarcane processing facilities are now reaching extraction levels of 97% (Moreira and Goldemberg, 1999). This extraction efficiency is achieved through use of multi-stage crushing and milling equipment, which imbibe pressed residuals with additional water between pressing stages (Chen and Chou, 1993; Hugot, 1960). The triangular distribution that describes extraction efficiency for the forage and whole-plant harvest systems is taken to be 95% ±2%.

Extraction efficiencies for mobile juice harvesters are considerably less than what is possible with stationary multistage equipment. Tests conducted with a prototype single-row tractor-pulled juice harvester show juice extraction similar to 3-roll milling equipment typically employed by syrup producers (McClune, 2004). Sweet sorghum juice extraction for a single pass through a 3-roll mill typically ranges from 42% to 58% for whole stalks stripped of leaves (Monroe and Bryan, 1984; Monroe et al., 1981; Monroe et al., 1984) and 37% for stalks with leaves (Monroe et al., 1981). In this study, we assume that 50% ±2% of the crop's total sugar is removed in the mobile juice harvest scenarios.

For each harvest scenario, it is assumed that the sugars contained in leaf matter are not available for extraction. This amounts to between 4% and 9% of total sugar content

(Monroe and Bryan, 1984) located in approximately 16% to 22% of the total crop biomass (Miller and McBee, 1993). We assume that 20% of harvested biomass is leaf matter containing 6.5% of the total fermentable sugars.

Results and Discussion

Sweet sorghum biomass production costs on a wet material basis are shown in Figure 3.2. Pre-harvest and harvest costs are indicated along with 5% and 95% confidence limits. Pre-harvest costs are identical in each scenario except for the hypothetical sweet/grain hybrid, which assume higher seed costs (2×). Costs with two different material transport options (i.e., in-field loading of forage into a tractor-pulled hi-dump wagon or directly into a transport truck) are shown for each harvester except for the tractor-pulled juice harvester. The TP juice harvester production costs are shown with and without baling of field-dried residuals. As indicated in Figure 3.2, the 4-row self-propelled harvesters have similar biomass production costs on a mass basis and are less expensive to operate than the 2-row tractor-pulled juice and forage harvesters. For comparable material handling options, biomass harvest costs are similar for the whole-plant, forage, and juice harvesters. The biomass materials produced in these scenarios, however, are not equivalent. For example, the juice from the juice harvester is partially processed, while the whole stalks from the forage and whole-plant harvesters must be pressed to obtain juice.

To compare the sorghum production scenarios' potential for producing fermentation feedstock, the costs are computed on an FC basis. As shown in Figure 3.3, the mobile juice harvester production costs (per Mg FC) are approximately 2 times greater than the forage and whole-plant-grain harvesters. This is a result of their inherently poor ability to extract fermentable carbohydrates in-field. These low extraction efficiencies could possibly be eliminated if multi-stage milling and residual imbibing capabilities are incorporated into a mobile harvester, but this is highly impractical.

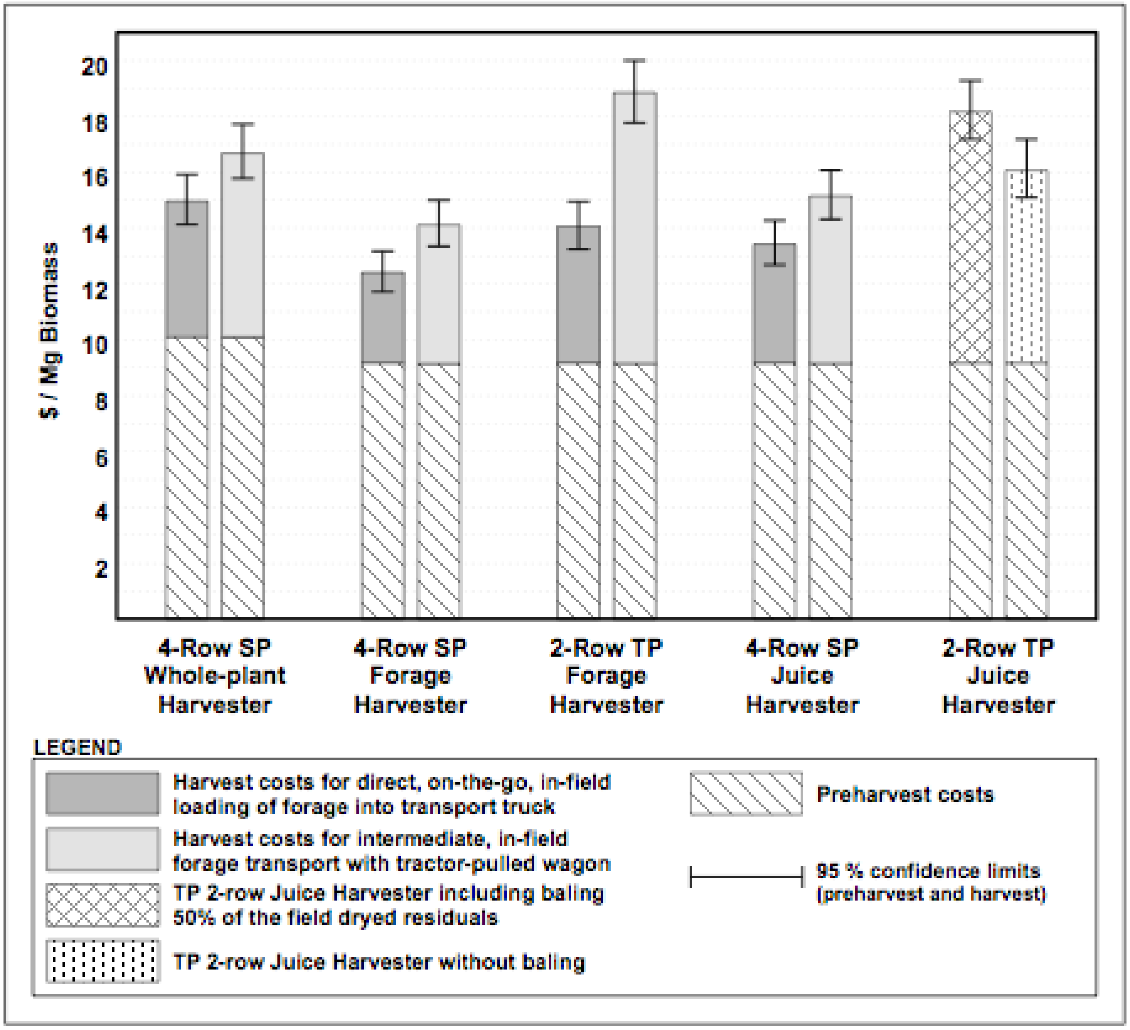

Figure 3.2. Sweet sorghum production cost estimates on a wet biomass basis

In addition to considering harvested fermentable carbohydrates, residuals from processing can also have considerable value, for example, as a fuel for process heat and generating electricity. Because of sweet sorghum's similarity to sugarcane, it is reasonable to assume that there will be considerable biomass energy potential in the pressed stalks, as in many sugarcane processing facilities (Woods, 2001). In some cases, it may also be possible to export electrical energy to a local power grid. High-moisture, high-sugar residuals produced by the mobile SP juice harvester are also ideal for ensilage. The value of these co-products, whether used for fuel or as a feed supplement, must also be considered when evaluating the viability of each harvest scenario.

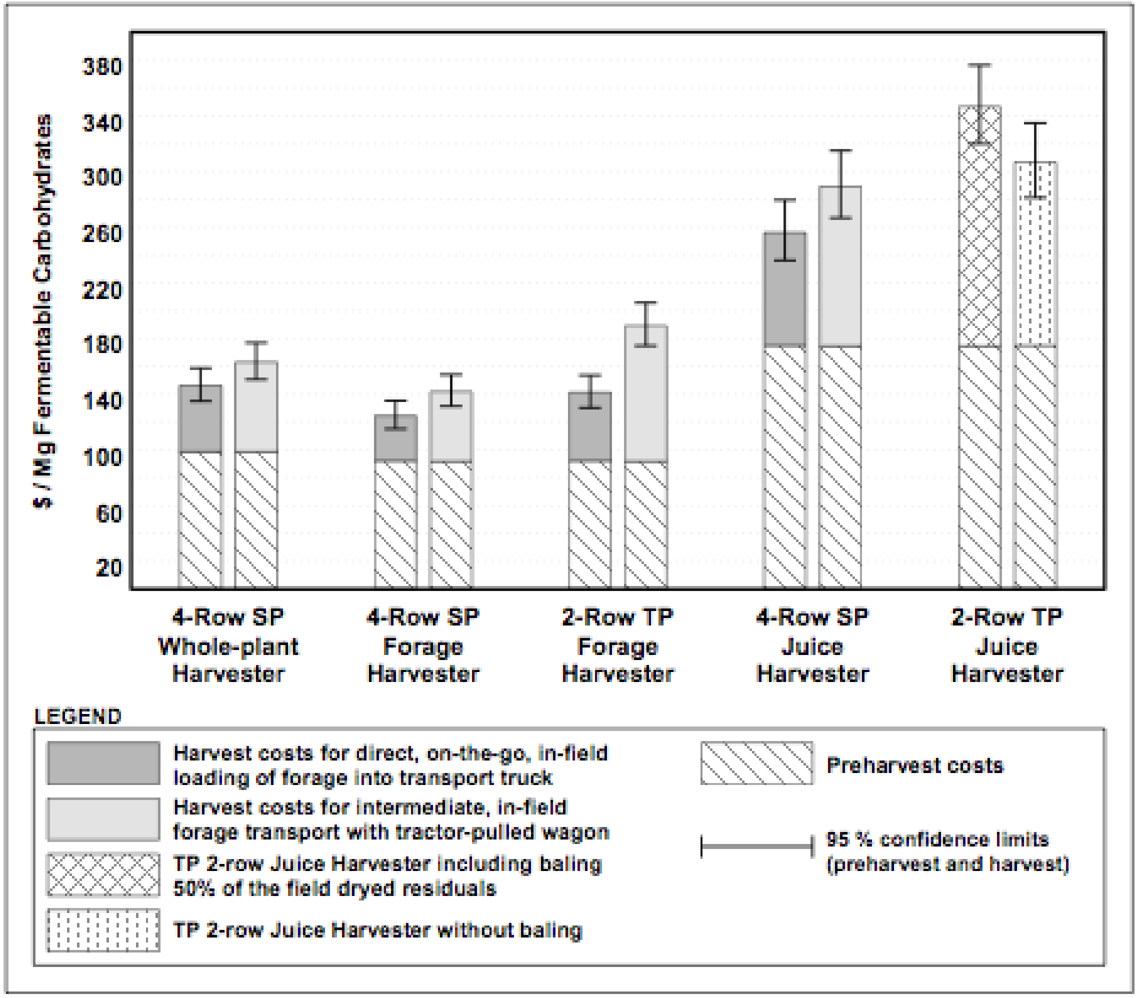

Figure 3.3. Sweet sorghum production cost estimates on an FC basis

The value of co-products is important in determining the net cost of fermentable carbohydrates. There is significant uncertainty in the value to be assigned to co-products, however, since their values depend on fluctuating market prices and they are produced through non-standard processes. The co-products considered are: combustible residuals from the forage, whole-plant-grain, and tractor-pulled juice harvester scenarios, and the ensiled residual stock material used as animal feed from the self-propelled juice harvester (this is considered the most practical use due relatively high moisture content).

Estimated values for co-products for each harvest scenario are shown in Figure 3.4. In this figure, the forage harvest options and the whole-plant-grain harvester are taken to use residuals to generate power for milling, fermentation, and distillation facilities. The lower heat value (LHV) for pressed sorghum residuals at 50% moisture content was estimated to be 6,500 kJ kg^{-1}. The values of fuel co-products used in this analysis are assumed to be \$4, \$6, and \$8 per GJ, which are less than average commercial natural gas prices reported during 2006 and 2007 (USDOE-EIA, 2007). The SP juice harvester also produces residuals ideal for ensilage, which for comparison purposes, were valued at \$15, \$20, and \$25 per wet Mg. For the TP juice harvester, field-dried and baled residuals (50% recovery) are also considered as a source of fuel with moisture content of 20% and LHV of 11,500 kJ kg^{-1}. In addition to residuals for fuel, the whole-plant-grain harvester also produces grain as a co-product. Due to the grain's relatively high moisture content and additional processing and drying requirements, the average price used to estimate grain net income is taken to be \$57 Mg^{-1} (Futures and Commodity Market News, 2007). In comparison, typical market prices paid to farmers for sorghum grain range from \$75 to \$80 Mg^{-1}. As indicated in Figure 3.4, the juice harvesters have higher valued co-products on a harvested FC basis, which results from the mobile juice harvester's limited ability to extract the majority of available FC (~50%). As a result of this, the juice harvesters generate a greater portion of biomass available for sale as co-products.

Figure 3.5 was generated using values of co-products to determine the net farm-gate cost of produced fermentable carbohydrates for each harvest scenario. As indicated, the 4-row SP forage harvester provides the best option for producing low-cost fermentable carbohydrates (\$6.9 Mg^{-1}) when field conditions permit the direct loading of chopped sweet sorghum into transport vehicles and residuals are used as a fuel for combustion valued at \$6 GJ^{-1}. If additional infield tractor-pulled transport is required to move harvested materials to the field's edge, then the expected FC cost increases to \$24 Mg^{-1}. In contrast, the TP juice harvester expected farm-gate FC cost is estimated to be much higher. For example, when residuals are left in field, the net expected cost of fermentable carbohydrates is predicted to be \$306 Mg^{-1}. When residuals are baled and used as fuel, net FC costs are reduced to \$184 and \$238 Mg^{-1} for residual fuel values taken at \$6 and \$4 GJ^{-1}, respectively. The SP juice harvester is also predicted to be considerably more expensive to operate than the SP forage and WPG harvesters. FC costs are estimated at \$68 to 101 Mg^{-1}, depending on the type of in-field transport and when residual are ensiled and valued at \$25 wet Mg^{-1}.

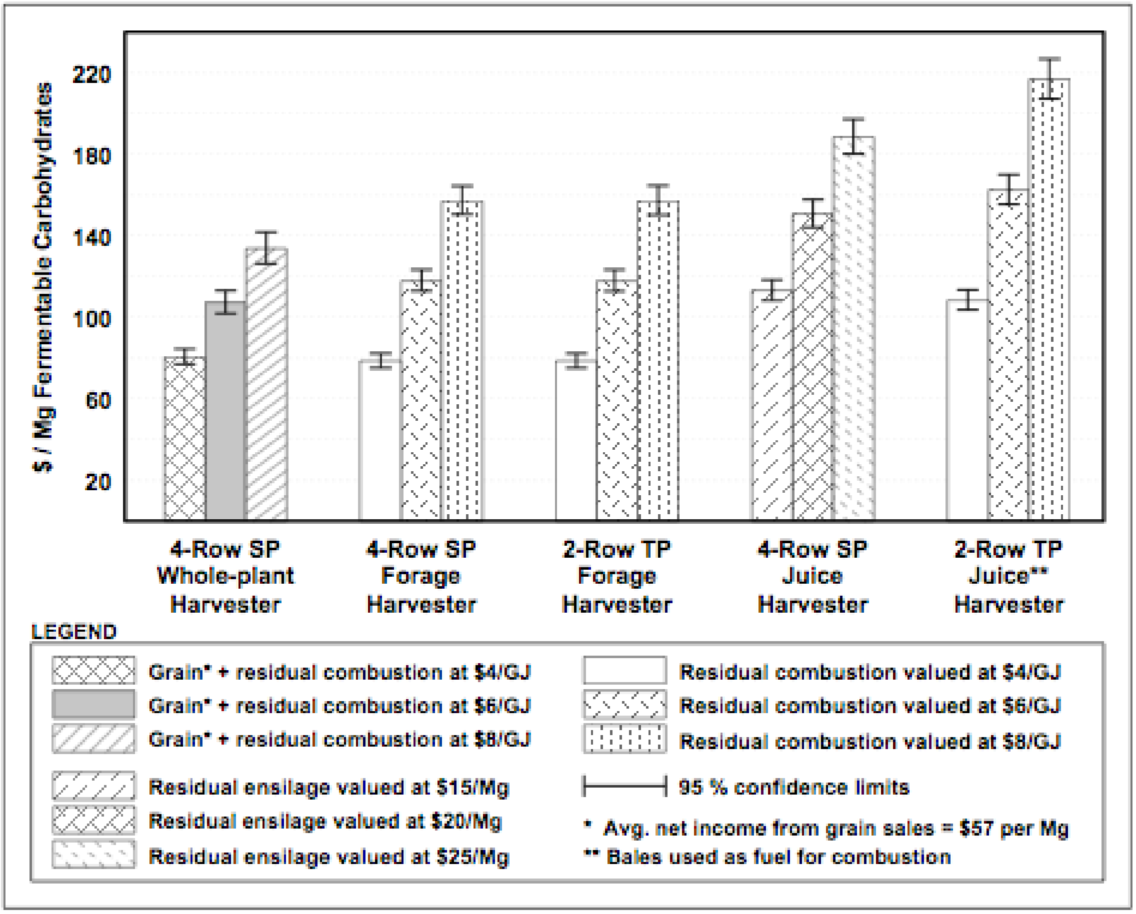

Figure 3.4. Co-products credits on an FC basis

It should be noted that improved varieties and hybrids could further reduce the net FC costs associated with sweet sorghum. Higher production levels have been readily obtained in other regions. For example, work with hybrid sweet/grain varieties in China (in a region with climatic conditions similar to the Upper Midwest) produced sweet biomass and grain yields of 25 and 5 Mg ha^{-1}, respectively (Hong-Tu and Xiu-Ying, 1986). At these levels of production, income from grain and residual co-products alone would pay for (and possibly exceed) the entire crop's production costs.

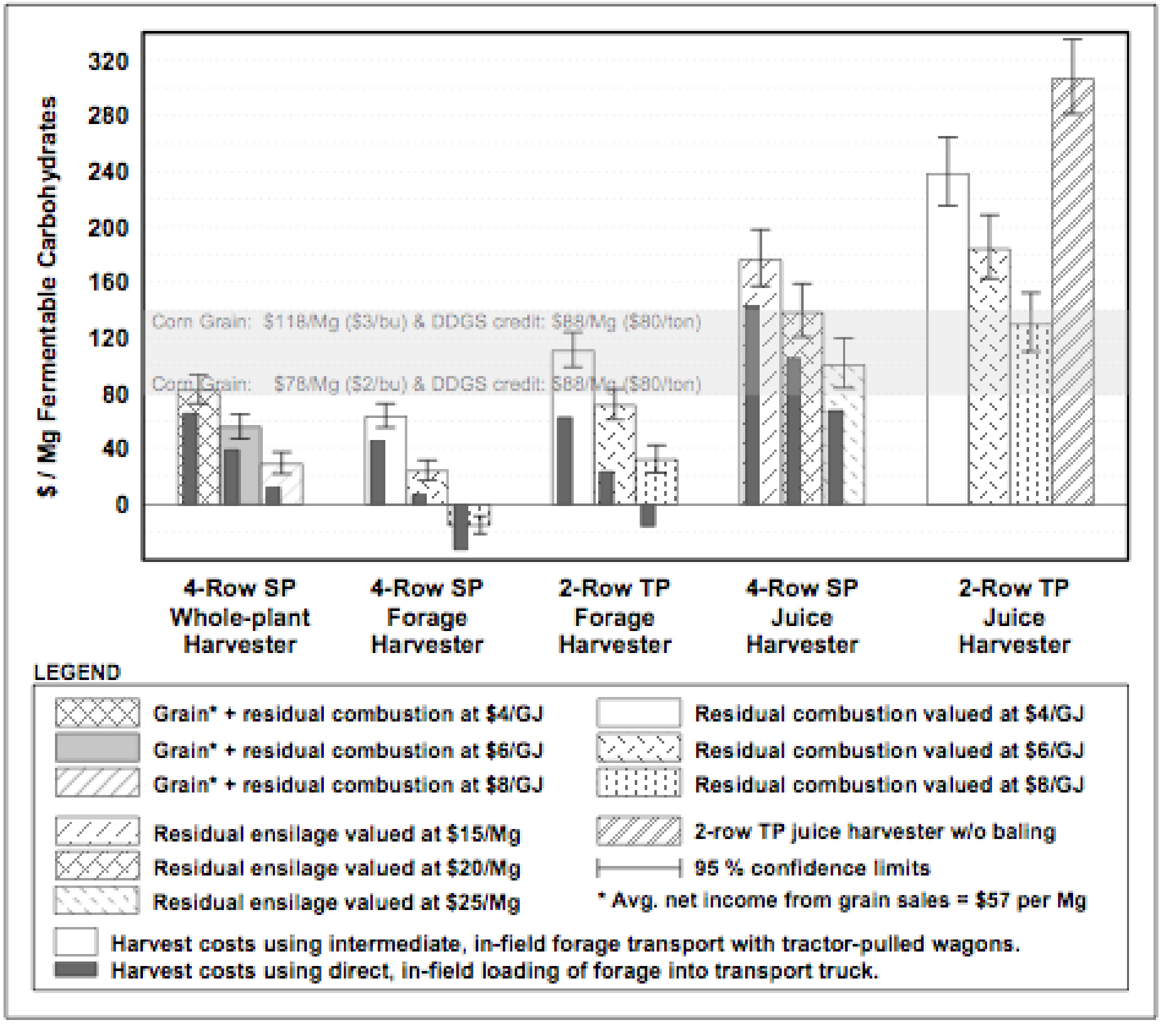

Figure 3.5. Net sweet sorghum production cost on an FC basis

Figure 3.5 also shows comparable FC cost for corn grain as a gray transparent bar with high and low boundaries at \$118 and \$78 Mg^{-1} (\$3 and \$2 bu^{-1}). These values include credit for co-production of distiller's dried grains and solubles (DDGS). As indicated, the net farm-gate FC cost of sweet sorghum harvested by 4-row SP forage harvester is considerably lower than the net costs associated with FC derived from corn grain. Estimates assume that corn grain containing 70% starch and 15% moisture content yields approximately 1.08 Mg FC Mg^{-1} starch (×1.11 stoichiometric conversion × 0.97 enzyme efficiency) with the co-production of 0.32 Mg DDGS Mg^{-1} corn (18 lb DDGS bu^{-1}) valued at \$88 Mg^{-1} (\$80 ton^{-1}). It is important to note, however, that this comparison does not include shipping costs associated with transporting wet biomass to a processing facility, nor does it consider the significant limited storability of freshly harvested sweet sorghum.

Sensitivity analysis tested the effects of sweet sorghum yield and machinery uncertainties for each model. In this study, sensitivity is measured by determining each tested variable's contribution to percent variance of the resultant distribution of likely FC costs generated by the Monte Carlo simulation. For example, results indicate that uncertainties associated with yield, harvester field capacity, and to a lesser extent the harvester's annual hourly use have the greatest influence on the variance of the resultant net farm-gate FC cost distribution generated for each harvest system model. Depending on the system considered (see fig. 1), the number of variables with defined uncertainty distributions varies from between 45 and 73. The lesser or greater number of tested variables largely depends on the modeled scenario and the number of preharvest and harvest operations/machinery. For example, the SP forage harvester with direct loading into transport truck (45 variables with defined uncertainties) require the least number of harvest operations/machinery, while the SP juice harvester with separate in-field transport of chopped, pressed biomass and juice require the highest number of harvest operations/machinery (73 variables with defined uncertainties). Each model incorporates the same preharvest machinery and field operations, including a total of 33 variables related to uncertainties in machinery list and purchase price, field capacity, annual hourly use, and maintenance costs. However, the sensitivity of the predicted FC cost distributions to the combined uncertainties associated with preharvest variables is found to be minimal, with contributions to variance ranging from only 1% to 4%. In contrast, depending on the particular modeled scenario, the combined uncertainties related to sweet sorghum yield, harvester field capacity, and harvester annual hourly use accounts for between 85% and 92% of the predicted FC cost distributions. Just as with preharvest machinery, the effects of uncertainties related to harvester list and purchase price, and repair and maintenance costs are minimal.

For close proximity feedstocks, low FC costs will offset higher transportation costs associated with moving wet biomass. Further analysis, however, is required to determine limits to maximum transport distances in conjunction with likely production densities surrounding a given processing facility. In addition, to address storability limitations, a number of studies have considered drying whole stalks, in-field whole stalk storage, or storage under cold (no freeze) conditions (Eiland et al., 1983; Eiland and Clayton, 1984; Parrish and Cundiff, 1985; Worley and Cundiff, 1992). These studies indicate that it is technically feasible to store whole stalks for up to four months, especially under cold, no-freeze conditions. Additional analysis indicated that the energy available from the combustion of residuals is sufficient to concentrate sweet sorghum juice to storable syrup, in addition to providing the necessary process heat and shaft power required to convert sweet sorghum FC to ethanol. The major limitation to these storage approaches, however, is their significant capital and infrastructure requirements, which include multi-effect evaporators that are used for just a few months each year, or very large structures that would be necessary to store undamaged whole stalks in an environment protected against extreme fluctuations in ambient temperatures. Another study has considered the direct production of ethanol in ensilage inoculated with yeast (Hunter, 1994). The study was able to successfully convert significant portions of sweet sorghum FC to ethanol; however, issues with separating ethanol from silage, ensilage storage losses (up to 40% in bunker style silos), and the possible use of silage as an alternative fermentation feedstock have yet to be examined for industrial-scale applications.

For the above-mentioned reasons, we believe that at present these methods are impractical. However, the seasonal application of sweet sorghum as a supplementary feedstock to corn dry mills/ethanol plants is feasible now. Preliminary analysis indicates that a two-month supply of sweet sorghum FC would result in enough dried residuals to provide nearly six months of a typical corn dry mill/ethanol plant's process heat requirements. This added biofuel not only potentially reduces operational costs of corn ethanol plants, but also has the benefit of significantly reducing their carbon footprint by replacing natural gas or coal. However, the effects of transportation costs and the capital requirements for adding sweet sorghum milling equipment to existing corn dry mills and future biorefineries will require additional analysis to determine if this option is economically viable.

Conclusions

The net cost of fermentable carbohydrates produced from sweet sorghum can be considerably lower than that of other biocommodity feedstocks such as corn, especially when using traditional forage harvest equipment in close proximity to processing facilities. Mobile juice-harvesting scenarios, however, do not appear to be economically competitive. Improvements in crop yields and co-production with grains can further increase the economic viability of sweet sorghum as an alternative source for fermentable carbohydrates. However, limitations due to material transport cost and storability must be addressed before fresh sweet sorghum can become an important source of fermentable carbohydrates.

Acknowledgements

This work was supported by the Iowa Energy Center (Grant No. 05-02). Our thanks to Dr. Michael D. Duffy, Dr. William Edwards, Dr. Mark H. Hanna, and Dr. Kevin J. Shinners for their advice and recommendations. We also thank Mr. Lee McClune for sharing ideas and test results from his work with mobile juice harvest equipment.

References

ASABE Standards. 2003a. D497.4: Agricultural machinery management data. St. Joseph, Mich.: ASABE.

ASABE Standards. 2003b. EP496.2: Agricultural machinery management. St. Joseph, Mich.: ASABE

Bohlmann, G. M. 2005. Biorefinery process economics. *Chem. Eng. Progress* 101(10): 37-43.

Buxton, D. R., I. C. Anderson, and A. Hallam. 1999. Performance of sweet and forage sorghum grown continuously, double-cropped with winter rye, or in rotation with soybean and maize. *Agron. J.* 91(1): 93-101.

Chen, J. C. P., and C. C. Chou. 1993. *Cane Sugar Handbook: A Manual for Cane Sugar Manufacturers and their Chemist.* 12th ed. New York, N.Y.: John Wiley and Sons.

Cundiff, J. S., and D. J. Parrish. 1983. Whole-stalk sweet sorghum storage. ASAE Paper No. 833058. St. Joseph, Mich.: ASAE.

Decisioneering, Inc. 2007. What is Monte Carlo Simulation? Denver, Colo.: Decisioneering, Inc. Available at: www.decisioneering.com/monte-carlo-simulation.html. Accessed February 2007.

Duffy, M., and D. Smith. 2007. Estimated costs of crop production in Iowa - 2007. Publication FM 1712. Ames, Iowa: Iowa State University Extension Service.

Edwards, W. 2007. Personal communication and unpublished 2007 machinery cost spreadsheet. Ames, Iowa: Iowa State University Extension Service.

Edwards, W., and D. Smith. 2006a. Iowa farm custom rate survey. Publication FM 1698. Ames, Iowa: Iowa State University Extension Service.

Edwards, W., and D. Smith. 2006b. Cash rental rates for 2006 survey. Publication FM 1851. Ames, Iowa: Iowa State University Extension Service.

Edwards, W., G. Ayers, and M. Boehlje. 2001. Machinery management: Estimating farm machinery costs. Publication PM 710. Ames, Iowa: Iowa State University Extension Service.

Eiland, B. R., and J. E. Clayton. 1984. Storage characteristics of sweet sorghum. ASAE Paper No. 843579. St. Joseph, Mich.: ASAE.

Eiland, B. R., J. E. Clayton, and W. L. Bryan. 1983. Losses of fermentable sugars in sweet sorghum during storage. *Trans. ASAE* 26(5): 1596-1600.

Futures and Commodity Market News. 2007. Sorghum grain prices. Available at: http://news.tradingcharts.com/futures/. Accessed February 2007.

Goldemberg, J. 1994. Brazilian alcohol program: An overview. *Energy for Sustainable Development* 1(1): 17-22.

Grassi, G., G. Tondi, and P. Helm. 2004. Small-sized commercial bioenergy technologies as an instrument of rural development. In *Biomass and Agriculture: Sustainability, Markets and Policies*, 277-287. Paris, France: OECD Publication Service.

Hanna, M. 2002. Ag decision maker: Estimating the field capacity of farm machinery. Publication File A3-24. Ames, Iowa: Iowa State University Extension Service.

Hanna, M. 2006. Personal communication. Ames, Iowa: Iowa State University Extension Service.

Hong-Tu, M., and H. Xiu-Ying. 1986. Breeding for sweet sorghum with high grain yield and sweet stalks. *Sorghum Newsletter* 29: 2-3.

Hugot, E. 1960. *Handbook of Cane Sugar Engineering.* New York, N.Y.: Elsevier Publishing.

Hunter, E. L. 1994. Development, sugar yield, and ethanol potential of sweet sorghum. MS thesis. Ames, Iowa: Iowa State University.

Hunter, E. L., and I. C. Anderson. 1997. Sweet sorghum. *Hort. Reviews* 21: 73-104.

Jose, H. D., and L. L. Brown. 1996. Costs of harvesting and hauling corn stalks in large round bales. Publication NF96-310. Lincoln, Neb.: University of Nebraska Cooperative Extension.

Kuepper, G. 1992. Sweet sorghum: Production and processing. Poteau, Okla.: Kerr Center for Sustainable Agriculture.

Lueschen, W. E., B. K. Putnam, B. K. Kanne, and T. R. Hoverstad. 1991. Agronomic practices for production of ethanol from sweet sorghum. *J. Prod. Agric.* 4(4): 619-625.

Lynd, L. R., C. E. Wyman, and T. U. Gerngross. 1999. Biocommodity engineering. *Biotech. Progress* 15(5): 777-793.

Lynd, L. R., C. Wyman, M. Laser, D. Johnson, and R. Landucci. 2005. Strategic biorefinery analysis: Review of existing biorefinery examples. NREL/SR-510-34895. Golden, Colorado: National Renewable Energy Laboratory.

Maasdam Syrup Mill. 2004. Personal communication on sweet sorghum production and mill operations. Lynnville, Iowa: Maasdam Sorghum Mills.

McClune, L. 2004. Personal communication: On-farm juice fermentation/juice storage systems and prototype 1-row tractor-pulled mobile juice harvester development and testing.

Miller, F. R., and G. G. McBee. 1993. Genetics and management of physiologic systems of sorghum for biomass production. *Biomass and Bioenergy* 5(1): 41-49.

Monroe, G. E., and H. R. Sumner. 1983. A harvest and handling system for sweet sorghum. ASAE Paper No. 843551. St. Joseph, Mich.: ASAE.

Monroe, G. E., and W. L. Bryan. 1984. Design factors for milling sweet sorghum. *Trans. ASAE* 27(4): 1211-1221.

Monroe, G. E., W. L. Bryan, H. R. Sumner, and R. L. Nichols. 1981. Sweet sorghum juice removal with 3-roll mills. ASAE Paper No. 813541. St. Joseph, Mich.: ASAE.

Monroe, G. E., R. L. Nichols, W. L. Bryan, and H. R. Sumner. 1984. Sweet sorghum juice extraction with 3-roll mills. *Trans. ASAE* 27(3): 651-654.

Moreira, J. R., and J. Goldemberg. 1999. The alcohol program. *Energy Policy* 27(4): 229-245.

Murray, D. 2005. Ethanol's potential: Looking beyond corn. Washington, D.C.: Earth Policy Institute. Available at: www.earth-policy.org/Updates/2005/Update49.htm. Accessed January 2006.

Parrish, D. J., and J. S. Cundiff. 1985. Long-term retention of fermentables during aerobic storage of bulked sweet sorghum. In *Proc. 5th Annual Solar and Biomass Workshop*, 137-140. Atlanta, Ga.

Perlack, R. D., L. L. Wright, A. F. Turhollow, R. L. Graham, B. J. Stokes and D. C. Erbach. 2005. Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. DOE/GO-102995-2135, ORNL/TM-2005/66. Oak Ridge, Tenn.: Oak Ridge National Laboratory. Available at: http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf. Accessed April 2006.

Putnam, D. H., W. E. Lueschen, B. K. Kanne, and T. R. Haverstad. 1991. A comparison of sweet sorghum cultivars and maize for ethanol production. *J. Prod. Agric.* 4(3): 377-381.

Rains, G. C., and J. S. Cundiff. 1993. Design and field testing of a whole-stalk sweet sorghum harvester. *Applied Eng. in Agric.* 9(1): 15-20.

Rains, G. C., J. S. Cundiff, and D. H. Vaughan. 1990. Development of a whole-stalk sweet sorghum harvester. *Trans. ASAE* 33(1): 56-62.

Rajvanshi, A. K., and N. Nimbkar. 2004. Sweet sorghum R&D at the Nimbkar Agricultural Research Institute. Phaltan, India: Nimbkar Agricultural Research Institute. Available at: http://nariphaltan.virtualave.net/sorghum.htm. Accessed January 2005.

Shinners, K. J. 2007. Personal communication: One-pass switchgrass harvester. Professor of Agricultural Engineering. Madison, Wisc.: Department of Biological Systems Engineering. University of Wisconsin.

Smith, G. A., and D. R. Buxton. 1993. Temperate zone sweet sorghum ethanol production potential. *Bioresource Tech.* 43(1): 71-75.

Smith D, Edwards W. 2005. 2005 Iowa farm costs and returns. ISU Extension Service Publication FM 1789. Iowa State University Extension Service. Ames, IA.

Turhollow, A. 1994. The economics of energy crop production. *Biomass and Bioenergy* 6(3): 229-241.

Undersander, D. J., W. E. Lueschen, L. H. Smith, A. R. Kaminski, J. D. Doll, K. A. Kelling, and E. S. Oplinger. 1990. Alternative field crops manual: Sorghum - syrup. Available at: www.hort.purdue.edu/newcrop/afcm/syrup.html. Accessed June 2005.

USDOE-EIA. 2007. Commercial natural gas prices. Washington, D.C.: U.S. Department of Energy, Energy Information Agency. Available at: http://tonto.eia.doe.gov/dnav/ng/hist/n3020us3m.htm. Accessed February 2007.

USDA-ERS. 2007. Feed grains database: Yearbook tables. Table 12 - Corn: Cash prices at principal markets. Washington, D.C.: USDA Economic Research Service. Available at: www.ers.usda.gov/Data/Feedgrains/StandardReports/YBtable12.htm. Accessed February 2007.

USDA-NASS. 2007. Agricultural statistics database: 2002 census of agriculture. Washington, D.C.: USDA National Agricultural Statistics Service. Available at: www.nass.usda.gov/index.asp. Accessed February 2007.

Wiedenfeld, R. P. 1984. Nutrient requirements and use efficiency by sweet sorghum. *Energy in Agric.* 3: 49-59.

Woods, J. 2001. The potential for energy production using sweet sorghum in southern Africa. *Energy for Sustainable Development* V(1): 31-38.

Worley, J. W., and J. S. Cundiff. 1992. Ethanol from sweet sorghum: A comparison of four harvesting/processing systems. In *Liquid Fuels from Renewable Resources*, 40-49. J. S. Cundiff, ed. St. Joseph, Mich.: ASAE.

Wyman, C. E. 1999. Biomass ethanol: Technical progress, opportunities, and commercial challenges. *Annual Review of Energy and the Environ.* 24: 189-226.

Zenk, P. 2005. Excellent for ethanol. *Hay and Forage Grower* (1 Nov. 2005). Available at: www.hayandforage.com/mag/farming_excellent_ethanol/index.html. Accessed 13 March 2006.

CHAPTER 4. PRODUCTION, TRANSPORTATION AND MILLING COSTS OF SWEET SORGHUM AS A FEEDSTOCK FOR CENTRALIZED BIOETHANOL PRODUCTION IN THE UPPER-MIDWEST

Modified from a paper published in *Bioresource Technology* [8]

Albert S. Bennett[9,10] and Robert P. Anex[3]

Abstract

Sweet sorghum has been identified as a possible ethanol feedstock because of its biomass yield and high concentration of readily fermentable sugars. It has found limited use, however, because of poor post-harvest storage characteristics and short harvest window in cooler climates. Previous research (Bennett and Anex, 2008) indicates that fermentable carbohydrates (FC) can be produced at less expense from sweet sorghum than from corn grain. Previous research, however, did not include costs associated with off-farm transportation, storage, or capital costs associated with milling and energy recovery equipment that are required to provide FC suitable for biological conversion. This study includes these additional costs and reevaluates sweet sorghum as a biocommodity feedstock.

A total of eight harvest-transport-processing options are modeled, including 4-row self-propelled and 2-row tractor-pulled forage harvesters, two different modes of in-field transport, fresh processing, on-farm ensilage and at-plant ensilage. Monte Carlo simulation and sensitivity analysis are used to account for system variability and compare scenarios.

Transportation costs are found to be significant ranging from $33 to $71 per Mg FC, with highest costs associated with at-plant ensilage scenarios. Economies of scale benefit

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larger milling equipment and boiler systems reducing FC costs by more than 50% when increasing annual plant capacity from 37.9 to 379 million liters. Ensiled storage of high moisture sweet sorghum in bunkers can lead to significant losses of FC (>20%) and result in systems with net FC costs well above those of corn-derived FC. Despite relatively high transport costs, seasonal, fresh processed sweet sorghum is found to produce FC at costs competitive with corn grain derived FC.

Introduction

Since the 1970's there has been considerable interest in developing biorenewable alternatives to petroleum-based commodity chemicals such as transportation fuels. The most prominent example is ethanol, which has emerged as a potentially important alternative transportation fuel. Considerable effort has gone into investigating the potential of different agricultural crops as feedstock for bioproduction of fuels and chemicals (Turhollow, 1994).

Low cost, plentiful supply and ease of conversion have made carbohydrates from corn and sugarcane the most likely feedstocks for biocommodities like ethanol. Cellulosic materials are generally thought to be the preferred feedstock for large-scale bio-production in the long-term, due to their larger ultimate supply and lower price compared to other carbohydrate sources (Perlack et al., 2005). Starch-rich materials, such as grains, have the advantage of established feedstock and processing infrastructure, and a more homogenous and reactive form of carbohydrate than that found in cellulosic materials. An advantage of both starch and sugar-rich materials over cellulosic materials is that they can be processed to sugar streams of sufficient purity to accommodate production of high-value products such as food, pharmaceuticals and fiber-grade polymers. Plant materials high in soluble sugars yield the most readily converted form of carbohydrate, requiring lower inputs of chemicals and energy for processing, and the technology for the extraction of sugars is fully mature and highly efficient, reducing processing costs. Sugar is the preferred carbohydrate feedstock for many high-value products and is also used to produce around half of the world's largest biocommodity, ethanol (Murray, 2005).

One of the most adaptable and highly productive sugar-rich plants is sorghum. Both sweet and grain varieties of sorghum are of interest as agricultural energy crops due to high yields, drought tolerance, relatively low input requirements and ability to produce high yields under a wide range of environmental conditions (Buxton et al., 1999; Grassi et al., 2004; Hunter, 1994; Hunter and Anderson, 1997; Miller and McBee, 1993). These qualities make sorghum a potentially important feedstock for bio-production, particularly in regions where conditions are not favorable for growing starch-rich crops such as maize.

Sweet sorghum is of particular interest because of the large volume of readily fermentable juice that can be expressed. Hunter and Anderson (1997) indicate that the sugar produced in sweet sorghum has the potential to yield up to 8,000 liters of ethanol per hectare or about twice the ethanol yield potential of maize grain and 30% greater than the average Brazilian sugarcane productivity of 6,000 l/ha (Luhnow and Samor, 2006). There are approximately 4000 cultivars of sweet sorghum distributed throughout the world (Grassi et al. 2004), providing a diverse genetic base from which to develop regionally specific, highly productive cultivars. In addition to producing large amounts of sugar-rich biomass, hybrids can be developed from crosses between grain-type seed parents and sweet-type pollen parents (Hunter and Anderson, 1997). The product of these crosses typically increase biomass yields and sugar content when compared to the original grain-type seed parents. Such hybrids can co-produce grain at levels approaching the yields of the grain-type seed parent (Miller and McBee, 1993). The co-produced, protein-rich grain can be consumed as food, animal feed, or converted to bioproducts like ethanol (Hunter, 1994; Hunter and Anderson, 1997; Rajvanshi and Nimbkar, 2004; Hong-Tu and Xiu-Ying, 1986).

One of the primary disadvantages of sorghum and other plants rich in soluble sugars is that they are only seasonally available and storage is expensive, making it difficult to use infrastructure efficiently and to schedule labor. To avoid spoilage, conversion must be initiated soon after harvest, and in temperate climates, such as the Midwest U.S.A., the harvest window is limited by freezing weather. If not handled properly, both delayed fermentation and freezing weather can lead to "souring" of juices characterized by loss of sugar content through production of organic acids and associated reduction in ethanol yield or failed fermentation (Cundiff and Parrish, 1983; Eiland et al., 1983; Eiland and Clayton, 1984; Monroe and Sumner, 1983; Parrish and Cundiff, 1983). Despite these limitations, sorghum remains attractive due to its high yield on less productive lands and high sugar content. Sorghum can potentially provide a secondary, low-cost feedstock for corn dry milling ethanol facilities. It can possibly be stored wet via ensilage or partially processed to a storable syrup and converted in dedicated conversion facilities. It could also be the seasonally low-priced feedstock for integrated biorefineries that will produce high-value products from a high-quality hexose feedstream as well as a biocommodity such as ethanol from cellulose-derived sugars (Bohlmann, 2005).

The practicality and economic viability of sorghum as an industrial feedstock depends on many factors including sorghum production cost, infrastructure costs, complexity of operation, transportation and market location, and co-product value. Among these, the cost of sorghum production may be the most important. For biocommodities, feedstocks have a large and often dominant impact on process economics, siting of facilities, environmental impacts, and process development (Lynd et al., 1999). Biorefineries that could utilize sorghum are expected to have cost structures similar to those of other modern refinery examples, such as petroleum refining and corn wet milling, in which the cost of feedstock represents a majority (60 to 70 percent) of the total product value (Lynd et al. 2005, Wyman 1999).

A previous study conducted by the authors determined that net production cost of fermentable carbohydrate (FC) from sweet sorghum calculated at the farm-gate, can be well below typical cost of FC derived from corn grain (Bennett and Anex, 2008). That study, however, did not consider costs associated with transportation of wet biomass to centralized processing facilities nor did it consider issues and costs associated with overcoming storability limitations and additional processing steps needed to extract fermentable carbohydrates from sweet sorghum. This study includes these additional costs and their impact on the economic viability of using FC derived from sweet sorghum as a biocommodity feedstock. Included are costs of transporting high moisture biomass, storage and additional milling costs unique to sweet sorghum. The representative location considered is Story County, Iowa; however parameters are evaluated over ranges representative of much of the upper Midwest. An engineering-economic cost methodology is used incorporating Monte Carlo simulation to develop ranges of likely net cost. Overall FC production, transportation and processing cost estimates build on sweet sorghum pre-harvest and harvest cost models for various harvest scenarios developed in previously reported work (Bennett and Anex, 2008).

Background and Assumptions

Study methodology defines values and scenarios based on existing literature and prior studies. Included parameters are related to farm-gate production and harvest costs, likely post-harvest processing and storage strategies, transportation costs, milling costs, and waste residual utilization. Eight different economic models incorporate these parameters and estimate the net cost of fermentable carbohydrates (after milling at ethanol plant). Monte Carlo simulation is used to generate and compare likely ranges in at-plant FC costs. Sensitivity analysis is used to identify key parameters that most effect likely FC cost distributions.

Monte Carlo Simulations

In this study Monte Carlo simulations are used to determine the expected value and likely range of FC costs for each of the harvest systems considered. Monte Carlo simulation is an analytical method that generates a distribution of results from which likely values can be inferred (Decisioneering, 2007). Each Monte Carlo simulation utilizes a large number of iterations (10,000 for this study) to generate a result distribution. For each iteration a randomly generated value is assigned to parameters of interest, which are related to crop yields, machinery performance and processing. Values for each parameter or variable of interest are generated according to a defined probability function that describes the likely distribution of parameter values within the Monte Carlo simulations. There are numerous types of continuous and discrete probability distributions that can be applied to Monte Carlo parameters, including normal, triangular, uniform, Poisson, lognormal, exponential, gamma, Pareto, logistic and Weibull (Decisioneering, 2007). This study utilizes triangular distributions to describe the likely range of values for machinery, yield and processing related parameters. When data is limited, which is the case in this study, a simple triangular distribution is used because they only require three defining points to generate a representative probability distribution, including a minimum, maximum and most likely value (Decisioneering, 2007).

Model Uncertainties

There are many uncertainties associated with estimating the cost to produce, deliver and process fermentable carbohydrates extracted from sweet sorghum. Variations in individual farms: their size, management practices, crop rotations, percent of rented versus owned farmland, land rental costs, available machinery, soil types and fertility, topography, microclimates, rainfall and temperature and levels of crop insurance (if available) can all effect production costs. Farm machinery operational costs also strongly effect farm production costs and are dependent on many factors including farming conditions, operator experience, actual machinery capital costs, interest and inflation rates, machinery life, annual use, repairs and maintenance, depreciation, field capacities, fuel costs and labor costs. More uncertainties involving post harvest processing, storage, transportation, densification, moisture content, specialized equipment, etc. further add to the variability and uncertainty in the likely cost of FC delivered to processing facility.

This study incorporates uncertainties associated with crop yields, farm machinery operations, FC extraction efficiency, capital investments in storage bunkers, milling machinery and solid fuel boiler systems along with variables related to transportation. Other farm-specific, harvest-system and post harvest invariant uncertainties such as herbicide, fertilizer and seed costs, land rent, percent land rented, labor hourly rate, interest and inflation rates, and fuel costs can also significantly affect the overall FC production costs. However, in all of the models developed for this study, these uncertainties are considered identical and therefore will not change the relative conclusions we can draw from the resultant probability distributions developed by each model and how they compare between different harvest and post harvest systems.

Preharvest and Harvest Machinery Operations and Cost Parameters

Preharvest and harvest machinery cost and performance parameters are incorporated into each model and include uncertainty in likely machinery list and purchase prices, annual use, field capacity and repairs and maintenance. List prices for machinery are based on values available through ISU Extension Service (Edwards, 2008). Actual list price of machinery can vary significantly especially when considering that power units with same horsepower can come with many different options and add-ons, not to mention the large number of independent manufactures of implements. An informal survey of machinery list prices found that values easily vary by ± 10% from the values used by ISU extension service. In this study uncertainty in machinery list price are assumed to follow a triangular distribution using these same values. The actual purchase price of machinery is assumed to have a 15% discount from the manufacture’s list price (Edwards, 2008) and it is not uncommon for discounts up to 20% (Shinners, 2007). This study simulates purchase price uncertainty with a triangular distribution based on a 15 ± 5% discount on manufacturer’s list price. Estimating the annual use (hours) of machinery is important in determining operational costs and any deviations from average annual use can significantly change operational costs. The uncertainty associated with annual equipment use on a given farm is dependent on many factors including crops grown, the size and condition of both farm and equipment, and operator experience. Likely annual hourly use values for power units and implements are available from ISU Extension Service (Edwards, 2008). Uncertainty estimates (approximately ± 40%) are based on ASABE and ISU published variations in field efficiencies and field speed, and the resulting range in times required to complete a typical farm operation (Edwards, 2008; ASABE, 2003b). The cost of repair and maintenance is dependent on many factors. Uncertainties related to machinery repair and maintenance are taken from ASABE Standards which provide formulas to calculate likely costs and stipulates that under normal conditions estimates will vary ± 25% (ASABE, 2003a). Harvest rates for the 4-row self-propelled harvesters are assumed to be 45.4 Mg h^{-1} ± 20% while the 2-row tractor pulled units are taken to operate at 16.3 Mg h^{-1} ± 20% (Hanna, 2002; Hanna, 2005).

Sorghum Cultural Practices and Preharvest Farm Production Costs

The cultural practices appropriate for sorghum grown as a biomass feedstock are assumed to be approximately the same as those for sorghum produced for food and feed purposes (Buxton et al., 1999; Hunter, 1994; Hunter and Anderson, 1997; Kuepper, 1992; Lueschen et al., 1991; Undersander et al., 1990; Wiedenfeld, 1984). In many ways sweet sorghum production is also comparable to corn production in the upper Midwest, especially when utilizing high-yield management practices on class 1 land (Maasdam, 2004; Edwards, 2008). Sorghum cultural practices and pre-harvest cost assumptions used here are based on Iowa State Extension publications, the experience of local sorghum producers and USDA-NASS census data (Duffy and Smith, 2008; Edwards, 2008; Edwards et al., 2001; Edwards and Smith, 2007a; Edwards and Smith, 2007b; USDA-NASS, 2007). Estimated pre-harvest costs are shown in Table 4.1.

On average, Iowa farmers with total income greater than $10,000, rent approximately 55% of their total farmland (USDA-NASS, 2007). Preharvest costs for each model assumes a prototypical Iowa farm with a 55% land rental rate, along with constant land rental costs of \$556 ha^{-1} (\$225 ac^{-1}) for high yield corn-soybean cropland. Cash equivalent land rental costs are taken directly from estimates published by ISU Extension Service (Duffy and Smith, 2008). However, growing demand for corn ethanol will likely drive land costs higher. Interest and inflation rates (7.21% and 1%, respectively), diesel costs (\$0.86 L^{-1}; \$3.25 gal^{-1}), hired labor costs (\$11 h^{-1}) and percent hired labor (8%) are assumed to be constant and are based on current machinery cost calculations and production cost data provided by ISU Extension Service (Edwards 2008, Smith and Edwards 2005). Fertilizer application costs are based on published custom rates

(Edwards and Smith 2007a). Fertilizer use is based on typical application rates and actual practices (Kuepper, 1992; Lueschen et al., 1991; Undersander et al., 1990; Wiedenfeld, 1984; Maasdam, 2004).

Table 4.1. Sweet sorghum preharvest cost estimates

Concept			**Fixed** ($ / ha)	**Variable** ($ / ha)	**Total** ($ / ha)
Preharvest Machinery (hired labor included)					
17' Tandom Disk, 105 hp tractor			$7.33	$6.68	**$14.01**
21' Field Cultivator, 105 hp tractor			$4.54	$5.94	**$10.49**
8-row Planter, 105 hp tractor			$12.22	$11.28	**$23.50**
8-row Cultivator, 105 hp tractor			$5.60	$6.20	**$11.79**
45' Sprayer (herbicide), 75 hp tractor			$1.62	$1.45	**$3.07**
Liquid Fertilizer Application				$11.86	**$11.86**
Seeds, chemicals, etc.	($ / kg)	(kg / ha)			
Seed	$13.23	2.80		$37.07	**$37.07**
Nitrogen	$1.01	44.8		$45.47	**$45.47**
Phosphate	$1.10	67.2		$74.13	**$74.13**
Potash	$0.60	67.2		$40.03	**$40.03**
Herbicide Application				$79.07	**$79.07**
Lime (yearly cost)				$17.30	**$17.30**
Crop Insurance				$17.30	**$17.30**
Miscellaneous				$24.71	**$24.71**
Interest on preharvest variable costs (at 8% for 8 months)				$20.19	**$20.19**
Land Rent					
Percent of Rented Land	55%				
Cash Rent Equivalent	$444.78		$305.79		**$305.79**
PREHARVEST COST TOTALS			$337.10	$398.66	**$735.76**

Sorghum Biomass Yield

Several studies of sweet sorghum production and potential ethanol yields have been conducted in the upper Midwest (Buxton et al., 1999; Hunter, 1994; Putnam et al., 1991; Smith and Buxton, 1993). Turhollow (1994) reported several cultivars consistently producing greater than 25 Mg dm ha^{-1} yr $^{-1}$. A comprehensive study of sweet sorghum grown in the North-Central region was conducted at Iowa State University between 1991 and 1993 (Hunter, 1994). Yields were compared among 11 cultivars grown at two Iowa locations over three consecutive years. This study was valuable because it included years with very different climatic conditions. For example, in 1993 a late planting date combined with climatic conditions that were very cool, wet and cloudy during key growth periods resulted in relatively low yields. During 1992 conditions were nearly ideal with warm sunny days and adequate rainfall during key growth periods and in 1991 yields were similar to averaged values. In Table 4.2, annual and averaged biomass and total sugar yield data are presented for six of the study's most productive cultivars. These values are representative of high-yield management practices on Class 1 land. Based on these data, the sweet sorghum post harvest process scenarios examined in this study each assume a triangular yield distribution with most likely yield of 17.3 Mg ha^{-1}, and a yield range of 15.8 to 18.4 Mg ha^{-1}.

Table 4.2. Sweet sorghum yield data and ethanol potential, Iowa State University (1991 to 1993)

		Dry Matter[a] (Mg ha^{-1})				Total Sugar[a] (Mg ha^{-1})				Potential Ethanol[b] (L ha^{-1})			
Sweet Sorghum Cultivar & Source		1991 yield	1992 high	1993 low	Ave. yield	1991 yield	1992 high	1993 low	Ave. yield	1991 yield	1992 high	1993 low	Ave. yield
Keller	Weslaco[c]	14.7	24.7	13.5	17.6	6.4	13.0	5.1	8.2	3,453	7,013	2,751	4,406
Wray	Weslaco[c]	16.1	23.8	11.6	17.2	6.9	12.3	4.1	7.8	3,722	6,635	2,212	4,190
Dale	MAFES[d]	15.5	21.4	10.6	15.8	6.6	12.2	4.4	7.7	3,560	6,581	2,374	4,172
Grassl	Weslaco[c]	21.0	23.8	10.5	18.4	7.6	11.7	3.6	7.6	4,100	6,312	1,942	4,118
Theis	MAFES[d]	15.7	22.0	12.1	16.6	6.0	10.9	5.0	7.3	3,237	5,880	2,697	3,938
M81E	MAFES[d]	18.2	22.3	13.9	18.1	6.6	10.7	4.1	7.1	3,560	5,772	2,212	3,848
Average		16.9	23.0	12.0	17.3	6.7	11.8	4.4	7.6	3,605	6,366	2,365	4,112

[a] Source data: Hunter (1994)

[b] 95% extraction of sugars, 1.76 kg fermentable carbohydrates per liter of ethanol produced

[c] Weslaco Experimental Station, Weslaco, TX

[d] Mississippi Agriculture and Forestry Experimental Station, Meridian, MS

In Table 4.2, total sugar content is positively correlated with dry matter yield. This relationship is the result of good growing conditions allowing the plant to produce both more biomass and sugar. Linear regression of the data in Table 4.2 yields the following equation,

$$TS = 0.62 \times DM - 3.17 \qquad (r^2 = 0.90) \qquad (1)$$

where, TS = total sugar, Mg ha^{-1}, and
DM = total dry matter, Mg ha^{-1}.

Equation 1 is used in Monte Carlo simulation of sorghum production costs to generate the corresponding total sugar values. For the range of biomass production values used (15.8 to 18.4 Mg ha^{-1}), equation 1 predicts total sugar content ranging from 6.1 to 8.5 Mg ha^{-1}, and a ratio of total sugar production to total dry matter ranging from 0.41 to 0.45.

Also included in Table 4.2 are estimates of ethanol potential assuming 95% sugar extraction efficiency based on highly developed sugarcane processing technologies (Chen and Chou, 1993; Goldemberg, 1994; Hugot, 1960; Moreira and Goldemberg, 1999; Worley and Cundiff, 1992). Analysis of potential ethanol yield assumes a sugar-to-ethanol conversion rate of 1.76 kg of fermentable carbohydrates (i.e., sugar) per liter of ethanol produced (Putnam et al., 1991). Sugar extraction efficiency from sweet sorghum biomass, however, will depend on the harvest system employed.

Sweet Sorghum Harvest Systems

In a previous study (Bennett and Anex, 2008), the authors developed spreadsheet models and conducted Monte Carlo simulations to estimate likely costs for a number of potential harvest systems (Bennett and Anex, 2008). Harvest systems that were considered included 2-row tractor-pulled (TP) and 4-row self-propelled (SP) forage harvesters, a 2-row TP and hypothetical 4-row SP mobile juice harvester (McClune, 2004) and a hypothetical 4-row SP whole-plant-grain (WPG) harvester. Each harvest system was modeled with two likely in-field transport options resulting in a total of ten harvester and on-farm transport scenarios. Table 4.3 shows the average estimated farm-gate values for both gross and net FC cost for each of the ten harvest scenarios considered (Bennett and Anex, 2008). These values assume an average recovery of 95% of the FC initially contained biomass harvested using forage and WPG harvesters (Chen and Chou, 1993; Goldemberg, 1994; Hugot, 1960; Moreira and Goldemberg, 1999; Worley and Cundiff, 1992) and 50% recovery of FC for biomass harvested using the mobile juice harvesters (McClune, 2004; Monroe and Bryan, 1984; Monroe et al., 1981; Monroe et al., 1984).

Table 4.3. Farm-gate fermentable carbohydrate cost estimates for sweet sorghum

Harvest Scenario	On-Farm Transport	FC [1] Cost $\$$ Mg^{-1}	Net FC Cost $\$$ Mg^{-1}
4-row SP Forage harvester [2]	Direct in-field loading into transport truck	$122	$4.95
4-row SP Forage harvester [2] (pulling hi-dump forage wagon)	TP hi-dump forage wagon to truck at field's edge	$139	$21.7
2-row TP Forage harvester [2]	Direct in-field loading into transport truck	$138	$21.1
2-row TP Forage harvester [2] (pulling hi-dump forage wagon)	TP hi-dump forage wagon to truck at field's edge	$185	$67.7
4-row SP Hypothetical WPG [2, 3]	Direct in-field loading into transport truck with separate TP grain wagon	$143	$36.5
4-row SP Hypothetical WPG [2, 3] (pulling hi-dump forage wagon)	TP hi-dump forage wagon to truck at field's edge w/ separate TP grain wagon	$159	$53.0
4-row SP Mobile juice harvester [4] (pulling tanker)	Direct in-field loading into transport truck with separate TP tanker	$259	$109
4-row SP Mobile juice harvester [4] (pulling tanker)	TP hi-dump forage wagon to truck at field's edge with separate TP tanker	$291	$141
2-row TP Mobile juice harvester [5] (pulling tanker)	50% residuals collected and baled, with separate TP tanker	$339	$177
2-row TP Mobile juice harvester [5] (pulling tanker)	Residuals remain in-field, with separate TP tanker	$299	$299

Source: Bennett and Anex 2008

[1] Based on average DM and FC yield of 17.3 and 7.6 Mg ha^{-1}, respectively

[2] Residuals used as a fuel for combustion valued at $6 GJ^{-1} and with a LHV of 6,500 kJ kg^{-1}

[3] Net grain co-production valued at $57 Mg^{-1}

[4] Residuals used for silage valued at $20 wet Mg^{-1}

[5] Field dried residuals used as a fuel for combustion valued at $6 GJ^{-1} and with a LHV of 11,500 kJ kg^{-1}

The SP forage harvester was found to provide the lowest expected on-farm FC costs, which, without considering off-farm transport and milling costs was found to have considerably lower costs than FC derived from corn grain (Bennett and Anex, 2008). In contrast, the mobile juice harvest scenarios were found to have net FC costs much higher than the best-case forage harvester. This cost disparity is largely due poor FC extraction efficiencies (50% versus 95%). The difference in extraction efficiency is due to the difficulty of implementing mobile versions of more efficient multi-staged, imbibed residual, extraction technologies applicable in stationary systems (such as are used to process sugarcane). As indicated by the values in Table 4.3, the use of residuals as a moderately priced fuel can significantly improve the overall economics of sweet sorghum as a feedstock for ethanol production (similar to the importance of DDGS in the overall economics of corn grain-to-ethanol). These values assume residuals have a lower heating value (LHV) of 6,500 kJ kg^{-1} (Bagasse Calorific Value, 2007) and are utilized, as in sugarcane processing, as an energy source. Values shown in Table 4.3 assume a residual purchase price of \$6 GJ^{-1}.

Because of the speculative nature of a WPG harvest system and impracticalities associated with mobile juice harvesters, this study considers only 2-row TP and 4-row SP forage harvest systems.

Sweet Sorghum Post-harvest Storage and Processing Strategies

Although there is considerable interest in sweet sorghum as a potential feedstock for ethanol production, its use on a large scale has been limited by a relatively short harvest window, especially in cooler climates such as in the upper Midwest, where frost and freezing conditions can lead to significant losses in fermentable carbohydrates (Cundiff and Parrish, 1983; Eiland et al., 1983; Eiland and Clayton, 1984; Parish and Cundiff, 1985; Worley and Cundiff, 1992). Chopped sweet sorghum, typical of that produced by a forage harvester, also needs to be processed quickly so as to minimize the rapid FC losses that occur within the first 24 hours after chopping (Cundiff and Parrish, 1983; Eiland et al., 1983; Eiland and Clayton, 1984). Because of these limitations, a dedicated fresh sweet sorghum processing facility that would require relatively large capital investment for milling machinery, fermentation tanks and distillation equipment would only operate for a few months each year. On the other hand, if a viable means of storing sweet sorghum for at least 6-8 months were available, the same volume of harvested sweet sorghum could be processed in smaller facilities reducing required capital investments while also providing more stable employment opportunities. One storage method that shows potential in the efficient use of capital and labor is the ensilage of sweet sorghum in large, covered bunkers.

A number of studies have considered methods other then ensilage as a means to overcome the limitations associated with short harvest windows and frost and freeze damage (Cundiff and Parrish, 1983; Parish and Cundiff, 1985). These include cool/cold (no freeze) storage and drying of whole-stalks, both of which were successfully used to store whole-stalks. Cool/cold storage was the better method and was able to successfully maintain whole-stalks up to 150 days without significant loss in FC (Cundiff and Parrish, 1983; Parish and Cundiff, 1985). However, these methods are impractical on an industrial scale due to the high-energy use, material handling and capital cost requirements of the very large climate-controlled structures that are needed to store bundled, undamaged whole-stalks. Others have suggested the use of on-farm fermentation in “low-cost” plastic bladders as a means to provide the farmer with an additional value-added product and reduce overall capital requirements associated with ethanol production (McClune, 2004). After a preliminary analysis, however, this method is also considered impractical due to relatively high capital requirements needed for fermentation/storage bladders capable of resisting extreme winter conditions common to the upper Midwest. Based on an initial investment of approximately $5,500 to $8,500 per hectare of sweet sorghum production, annualized bladder costs are estimated to be between $0.23 and $0.35 per liter of ethanol production capacity. These estimates do not consider feedstock costs, distillation costs, additional labor and maintenance issues associated with pumping large volumes of juice into fermentation bladders (from 25,000 to 50,000 liters per ha) during a short harvest window and under on-farm, non-sterile, ambient temperature conditions, nor did it consider the likely operational difficulties and costs associated with trying to clean and sterilize many large bladders after each production cycle. Another possible means to store FC would be to concentrate extracted juice into syrup and use the syrup as a feedstock for year-round fermentation. A preliminary analysis indicates that there is more than enough energy in residuals to provide the process heat needed to convert juice to syrup. However, the capital costs associated with multi-effect evaporators, large solid fuel boilers and residual drying equipment (used for only a few months each year) are prohibitive. For example, investment capital (syrup production only) for 100 hectares of sweet sorghum could easily exceed one million dollars with annualized costs above $0.20 per liter of ethanol production capacity.

The authors believe there are two most likely scenarios for utilizing sweet sorghum as a feedstock for industrial scale ethanol production in the upper Midwest: The first scenario would utilize fresh harvested sweet sorghum as a supplemental, seasonal feedstock in existing dry grind grain based (corn or sorghum) ethanol production facilities. The second scenario would solve the storage problem by ensiling sweet sorghum so that it can be used year-round as a supplemental feedstock in conversion facilities along with other feedstocks such as corn grain.

Fresh Harvested Sweet Sorghum as a Seasonal Feedstock

The utilization of fresh harvested sweet sorghum as a supplemental, seasonal feedstock in existing dry grind grain based (corn or sorghum) ethanol production facilities is interesting because all the residual material (pressed stalks) can be used to provide plant process heat. For example, a two-month sweet sorghum harvest can supply 100% of a corn dry mill's fermentation substrate plus provide sufficient fuel for approximately six months of the facility's total process heat requirements. The disadvantage to this approach is that these dry grind facilities would need to add high volume milling machinery typical of the sugarcane industry plus additional material handling and residual drying equipment that would be used for only a few months each year.

For seasonal fresh feedstock applications, this study assumes a harvest window of two months. During that time the dry mill grain ethanol plant is assumed to be dedicated to using 100% sweet sorghum as its ethanol feedstock, with excess residuals dried to 20% moisture content and stored for later use as fuel (LHV of 11,500 kJ kg^{-1} (Bagasse Calorific Value, 2007)). Both 2-row TP and 4-row SP forage harvesters are modeled including two on-farm in-field transport options. The first of which assumes an idealistic case in which chopped sweet sorghum is blown directly into a transport truck traveling in-field along side the harvester. The second in-field transport option assumes chopped sweet sorghum is blown into a hi-dump wagon pulled by the harvester. In this case, a second TP hi-dump forage wagon used to transfer material between the harvester and a transport truck waiting at the field's edge. Table 4.4 shows harvest and on-farm in-field transport options for the four models that consider seasonal fresh processing of sweet sorghum.

Table 4.4. Harvester and on-farm transport options for seasonal, fresh processed sweet sorghum

Option	Harvest Scenario	On-Farm Transport
1	Forage harvester, 4-row SP	Direct in-field loading into transport truck
2	Forage harvester, 4-row SP, pulling hi-dump forage wagon	TP hi-dump forage wagon to truck at field's edge
3	Forage harvester, 2-row TP	Direct in-field loading into transport truck
4	Forage harvester, 2-row TP, pulling hi-dump forage wagon	TP hi-dump forage wagon to truck at field's edge

Sweet Sorghum Ensilage as a Supplemental Year-Round Feedstock

When compared to a stand-alone facility dedicated to processing fresh sorghum over a short harvest window, the use of ensiled sweet sorghum as a supplemental year-round feedstock for existing dry grind grain ethanol plants has the advantage of reducing the capital requirements needed to invest in specialize milling machinery and solid fuel boilers. Ensiled sorghum can also provide a year-round supply of environmentally friendly residuals for use as a fuel for process heat. Disadvantages include significant FC losses during ensilage, especially if bunkers are poorly covered, have inadequate packing and/or filled with materials that have excessively high moisture content. Ideal moisture content (MC) for ensilage in bunkers is between 65 and 70%. This range is lower than the average wet basis moisture content of the sweet sorghum cultivars harvested by Hunter (1994), which was reported to be 74.9% (varied 71.1% to 77.9%) for the entire study including all eleven cultivars, at both locations and for cool-wet versus warm-sunny climatic conditions. When excluding data from the cool-wet year and using data only from the six best cultivars the average moisture changes slightly to 74.4% (range 72.3 to 76.4%). For this study the moisture content at harvest is assumed to range from 72% to 78%. To simplify the model it is assumed that plastic covers and packing densities are adequate and only moisture content will dictate actual dry matter losses. Also, because FC is much more readily degraded than cellulose and lignin, it is assumed that all dry matter losses are comprised of only fermentable carbohydrates. Data published by Midwest Plan Service (1987) was used to develop a linear relation (% DM loss = 0.64 x %MC - 35) including seepage, gaseous and surface spoilage losses for bunkers with moisture content between 70% and 80%. Using this relation, for example, dry matter loss for ensiled sweet sorghum with initial moisture content of 75% is estimated at 13%. If the crop's initial FC content is 50%, then a total of 26% of the crop's FC content will be lost during ensilage.

Another disadvantage of ensilage is the need for large storage volumes, especially for facilities dedicated to using only sweet sorghum as a feedstock. For example, a plant with an annual production of 190 million liters of ethanol (50 million gallons) ferments approximately 334,400 Mg of FC. If 20% of sweet sorghum's FC is lost during ensilage then nearly 795,000 Mg of DM with 47.5% FC would need to be harvested and stored in bunkers. When packing to a DM density of 224 kg m^{-3} (14 lb ft^{-3}), the total volume needed for storage is approximately 3.55 million cubic meters or 835 individual bunkers each with a maximum height of 6 m (20 ft) and storage volume of 4250 m^3 (150,000 ft^3). If located at the ethanol facility, then nearly 85 hectares (210 acres) of land would be needed for feedstock storage and access to bunkers. Another consideration for the use of sweet sorghum as a feedstock, is that only 15 to 20% of the generated residuals are needed to provide process heat for a typical grain based ethanol plant. That means a 190 million liter ethanol plant dedicated to using only sweet sorghum will produce annually between than 700,000 and 900,000 Mg of unused residuals that need to be either dried for storage, combusted for energy exports or converted to other co-products. Preliminary analysis indicates that when considering the overall net cost of fermentable carbohydrates derived from sweet sorghum, it is not economically viable to use residuals as a very low cost fuel to supply a local grid with electricity. For that reason, and for lack of economic information regarding other residual-based co-products, this study only considers milling ensilage as a supplemental feedstock to the point where enough residuals are generated and combusted on a daily basis to meet 100% of the plant's daily process heat requirements (i.e. 8350 kJ L^{-1} or 30,000 BTU gal^{-1} (ICM Inc., 2008)**)**. It is assumed that no residuals remain or require disposal. Although not considered by this study, if an excess of residual is available, it is conceivable that these materials could be sold for additional profit or at least cover their processing costs.

In order to evaluate the viability of ensiled sweet sorghum as a supplementary feedstock, capital investments, filling costs, storage losses, and unloading costs are modeled and compared over a number of likely production scenarios. Capital expenses for the construction of bunkers are based on an inflation-adjusted spreadsheet developed by Holmes (2003). Each bunker is assumed to have concrete walls and floor, use a plastic cover and have a 20-year expected life.

Three different ensilage systems are considered, including two 4-bunker (on-farm) complexes, one for a production area of 20 ha and a second complex for a production area of 100 ha. The 20 ha operation is assumed to represent a small farm operation using a 2-row TP harvester while the 100 ha unit is assumed to represent a larger operation with access to a 4-row SP harvester. Bunkers are sized using the assumption that each bunker is filled within 3 days, which increases uniformity in moisture and quality while reducing exposure to precipitation and excessive air during filling (Saxe, 2007). When using the 3-day design criteria, the unit cost for each bunker only changes slightly with an increase or decrease in production area, i.e. ensilage costs are largely dependent on the type of harvest system and not the area harvested (assuming harvest volume remains the same over the life to the bunker complex). As a result, only two on-farm ensilage options are considered by this study. The third bunker system considered assumes at-plant ensilage using 4-row SP harvesters and multiple 10-bunker modules where the number of modules depends on the size of the ethanol facility. Table 4.5 lists the modeled ensilage options including harvester, corresponding production area, on-farm transport, number of tractors used for packing and the size and annualized capital cost of bunkers.

Table 4.5. Harvester, production area, on-farm transport, packing and bunker options for ensiled sweet sorghum

		Area		**Packing Tractor**		**Bunker**		**Cost per**
Option	**Harvest Scenario**	**ha**	**On-Farm Transport**	**No**	**Mg min $^{-1}$**	**No**	**m ^{3}**	**Mg FC**
ON-FARM ENSILAGE:								
5	4-row SP Forage harvester	100	Three TP forage wagons	3	3.6	4	2830	$36.50
6	2-row TP Forage harvester	20	Two TP forage wagons	1	3.3	4	560	$66.13
AT-PLANT ENSILAGE:								
7	4-row SP Forage harvester	n/a	Direct in-field loading into transport truck	3	3.6	n/a	4250	$27.75
8	4-row SPFH, pulling hi-dump forage wagon	n/a	TP hi-dump wagon to truck at field's edge	3	3.6	n/a	4250	$27.75

Ensilage related variables used in Monte Carlo simulations include annualized bunker costs, initial crop MC and ensilage MC (during transport). The most likely annualized costs for bunkers are shown in Table 4.5. For annualized costs, high and low values used in the triangular distributions are taken at ± 20% of most likely values so as to represent possible variations in design, material costs and contractor fees. To represent uncertainties in moisture content at harvest and after ensilage, most likely values are assumed to be 75% and 60% respectively. Initial crop MC at harvest is assumed to have a low and high value of 72% and 78%. The low and high value for ensilage MC is taken at 54% and 66%.

Feedstock Transportation Costs

The data presented in Table 4.3 only considers on-farm preharvest and harvest costs up to the point where fresh harvested material is dumped directly into a transport truck traveling either alongside the harvester or located at the field's edge. The costs of the transport truck (driver, diesel, etc.) and off-farm transportation are not included.

This study builds on the models used to calculate Table 4.3, including truck transport and off-farm transportation costs. Transportation from farm to centralized processing of stored silage or fresh harvested feedstocks assumes the use of tractor-trailers that cost $100 h $^{-1}$ (includes driver and diesel) (Sokhansanj, 2006) with a maximum haul weight of 36 Mg independent of moisture and FC content. On average each 36 Mg load is assumed to carry 3.6 Mg FC when transported fresh harvested sweet sorghum (75% MC, 40% FC) and 4.0 Mg FC when transporting silage (60% MC, 27% FC). Feedstock for on-farm ensilage is transported with TP wagons, which transfers fresh harvested material to on-farm storage bunkers.

Overall transport time is a function of waiting time, loading time, distance and speed from farm to paved road, distance and speed on paved road to centralized processing facility, unload time and return speed on paved and unpaved roads. Assumptions include a 40 minute wait and loading time, a 30 minute weighing and unload time, 1.5 km (one-way) of on-farm unpaved roads, and hauling and return travel speeds on unpaved roads of 20 and 30 km h^{-1} versus 80 and 90 km h^{-1} on paved roads. For both the 20 and 100 ha production units it is assumed that a large front-end loader unloads bunkers at an average rate of 36 Mg per 40 minutes at a cost of \$55 h^{-1}. Overall distances traveled are considered for three different size ethanol plants including 37.9, 189 and 379 million liters per year (10, 50 and 100 million gallons per year). The percentage of land area planted in sweet sorghum around a given ethanol processing facility also affects average transportation distance. In this study, percent plantation is compared at three levels. These include a relatively low-density plantation that considers a 2.0% land area coverage for fresh processed scenarios and 3.2% for ensiled scenarios. Higher plantation densities include 16% and 30% for fresh scenarios and 25.3% and 47.4% for ensiled scenarios. The different percentage values used for both low and high-density land-coverage results from differences in FC yields between fresh and ensiled scenarios. These values are adjusted so as to compare each fresh and ensiled scenario (for the same ethanol plant capacity) using an equal production area. A winding factor of 1.2 is included to account for indirect routes a transport truck might need to travel in order to reach a given processing facility (Sokhansanj, 2006). This factor is applied to the average straight-line travel distance, which is calculated by taking the radius for ½ of the total production area required to supply a given ethanol plant.

There is considerable uncertainty related to the actual time required to transport either silage or fresh harvested materials from farm to a processing facility. To simulate these uncertainties, transportation variables are described by triangular distributions a shown in Table 4.6.

Table 4.6. Transportation variables - triangular distribution parameters

Simulated Variables	Units	Low Value	Most Likely	High Value
Unload Bunker (Front-end loader)	$ h $^{-1}$	$44	$55	$66
Tractor Trailer (w/ driver & diesel)	$ h $^{-1}$	$80	$100	$120
Tractor Trailer Load Time	h	0.53	0.67	0.80
Tractor Trailer Unload Time	h	0.40	0.50	0.60
Winding Factor		1.00	1.20	1.44
Unpaved Roads	km	1.20	1.50	1.80
Unpaved Haul Speed	km h $^{-1}$	16.0	20.0	24.0
Unpaved Return Speed	km h $^{-1}$	24.0	30.0	36.0
Paved Haul Speed	km h $^{-1}$	64.0	80.0	96.0
Paved Return Speed	km h $^{-1}$	72.0	90.0	108.0

Capital Cost Estimates for Milling Equipment and Residual-Fueled Boiler

Construction and equipment budgets for facilities capable of milling large volumes of sweet sorghum (similar to what a typical sugarcane facility might process) were obtained from ICM Inc. (2008). Milling equipment capital costs are estimated at $27 million dollars for a ethanol facility capable of producing 182 million liters per year (48 million gallons per year). Mill power requirements and resultant cost estimates are based on equipment data traditionally used to process sugarcane (Hugot, 1960). A sizing exponent of 0.65 is used to estimate overall milling capital requirements for different processing rates and based on published data for hoppers, conveyors and roller mills (Brown, 2003).

Capital cost estimates for a solid fuel boiler capable of burning high moisture residuals (up to 50% MC) were based on equipment and installation cost of $1,250,000 for a 6860 kW boiler (Zebley, 2005), a contingency fee of $225,000 an auxiliary facility cost of $147,500 and a sizing exponent of 0.50 (Brown, 2003).

Capital cost uncertainty for both milling machinery and solid fuel boilers assumes a triangular distribution using a cost differential of ± 20%.

Residual Combustion Credits

As with sugarcane, sweet sorghum can be processed to provide a liquid stream of fermentable carbohydrates as well as pressed stalk residuals that can be burned to provide process heat and shaft power (for direct use and/or electrical power generation). In this study the ensilage scenarios are assumed to generate residuals with 50% MC after milling. Residuals are burned continuously to provide the ethanol plant 100% of its daily process heat requirements. The LHV of the high moisture residuals is taken to be 6,500 kJ kg^{-1} (Bagasse Calorific Value, 2007). For the fresh harvested seasonal scenarios, it is assumed that the high moisture residuals are combusted to provide 100% of the plant's daily required process heat plus addition heat for drying excess residuals to 20% MC. Stored residuals are assumed to have a LHV of 11,500 kJ kg^{-1} (Bagasse Calorific Value, 2007) and require approximately 4850 kJ per kg of evaporated water for drying. Combustion credits are calculated at three price levels including \$4, \$6 and \$8 per GJ.

Results and Discussion

Preharvest, Harvest and Ensilage Cost Estimates

Preharvest and harvest costs (at farm-gate) for both fresh harvested and ensiled sweet sorghum scenarios are shown in Figure 4.1 and compared on a fermentable carbohydrate basis. Also apparent is the high cost of the ensilage options, which for smaller, less efficient harvest and storage options can easily exceed \$450 per Mg of harvested FC (excluding transport costs and credits for residual co-products). These high costs are largely a result of significant FC loss during storage and additional heavy tractors required for packing bunker silos and moving material between field and bunkers. For comparative purposes, Figure 4.1 also shows a range of production costs on a FC basis (from \$246 to \$184 Mg^{-1}) for corn with production costs of \$157 and \$118 Mg^{-1} (\$4.00 and \$3.00 bu^{-1}). As shown fresh processed sweet sorghum has FC production cost below indicated FC production costs for corn grain. Grain values exclude storage costs and assume a 70% starch content.

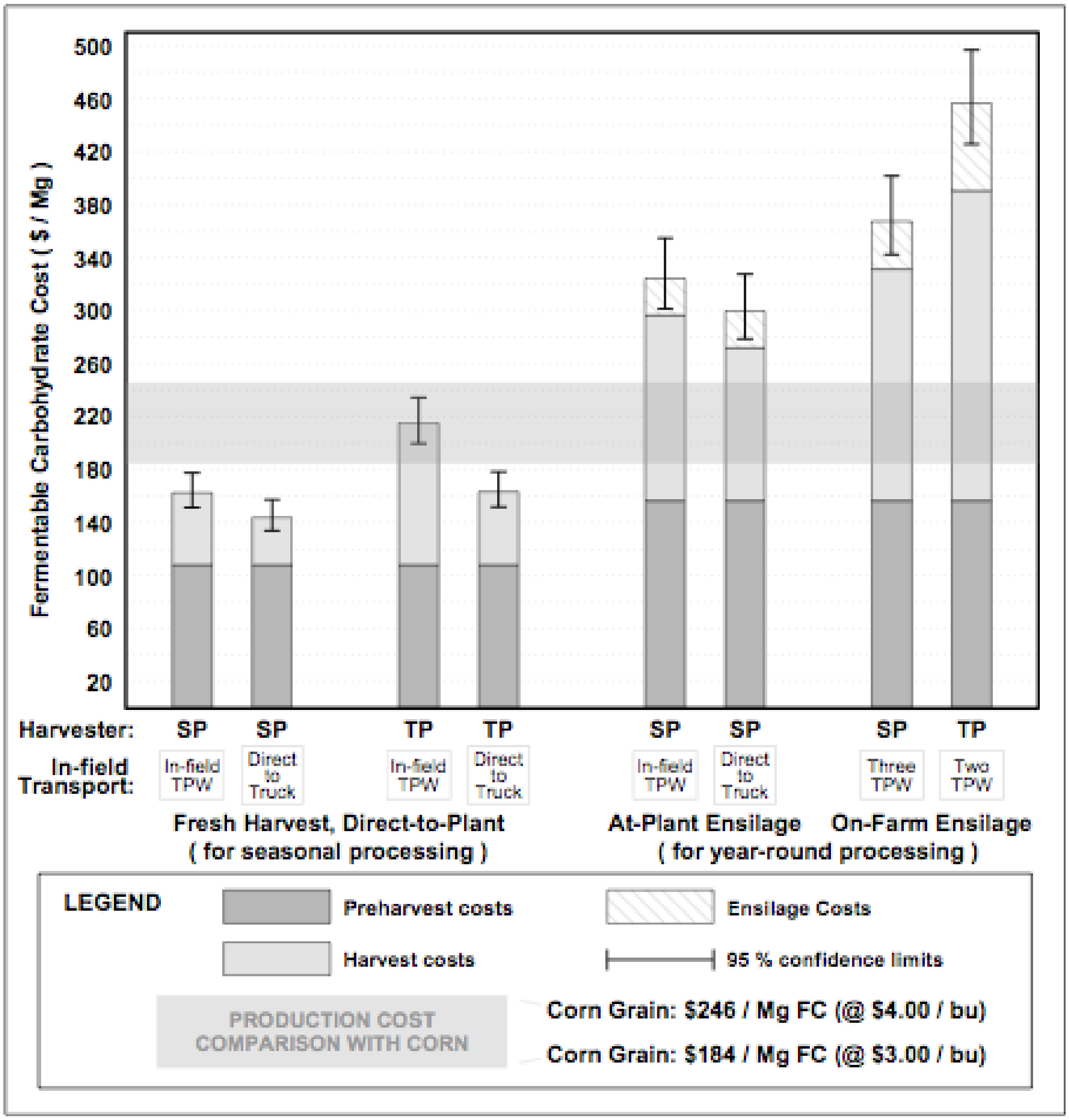

Figure 4.1. Sweet sorghum preharvest, harvest and ensilage costs per Mg fermentable carbohydrates. See Tables 4.4 and 4.5 for option description.

Transport Cost Estimates

Transporting low bulk density material such as fresh harvested or ensiled sweet sorghum significantly contribute to overall costs. Figure 4.2 details transport costs for both fresh and ensiled scenarios for ethanol plant capacities ranging from 37.9 to 379 million liters per year at three levels of plantation density (i.e. percent land area surrounding the conversion facility planted in sweet sorghum). For off-farm transport of fresh sweet sorghum, plantation densities are assumed to be 2.0%, 16.0% and 30.0%. Because ensiled scenarios produce less FC on a per hectare basis, plantation densities are increase (3.2%, 25.3% and 47.4%, respectively) so as to match fresh and ensiled scenarios with comparable transport distances and areas required to supply feedstock.

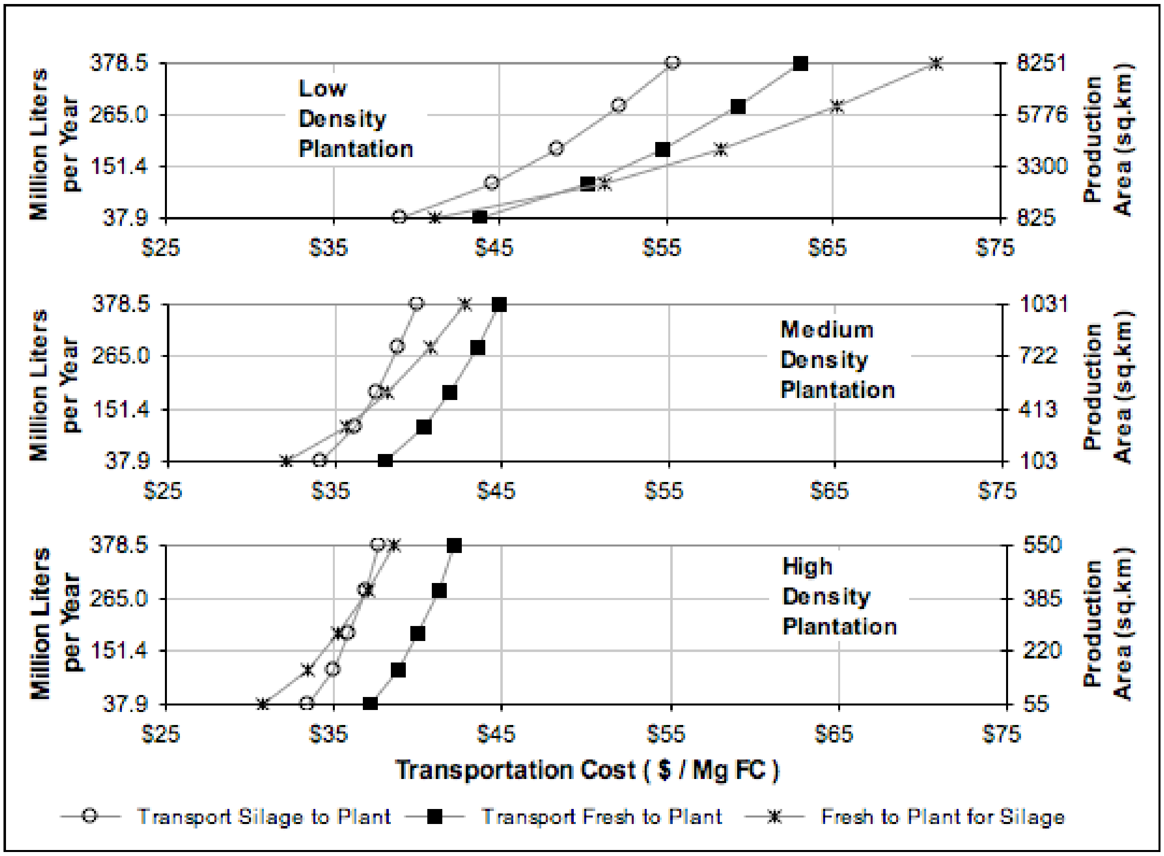

Figure 4.2. Off-farm transportation cost estimates for fresh and ensiled sweet sorghum at three plantation densities and for ethanol plant capacities ranging from 37.9 to 379 million liter / year

As indicated in Figure 4.2, the cost of fresh material for at-plant ensilage results in the greatest transport costs on an Mg FC basis, which for a large capacity plant are estimated to range from $39 to $71 Mg $^{-1}$ for respective high and low plantation density. This higher cost results from both moisture and DM losses occurring at the ethanol plant during the ensilage process. In contrast, because there are minimal at-plant DM losses when receiving fresh or on-farm ensiled feedstocks (for immediate processing) the same large facility is able to reduce FC transport costs to between \$38 to \$63 Mg^{-1}. When transporting the same fresh or on-farm ensiled feedstocks (for immediate processing) to smaller ethanol production facilities, FC transport costs range between \$33 to \$44 Mg^{-1}.

Annualized Cost Estimates for Milling Machinery and Solid Fuel Boilers

In addition to transportation costs, the capital investments required to purchase and install specialized milling equipment and solid fuel boilers capable of utilizing residuals must also be considered in evaluating the viability of sweet sorghum as a supplemental feedstock to existing grain based ethanol production facilities. Figure 4.3 shows the combined projected annualized capital costs for milling and boiler installations for both fresh harvested and ensiled scenarios for five different plant capacities. As shown, the annualized capital costs (on a Mg FC basis) in the fresh harvested, seasonally processed sorghum scenarios are more than double those in the ensiled sorghum scenarios. This is a result of the larger capacity equipment needed to process fresh harvest sweet sorghum over a two month harvest window versus year-round processing of ensiled feedstocks. Economies of scale benefit larger milling equipment and boiler systems reducing FC costs by more than 50% when increasing annual plant capacity from 37.9 to 379 million liters.

Residual Combustion Credits

Sweet sorghum is a more viable supplemental feedstock if there is an economic value to residuals that are co-produced during the extraction of fermentable carbohydrates because they are used as a fuel for process heat generation (as is common in sugarcane processing facilities). Figure 4.4 shows estimated combustion credits in \$ GJ^{-1} from expected residual production for both fresh and ensiled scenarios at three different value levels: \$4, \$6 and \$8 per GJ. These comparisons are made on an energy basis; the capital and operational costs of combustion equipment are not included in the analysis. As shown, ensiled sweet sorghum has higher potential combustion value on a per FC basis, because of likely storage losses in excess of 20% of the crop’s initial FC content.

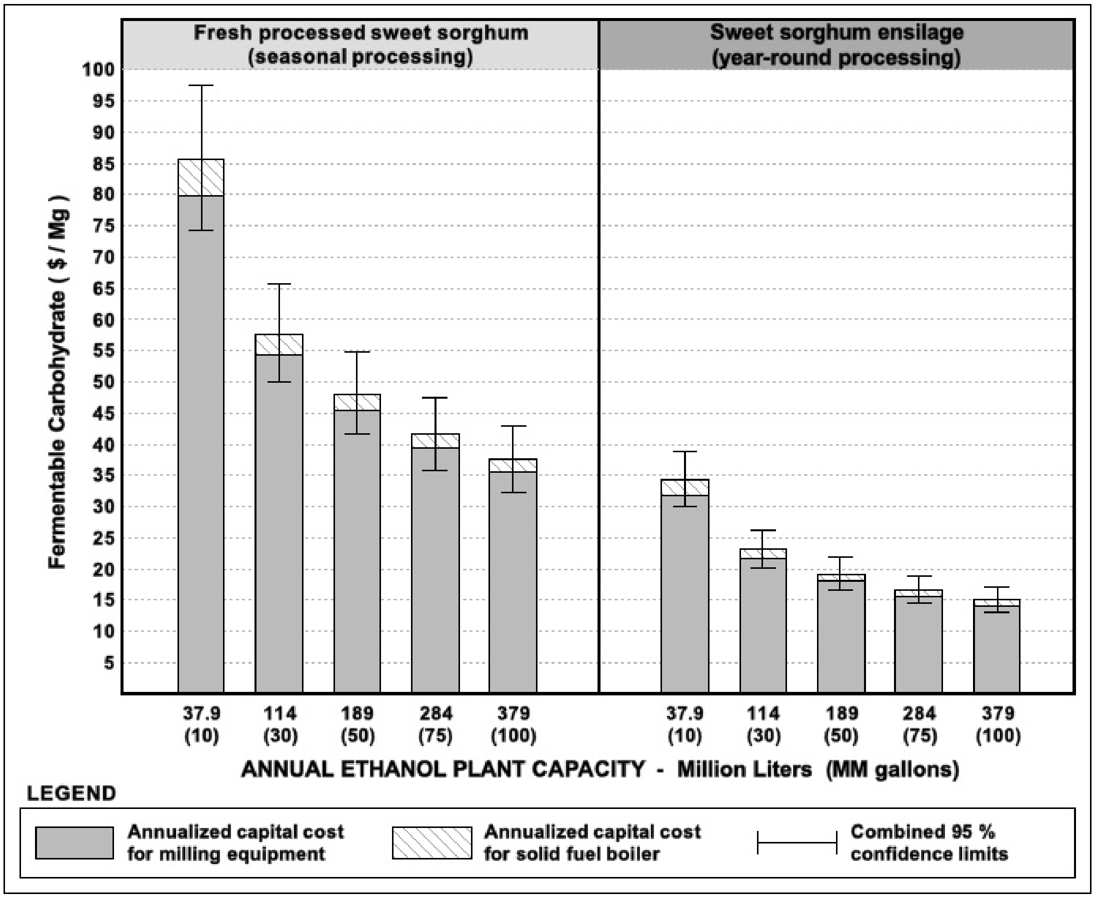

Figure 4.3. Sweet sorghum milling and boiler costs per Mg fermentable carbohydrates

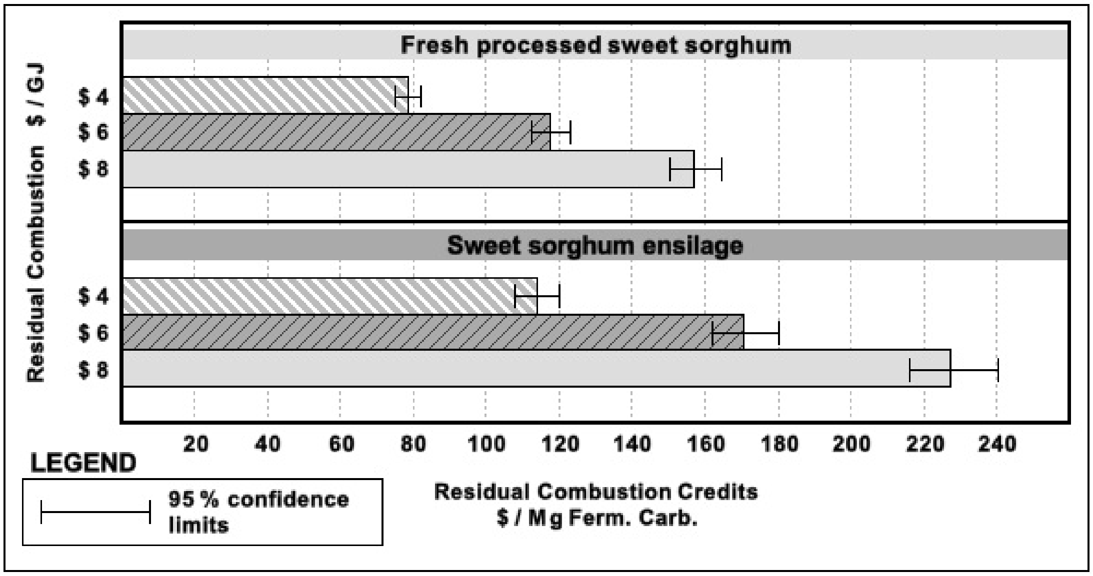

Figure 4.4. Combustion credits per Mg fermentable carbohydrates

Net Fermentable Carbohydrate Cost Estimates

The overall net costs of fermentable carbohydrates for the fresh harvested and ensilage scenarios are shown in Figure 4.5. The eight harvester options described in tables 4.4 and 4.5 are compared at four levels of residual combustion credit ($0, $4, $6 and $8 per GJ) and three ethanol plant capacities including 37.9, 189 and 379 million liters y $^{-1}$ (10, 50 and 100 MM gallons y $^{-1}$). Also indicated are comparable values of fermentable carbohydrates derived from corn grain, including $236 Mg^{-1} ($6.00 bu^{-1}) and $157 Mg^{-1} ($4.00 bu^{-1}) and with a $220 and 149 Mg^{-1} DDGS credit, respectively ($200 and 135 ton^{-1}). DDGS Credits are estimated to be valued at approximately 90% of the value of corn on a dry basis (ICM Inc., 2008). The lowest plantation density for fresh and ensiled processing scenarios (2% and 3.2% of the area surrounding ethanol plant) is used to generate figure 4.5. As indicated, fresh process scenarios are able to produce FC at costs well below ensiled scenarios, especially those that ensile on-farm. They are also able to produce FC at cost below comparable FC derived from corn grain when including combustion credits for process residuals. For example, our models indicate the SP forage harvest scenario using in-field TP wagons can deliver to a 189 million liter plant FC with net costs ranging from $110 to $188 Mg $^{-1}$, for residual combustion credits of $8 to $4 GJ $^{-1}$. These values are largely lower than corn based FC (with DDGS credit), which is estimated to cost between $171 and $258 Mg $^{-1}$ for grain valued at $236 and $157 Mg $^{-1}$ ($6 and $4 bu $^{-1}$).

Higher plantations densities show similar trends but are able to product FC at lower net cost because of lower off-farm transport costs. Reductions in net FC cost can range from 3% to 24%. Highest FC cost reductions are associated with $8 GJ $^{-1}$ combustion credits at the highest plantation density.

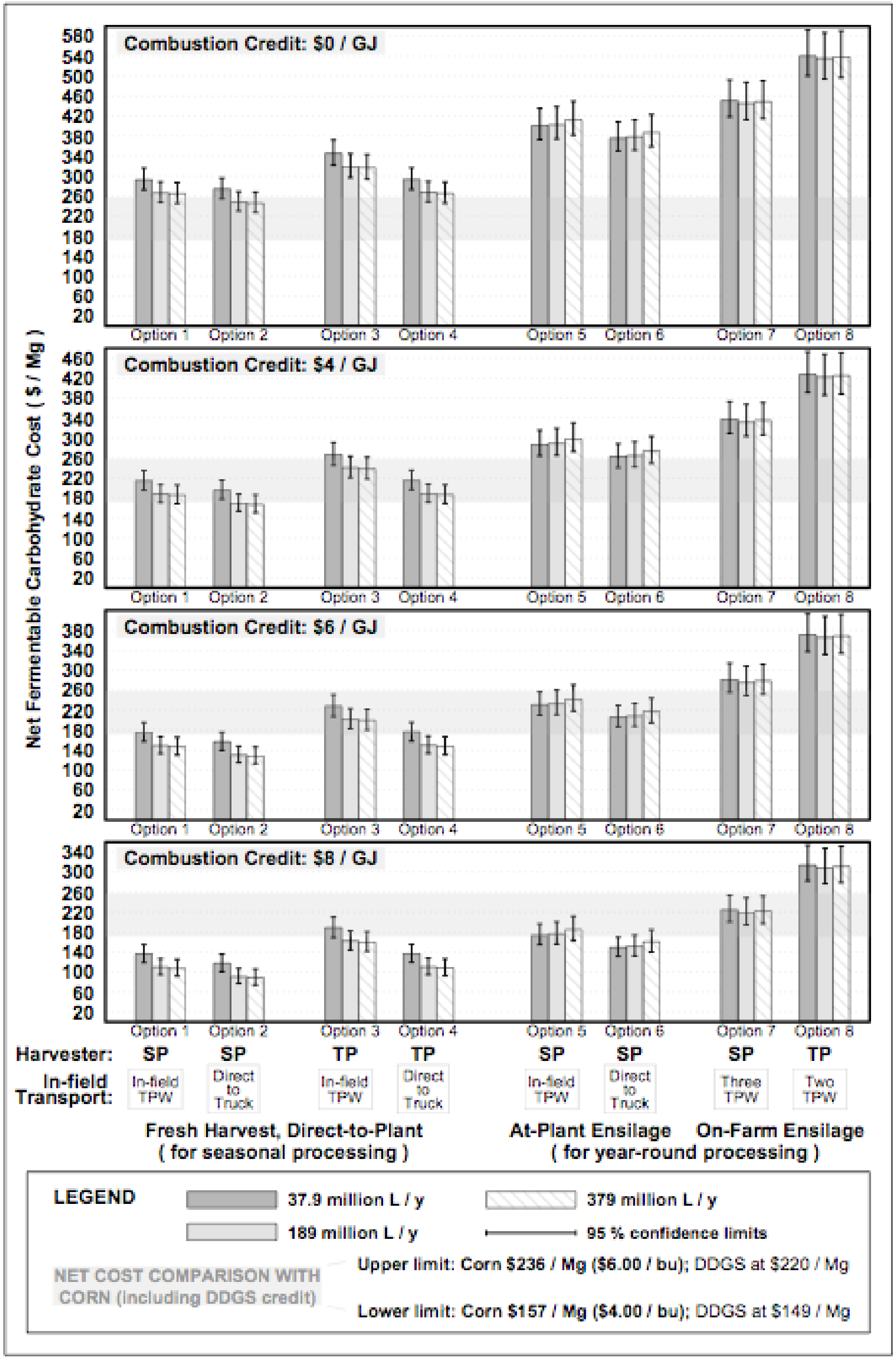

Figure 4.5. Sweet sorghum net fermentable carbohydrate costs for a low density plantation surrounding ethanol plants with production capacities of 37.9, 189 and 379 million liters/year (10, 50 and 100 MM gal/year). See Tables 4.4 and 4.5 for option description.

Monte Carlo Simulations and Sensitivity Analysis

For each of the eight seasonal and ensilage options modeled in this study (see Tables 4.4 and 4.5), between 57 and 119 variables are used to generate the Monte Carlo result distributions that estimate the likely net cost of FC produced from sweet sorghum. Each variable is predefined with a probability function that contributes to a percentage of the variance of corresponding Monte Carlo result distributions. The models with the highest number of simulated variables are related to on-farm ensilage, which require additional machinery for packing bunkers and on-farm transport. The model with the least number of simulated variables is the SP forage harvester the directly loads transport trucks in-field for fresh processing at an ethanol plant. Each of the eight modeled options also incorporate run variations over five levels of ethanol plant capacity where each plant capacity has three levels of crop plantation densities and each crop density incorporates four levels of residual combustion credits.

After inspection of raw sensitivity data it was noted that results from each of the eight model options show similar sensitivity trends when comparing different plant capacities, different crop densities and different residual combustion credits. So as to simplify reporting and provide general information on trends, sensitivities are averaged over all combinations for plant capacities, crop density and residual combustion credits. Table 4.7 shows the average percent variance for each of the eight harvest-transport-processing options. Variance in simulated Monte Carlo result distributions are generated by variations over each variable’s assigned probability functions. As indicated, models for fresh processed options (see table 4.4) show greatest sensitivity to biomass yield followed by capital costs of milling equipment and moisture content at harvest. Ensiled options (table 4.5) are also most sensitive to biomass yield, however, these options show secondary sensitivities to variations related to harvest equipment field capacity and annual hours. Percentages are shown as either a positive or negative numbers, which indicate a positive or negative correlation to an increase in variable values.

Table 4.7. Net FC cost sensitivity analysis - Selected variables and associated contribution to variance of resultant Monte Carlo distributions. See Tables 4.4 and 4.5 for option description.

	Average Contribution to Monte Carlo Result Distribution Variance							
	Fresh Processed Options				**Ensilage Options**			
Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Biomass Production	-38.9%	-32.9%	-44.2%	-34.4%	-65.1%	-63.8%	-72.8%	-66.7%
Harvest Machinery[1] Field Capacity	-8.0%	-8.8%	-16.9%	-16.2%	-11.9%	-12.6%	-8.9%	-14.3%
Harvest Machinery[1] Annual Hours	-3.6%	-3.7%	-5.2%	-6.3%	-6.3%	-6.1%	-4.1%	-6.4%
Percent Sugar Recovery	-0.6%	-0.6%	-1.0%	-0.9%	-0.9%	-0.9%	-0.8%	-1.1%
Milling Equipment Capital Cost	14.6%	18.1%	10.0%	13.3%	1.0%	1.3%	0.6%	0.4%
Tractor-trailer Cost	13.1%	14.8%	7.3%	11.1%	5.2%	5.9%	2.9%	1.5%
Moisture Content at Harvest	13.5%	13.3%	8.3%	11.3%	1.9%	2.0%	0.0%	0.0%
Tractor-trailer Load Time	1.3%	1.4%	0.9%	1.0%	1.4%	1.3%	0.4%	0.1%
Bunker Capital Cost	-	-	-	-	2.2%	1.9%	2.2%	4.5%
Combined Influence on Variance	78.0%	74.2%	81.9%	79.4%	94.9%	94.5%	92.2%	94.6%

[1] All harvest machinery including in-field tractor-pulled wagons and bunker packing tractors, when applicable.

Ensilage in Vertical Silos

In this study only bunkers were considered for ensilage storage. This is due to higher capital costs and significant seepage losses associated with high moisture ensilage in large vertical silos. However, after further consideration vertical silos may merit more detailed analysis, especially if located at the ethanol facility where capital investments may benefit from economies of scale, automated loading and unloading, and significantly reduced harvest costs resulting from the elimination of heavy equipment needed to pack and unload bunkers. Furthermore, if vertical silos are located at the ethanol plant, then it may be possible to continuously collect seepage and immediately process it as a FC rich stream, thus eliminating the very large FC losses typically associated with seepage. Preliminary analysis, which assumes a 40% reduction in FC losses and capital costs approximately double bunkers, indicates that large vertical silos operate with net FC costs well below bunkers and slightly more expensive than the fresh, seasonal, 2-row TP forage harvester options describe in this study.

Conclusions

Fresh harvested sweet sorghum that is seasonally processed as a supplemental FC and fuel feedstock for existing ethanol production facilities appears to be economically viable when compared to corn. For example, when combustion credits are between \$6 and \$8 GJ^{-1}, sweet sorghum FC costs are estimated to range from \$91 to \$149 Mg^{-1} for a medium sized ethanol plant at a low-density plantation level. This compares favorably to corn FC costs of \$171 to \$258 Mg^{-1} for corn valued at \$157 to \$236 Mg^{-1} (\$4 to \$6 bu^{-1}), respectively. In contrast, scenarios using ensilage to store sweet sorghum in bunker silos for year-round use as a supplement feedstock are much more expensive to operate, and in most cases, have net costs well above FC derived from corn grain. For the same medium sized ethanol plants and low-density plantation, FC costs can reach as high as \$365 Mg^{-1} for on-farm ensilage with \$6 residual credit. At-plant ensilage scenarios are more economical than on-farm ensilage with comparable FC costs and range from \$151 to \$232 Mg^{-1}. In the analyzed cases that show lower FC costs than comparable FC from corn grain, residual combustion credit is an essential component in developing an economically viable production and process model for sweet sorghum.

Acknowledgements

This work was supported by the Iowa Energy Center under grant number 05-02. Our thanks to Dr. Michael D. Duffy, Dr. William Edwards and Dr. Mark H. Hanna for their advice and recommendations.

References

ASABE. 2003a. Agricultural machinery management data. American Society of Agricultural and Biological Engineers. *ASAE Standard* D497.4 FEB03.

ASABE. 2003b. Agricultural machinery management. American Society of Agricultural and Biological Engineers. *ASAE Standard* EP496.2 FEB03.

Bagasse Calorific Value. 2007. (Available at www.sugartech.co.za/extraction/bagasseCV/index.php. Accessed February 2007).

Bennett, A.S. and R.P. Anex. 2008. Farm-Gate Production Costs of Sweet Sorghum as a Bioethanol Feedstock. *Transactions of the ASABE*, 51(2): 603-613.

Bohlmann, G.M. 2005. Biofrinery process economics. *Chemical Engineering Progress*. ABI/INFORM Trade & Industry. October 2005 101(10):37

Brown, R.C. 2003. *Biorenewable resources, engineering new products from agriculture*. Ames, Iowa: Iowa State Press.

Buxton, D.R., Anderson, I.C. and A. Hallam. 1999. Performance of sweet and forage sorghum grown continuously, double-cropped with winter rye, or in rotation with soybean and maize. *Agronomy Journal*, 91:93-101.

Chen, J.C.P. and C.C. Chou. 1993. *Cane sugar handbook, a manual for cane sugar manufacturers and their chemist*, 12th Edition. New York: John Wiley and Sons.

Cundiff, J.S. and D.J. Parrish. 1983. Whole-stalk sweet sorghum storage. ASABE Paper No. 83-3058. ASABE, St. Joseph, MI.

Decisioneering, Inc. 2007. What is Monte Carlo Simulation? (Accessed February 2007. Available at http://www.decisioneering.com/monte-carlo-simulation.html).

Duffy, M. and D. Smith. 2008. Estimated costs of crop production in Iowa - 2008. ISU Extension Service Publication FM 1712, Iowa State University Extension Service. Ames, IA.

Edwards, W. 2008. Personal communication and unpublished machinery cost 2005 and 2008 Excel® spreadsheet. Iowa State University Extension Service. Ames, IA.

Edwards, W., Ayers, G. and M. Boehlje. 2001. Machinery management – estimating farm machinery costs. ISU Extension Service Publication PM 710, Iowa State University Extension Service, Ames, IA.

Edwards, W. and D. Smith. 2007a. Iowa farm custom rate survey. ISU Extension Service Publication FM 1698, Iowa State University Extension Service, Ames, IA.

Edwards, W. and D. Smith. 2007b. Cash rental rates for 2007 survey. ISU Extension Service Publication FM 1851, Iowa State University Extension Service. Ames, IA.

Eiland, B.R., Clayton, J.E. and W.L. Bryan. 1983. Losses of fermentable sugars in sweet sorghum during storage. *Transactions of the ASAE*, 26:1596-1600.

Eiland, B.R. and J.E. Clayton. 1984. Storage characteristics of sweet sorghum. ASAE Paper No. 84-3579. ASAE, St. Joseph, MI.

Goldemberg, J. 1994. Brazilian alcohol program: an overview. *Energy for Sustainable Development*, 1(1):17-22.

Grassi, G., Tondi, G. and P. Helm. 2004. Small-sized commercial bioenergy technologies as an instrument of rural development. *Biomass and Agriculture: Sustainability, Markets and Policies*. OECD Publication Service, Paris, p. 277-287.

Hanna, M. 2002. Ag decision maker: Estimating the field capacity of farm machinery. Iowa State University Extension Publication File A3-24. Ames, IA.

Hanna, M. 2005. Personal communication. Iowa State University Extension Service.

Holmes, B.J. 2003. Cost of Forage Storage Spreadsheet. (Available at http://www.uwex.edu/ces/crops/uwforage/storage.htm. Accessed February 2007).

Hong-Tu. M and H. Xiu-Ying. 1986. Breeding for sweet sorghum with high grain yield and sweet stalks. *Sorghum Newsletter,* 29:2-3.

Hugot, E. 1960. *Handbook of cane sugar engineering*. New York: Elsevier Publishing Company.

Hunter, E.L. 1994. Development, sugar yield, and ethanol potential of sweet sorghum. Iowa State University Masters Thesis, Ames, IA.

Hunter, E.L. and I.C. Anderson. 1997. Sweet sorghum. *Horticultural Reviews*, 21:73-104.

ICM Inc. 2008. Personal communication. Engineering, Procurement and Construction firm dedicated to development of US dry mill Ethanol Industry. 310 N. First St., Colwich, KS, 67030.

Kuepper, G. 1992. Sweet sorghum: Production and processing. Kerr Center for Sustainable Agriculture. Poteau, OK.

Lueschen, W.E., Putnam, B.K., Kanne, B.K. and T.R. Hoverstad. 1991. Agronomic practices for production of ethanol from sweet sorghum. *Journal of Production Agriculture*, 4:619-625.

Luhnow, D. and G. Samor. 2006. WSJ article: It weans off energy imports. *Wall Street Journal*, January 9, 2006.

Lynd, L.R., Wyman, C.E. and T.U. Gerngross. 1999. Biocommodity engineering. *Biotechnology Progress,* 15:777-793.

Lynd, L.R., Wyman, C., Laser, M., Johnson, D. and R. Landucci. 2005. Strategic biorefinery analysis: Review of existing biorefinery examples. NREL/SR-510-34895. National Renewable Energy Laboratory, Colorado.

Maasdam Syrup Mill. 2004. Personal communication on sweet sorghum production and mill operations.

McClune, L. 2004. Personal communication: On-farm juice fermentation/juice storage systems and prototype 1-row tractor pulled mobile juice harvester development and testing.

Midwest Plan Service. 1987. *Beef housing and equipment handbook.* Ames, Iowa.

Miller, F.R. and G.G. McBee. 1993. Genetics and management of physiologic systems of sorghum for biomass production. *Biomass and Bioenergy*, 5:41-49.

Monroe, G.E. and W.L. Bryan. 1984. Design factors for milling sweet sorghum. *Transactions of the ASABE*, 27:1211-1221.

Monroe, G.E., Bryan, W.L., Sumner, H.R. and R.L. Nichols. 1981. Sweet sorghum juice removal with 3-roll mills. ASABE Paper No. 81-3541. ASABE, St. Joseph, MI.

Monroe, G.E., Nichols, R.L., Bryan, W.L. and H.R. Sumner. 1984. Sweet sorghum juice extraction with 3-roll mills. *Transactions of the ASABE*, 26:651-654.

Monroe, G.E. and H.R. Sumner. 1983. A harvest and handling system for sweet sorghum. ASAE Paper No. 84-3551. ASAE, St. Joseph, MI.

Moreira, J.R. and J. Goldemberg. 1999. The alcohol program. *Energy Policy*, 27:229-245.

Murray, D. 2005. Ethanol's potential: Looking beyond corn. Earth Policy Institute. (Available at http://www.earth-policy.org/Updates/2005/Update49.htm, accessed January 2006).

Parrish, D.J. and J.S. Cundiff. 1985. Long-term retention of fermentables during aerobic storage of bulked sweet sorghum. *Proc. 5th Annual Solar and Biomass Workshop.* Atlanta, GA, p.137-140.

Perlack, R. D., L. L. Wright, A. F. Turhollow, R. L. Graham, B. J. Stokes and D. C. Erbach. 2005. Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. DOE/GO-102995-2135, ORNL/TM-2005/66. Oak Ridge, Tenn.: Oak Ridge National Laboratory. Available at: http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf. Accessed April 2006.

Putnam, D.H., Lueschen, W.E., Kanne, B.K. and T.R. Haverstad. 1991. A comparison of sweet sorghum cultivars and maize for ethanol production. *Journal of Production Agriculture*, 4:377-381.

Rajvanshi AK, Nimbkar N. Sweet sorghum R&D at the Nimbkar Agricultural Research Institute. 2004. Nimbkar Agricultural Research Institute, Phaltan, India. (Available at http://nariphaltan.virtualave.net/sorghum.htm, accessed January 2005).

Saxe, C. 2007. Managing forage in bunker silos. Focus on Forage. Vol 3: No. 6. University of Wisconsin Extension Service. (Available at http://www.uwex.edu/ces/crops/uwforage/ManageBunker.html. accessed February 2007).

Shinners KJ. 2007. Personal communication – one-pass switchgrass harvester. Professor of Agricultural Engineering. Department of Biological Systems Engineering. University of Wisconsin, Madison, WI.

Smith, D, and W. Edwards. 2005. 2005 Iowa farm costs and returns. ISU Extension Service Publication FM 1789. Iowa State University Extension Service. Ames, IA.

Smith, G.A. and D.R. Buxton. 1993. Temperate zone sweet sorghum ethanol production potential. *Bioresource Technology*, 43:71-75.

Sokhansanj, S. 2006. Overview of the Integrated Biomass Supply Analysis & Logistics (IBSAL model). Oak Ridge National Laboratory. Oak Ridge, Tennessee.

Turhollow, A. 1994. The economics of energy crop production. *Biomass and Bioenergy*, 6(3):229-241.

Undersander, D.J., Lueschen, W.E., Smith, L.H., Kaminski, A.R., Doll, J.D. and K.A. Kelling. 1990. Alternative field crops manual: sorghum-syrup. (Available at http://corn.agronomy.wisc.edu/AlternativeCrops/SorghumSyrup.htm. accessed June 2005).

USDA-NASS. 2007. Agricultural statistics database; 2002 census of agriculture. United States Department of Agriculture National Agricultural Statistics Service. (Accessed February 2007. Available at http://www.nass.usda.gov/index.asp).

Wiedenfeld, R.P. 1984. Nutrient requirements and use efficiency by sweet sorghum. *Energy in Agriculture*, 3:49-59.

Worley, J.W. and J.S. Cundiff. 1992. Ethanol from sweet sorghum: A comparison of four harvesting/processing systems. In J.S. Cundiff (ed.) *Liquid Fuels from Renewable Resources*. St. Joseph, MI: ASABE, p. 40-49.

Wyman, C.E. 1999. Biomass ethanol: Technical progress, opportunities, and commercial challenges. *Annual Review of Energy and the Environment*, 24:189-226.

Zebley, G. 2005. Personal communication, Hurst Boiler and Welding Co., Inc. Coolidge, GA.

CHAPTER 5. ECONOMIC ANALYSIS OF SINGLE- AND DOUBLE-CROPPING SYSTEMS FOR GRAIN AND BIOMASS PRODUCTION

Paper in preparation for publication

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Abstract

Double cropping systems show particular promise for co-production of grain and biomass feedstocks and potentially can allow for greater utilization of grain crop residues. However, additional costs and risks associated with producing two crops instead of one could make biomass-double crops less attractive for producers despite productivity advantages. Detailed techno-economic models of both single cropped corn and double cropped triticale-corn were developed. Monte Carlo simulation techniques were also incorporated and used to determine result distributions and expected financial return to management. Results show double cropped triticale-corn to be at a significant economic disadvantage. The cost benefits associated with using less equipment combined with availability of risk mitigating crop insurance and government subsidies will likely limit farmer interest and clearly indicate that traditional single-crop corn will provide greater financial returns to management.

Introduction

Although not commercially available at present, as much as 830 million Mg of biomass, the equivalent of 248 GL of additional ethanol capacity (assuming 300 L ethanol Mg biomass^{-1}) could be produced in the US each year with the introduction of cellulosic conversion technologies (Perlack et al., 2005; McAloon, 2000). It is anticipated that crop residues and dedicated biomass crops will serve as the primary feedstocks for the production of ethanol from cellulose. Relative to dedicated energy crops, crop residues

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offer the advantage of grain and biomass feedstock co-production on high productivity farmland. On the other hand, important environmental services provided by crop residues may preclude their removal at all locations or in all years (Mann et al., 2002; Wilhelm et al., 2004), thus limiting cellulosic feedstock availability from grain based farming systems.

Double cropping systems represent an alternative for grain and biomass feedstock co-production. In a double cropping system, a fall-seeded, spring-harvested cover crop is sequenced between primary grain crops. Double cropping systems show particular promise for co-production of grain and biomass feedstocks because the cover crop in the system serves as a source of additional biomass and also as a soil cover following primary crop harvest, potentially allowing for greater utilization of grain crop residues. Agronomic studies focusing on biomass-based double cropping systems in the Midwestern US have concluded that double cropping generally offer productivity advantages over single cropping systems (Helsel and Wedin, 1981; Buxton et al., 1999; Heggenstaller et al., 2008). However, additional costs and risks associated with producing two crops instead of one could make biomass-double crops less attractive for producers despite productivity advantages (Crookston et al., 1978). On the other hand, double cropping could also spread the fixed costs of production over a larger volume of output and contribute to improved cash flow. Lower fixed costs for the second crop each season could also increase net farm income. Previous studies have evaluated the potential economic and risk advantages of double crops relative to sole-crops (Harper et al., 1991; Burton et al., 1996). These studies however, have focused exclusively on double cropping systems comprised of spring and fall harvested grain crops. In general, double grain cropping is practiced only south of 40ºN where growing season length allows for the full reproductive development of two grain-bearing crops (Fageria, 1992). Double cropping systems that include two biomass crops, or a pairing of grain and biomass crops are potentially adapted over a much wider geographic area. To date, no studies have provided an economic assessment of double cropping systems designed to generate biomass, or for co-production of biomass and grain.

The objective of the current study is to apply an engineering-economic cost methodology in conjunction with Monte Carlo simulations and probabilistic estimates for yields and production parameters to model likely farm-gate economic returns to management for a corn grain system and two prototypical double-cropping systems on high productivity Iowa cropland typically managed with corn-soybean rotations. Double cropping systems considered in our analysis included fall-seeded forage triticale (planted after soybean), succeeded by corn in order to investigate a double-cropping system organized for biomass and grain co-production.

Double-crop production scenarios were parameterized with data from field research trials conducted at the Iowa State University Agronomy Farm, located in Boone County, Iowa, US. Expanded details regarding crop management practices employed in these studies are presented in Heggenstaller et al. (2008). Representative locations for corn produced on prime cropland include Iowa's ten best corn-yielding counties (USDA-NASS, 2007). Although based on only ten counties, results from this study can be considered representative of many similar regions throughout the upper Midwest USA. Our study methodology defines values and scenarios based on existing literature, prior studies and personal communication with specialists. Parameters related to farm-gate production costs, harvest costs and a range of potential market pricings for biomass and corn grain are included.

Methods

Economic Models

Two different economic models were developed with one representing the double cropping systems, and one model for corn and stover production using current production costs and market pricing trends. Each model is formulated in a Microsoft Excel spreadsheet. Crystal Ball software, an Excel add-on package, is used to evaluate uncertainty through Monte Carlo simulations that generate distributions describing likely before tax returns to management (Decisioneering, Inc., 2007). A graphical representation of model structure and key variables incorporated into each cost model and Monte Carlo simulation is presented in Figure 5.1.

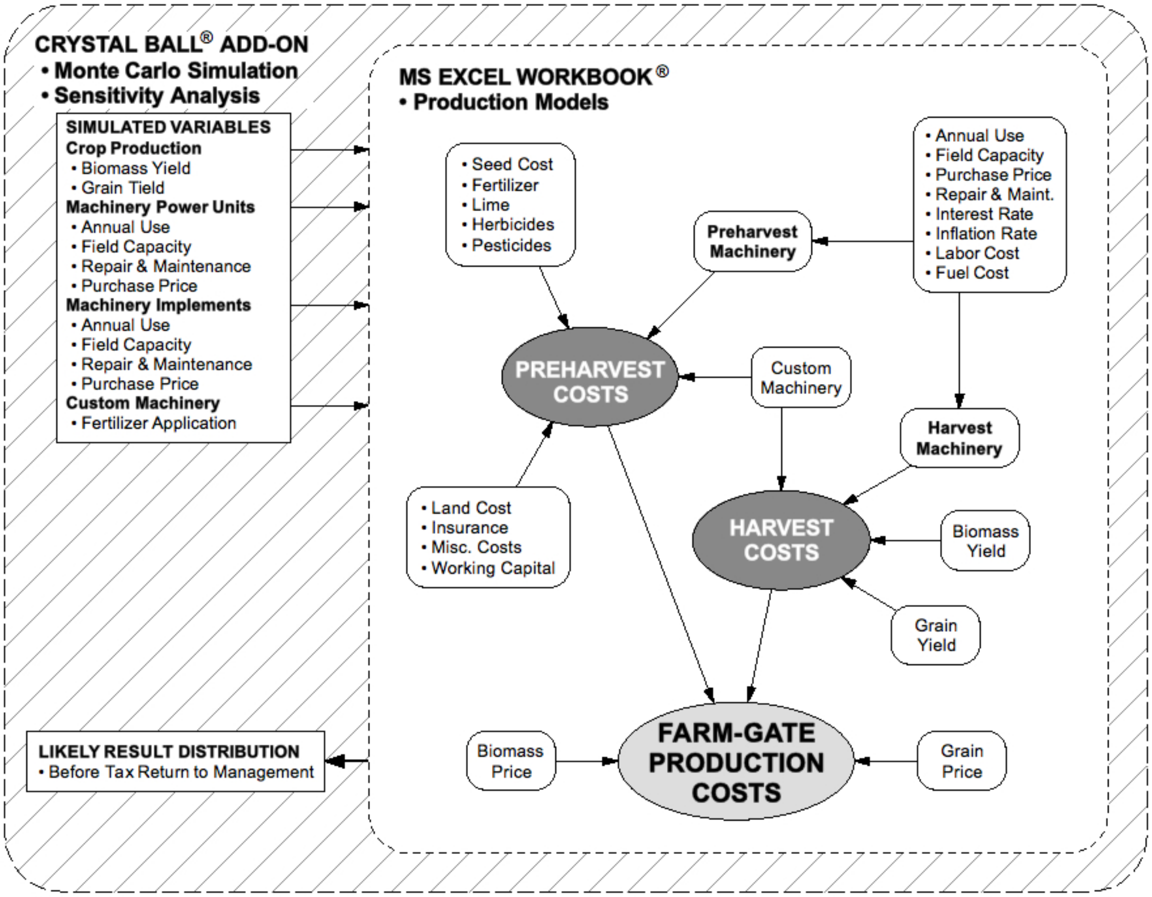
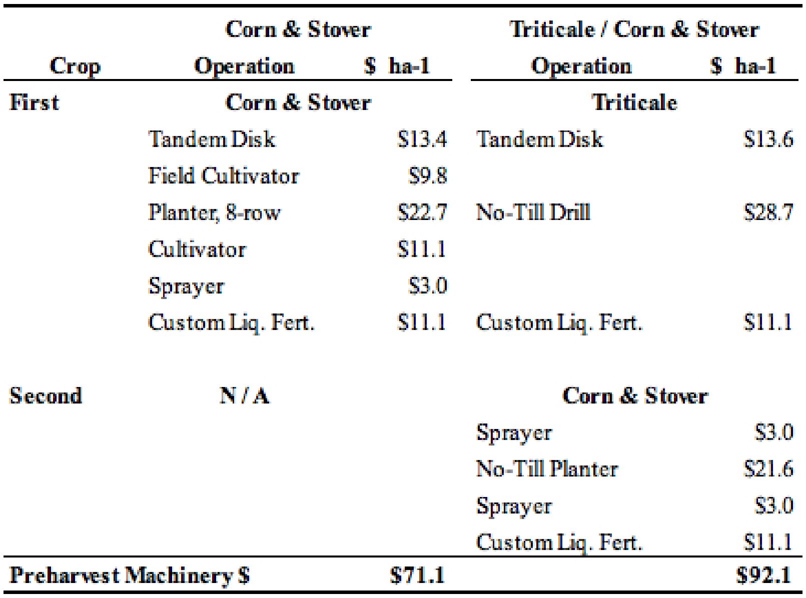


Figure 5.1. Flow diagram: MS Excel-based production model and Crystal Ball Monte Carlo simulation.

Preharvest production costs are based on typical Iowa farm management practices, material costs and machinery costs, as described in Duffy and Smith (2008), Edwards (2008), Edwards et al. (2001), Smith and Edwards (2005), and by personal communications with extension specialists (Edwards, 2005; Edwards, 2008; Hanna, 2006). Biomass harvest costs for both corn stover and double crop systems assume one-pass systems that blow chopped biomass directly into a forage wagon pulled by a separate tractor traveling alongside the harvester. Costs associated with storage, drying, densification and off-farm transportation of biomass were not considered. The justification for these exclusions include the possibility for optimistic scenarios where innovative transport, drying and densification schemes combined with small-scale, distributed processing facilities or direct on-farm utilization of biomass, which might reduce post-harvest transport and processing costs to the point where they are comparable with corn grain's current post-harvest costs. Present trends toward large-scale centralized processing, however, combined with the relatively low bulk density of biomass will add considerable costs to this study's farm-gate analysis of biomass well above costs associated with processing corn grain.

Preharvest machinery costs depend on the specific management practices utilized for each production scenario. Estimated preharvest machinery and operations costs are shown below in Table 5.1.

Table 5.1. Estimated preharvest machinery operations and costs



	Corn & Stover		**Triticale / Corn & Stover**	
Crop	**Operation**	**$ ha-1**	**Operation**	**$ ha-1**
First	**Corn & Stover**		**Triticale**	
	Tandem Disk	$13.4	Tandem Disk	$13.6
	Field Cultivator	$9.8		
	Planter, 8-row	$22.7	No-Till Drill	$28.7
	Cultivator	$11.1		
	Sprayer	$3.0		
	Custom Liq. Fert.	$11.1	Custom Liq. Fert.	$11.1
Second	**N / A**		**Corn & Stover**	
			Sprayer	$3.0
			No-Till Planter	$21.6
			Sprayer	$3.0
			Custom Liq. Fert.	$11.1
Preharvest Machinery $		**$71.1**		**$92.1**

Preharvest machinery utilized for double crop systems are based on actual practices from field research trials (Heggenstaller et al., 2008), while corn production assumes literature estimates for preharvest operations commonly used for corn production in Iowa (Duffy and Smith, 2008). Estimates of income, average production costs and before tax return to management for each model are shown in Table 5.2. Estimates assume farm-gate grain sales at \$186 dry Mg^{-1} (\$4.00 bu^{-1}), 100% stover recovery with 1:1 grain-to-stover ratio (dry basis) and biomass with farm-gate sale price of \$77.2 dry Mg^{-1} (\$70 ton^{-1}). Government subsidies to corn included income from direct, counter cyclical and loan deficiency subsidy payments (USDA-ERS, 2007a). Corn crop insurance indemnity payment calculations were based on a multiple peril policy with a Risk Management Agency indemnity price of \$86.6 Mg^{-1} (15.5% wet basis moisture content, \$2.20 bu^{-1}), 75% coverage level, 4.4% premium rate and 0.45 subsidy factor (Hofstrand and Edwards, 2003). It is assumed that triticale and sorghum x sudangrass would not benefit from government subsidies or crop insurance.

Operating costs for preharvest and harvest machinery were based on ASABE standards (ASABE, 2003a; ASABE, 2003b) and ISU Extension Service recommendations (Edwards, 2008; Edwards et al., 2001). Cost estimates included machinery list and purchase prices, expected life, salvage value, annual hours of use, implement power requirements, repair and maintenance costs, fuel and lubricant costs, depreciation, field capacity, field efficiency and field speed. One-pass corn grain and stover harvest costs used machinery capital cost estimates and field capacity currently being realized by field researchers in Iowa (Krapfl, 2006). One-pass biomass harvests assume machinery capital cost estimates and field capacity similar to large 377 kW (500 HP) self-propelled forage harvester with an average field capacity of 45.4 Mg h^{-1} (Shinners, 2007). Costs associated with seeding corn and grain hauling, drying and handling are assumed to be proportional to corn grain yields (Duffy and Smith, 2008).

Fertilizer application assumed the use of custom operators with costs based on published costs for this service (Edwards and Smith, 2007). Nutrient replacement rates are shown in Table 5.3 and based on the removal of nitrogen, phosphorous and potassium by harvested grain and biomass. Nutrients removal by harvested corn grain and stover in the sole-crop systems were set according to values published by the Natural Resources Conservation Service (USDA-NRCS, 2007). For double-cropping systems nutrient removal is based on concentrations reported by (Heggenstaller et al., 2008).

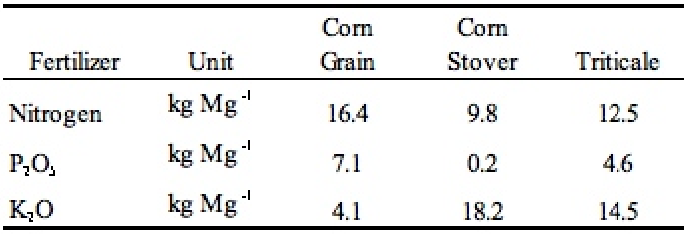
Table 5.2. Income, production costs and before tax return to management for corn (w/ stover) and double crop systems on high productivity Iowa corn-soybean cropland

BIOMASS PRODUCTION AND INCOME				
Description	Units	Corn / Stover	Triticale / Corn / Stover	Triticale / Sorg. x Sudan.
Biomass (dry matter)				
Corn Stover	Mg ha^{-1}	9.4	7.8	
Corn Grain	Mg ha^{-1}	9.4	7.8	
Triticale	Mg ha^{-1}		7.5	7.8
Sorg. x Sudan.	Mg ha^{-1}			15.2
Farm-gate Income				
Biomass	\$ ha^{-1}	\$724.6	\$1,182.0	\$1,781.6
Grain	\$ ha^{-1}	\$1,750.1	\$1,462.1	\$0.0
Government Subsidies	\$ ha^{-1}	\$88.6	\$82.3	\$0.0
Insurance Indemnity Payment	\$ ha^{-1}	\$0.0	\$0.0	\$0.0
Total Income		\$2,563.2	\$2,726.4	\$1,781.6
PREHARVEST MACHNIERY[a] AND MATERIALS				
1st Seed Appl. (corn: k ha^{-1})	kg ha^{-1}	86.5	113.7	145.7
2nd Seed Appl. (corn: k ha^{-1})	kg ha^{-1}		145.7	16.8
1st Seed Cost [b]	\$ ha^{-1}	\$181.6	\$238.7	\$64.2
2nd Seed Cost [b]	\$ ha^{-1}		\$64.2	\$14.8
Nitrogen @ \$1.01 kg^{-1}	\$ ha^{-1}	\$249.5	\$270.9	\$235.5
P_2O_5 @ \$1.10 kg^{-1}	\$ ha^{-1}	\$75.9	\$102.6	\$120.4
K_2O @ \$0.60 kg^{-1}	\$ ha^{-1}	\$124.5	\$129.2	\$267.6
Herbicide	\$ ha^{-1}	\$76.6	\$98.8	\$49.4
Insecticide	\$ ha^{-1}	\$4.9	\$4.9	\$0.0
Lime	\$ ha^{-1}	\$17.3	\$17.3	\$17.3
Crop Insurance	\$ ha^{-1}	\$35.5	\$32.6	\$0.0
Miscellaneous	\$ ha^{-1}	\$24.7	\$24.7	\$24.7
Preharvest Machinery	\$ ha^{-1}	\$71.1	\$92.1	\$89.1
Working Capital (8 months, 8%)	\$ ha^{-1}	\$40.6	\$55.3	\$45.1
Land (55% of \$556 ha^{-1})	\$ ha^{-1}	\$305.8	\$305.8	\$305.8
HARVEST[a]				
One-pass Corn/stover Combine	\$ ha^{-1}	\$71.4	\$71.4	
Grain Hualing Costs	\$ ha^{-1}	\$21.3	\$19.0	
Grain Drying Costs	\$ ha^{-1}	\$111.2	\$98.8	
Grain Handling Costs	\$ ha^{-1}	\$6.7	\$5.9	
Biomass Harvester - first pass	\$ ha^{-1}		\$87.4	\$87.4
Biomass Harvester - second pass	\$ ha^{-1}			\$128.5
Total Cost	\$ ha^{-1}	\$1,418.6	\$1,719.9	\$1,450.0
Before Tax Return to Management	\$ ha^{-1}	\$1,144.7	\$1,006.5	\$331.6

[a] 7.2 % interest rate / 1% inflation rate / \$0.73/L diesel / \$11/h hired labor / 8% hired labor

[b] Corn = \$2.10 k^{-1} / Triticale = \$0.44 kg^{-1} / Sorghum x Sudagrass = \$0.88 kg^{-1}

Table 5.3. Nutrient replacement



Fertilizer	Unit	Corn Grain	Corn Stover	Triticale
Nitrogen	kg Mg^{-1}	16.4	9.8	12.5
P_2O_5	kg Mg^{-1}	7.1	0.2	4.6
K_2O	kg Mg^{-1}	4.1	18.2	14.5

Crop insurance costs associated with corn production are based on the average values reported for Iowa (Smith and Edwards, 2005). Minor adjustments to insurance costs are made to reflect variations associated with the lower corn yield potentials of the triticale-corn double crop system.

Monte Carlo Simulations

In this study Monte Carlo simulations are used to determine the expected value and likely range of before tax return to farm management for each of the cropping systems considered. Monte Carlo simulation is an analytical method that generates a distribution of results from which likely values can be inferred (Decisioneering, 2007; Metropolis and Ulam, 1949; Savvides, 1994). Each Monte Carlo simulation utilizes a large number of iterations (10,000 for this study) to generate a result distribution. For each iteration, a randomly generated value is assigned to parameters of interest, which are related to crop yields, and machinery performance and costs. Values for each parameter or variable of interest are generated according to a define probability function that describes the likely distribution of parameter values within the Monte Carlo simulations. There are numerous types of continuous and discrete probability distributions that can be applied to Monte Carlo parameters, including normal, triangular, uniform, Poisson, lognormal, exponential, gamma, beta, Pareto, logistic and Weibull (Decisioneering, 2007). Due to limited availability of data, we utilized simple triangular distributions to describe the likely range in machinery related parameters and double crop yields. In the case of machinery, three parameter triangular distributions (minimum, mean, and maximum) are based on values published by American Society for Agricultural and Biological Engineers (ASABE, 2003a). For double-crop yields, triangular distributions were parameterized using the minimum, mean, and maximum plot-yields observed by Heggenstaller et al. (2008). Sole cropped corn yield was characterized by beta distribution.

Model Parameters and Uncertainties

There are many uncertainties associated with estimating actual farm profitability. Variations in individual farms: their size, management practices, percent of rented versus owned farmland, land rental costs, available machinery, soil types and fertility, topography, microclimates, rainfall and temperature, levels of crop insurance, government subsidies and markets can all effect the profitability of a given farming operation. Machinery operational costs are also dependent on many factors including farming conditions, actual machinery capital costs, interest and inflation rates, machinery life, annual use, repairs and maintenance, depreciation, field capacities, fuel costs and labor costs. All of these uncertainties add to the variability in profitability of a given farming operation.

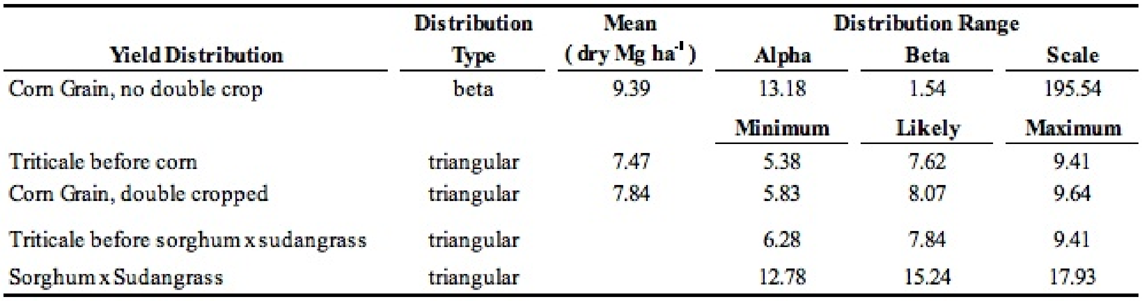
Our analysis focuses on the uncertainties associated with crop yields and machinery operations resulting from inherent differences in yields and machinery utilized for different cropping systems. Other farm-specific, crop invariant uncertainties such as land rent, percent land rented, labor hourly rates, interest and inflation rates, and fuel costs can also significantly affect the overall profitability of a given farming operation. However, in all of the models developed for this study, these uncertainties were considered identical and therefore do not change the relative conclusions among cropping systems.

On average, Iowa farmers with total income greater than \$10,000, rent approximately 55% of their total farmland (USDA-NASS, 2007). Therefore, each model assumes a prototypical Iowa farm with 55% rented land, and a constant land rental rate of \$556 ha^{-1} (\$225 ac^{-1}), which is consistent with current rates for high productivity corn-soybean cropland in central Iowa (Duffy and Smith, 2008). Interest and inflation rates (7.2% and 1% respectively), diesel costs (\$0.73 L^{-1}; \$2.75 gal^{-1}), hired labor costs (\$11 h^{-1}) and percent hired labor (8%), also assumed to be constant, are based on current machinery cost calculations and production cost data provided by ISU Extension Service (Edwards, 2008; Smith and Edwards, 2005).

Uncertainty in sole-crop corn yield is represented by a beta probability distribution generated from published 2001-2005 county data for Iowa's ten most productive counties including Boone, Bremer, Cedar, Grundy, Hamilton, Hardin, Jasper, Marshall, Scott and Webster (USDA-NASS, 2007). Fifty yield values are fit to beta distributions with a Kolmogorov-Smirnov (K-S) "goodness-of-fit" statistic of 0.087 with a five-year average yield of 11.1 Mg ha $^{-1}$ (177 bu ac $^{-1}$; 15.5% moisture content, wet basis).

Historical double crop production data for triticale/corn is not available for central Iowa, however, uncertainty in yield potentials can be simulated by triangular distributions using likely yield values and distribution range based on production experience and unpublished data generated by one of the authors. Table 5.4 shows average yields, standard deviations and distribution range used to simulate production uncertainties.

Table 5.4. Distribution parameters for modeled production systems



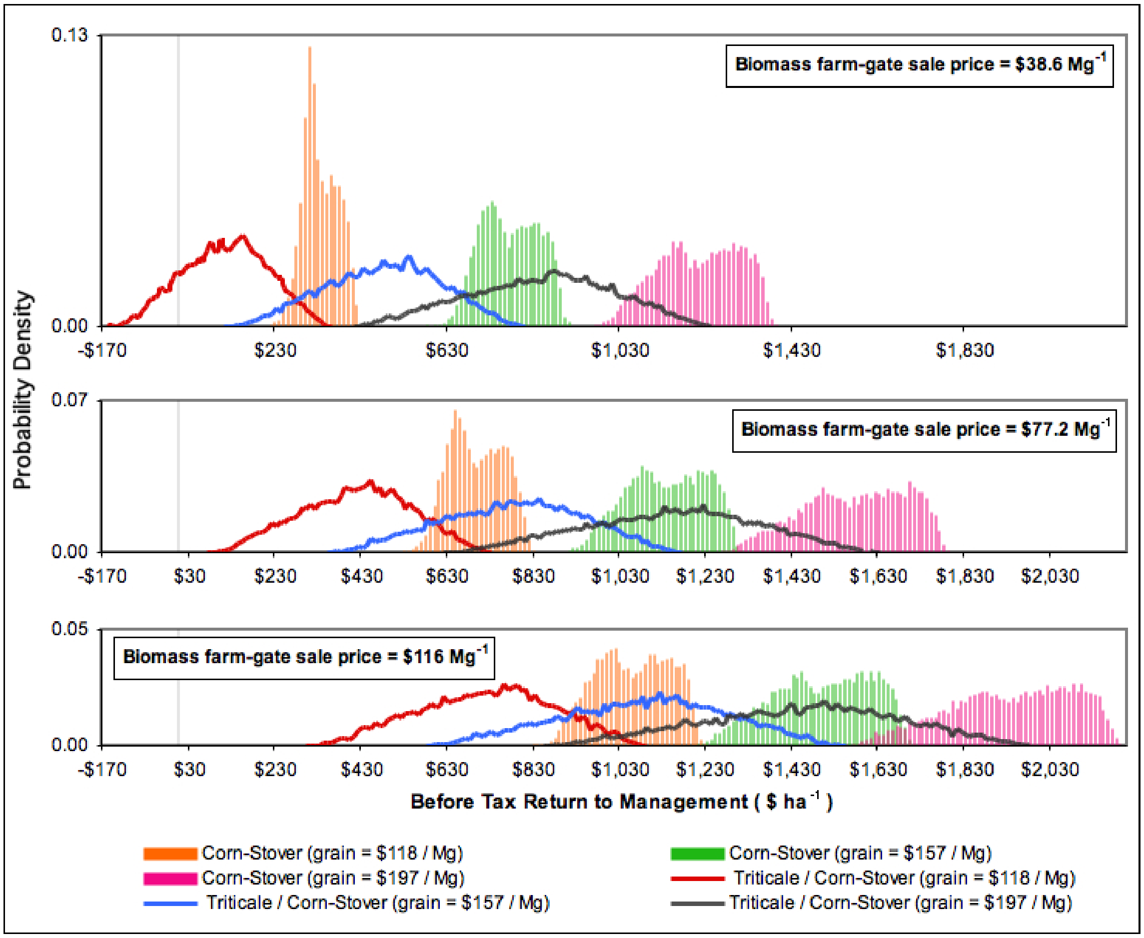
Yield Distribution	Distribution Type	Mean (dry Mg ha^{-1})	Distribution Range Alpha	 Beta	 Scale
Corn Grain, no double crop	beta	9.39	13.18	1.54	195.54
			Minimum	Likely	Maximum
Triticale before corn	triangular	7.47	5.38	7.62	9.41
Corn Grain, double cropped	triangular	7.84	5.83	8.07	9.64
Triticale before sorghum x sudangrass	triangular		6.28	7.84	9.41
Sorghum x Sudangrass	triangular		12.78	15.24	17.93

Machinery cost and performance parameters were incorporated into each model and included uncertainty in machinery list and purchase prices, annual use, field capacity and repairs, and maintenance (Edwards, 2008). Actual list price of machinery can vary significantly especially considering the large number of independent implement manufacturers, and that power units with same horsepower can come with many different options and add-ons. An informal survey of machinery list prices found that values easily vary by ± 10% from published values. In the current study, uncertainty in machinery list price was assumed to follow a triangular distribution using these same values,and the purchase price of machinery was assumed to have a 15% discount from the manufacture's list price (Edwards, 2008). In practice, it is not uncommon for discounts up to 20% (Shinners, 2007). Therefore, purchase price uncertainty was simulated with a triangular distribution incorporating a 15 ± 5% discount from manufacturer's list price. Estimating the annual use (hours) of machinery is important in determining operational costs and any deviations from average annual use can significantly change operational costs. The uncertainty associated with annual equipment use on a given farm is dependent on many factors including crops grown, the size and condition of both farm and equipment, and operator experience. Likely annual use values for power units and implements were derived from Edwards (2008). Uncertainty estimates (approximately ± 40%) are based on ASABE and ISU published variations in field efficiencies and field speed, and the resulting range in times required to complete a typical farm operations (Edwards, 2008; ASABE, 2003a). Uncertainties related to machinery repair and maintenance were drawn from ASABE Standards which provide formulas to calculate likely costs and stipulates that under normal conditions estimates will vary ± 25% (ASABE, 2003a). Field capacity of forage harvest machinery is assumed to have a likely harvest rate of 45.3 Mg h^{-1} ± 20% (Hanna, 2006).

Results and Discussion

Figure 5.2 compares single crop corn (with 100% stover collection) to triticale doubled cropped with corn and stover (100% collection). Income is calculated at three levels of biomass pricing: \$38.6, \$77.2 and \$116 dry Mg^{-1} (\$35, \$70 and \$105 ton^{-1}) and three levels of corn grain pricing including \$118, \$157 and \$197 wet Mg^{-1} (\$3, \$4 and \$5 bu^{-1} at 15.5% moisture content). In all cases single crop corn generates significantly greater returns to management than the double crop triticale and corn.

Figure 5.2. Probability density distributions comparing return to management for corn with stover [a] collection and double cropped triticale (as feed) with corn & stover [a] grown on high productivity cropland (bin = $10)



[a] 100% stover collection

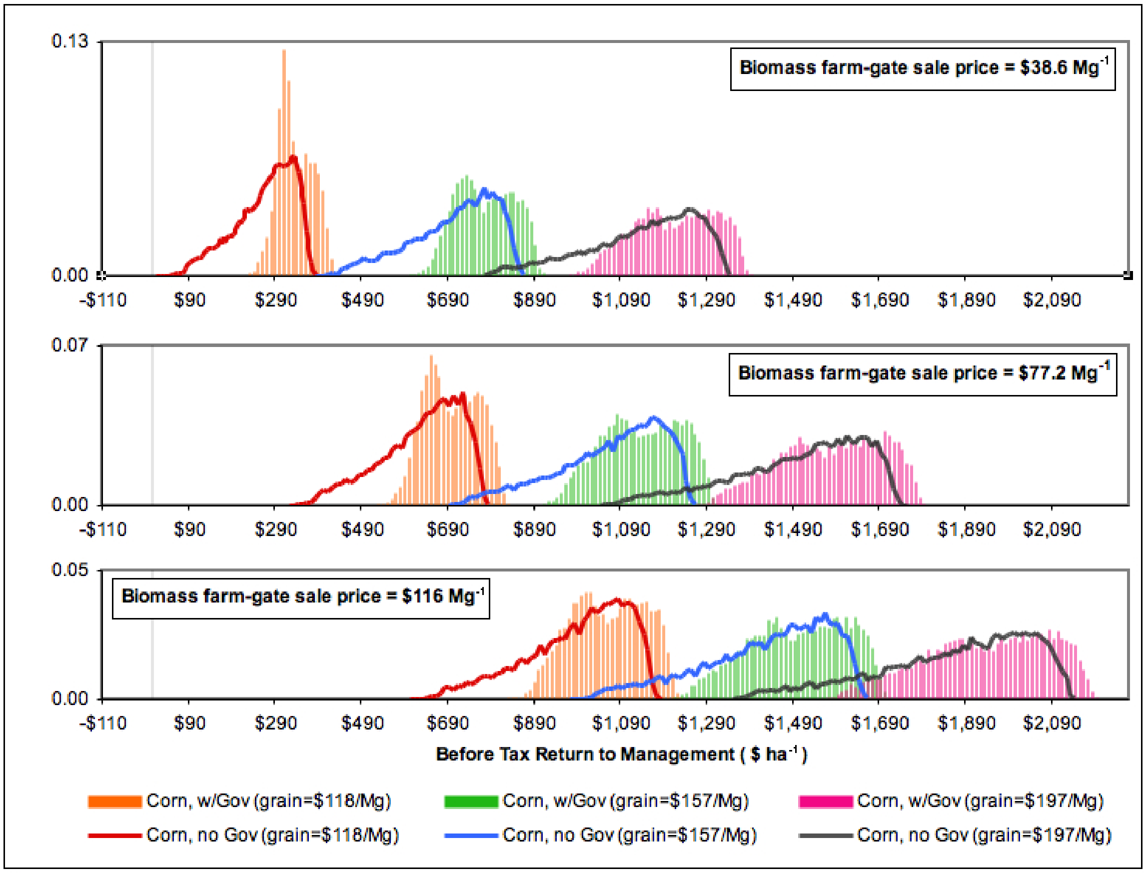
The financial advantage of single crop corn is further exemplified in Table 5.5, which lists expected returns, standard deviation and 5% exceedence values for each simulation shown in Figure 5.2. Five percent exceedence represents the value where 95% of the estimated returns to management are equal to or greater than the 5% exceedence value. Also evident in Figure 5.2 are the greater distribution variance associated with double cropped scenarios. This tighter variance shown by single cropped corn results from the fact that corn benefits from available government subsidies and insurance programs that help mitigate risk. Because of a likely late planting date for corn double cropped after triticale, it is assumed that insurance benefits and government subsidies would not be available.

Table 5.5. Expected returns, standard deviations and 5% exceedence values for single cropped corn-stover and double cropped triticale / corn-stover

	Farm-gate Market Pricings				Expected	Std	5%
	Grain Price		Biomass		Return	Dev.	Exceed.
High Yield Cropland	**$\$\ \mathrm{Mg}^{-1}$**	**$\$\ \mathrm{bu}^{-1}$**	**$\$\ \mathrm{Mg}^{-1}$**	**$\$\ \mathrm{ton}^{-1}$**	**$\$\ \mathrm{ha}^{-1}$**	**$\$\ \mathrm{ha}^{-1}$**	**$\$\ \mathrm{ha}^{-1}$**
Corn Grain & Stover	$118.1	$3.00	$38.6	$35	**$330.4**	$39.6	**$270.5**
- 100% stover collection	$157.5	$4.00	$38.6	$35	**$768.0**	$65.8	**$665.7**
- 1:1 stover to grain ratio	$196.9	$5.00	$38.6	$35	**$1,205.5**	$94.2	**$1,046.5**
Corn Grain & Stover	$118.1	$3.00	$38.6	$35	$256.5	$69.1	$121.3
- 100% stover collection	$157.5	$4.00	$38.6	$35	$694.0	$98.6	$498.4
- no subsidies, no insurance	$196.9	$5.00	$38.6	$35	$1,131.6	$128.0	$879.1
Triticale Feed - 1st crop	$118.1	$3.00	$38.6	$35	$107.9	$97.3	($57.9)
Corn & Stover - 2nd crop	$157.5	$4.00	$38.6	$35	$473.5	$132.5	$248.6
- no subsidies, no insurance	$196.9	$5.00	$38.6	$35	$839.0	$167.6	$549.9
Corn Grain & Stover	$118.1	$3.00	$77.2	$70	**$692.8**	$61.5	**$599.2**
- 100% stover collection	$157.5	$4.00	$77.2	$70	**$1,130.3**	$90.0	**$980.0**
- 1:1 stover to grain ratio	$196.9	$5.00	$77.2	$70	**$1,567.8**	$119.0	**$1,359.8**
Corn Grain & Stover	$118.1	$3.00	$77.2	$70	$618.8	$93.4	$434.3
- 100% stover collection	$157.5	$4.00	$77.2	$70	$1,056.3	$123.6	$812.1
- no subsidies, no insurance	$196.9	$5.00	$77.2	$70	$1,493.8	$152.8	$1,189.4
Triticale Feed - 1st crop	$118.1	$3.00	$77.2	$70	$410.6	$125.5	$198.9
Corn & Stover - 2nd crop	$157.5	$4.00	$77.2	$70	$776.1	$161.4	$501.3
- no subsidies, no insurance	$196.9	$5.00	$77.2	$70	$1,141.7	$197.4	$804.0
Corn Grain & Stover	$118.1	$3.00	$115.8	$105	**$1,055.1**	$84.5	**$916.1**
- 100% stover collection	$157.5	$4.00	$115.8	$105	**$1,492.6**	$113.4	**$1,295.0**
- 1:1 stover to grain ratio	$196.9	$5.00	$115.8	$105	**$1,930.1**	$143.3	**$1,673.2**
Corn Grain & Stover	$118.1	$3.00	$115.8	$105	$981.1	$117.2	$751.0
- 100% stover collection	$157.5	$4.00	$115.8	$105	$1,418.6	$147.8	$1,125.4
- no subsidies, no insurance	$196.9	$5.00	$115.8	$105	$1,856.2	$177.0	$1,508.9
Triticale Feed - 1st crop	$118.1	$3.00	$115.8	$105	$410.6	$125.5	$198.9
Corn & Stover - 2nd crop	$157.5	$4.00	$115.8	$105	$1,078.8	$191.1	$750.2
- no subsidies, no insurance	$196.9	$5.00	$115.8	$105	$1,444.4	$227.6	$1,054.4

The value and importance of government subsidies are further exemplified in Figure 5.3, which compares single cropped corn and stover with and without government subsidies and crop insurance. Once again, as is evident by tighter curve variance and higher expected returns, that government subsidies and crop insurance benefit growers by reducing their risk.

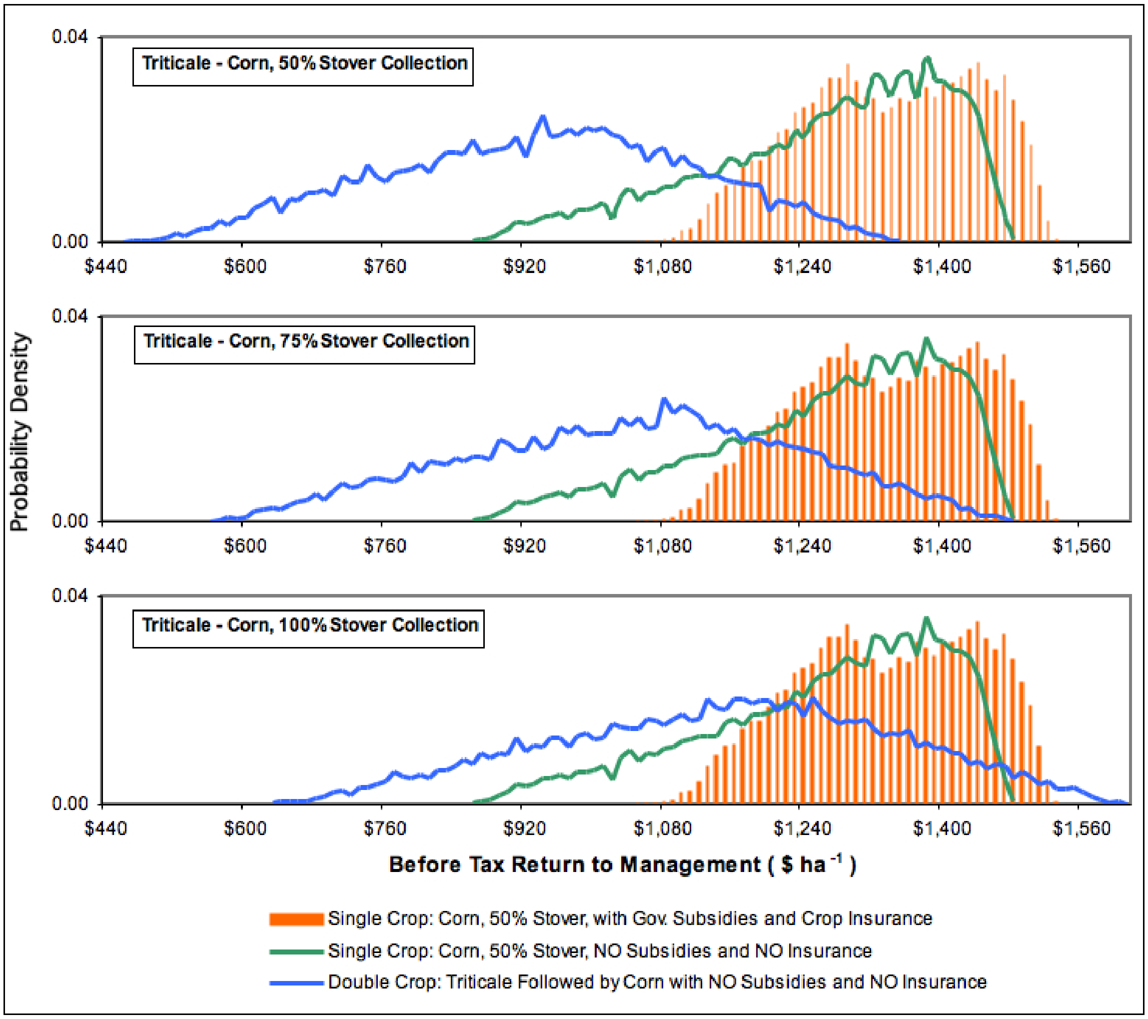
Figure 5.3. Probability density distributions comparing return to management for government subsidized and crop insured corn & stover [a], with corn & stover [a] grown without subsidies or crop insurance (bin = $10)



[a] 100% stover collection

It is unlikely in practice that most farmers would remove 100% of stover. To take this into consideration the single crop corn model was run assuming 50% stover collection and compared to triticale-corn that assumes 50%, 75% and 100% stover collection. Once again, the financial benefits of single crop corn over double cropping scenarios are readily apparent as shown in Figure 5.4. As indicated, double crop triticale-corn has considerably lower return to management even when collecting 100% stover. This is a result of higher production costs associated with double cropping scenarios and lower corn grain production due to later planting dates.

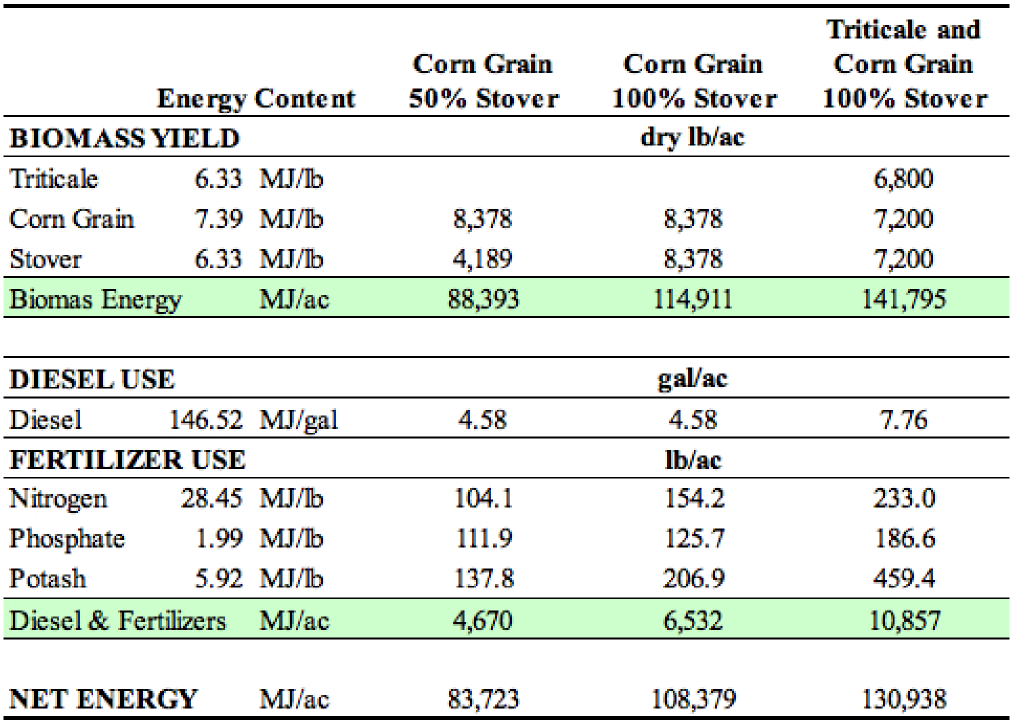
Figure 5.4. Probability density distributions of single cropped corn with and without government subsidies and crop insurance, compared to double cropped triticale[a] followed by corn & stover (bin = $10)



[a] Triticale as feed with 100% collection

Although expected economic returns are not currently competitive with single crop corn and stover, an interesting result of this analysis shows that double cropped scenarios can potentially yield a greater net energy gain than single crop corn. As shown in Table 5.6 the net energy production related to double cropped triticale-corn is significantly greater than single crop corn which could present future value as more emphasis is placed on developing bio-based fuel and chemical feedstocks.

Table 5.6. Net Energy – Biomass yield versus diesel and fertilizer use



	Energy Content		Corn Grain 50% Stover	Corn Grain 100% Stover	Triticale and Corn Grain 100% Stover
BIOMASS YIELD				**dry lb/ac**	
Triticale	6.33	MJ/lb			6,800
Corn Grain	7.39	MJ/lb	8,378	8,378	7,200
Stover	6.33	MJ/lb	4,189	8,378	7,200
Biomas Energy		MJ/ac	88,393	114,911	141,795
DIESEL USE				**gal/ac**	
Diesel	146.52	MJ/gal	4.58	4.58	7.76
FERTILIZER USE				**lb/ac**	
Nitrogen	28.45	MJ/lb	104.1	154.2	233.0
Phosphate	1.99	MJ/lb	111.9	125.7	186.6
Potash	5.92	MJ/lb	137.8	206.9	459.4
Diesel & Fertilizers		MJ/ac	4,670	6,532	10,857
NET ENERGY		MJ/ac	83,723	108,379	130,938

Conclusions

The results of this study indicate that the potential financial returns to management clearly benefit single crop corn production over the more equipment intensive, double cropping scenarios such as triticale followed by corn. Interestingly, the use of double cropping methods can provide potentially greater net energy gains per unit farmland, a concept, which will be important as we move toward replacing fossil fuels with biomass feedstocks. However, the added expense and effort in operating a second cropping cycle combined with lack of insurance and subsidies for new production models for biomass crops that are worth considerably less than corn grain, will make it difficult for Upper Midwest farmers to justify adding these production schemes to their typical corn and soybean rotations. Although not analyzed here, if farmers were compensated for ecosystem services associated with double crops, such as improved water quality, double cropping systems would be more financially attractive.

References

ASABE. 2003a. Agricultural machinery management data. American Society of Agricultural Engineers. *ASABE Standard* D497.4 FEB03.

ASABE. 2003b. Agricultural machinery management. American Society of Agricultural Engineers. *ASABE Standard* EP496.3 FEB03.

Babcock BA. 2007. Personal communication. Department of Ecomonics, Iowa State University.

Burton, R.O. Jr., M.F. Crisostomo, P.T. Berends, K.W. Kelley, and O.H. Buller. 1996. Risk/Return analysis of double-cropping and alternative crop rotations with and without government programs. *Review of Agricultural Economics*. 18:681-692.

Buxton, D.R., I.C. Anderson, and A. Hallam. 1999. Performance of sweet and forage sorghum grown continuously, double-cropped with winter rye, or in rotation with soybean and maize. *Agronomy Journal*. 91:93-101.

Crookston, R.K., C.A. Fox, D.S. Hill, and D.N. Moss. 1978. Agronomic Cropping for maximum biomass production. *Agronomy Journal*. 70:899-902.

Decisioneering, Inc. 2007. What is Monte Carlo Simulation? (Accessed February 2007. Available at http://www.decisioneering.com/monte-carlo-simulation.html).

Duffy M, Smith D. 2005. Estimated costs of crop production in Iowa - 2005. ISU Extension Service Publication FM 1712. Iowa State University Extension Service. Ames, IA.

Duffy M, Smith D. 2008. Estimated costs of crop production in Iowa - 2008. ISU Extension Service Publication FM 1712. Iowa State University Extension Service. Ames, IA.

Edwards W, Ayers G, Boehlje M. 2001. Machinery management – estimating farm machinery costs. ISU Extension Service Publication PM 710. Iowa State University Extension Service, Ames, IA.

Edwards W, Smith D. 2007. Iowa farm custom rate survey. ISU Extension Service Publication FM 1698. Iowa State University Extension Service, Ames, IA.

Edwards W. 2005. Personal communication – 2005 machinery cost spreadsheet (unpublished), Iowa State University Extension Service, Ames, IA.

Edwards W. 2008. Personal communication – 2008 machinery cost spreadsheet (unpublished), Iowa State University Extension Service, Ames, IA.

Fageria, N.K. 1992. *Maximizing Crop Yields*. CRC Press. Boca Raton, FL.

Hanna M. 2006. Personal communication – forage harvester field capacity. Iowa State University Extension Service, Ames, IA.

Harper, J.K., J.R. Williams, R.O. Burton Jr., and K.W. Kelley. 1991. Effect of risk preferences on incorporation of double-crop soybeans into traditional rotations. *Review of Agricultural Economics*. 13:185-200.

Heggenstaller, A.H., R.P. Anex, M. Liebman, D.N. Sundberg, and L. R. Gibson. In review. Productivity and nutrient dynamics in bioenergy double-cropping systems. *Agronomy Journal*.

Helsel, R. Z., W.F. Wedin. 1981. Harvested dry matter from single and double-cropping systems. *Agronomy Journal*. 73: 895-900.

Hofstrand D, Edwards W. 2003. Multiple peril crop insurance. ISU Extension Service Publication FM 1826. Iowa State University Extension Service, Ames, IA.

Krapfl M. 2006. Iowa State researchers developing machinery to harvest corn stalks and leaves. Iowa State University News Service, Ames IA. (Accessed February 2007. Available at http://www.iastate.edu/~nscentral/news/2006/dec/stover.shtml).

Mann, L., V. Tolbert , and J. Cushman. 2002. Potential environmental effects of corn (Zea mays L.) stover removal with emphasis on soil organic matter and erosion. *Agriculture, Ecosystems and Environment*. 89: 149-166.

Marshall AJ, Gallaher RN, Wang KH, McSorley R. 2002. Partitioning of dry matter and minerals in sunn hemp. *Proc. of 25th Annual Southern Conservation Tillage Conference for Sustainable Agriculture*. Auburn, AL 24-26 June 2002.

McAloon, A., F. Taylor, W. Yee, K. Ibsen, and R. Wooley. 2000. Determining the cost of producing ethanol from cornstarch and lignocellulosic feedstocks. Tech. Rep. NREL/TP-580-28893. National Renewable Energy Lab., Golden, CO.

Metropolis, N. and S. Ulam. 1949. The Monte Carlo Method. *Journal of the American Statistical Association*. Vol. 44, Number 247, September 1949.

Perlack, R.D., L.L. Wright., A.F. Turhollow, R.L. Graham, B.J. Stokes and D.C. Erbach. 2005. Biomass as a feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. United States Departments of Energy and Agriculture.Washington D.C.

Savvides, S.C. 1994. Risk analysis in investment appraisal. *Project Appraisal Journal*, Vol. 9, Number 1, Pages 3-18, March 1994.

Shinners KJ. 2007. Personal communication – one-pass biomass harvester. Professor of Agricultural Engineering. Department of Biological Systems Engineering. University of Wisconsin, Madison, WI.

Smith D, Edwards W. 2005. 2005 Iowa farm costs and returns. ISU Extension Service Publication FM 1789. Iowa State University Extension Service. Ames, IA.

Solomon, B.D., J.R. Barnes, and K.E. Halvorsen. 2007 Grain and cellulosic ethanol: History, economics, and energy policy. *Biomass and Bioenergy*. 31: 416-425.

Urbanchuk, JM. 2006. Contribution of the ethanol industry to the economy of the United States. Prepared for the Renewable Fuels Association, Washington, DC, 2006.

USDA-ERS. 2007a. 2002 Farm Bill: provisions and economic implications. United States Department of Agriculture Economic Research Service. (Accessed February 2007. Available at http://www.ers.usda.gov/Features/farmbill/titles/titleIcommodities.htm).

USDA-ERS. 2007b. Feed grains database: Yearbook tables, table 12. United States Department of Agriculture Economic Research Service. (Accessed February 2007. Available at http://www.ers.usda.gov/Data/Feedgrains/StandardReports/YBtable12.htm).

USDA-NASS. 2007. Agricultural statistics database; 2002 census of agriculture. United States Department of Agriculture National Agricultural Statistics Service. (Accessed February 2007. Available at http://www.nass.usda.gov/index.asp).

USDA-NRCS. 2007. Nutrient content of crops: Nutrients removed by harvest. United States Department of Agriculture Natural Resources Conservation Service. (Accessed February 2007. Available at http://npk.nrcs.usda.gov/).

Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden. 2004 Crop and soil productivity response to corn residue removal: A literature review. *Agronomy Journal*. 96:1-17.

CHAPTER 6. GENERAL CONCLUSION

General Discussion

Techno-economic analysis is a tool that can be used to evaluate whether or not an existing or proposed process is feasible and that can guide research to improve process economics. Techno-economic (T-E) analysis explores the relationships between the technical and economic aspects of a process or system and provides a means of quantifying the trade-offs between system characteristics and identifying process bottlenecks. This dissertation describes a series of T-E studies of the harvesting, transporting and processing of biomass to produce biofuels and bioenergy. These studies examine the interplay of system technologies and economies of scale and help identify new pathways that can lead toward a viable biobased economy.

One area that is of significant interest is identifying possible biomass utilization opportunities that favor smaller scales and benefit family farms and rural communities. The successful development of farm- to community-scale biomass conversion and utilization technologies will require that capital expenditures and operational costs are low so that these systems can compete in markets that favor much larger systems due to the economies of scale found in industries that utilize energy-dense fossil fuels. In this dissertation, drying shelled corn with heat generated by combusting corn stover has been identified to be one possible scenario where biomass, under certain conditions, can be economically utilized on a local basis. After modeling capital and operational costs, this study found that there is a clear advantage, however, to larger community-scaled systems (typically used at grain elevators) relative to smaller farm-scale, stover-fired CHP corn dryer configurations. Two limiting factors for the use of smaller systems are the high cost of commercial solid fuel boilers and low utilization factor when dedicated solely to drying corn, i.e. one to two months per year. With respect to lowering capital costs, there are numerous examples of farm ingenuity economically solving important problems. With this in mind, it is easy to speculate with enough farm ingenuity combined with extension services and due diligence, that safe, low-cost, efficient, small-scale batch biomass combustors can be developed. Also, sharing infrastructure with other farm structures and enterprises, for example heating greenhouses and other structures, or electricity generation, provides opportunities for increasing equipment utilization and allowing for much shorter infrastructure payback periods. In comparison, community based dryers, when shared with district heating, cooling and/or electrical power generation project show very short payback periods, in some cases only two to three years. When operating in a well integrated, CHP system, they also have the potential to utilize biomass as a very efficient fuel source, with efficiencies well above typical power utilities. With the right cost structure and adequate equipment utilization, on-farm power generation and recovery of waste heat can go a long way towards promoting rural development and reducing the need to transport biomass to larger centralized facilities.

This study has also focused on sweet sorghum as a potential sugar-yielding biomass crop that can be grown in the Upper Midwest. Sweet sorghum is similar to sugarcane in appearance, as a crop that utilizes C4 photosynthesis, and in fermentable carbohydrate content. After extracting sugars, the residuals are much like sugarcane bagasse, which can readily be used as a fuel. As an annual crop, however, cultural requirements for sweet sorghum in the U.S. are different from perennial sugarcane grown in the tropics. In many ways the production of sweet sorghum in the Upper Midwest is very similar to its close relative maize.

To explore the viability of adding sweet sorghum to Upper Midwest crop rotations, comparisons were made among a number of potential harvest systems. Scenarios analyzed include a mobile juice harvester, traditional forage/silage harvesters and a hypothetical one-pass harvester designed to collect grain heads and chop fermentable carbohydrate-rich stalks as separate streams. It was found that due to anticipated extraction inefficiencies mobile juice harvesters and on-farm processing into ethanol is not economically viable. In contrast, modeling and Monte Carlo simulations clearly show that existing forage/silage harvest technologies could be utilized by Upper Midwest farmers in an economically viable scenario that is readily available to U.S. farmers. This scenario is viable assuming delivery to a nearby processing facility and chopped materials are processed within a short period of time, i.e. less than 24 hours.

Installing sugarcane press/extraction equipment, however, represents a very significant capital investment. This study considers these additional costs and economies of scale when installed into the front-end of existing corn dry-grind ethanol facilities. It also examines costs and logistical issues surrounding the potential storage as ensilage as a means to extend a very short harvest window and cost associated with the transportation of high moisture fresh harvested and ensiled sweet sorghum. Sweet sorghum shows considerable potential when used as a supplement feed stock for existing dry-grind ethanol facilities. Its viability is completely dependent, however, on the utilization of residuals as a fuel feed stock. For example, utilizing sweet sorghum as a supplemental feedstock for just two months per year in an existing ethanol plant will supply enough fuel residuals to provide process heat for six months. Attempts to extend harvest window, however, by storing silage in on-farm or at-plant bunkers was found to be cost prohibitive due to excessive fermentable carbohydrate loss during storage.

Moving further south will likely benefit the use of sweet sorghum as an alternative bioethanol feedstock. In addition to longer harvest windows, when freeze risks are minimized, whole stalk harvest systems and in-field storage can be utilized to further extend harvest windows and facilitate transport and processing logistics. Resultant capital costs for front-end sugar extraction equipment can be significantly reduced, further increasing the potential economic returns to ethanol plants and producers. The large volumes of residuals can provide all the plant’s process heat and electrical power, plus providing additional capacity for sale of electricity back to the grid and essentially eliminating the plant’s need for fossil fuels.

This dissertation also considered the need to produce large quantities of biomass and explored production scenarios that promote the double cropping of both biomass and feed/food crops. It was shown that double crop triticale-corn production scenarios are likely to provide a lower return to management than single crop corn when both are grown on high productivity cropland in the Upper Midwest. This is largely because of the high value of corn grain compared to the likely value of biomass. The additional work and risk associated with double cropping systems will likely limit interest in these systems by Upper Midwest farmers. Interestingly, the models were also used as a basis to evaluate potential net energy production, which found double cropped triticale with corn provided significantly higher net energy yields than single cropped corn. These higher yields may prove more valuable if petroleum prices rise and as conversion of cellulosic feedstocks becomes more mainstream and essential to the future production of liquid transportation fuels and commodity chemicals. Once again, moving further south will likely provide greater biomass yield potential to the point that farmers will find it attractive to diversify their cropping systems by including biomass as an alternative crop.

Recommendations for Future Research

Additional techno-economic analyses focusing on detailed study and simulations of shared farm- and community-scaled, biomass-fired CHP systems can provide valuable information to policy makers and future investors. There are many small rural communities that would benefit from the additional opportunities that would surround local use of biomass, including building and operating new infrastructure for district heating, absorption based cooling and local electrical power generation. One area of research that could benefit farm- and small businesses is the promotion of the commercial development of small, batch bale combustors. It seems likely that a more economical batch firebox combustor could be adapted to existing low cost package boilers and greatly reduce capital investment. Developing design and safety guidelines and sharing information via extension services could allow small farms and business to build and operate pre-engineered systems with the ultimate goal of providing more biomass related opportunities for rural development.

The combined application of techno-economic analysis with Monte Carlo simulation has proven to be a valuable tool for the evaluation of sweet sorghum as a new biomass crop high in FC and fuel fiber. Although analysis shows sweet sorghum to be viable in the Upper Midwest, one can easily envision significant resistance by ethanol plant owners to making the very large capital investments needed to process sweet sorghum over a very short harvest window. It is also likely that farmers will be unwilling to commit to a sweet sorghum crop rotation without a guaranteed market. More likely, is the use of sweet sorghum in southern U.S. where much longer harvest season would significantly benefit ethanol facilities and growers. There are numerous sweet sorghum scenarios that should be studied using the models and simulation tools developed for this study. These might include simulating the simple extension of harvest windows, or possibly studying the use of existing cane harvest technologies, evaluating in-field stalk storage as a means to extend harvest window, or possibly incorporating cellulosic ethanol scenarios into both Upper Midwest and Southern sweet sorghum models. Models including costs associated with environmental impacts, opportunities for carbon crediting and government subsidies can provide valuable information for local policy makers and national political interests.

The methods, models and simulations developed for this study's detailed analysis of sweet sorghum, corn and double cropping scenarios can be readily modified by experienced MS Excel® and Crystal Ball® users and used to describe a wide and diverse range of crop production and utilization scenarios. Copies of the models developed for this study are included in the accompanying CD.

Finally, after completion of this study, the author strongly recommends the integrated use of traditional techno-economic analysis, with now widely available Monte Carlo simulation tools. The ability to evaluate the uncertainties associated with new processes and systems, is an invaluable tool. These combined tools should become standard practice not just for the study of new crop production and utilization scenarios, but for any proposed industrial, commercial or agricultural process or system.

APPENDIX
MODEL DESCRIPTION

Production Models

For chapters 3 and 4 specific models were developed to describe production scenarios related to sweet sorghum systems. Additional models describing double cropped triticale with corn are discussed in Appendix B. Table A-1 shows the list of models developed for this study. Each model is comprised of an Excel® workbook with multiple worksheets. The first worksheet in each model is used to input crop production characteristics, preharvest machinery and materials, and harvest machinery. For models that consider post-harvest analysis such as discussed in Chapter 4 (Production, Transportation and Milling Costs of Sweet Sorghum as a Feedstock for Centralized Bioethanol Production in the Upper-Midwest), a second worksheet is added to model transportation and postharvest processing. Each model also incorporates three lookup reference tables that describe machinery performance and cost parameters. The same three reference tables are replicated in each model's workbook.

Monte Carlo simulations are also incorporated into each model workbook using Crystal Ball® which is an Excel® add-on. Because of limitations associated with Crystal Ball® all inputs and calculation related to crop production characteristics, preharvest machinery and materials, and harvest machinery are located in the first worksheet which allows users to incorporate correlations between variables used in the Monte Carlo simulations. For example, Crystal Ball® allows the user to negatively correlate forage harvester field speed with crop yield (i.e. the greater the yield the more material harvester per hectare and therefore a slower field speed), however, in order to make that correlation both variables must be in the same worksheet.

Production Model Reference Tables

As indicated above, each model developed utilizes the same reference tables describing farm machinery performance and cost parameters, including published and unpublished information for implements, power units and custom farm rates (ASABE, 2003a;

ASABE, 2003b; Edwards, 2007; Edwards and Smith, 2006; Hanna 2006). Actual spreadsheet models are also included on the CD accompanying this dissertation.

Table A-1. Description and file names for models used in Chapters 3, 4 and Appendix B

Model	Model Description	File Name
CHAPTER 3.	Farm-Gate Production Costs of Sweet Sorghum	
1	Whole plant and grain harvester with intermediate in-field collection of chopped sweet sorghum using tractor-pulled forage wagons	1_WPGH_TPFW.xls
2	Whole plant and grain harvester with direct in-field loading of chopped sweet sorghum into transport trucks	2_WPGH_noTPFW.xls
3	Self-propelled forage harvester with intermediate in-field collection of chopped sweet sorghum using tractor-pulled forage wagons	3_SPFH_TPFW.xls
4	Self-propelled forage harvester with direct in-field loading of chopped sweet sorghum into transport trucks	4_SPFH_noTPFW.xls
5	Tractor-pulled forage harvester with intermediate in-field collection of chopped sweet sorghum using tractor-pulled forage wagons	5_TPFH_TPFW.xls
6	Tractor-pulled forage harvester with direct in-field loading of chopped sweet sorghum into transport trucks	6_TPFH_noTPFW.xls
7	Self-propelled juice harvester with intermediate in-field collection of pressed residuals using tractor-pulled forage wagons	7_SPJh_TPFW.xls
8	Self-propelled juice harvester with attached tanker and direct in-field loading of pressed residuals into transport trucks	8_SPJh_noTPFW.xls
9	Tractor-pulled juice harvester with separate tractor-pulled tanker. Press residuals left in-field for baling or ammendment to soil	9_TPJh_TPTnkr.xls
CHAPTER 4.	Production, Transportation and Milling Costs of Sweet Sorghum	
1	Self-propelled forage harvester with intermediate in-field collection of chopped sweet sorghum using tractor-pulled forage wagons to load transport trucks at fields edge	1_SPFH_TPFW.xls
2	Self-propelled forage harvester with direct in-field loading of chopped sweet sorghum into transport trucks	2_SPFH_noTPFW.xls
3	Tractor-pulled forage harvester with intermediate in-field collection of chopped sweet sorghum using tractor-pulled forage wagons to load transport trucks at fields edge	3_TPFH_TPFW.xls
4	Tractor-pulled forage harvester with direct in-field loading of chopped sweet sorghum into transport trucks	4_TPFH_noTPFW.xls
5	SP forage harvester with intermediate in-field collection of chopped sweet sorghum using TP wagons to load transport trucks for at-plant ensillage of chopped sweet sorghum	5_SPFH_Frsh2Plnt4Sllg_TPFW.xls
6	SP forage harvester with direct in-field loading of chopped sweet sorghum into transport trucks for at-plant ensillage of chopped sweet sorghum	6_SPFH_Frsh2Plnt4Sllg_noTPFW.xls
7	Self-propelled forage harvester with intermediate in-field collection of chopped sweet sorghum using tractor-pulled wagons for on-farm storage via ensillage	7_SPFH_Sllg4Plnt_3TPFW.xls
8	Tractor-pulled forage harvester with intermediate in-field collection of chopped sweet sorghum using tractor-pulled wagons for on-farm storage via ensillage	8_TPFH_Sllg4Plnt_2TPFW.xls
CHAPTER 5.	Double Cropped Triticale Compared to Single Cropped Corn/Stover	
1	Self-propelled single pass grain and stover harvester to load transport trucks at fields edge	1_Corn&Stover.xls
2	SP forage harvester with direct in-field loading of chopped triticale into transport trucks; SP single pass grain and stover harvester to load transport trucks at fields edge	2_Dbl_Triticale-Corn&Stover.xls
3	SP forage harvester w/ direct in-field loading of chopped triticale into transport trucks; SP harvester w/ direct in-field loading of chopped sorg. sudangrass into transport trucks	3_Dbl_Triticale-SorgSudan.xls

Table A-2 shows values for implement list price, power unit requirement, annual use (hours), economic life, the implement’s working width, salvage value calculation coefficients, repair costing factors, field efficiency, field speed and fuel multiplier. These reference values were derived from machinery cost spreadsheet developed at Iowa State University Extension Service, which in turn is based on ASABE Standards (Edwards and Smith, 2006; ASABE, 2003a; ASABE, 2003b). To facilitate Monte Carlo simulations, likely range in field efficiency and field speed were included and based on values published by ASABE (ASABE, 2003a).

Table A-3 shows values for user defined harvest implements including list price, power unit requirement, annual use, economic life, width, salvage value calculation coefficients and repair costing factors, which are based on ASABE Standards (ASABE, 2003a). Instead of field efficiency and field speed, a likely range in field capacities are determined assuming a variation in harvest rate (ton ac^{-1}) of ± 20% (Hanna, 2006).

Power unit list price, horsepower, annual use, economic life, salvage value calculation coefficients and repair costing factors are shown in Table A-4. Values are based on Iowa State University Extension Service and published ASABE Standards (ASABE, 2003a; ASABE, 2003b; Edwards, 2007; Edwards and Smith, 2006; Hanna, 2006).

Cost ranges for custom farm machinery are shown Table A-5. Values are derived from Iowa State University Extension surveys and are represented by three numbers including high, average and low costs per unit operation (Edwards and Smith 2006).

In addition to reference tables, each model provides inputs fields that incorporate crop yields, estimated gross income, seed and chemical use and costs, land rental, labor, diesel and working capital costs. Tables A-6 and A-7 show input values used in the double-cropped triticale with corn model. Inputs into other listed model (see Table A-1) are similar to Tables A-6 and A-7.

Table A-2. ISU Extension implement list price, economic life, annual use, width, salvage value coefficients, repair cost factors, field efficiency, field speed and fuel multipliers

Code no.	Description	Power Unit No.	List price	Economic Life (yrs)	Annual Use (hrs)	Width	Salvage Value Coefficients				Repair $ factors		Field efficiency			Field speed (mph)			Field capacity (ac/hr)			Fuel Multiplier
							C_1	C_2	expl	expon	RF_1	RF_2	Typical	low	high	Typical	low	high	Typical	low	high	
1	5-16MOLDBOARD	3	17,600	15	120	6.70	0.7382	0.051	0.5	2	0.29	1.8	0.85	0.7	0.9	5	3	6	3.45	1.71	4.39	1.20
2	6-16 MOLDBOARD	4	21,000	15	120	8.00	0.7382	0.051	0.5	2	0.29	1.8	0.85	0.7	0.9	5	3	6	4.12	2.04	5.24	1.20
3	7-16 MOLDBOARD	5	24,200	15	120	9.30	0.7382	0.051	0.5	2	0.29	1.8	0.85	0.7	0.9	5	3	6	4.79	2.37	6.09	1.20
4	8-18 MOLDBOARD	6	27,500	15	120	12.00	0.7382	0.051	0.5	2	0.29	1.8	0.85	0.7	0.9	5	3	6	6.18	3.05	7.85	1.20
5	Subsoiler 12.5 ft	7	16,500	15	120	12.50	0.7382	0.051	0.5	2	0.29	1.8	0.85	0.7	0.9	5	4	6.5	6.44	4.24	8.86	1.40
6	Subsoiler 17.5 ft.	8	23,100	15	120	17.50	0.7382	0.051	0.5	2	0.29	1.8	0.85	0.7	0.9	5	4	6.5	9.02	5.94	12.41	1.40
7	11 FT. CHISEL PLOW	3	6,900	15	120	11.00	0.7382	0.051	0.5	2	0.28	1.4	0.85	0.7	0.9	5.5	4	6.5	6.23	3.73	7.80	1.35
8	15FT. CHISEL PLOW	5	9,500	15	120	15.00	0.7382	0.051	0.5	2	0.28	1.4	0.85	0.7	0.9	5.5	4	6.5	8.50	5.09	10.64	1.35
9	20 FT. CHISEL PLOW	7	15,600	15	120	20.00	0.7382	0.051	0.5	2	0.28	1.4	0.85	0.7	0.9	5.5	4	6.5	11.33	6.79	14.18	1.35
10	25 FT. CHISEL PLOW	8	21,000	15	120	25.00	0.7382	0.051	0.5	2	0.28	1.4	0.85	0.7	0.9	5.5	4	6.5	14.17	8.48	17.73	1.35
11	STALK CHOPPER 6 FT.	1	11,300	15	120	6.00	0.7911	0.0913	0.5	2	0.28	1.4	0.8	0.7	0.9	5	4	7	2.91	2.04	4.58	0.70
12	FLAIL CHOPPER, 10 FT.	2	9,700	15	120	10.00	0.7911	0.0913	0.5	2	0.28	1.4	0.8	0.7	0.9	5	4	7	4.85	3.39	7.64	1.00
13	FLAIL CHOPPER, 15 FT.	3	14,700	15	120	15.00	0.7911	0.0913	0.5	2	0.28	1.4	0.8	0.7	0.9	5	4	7	7.27	5.09	11.45	1.00
14	17 FT. TANDEM DISK	3	18,300	15	120	17.00	0.8906	0.1095	0.5	2	0.18	1.7	0.83	0.7	0.9	6	4	7	10.26	5.77	12.98	1.00
15	21 FT. TANDEM DISK	4	24,900	15	120	21.00	0.8906	0.1095	0.5	2	0.18	1.7	0.83	0.7	0.9	6	4	7	12.68	7.13	16.04	1.00
16	24 FT. TANDEM DISK	5	33,000	15	120	24.00	0.8906	0.1095	0.5	2	0.18	1.7	0.8	0.7	0.9	6	4	7	13.96	8.15	18.33	1.00
17	30 FT. TANDEM DISK	7	42,100	15	120	30.00	0.8906	0.1095	0.5	2	0.18	1.7	0.8	0.7	0.9	6	4	7	17.45	10.18	22.91	1.00
18	OFF-SET DISK, 12 FT.	3	13,100	15	120	12.00	0.8906	0.1095	0.5	2	0.18	1.7	0.85	0.7	0.9	5.5	4	7	6.80	4.07	9.16	1.10
19	OFF-SET DISK, 16 FT.	5	18,300	15	120	16.00	0.8906	0.1095	0.5	2	0.18	1.7	0.85	0.7	0.9	5.5	4	7	9.07	5.43	12.22	1.10
20	OFF-SET DISK, 20 FT.	7	24,400	15	120	20.00	0.8906	0.1095	0.5	2	0.18	1.7	0.83	0.7	0.9	5.5	4	7	11.07	6.79	15.27	1.10
21	OFF-SET DISK, 22 FT.	8	30,800	15	120	22.00	0.8906	0.1095	0.5	2	0.18	1.7	0.83	0.7	0.9	5.5	4	7	12.17	7.47	16.80	1.10
22	PT HARROW, 5 section	1	12,100	15	60	20.00	0.8906	0.1095	0.5	2	0.27	1.4	0.85	0.7	0.9	7	5	8	14.42	8.48	17.45	1.00
23	PT HARROW, 7 section	2	14,700	15	60	28.00	0.8906	0.1095	0.5	2	0.27	1.4	0.85	0.7	0.9	7	5	8	20.19	11.88	24.44	1.00
24	DISK /SPRAYER, 21 FT.	5	30,600	15	120	21.00	0.8906	0.1095	0.5	2	0.18	1.7	0.8	0.7	0.9	6	4	7	12.22	7.13	16.04	1.00
25	FLD. CULT., 21 FT.	3	14,700	15	120	21.00	0.8906	0.1095	0.5	2	0.27	1.4	0.85	0.7	0.9	7	5	8	15.15	8.91	18.33	1.50
26	FLD. CULT., 27 FT.	5	23,700	15	120	27.00	0.8906	0.1095	0.5	2	0.27	1.4	0.83	0.7	0.9	7	5	8	19.01	11.45	23.56	1.50
27	FLD. CULT., 34 FT.	6	30,800	15	120	34.00	0.8906	0.1095	0.5	2	0.27	1.4	0.83	0.7	0.9	7	5	8	23.94	14.42	29.67	1.50
28	FLD. CULT., 42 FT.	7	41,000	15	120	42.00	0.8906	0.1095	0.5	2	0.27	1.4	0.8	0.7	0.9	7	5	8	28.51	17.82	36.65	1.50
29	DISK/FLD CULT. 22 FT.	6	29,800	15	120	42.00	0.8906	0.1095	0.5	2	0.27	1.4	0.8	0.7	0.9	6	4	7	24.44	14.25	32.07	1.50
30	DISK/FLD CULT. 30 FT.	8	39,600	15	120	42.00	0.8906	0.1095	0.5	2	0.27	1.4	0.8	0.7	0.9	6	4	7	24.44	14.25	32.07	1.50
31	BULK FERT. 40 FT.	3	12,800	15	60	40.00	0.8826	0.0778	0.5	2	0.63	1.3	0.7	0.6	0.8	6	4	7	20.36	11.64	27.15	1.00
32	NH3 APPL. 13 knife	6	22,000	15	120	25.00	0.8906	0.1095	0.5	2	0.63	1.3	0.65	0.6	0.8	5	3	6	9.85	5.45	14.55	0.80
33	CP W/ NH3 APP. 20 FT.	5	18,700	15	120	20.00	0.8906	0.1095	0.5	2	0.63	1.3	0.65	0.6	0.8	5	3	6	7.88	4.36	11.64	1.00
34	GR. DRILL, 12 FT.	2	14,700	15	100	12.00	0.8826	0.0778	0.5	2	0.32	2.1	0.7	0.55	0.8	6	4	7	6.11	3.20	8.15	1.00
35	GR. DRILL, 20 FT.	3	26,900	15	100	20.00	0.8826	0.0778	0.5	2	0.32	2.1	0.7	0.55	0.8	6	4	7	10.18	5.33	13.58	1.00
36	GR. DRILL, 30 FT.	4	42,400	15	100	30.00	0.8826	0.0778	0.5	2	0.32	2.1	0.7	0.55	0.8	6	4	7	15.27	8.00	20.36	1.00
37	No-Till Drill 15FT	4	33,000	15	100	15.00	0.8826	0.0778	0.5	2	0.32	2.1	0.7	0.55	0.8	6	4	7	7.64	4.00	10.18	1.00
38	PLANTER, 6 row narrow	2	16,500	15	100	15.00	0.8826	0.0778	0.5	2	0.32	2.1	0.65	0.5	0.75	5	4	7	5.91	3.64	9.55	1.00
39	PLANTER, 8 row narrow	3	26,400	15	100	20.00	0.8826	0.0778	0.5	2	0.32	2.1	0.65	0.5	0.75	5	4	7	7.88	4.85	12.73	1.00
40	PLANTER, 12 row narrow	4	40,000	15	100	30.00	0.8826	0.0778	0.5	2	0.32	2.1	0.63	0.5	0.75	5	4	7	11.45	7.27	19.09	1.00
41	PLANTER, 16 row narrow	4	55,100	15	100	40.00	0.8826	0.0778	0.5	2	0.32	2.1	0.63	0.5	0.75	5	4	7	15.27	9.70	25.45	1.00
42	NT PLANTER, 8 row narrow	3	29,900	15	100	20.00	0.8826	0.0778	0.5	2	0.32	2.1	0.65	0.5	0.75	5	4	7	7.88	4.85	12.73	1.00
43	NT PLANTER, 12 row narrow	4	44,100	15	100	30.00	0.8826	0.0778	0.5	2	0.32	2.1	0.65	0.5	0.75	5	4	7	11.82	7.27	19.09	1.00
44	BROADCAST SEEDER	1	5,500	15	60	20.00	0.8826	0.0778	0.5	2	0.32	2.1	0.65	0.5	0.75	5	4	7	7.88	4.85	12.73	0.50

Table A-2. Continued

Code		Power	List	Economic	Annual		Salvage Value Coefficients				Repair $ factors		Field efficiency			Field speed (mph)			Field capacity (ac/hr)			Fuel
no.	Description	Unit No.	price	Life (yrs)	Use (hrs)	Width	C_1	C_2	expl	expon	RF_1	RF_2	Typical	low	high	Typical	low	high	Typical	low	high	Multiplier
45	ROTARY HOE, 20 FT.	3	7,400	15	60	20.00	0.8906	0.1095	0.5	2	0.23	1.4	0.8	0.7	0.85	10	8	12	19.39	13.58	24.73	1.00
46	ROTARY HOE, 30 FT.	4	12,200	15	60	30.00	0.8906	0.1095	0.5	2	0.23	1.4	0.8	0.7	0.85	10	8	12	29.09	20.36	37.09	1.00
47	ROTARY HOE, 40 FT.	5	18,300	15	60	40.00	0.8906	0.1095	0.5	2	0.23	1.4	0.78	0.7	0.85	10	8	12	37.82	27.15	49.45	1.00
48	CULTIVATOR, 6 row narrow	2	5,900	15	120	20.00	0.8906	0.1095	0.5	2	0.17	2.2	0.8	0.7	0.9	4	2.5	6	7.76	4.24	13.09	1.00
49	CULTIVATOR, 8 row narrow	3	8,000	15	120	15.00	0.8906	0.1095	0.5	2	0.17	2.2	0.8	0.7	0.9	7	5	8	10.18	6.36	13.09	1.00
50	CULTIVATOR, 12 row narrow	5	15,400	15	120	20.00	0.8906	0.1095	0.5	2	0.17	2.2	0.8	0.7	0.9	7	5	8	13.58	8.48	17.45	1.00
51	SP SPRAYER 90 FT.	9	0	15	150	90.00	0.8826	0.0778	0.5	2	0.41	1.3	0.63	0.5	0.8	13	10	14	89.35	54.55	122.18	1.00
52	SPRAYER, 45 FT.	1	6,500	15	100	45.00	0.8826	0.0778	0.5	2	0.41	1.3	0.65	0.5	0.8	6	3	7	21.27	8.18	30.55	0.50
53	SPRAYER, 90 FT.	2	31,500	15	100	90.00	0.8826	0.0778	0.5	2	0.41	1.3	0.65	0.5	0.8	6	3	7	42.55	16.36	61.09	1.00
54	CORN HEAD, 4 row narrow	10	24,100	15	180	10.00	1.1318	0.1645	0.5	2	0.12	2.3	0.73	0.6	0.75	3.8	2	5	3.36	1.45	4.55	0.60
55	CORN HEAD, 6 row narrow	11	31,500	15	180	15.00	1.1318	0.1645	0.5	2	0.12	2.3	0.73	0.6	0.75	3.8	2	5	5.04	2.18	6.82	0.75
56	CORN HEAD, 8 row narrow	12	39,900	15	180	20.00	1.1318	0.1645	0.5	2	0.12	2.3	0.7	0.6	0.75	3.8	2	5	6.45	2.91	9.09	0.75
57	CORN HEAD, 12row narrow	13	60,900	15	180	30.00	1.1318	0.1645	0.5	2	0.12	2.3	0.68	0.6	0.75	3.8	2	5	9.40	4.36	13.64	1.00
61	GR. PLAT., SB 15 FT.	10	20,300	15	120	15.00	1.1318	0.1645	0.5	2	0.12	2.3	0.73	0.6	0.75	4	2	5	5.31	2.18	6.82	0.80
62	GR. PLAT., SB 20 FT.	11	23,100	15	120	20.00	1.1318	0.1645	0.5	2	0.12	2.3	0.7	0.6	0.75	4	2	5	6.79	2.91	9.09	0.80
63	GR. PLAT., SB 25 FT.	12	25,200	15	120	25.00	1.1318	0.1645	0.5	2	0.12	2.3	0.7	0.6	0.75	4	2	5	8.48	3.64	11.36	0.80
64	GR. PLAT., SB 30 FT.	13	28,300	15	120	30.00	1.1318	0.1645	0.5	2	0.12	2.3	0.68	0.6	0.75	4	2	5	9.89	4.36	13.64	0.80
65	GR. PLAT., GR. 18 FT.	10	19,300	15	120	18.00	1.1318	0.1645	0.5	2	0.12	2.3	0.73	0.6	0.75	4	2	5	6.37	2.62	8.18	0.70
66	GR. PLAT., GR. 25 FT.	12	27,600	15	120	25.00	1.1318	0.1645	0.5	2	0.12	2.3	0.7	0.6	0.75	4	2	5	8.48	3.64	11.36	0.70
67	HAUL GRAIN, 200 BU	3	4,700	15	300	20	0.9427	0.1111	0.5	2	0.19	1.3	0.68	0.6	0.8	7	5	8	11.54	7.27	15.52	1.00
68	HAUL GRAIN, 300 BU	5	6,800	15	300	30	0.9427	0.1111	0.5	2	0.19	1.3	0.68	0.6	0.8	7	5	8	17.31	10.91	23.27	1.00
69	CORN PICKER, 2 row wide	3	17,600	25	170	6.00	1.1318	0.1645	0.5	2	0.056	1.8	0.65	0.6	0.75	3	2	4	1.42	0.87	2.18	0.50
70	GRAIN CART, 500 BU.	6	19,300	15	300	30.00	0.9427	0.1111	0.5	2	0.19	1.3	0.68	0.6	0.8	5	4	7	12.36	8.73	20.36	0.50
71	HAUL SILAGE, 14 ft	4	14,300	15	140	5	0.9427	0.1111	0.5	2	0.16	1.6	0.8	0.7	0.9	7	5	8	3.39	2.12	4.36	1.30
72	MOW. CONDIT., 9 FT.	2	16,500	15	120	9.00	0.7557	0.0672	0.5	2	0.18	1.6	0.83	0.75	0.9	7	5	12	6.34	4.09	11.78	1.00
73	MOW. CONDIT., 12 FT.	3	20,100	15	120	12.00	0.7557	0.0672	0.5	2	0.18	1.6	0.83	0.75	0.9	7	5	12	8.45	5.45	15.71	1.00
74	MOW. CONDIT., 15 FT.	4	24,400	15	120	15.00	0.7557	0.0672	0.5	2	0.18	1.6	0.83	0.75	0.9	7	5	12	10.56	6.82	19.64	1.00
75	ROTARY MOWER	1	6,000	15	120	6.00	0.7557	0.0672	0.5	2	0.18	1.6	0.83	0.75	0.9	7	5	12	4.23	2.73	7.85	0.50
76	RAKE, 9 FT.	1	5,600	15	120	9.00	0.7911	0.0913	0.5	2	0.17	1.4	0.83	0.7	0.9	6	4	8	5.43	3.05	7.85	0.50
77	RAKE, 14 FT.	2	9,100	15	120	14.00	0.7911	0.0913	0.5	2	0.17	1.4	0.8	0.7	0.9	6	4	8	8.15	4.75	12.22	0.50
78	SQ. BALER, 14 FT.	3	20,500	15	120	14.00	0.8521	0.1014	0.5	2	0.23	1.8	0.75	0.6	0.85	4	2.5	6	5.09	2.55	8.65	0.40
79	RD. BALER, 14 FT.	3	14,900	15	120	14.00	0.8521	0.1014	0.5	2	0.43	1.8	0.65	0.55	0.75	3.5	3	6	3.86	2.80	7.64	0.50
80	STACKER, 14 FT.	4	21,500	15	120	14.00	0.8521	0.1014	0.5	2	0.43	1.8	0.8	0.7	0.9	3.5	3	6	4.75	3.56	9.16	0.50
81	LARGE SQ BALER	3	64,100	15	120	24.00	0.8521	0.1014	0.5	2	0.43	1.8	0.8	0.7	0.9	3.5	3	6	8.15	6.11	15.71	1.00
82	HAY WAGON	1	3,600	15	120	14	0.9427	0.1111	0.5	2	0.16	1.6	1	1	1	7	5	8	11.88	8.48	13.58	1.30
83	FORAGE CHOP., 7 FT.	4	31,500	15	200	7.00	1.1318	0.1645	0.5	2	0.15	1.6	0.7	0.6	0.85	3.5	1.5	5	2.08	0.76	3.61	0.60
84	FORAGE CHOP., 10 FT.	6	36,700	15	200	10.00	1.1318	0.1645	0.5	2	0.15	1.6	0.7	0.6	0.85	3.5	1.5	5	2.97	1.09	5.15	0.60
85	FORAGE BLOWER	2	7,800	15	100	30.00	0.9427	0.1111	0.5	2	0.16	1.6	0.83	0.7	0.9	7	5	8	21.13	12.73	26.18	1.00
86	SP WINDROWER 15 FT	16	0	15	200	15.00	0.7911	0.0913	0.5	2	0.16	1.6	0.83	0.7	0.85	6.8	3	8	10.26	3.82	12.36	1.00
87	SP WINDROWER 21 FT	17	0	15	200	21.00	0.7911	0.0913	0.5	2	0.16	1.6	0.8	0.7	0.85	6.8	3	8	13.85	5.35	17.31	1.00
92	RD. BALER, 14 FT.	3	14,900	15	120	14.00	0.8521	0.1014	0.5	2	0.43	1.8	0.65	0.55	0.75	3.5	3	6	3.86	2.80	7.64	0.50

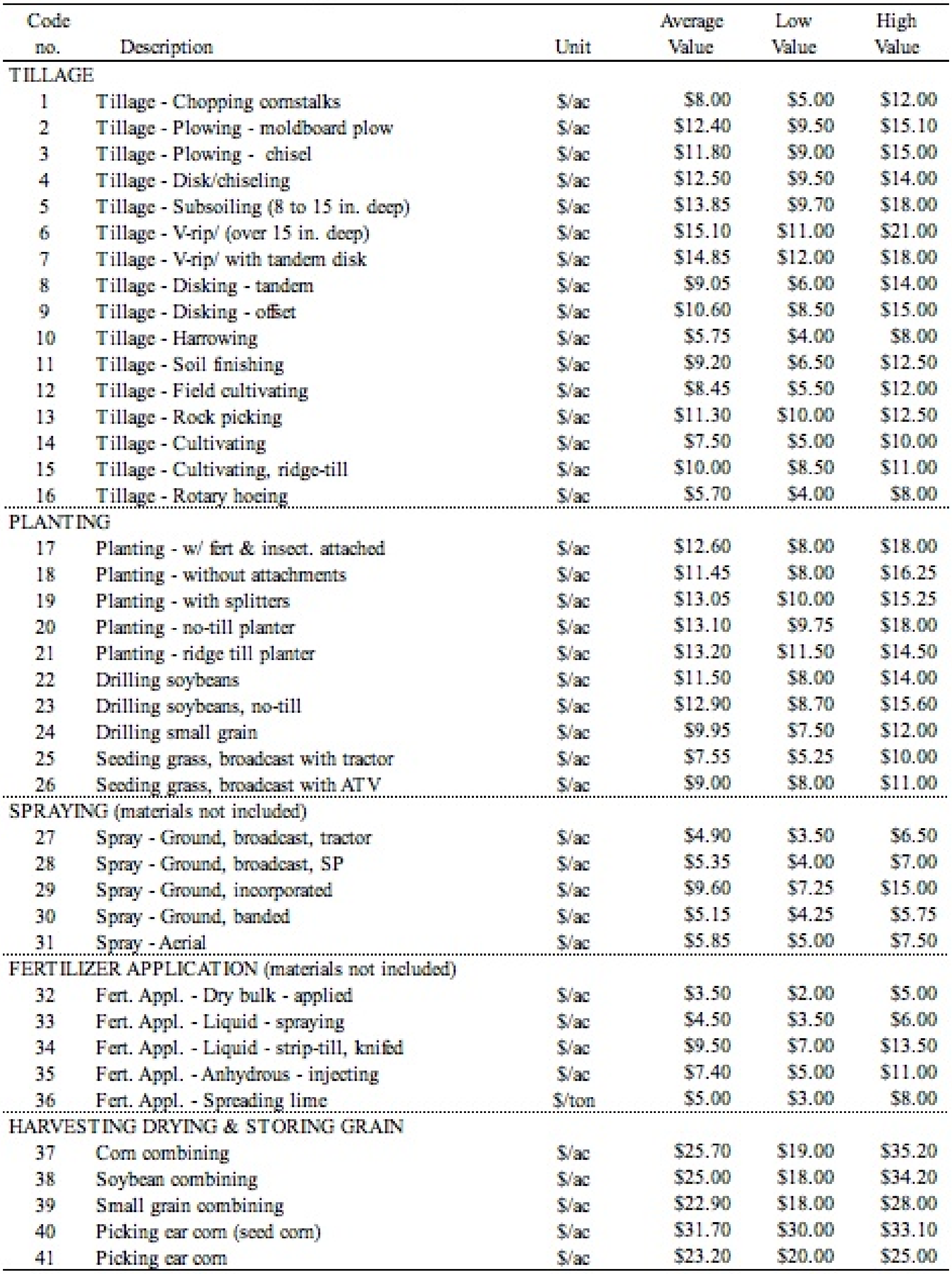
Table A-3. User defined harvest implement list price, econimic life, annual use, salvage value coefficients, repair cost factors, harvest rate and fuel multipliers

Code		Power	List	Economic	Annual	Salvage Value Coefficients				Repair $ factors		Forage Harvest Rate (ton/h)				Field capacity (ac/hr)			Fuel
no.	Description	Unit No.	price	Life (yrs)	Use (hrs)	C_1	C_2	exp1	expon	RF_1	RF_2	Typical	80%	120%	ton/ac	Typical	low	high	Multiplier
89	Triticale SIL HD, 4ROW	15	25,000	15	200	1.1318	0.1645	0.5	2	0.12	2.3	50.0	40.0	60.0	5.00	10.00	8.00	12.00	1.00
90	CornBiomass SIL HD, 4ROW	15	25,000	15	200	1.1318	0.1645	0.5	2	0.12	2.3	50.0	40.0	60.0	13.00	3.85	3.08	4.62	1.00
91	SorgSudBiomass SIL HD, 4ROW	15	25,000	15	200	1.1318	0.1645	0.5	2	0.12	2.3	50.0	40.0	60.0	11.00	4.55	3.64	5.45	1.00
92	Grass Cutting Head	18	32,000	15	200	1.1318	0.1645	0.5	2	0.12	2.3					9.00	8.00	10.00	1.00
93	Grass Cutting Head	18	32,000	15	200	1.1318	0.1645	0.5	2	0.12	2.3	50.0	40.0	60.0	15.29	3.27	2.62	3.93	1.00
94	CornBiomass SIL Head, 4ROW	15	27,600	15	200	1.1318	0.1645	0.5	2	0.12	2.3	50.0	40.0	60.0	30.87	1.62	1.30	1.94	1.00
95	TP Hi-dump Forage Box	3	27,600	15	200	0.791	0.091	0.5	2	0.19	1.3	50.0	40.0	60.0	30.87	1.62	1.30	1.94	1.00
96	TP Hi-dump Forage Box, w/ scale	3	33,100	15	200	0.791	0.091	0.5	2	0.19	1.3	50.0	40.0	60.0	30.87	1.62	1.30	1.94	1.00
97	TP Forage Harvester, 2ROW	7	33,100	15	200	0.791	0.091	0.5	2	0.16	1.6	18.0	14.4	21.6	30.87	0.58	0.47	0.70	1.00
98	TP Hi-dump Forage Box	3	27,600	15	200	0.791	0.091	0.5	2	0.19	1.3	18.0	14.4	21.6	30.87	0.58	0.47	0.70	1.00
99	TP Hi-dump Forage Box, w/ scale	3	33,100	15	200	0.791	0.091	0.5	2	0.19	1.3	18.0	14.4	21.6	30.87	0.58	0.47	0.70	1.00
100	WPG SIL Head, 4ROW	15	65,000	15	200	1.1318	0.1645	0.5	2	0.12	2.3	50.0	40.0	60.0	30.87	1.62	1.30	1.94	1.00
101	TP Wagon for grain heads	3	4,700	15	300	0.9427	0.1111	0.5	2	0.19	1.3	50.0	40.0	60.0	30.87	1.62	1.30	1.94	1.00
102	SPJh Juice Head, 4ROW	15	35,000	15	200	1.1318	0.1645	0.5	2	0.12	2.3	50.0	40.0	60.0	30.87	1.62	1.30	1.94	1.00
103	TP Juice Tanker	3	3,300	15	300	0.791	0.091	0.5	2	0.19	1.3	50.0	40.0	60.0	30.87	1.62	1.30	1.94	1.00
104	TPJh Juice Head, 2ROW	7	35,000	15	200	1.1318	0.1645	0.5	2	0.12	2.3	18.0	14.4	21.6	30.87	0.58	0.47	0.70	1.00
105	TP Juice Tanker	1	3,300	15	300	0.791	0.091	0.5	2	0.19	1.3	18.0	14.4	21.6	30.87	0.58	0.47	0.70	1.00
103	Bunker Packing	7	500	15	200	1.1318	0.1645	0.5	2	0.12	2.3	50.0	40.0	60.0	30.87	1.62	1.30	1.94	1.00
104	Bunker Packing	7	500	15	200	1.1318	0.1645	0.5	2	0.12	2.3	18.0	14.4	21.6	30.87	0.58	0.47	0.70	1.00
105	TP Forage Box	3	17,600	15	200	0.791	0.091	0.5	2	0.19	1.3	50.0	40.0	60.0	30.87	1.62	1.30	1.94	1.00
106	TP Forage Box	3	17,600	15	200	0.791	0.091	0.5	2	0.19	1.3	18.0	14.4	21.6	30.87	0.58	0.47	0.70	1.00

Table A-4. Power unit list price, economic life, annual use, horsepower, salvage value coefficients and repair cost factors

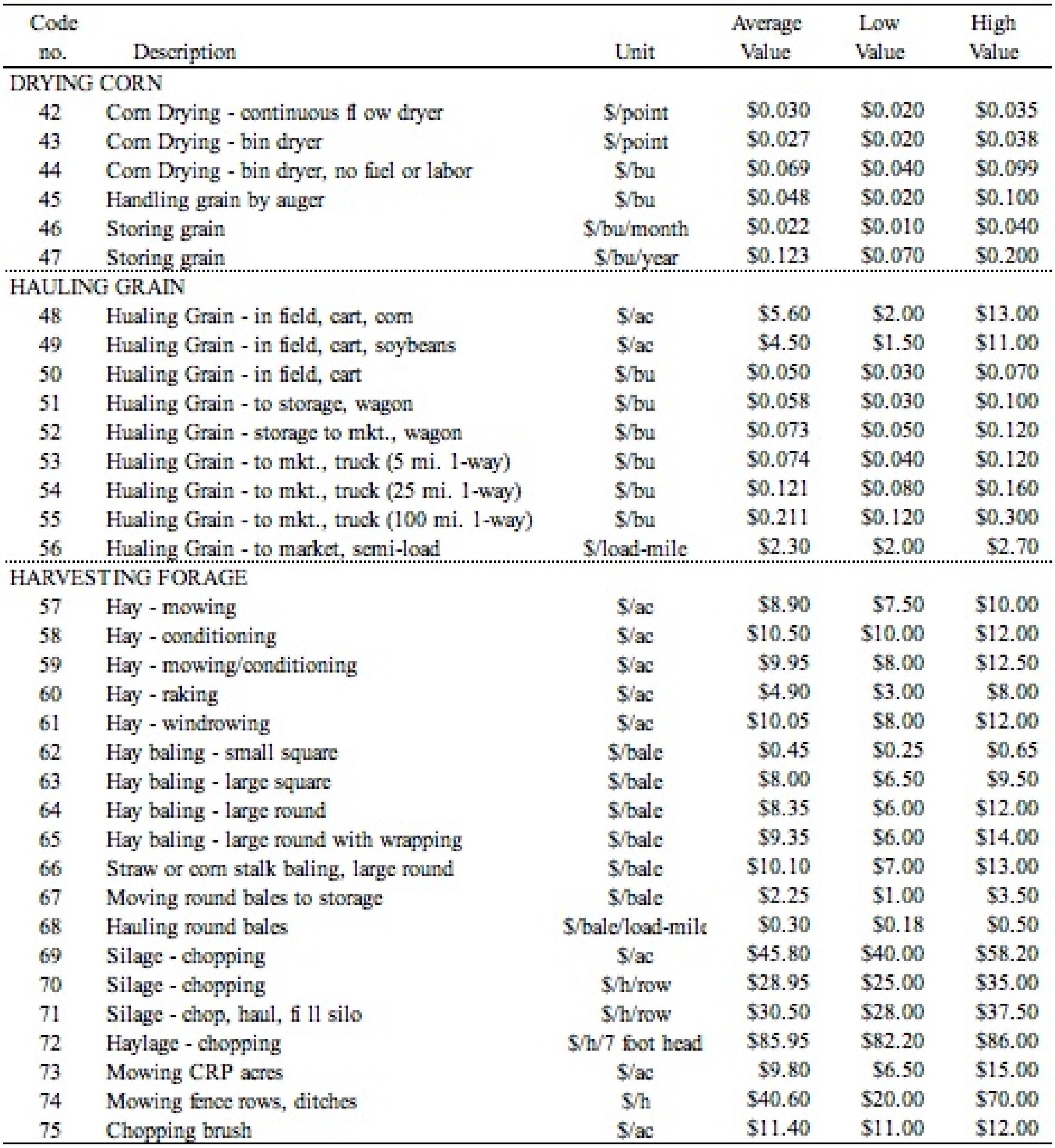
Code no.	Description	List price	Economic Life (yrs)	Annual Use (hrs)	HP	Salvage Value Coefficients C_1	C_2	exp1	C_3	exp2	expon	Repair cost factors RF_1	RF_2
1	75 HP TRACTOR	38,800	20	400	75	0.9809	0.0934	0.5	0.0058	0.5	2	0.007	2
2	95 HP TRACTOR	47,400	20	400	95	0.9421	0.0997	0.5	0.0008	0.5	2	0.007	2
3	105 HP TRACTOR	78,700	20	400	105	0.9421	0.0997	0.5	0.0008	0.5	2	0.007	2
4	125 HP TRACTOR	96,600	20	400	125	0.9421	0.0997	0.5	0.0008	0.5	2	0.007	2
5	145 HP TRACTOR	105,000	20	400	145	0.9421	0.0997	0.5	0.0008	0.5	2	0.007	2
6	165 HP TRACTOR	115,700	20	400	165	0.9756	0.1187	0.5	0.0019	0.5	2	0.007	2
7	185 HP TRACTOR	131,200	20	400	185	0.9756	0.1187	0.5	0.0019	0.5	2	0.003	2
8	225 HP TRACTOR	157,500	20	400	225	0.9756	0.1187	0.5	0.0019	0.5	2	0.003	2
9	SP SPRAYER 90 FT.	184,100	15	150	200	0.8826	0.0778	0.5			2	0.41	1.3
10	235 HP COMBINE	157,500	20	300	235	1.1318	0.1645	0.5	0.0079	0.5	2	0.020	2.1
11	275 HP COMBINE	194,200	20	300	275	1.1318	0.1645	0.5	0.0079	0.5	2	0.020	2.1
12	325 HP COMBINE	210,000	20	300	325	1.1318	0.1645	0.5	0.0079	0.5	2	0.020	2.1
13	375 HP COMBINE	244,600	20	300	375	1.1318	0.1645	0.5	0.0079	0.5	2	0.020	2.1
14	225 HP FORG HARV	181,600	20	300	225	1.1318	0.1645	0.5	0.0079	0.5	2	0.020	1.8
15	290 HP FORG HARV	220,500	20	300	290	1.1318	0.1645	0.5	0.0079	0.5	2	0.020	1.8
16	SP WINDROWER 15 FT	61,700	20	200	100	0.7911	0.0913	0.5			2	0.060	2
17	SP WINDROWER 21 FT	82,700	20	200	120	0.7911	0.0913	0.5			2	0.060	2

Table A-5. Custom Machinery Cost Survey



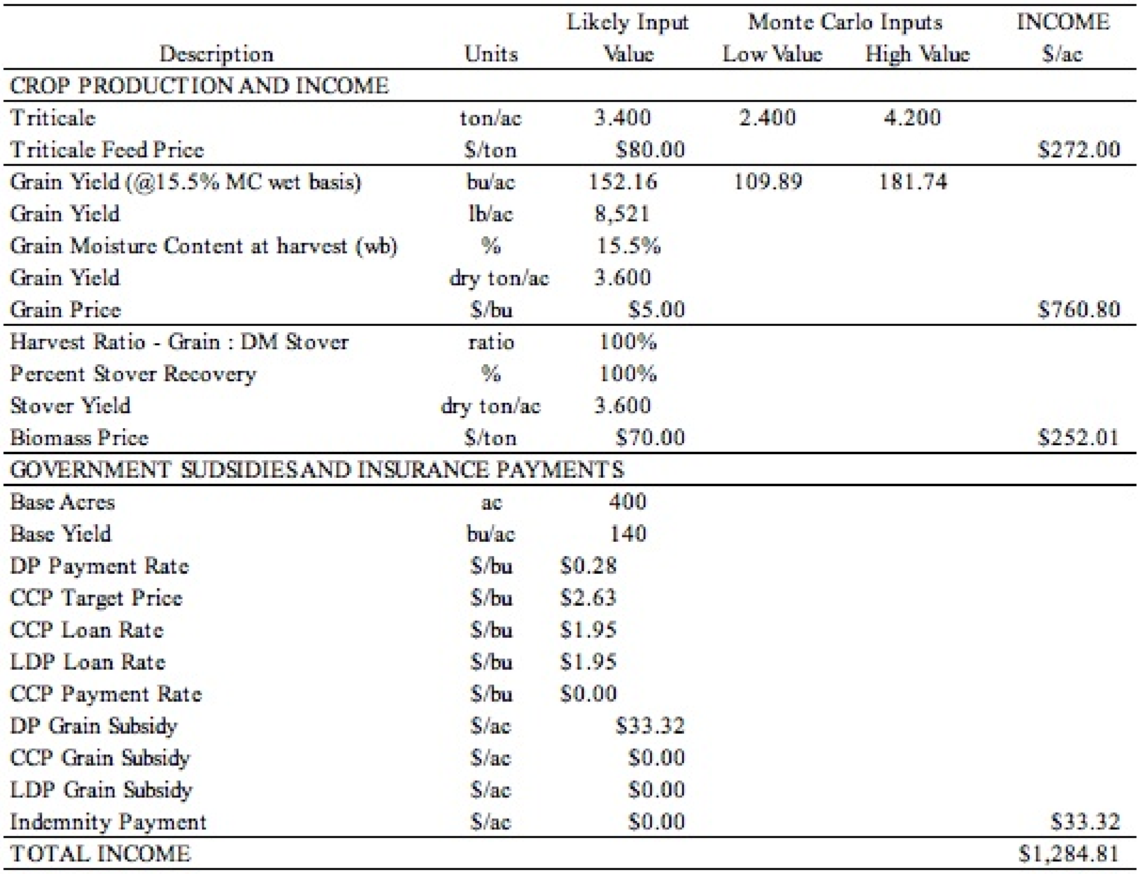
Code no.	Description	Unit	Average Value	Low Value	High Value
TILLAGE					
1	Tillage - Chopping cornstalks	$/ac	$8.00	$5.00	$12.00
2	Tillage - Plowing - moldboard plow	$/ac	$12.40	$9.50	$15.10
3	Tillage - Plowing - chisel	$/ac	$11.80	$9.00	$15.00
4	Tillage - Disk/chiseling	$/ac	$12.50	$9.50	$14.00
5	Tillage - Subsoiling (8 to 15 in. deep)	$/ac	$13.85	$9.70	$18.00
6	Tillage - V-rip/ (over 15 in. deep)	$/ac	$15.10	$11.00	$21.00
7	Tillage - V-rip/ with tandem disk	$/ac	$14.85	$12.00	$18.00
8	Tillage - Disking - tandem	$/ac	$9.05	$6.00	$14.00
9	Tillage - Disking - offset	$/ac	$10.60	$8.50	$15.00
10	Tillage - Harrowing	$/ac	$5.75	$4.00	$8.00
11	Tillage - Soil finishing	$/ac	$9.20	$6.50	$12.50
12	Tillage - Field cultivating	$/ac	$8.45	$5.50	$12.00
13	Tillage - Rock picking	$/ac	$11.30	$10.00	$12.50
14	Tillage - Cultivating	$/ac	$7.50	$5.00	$10.00
15	Tillage - Cultivating, ridge-till	$/ac	$10.00	$8.50	$11.00
16	Tillage - Rotary hoeing	$/ac	$5.70	$4.00	$8.00
PLANTING					
17	Planting - w/ fert & insect. attached	$/ac	$12.60	$8.00	$18.00
18	Planting - without attachments	$/ac	$11.45	$8.00	$16.25
19	Planting - with splitters	$/ac	$13.05	$10.00	$15.25
20	Planting - no-till planter	$/ac	$13.10	$9.75	$18.00
21	Planting - ridge till planter	$/ac	$13.20	$11.50	$14.50
22	Drilling soybeans	$/ac	$11.50	$8.00	$14.00
23	Drilling soybeans, no-till	$/ac	$12.90	$8.70	$15.60
24	Drilling small grain	$/ac	$9.95	$7.50	$12.00
25	Seeding grass, broadcast with tractor	$/ac	$7.55	$5.25	$10.00
26	Seeding grass, broadcast with ATV	$/ac	$9.00	$8.00	$11.00
SPRAYING (materials not included)					
27	Spray - Ground, broadcast, tractor	$/ac	$4.90	$3.50	$6.50
28	Spray - Ground, broadcast, SP	$/ac	$5.35	$4.00	$7.00
29	Spray - Ground, incorporated	$/ac	$9.60	$7.25	$15.00
30	Spray - Ground, banded	$/ac	$5.15	$4.25	$5.75
31	Spray - Aerial	$/ac	$5.85	$5.00	$7.50
FERTILIZER APPLICATION (materials not included)					
32	Fert. Appl. - Dry bulk - applied	$/ac	$3.50	$2.00	$5.00
33	Fert. Appl. - Liquid - spraying	$/ac	$4.50	$3.50	$6.00
34	Fert. Appl. - Liquid - strip-till, knifed	$/ac	$9.50	$7.00	$13.50
35	Fert. Appl. - Anhydrous - injecting	$/ac	$7.40	$5.00	$11.00
36	Fert. Appl. - Spreading lime	$/ton	$5.00	$3.00	$8.00
HARVESTING DRYING & STORING GRAIN					
37	Corn combining	$/ac	$25.70	$19.00	$35.20
38	Soybean combining	$/ac	$25.00	$18.00	$34.20
39	Small grain combining	$/ac	$22.90	$18.00	$28.00
40	Picking ear corn (seed corn)	$/ac	$31.70	$30.00	$33.10
41	Picking ear corn	$/ac	$23.20	$20.00	$25.00

Table A-5. Continued



Code no.	Description	Unit	Average Value	Low Value	High Value
DRYING CORN					
42	Corn Drying - continuous flow dryer	$/point	$0.030	$0.020	$0.035
43	Corn Drying - bin dryer	$/point	$0.027	$0.020	$0.038
44	Corn Drying - bin dryer, no fuel or labor	$/bu	$0.069	$0.040	$0.099
45	Handling grain by auger	$/bu	$0.048	$0.020	$0.100
46	Storing grain	$/bu/month	$0.022	$0.010	$0.040
47	Storing grain	$/bu/year	$0.123	$0.070	$0.200
HAULING GRAIN					
48	Hualing Grain - in field, cart, corn	$/ac	$5.60	$2.00	$13.00
49	Hualing Grain - in field, cart, soybeans	$/ac	$4.50	$1.50	$11.00
50	Hualing Grain - in field, cart	$/bu	$0.050	$0.030	$0.070
51	Hualing Grain - to storage, wagon	$/bu	$0.058	$0.030	$0.100
52	Hualing Grain - storage to mkt., wagon	$/bu	$0.073	$0.050	$0.120
53	Hualing Grain - to mkt., truck (5 mi. 1-way)	$/bu	$0.074	$0.040	$0.120
54	Hualing Grain - to mkt., truck (25 mi. 1-way)	$/bu	$0.121	$0.080	$0.160
55	Hualing Grain - to mkt., truck (100 mi. 1-way)	$/bu	$0.211	$0.120	$0.300
56	Hualing Grain - to market, semi-load	$/load-mile	$2.30	$2.00	$2.70
HARVESTING FORAGE					
57	Hay - mowing	$/ac	$8.90	$7.50	$10.00
58	Hay - conditioning	$/ac	$10.50	$10.00	$12.00
59	Hay - mowing/conditioning	$/ac	$9.95	$8.00	$12.50
60	Hay - raking	$/ac	$4.90	$3.00	$8.00
61	Hay - windrowing	$/ac	$10.05	$8.00	$12.00
62	Hay baling - small square	$/bale	$0.45	$0.25	$0.65
63	Hay baling - large square	$/bale	$8.00	$6.50	$9.50
64	Hay baling - large round	$/bale	$8.35	$6.00	$12.00
65	Hay baling - large round with wrapping	$/bale	$9.35	$6.00	$14.00
66	Straw or corn stalk baling, large round	$/bale	$10.10	$7.00	$13.00
67	Moving round bales to storage	$/bale	$2.25	$1.00	$3.50
68	Hauling round bales	$/bale/load-mil	$0.30	$0.18	$0.50
69	Silage - chopping	$/ac	$45.80	$40.00	$58.20
70	Silage - chopping	$/h/row	$28.95	$25.00	$35.00
71	Silage - chop, haul, fill silo	$/h/row	$30.50	$28.00	$37.50
72	Haylage - chopping	$/h/7 foot head	$85.95	$82.20	$86.00
73	Mowing CRP acres	$/ac	$9.80	$6.50	$15.00
74	Mowing fence rows, ditches	$/h	$40.60	$20.00	$70.00
75	Chopping brush	$/ac	$11.40	$11.00	$12.00

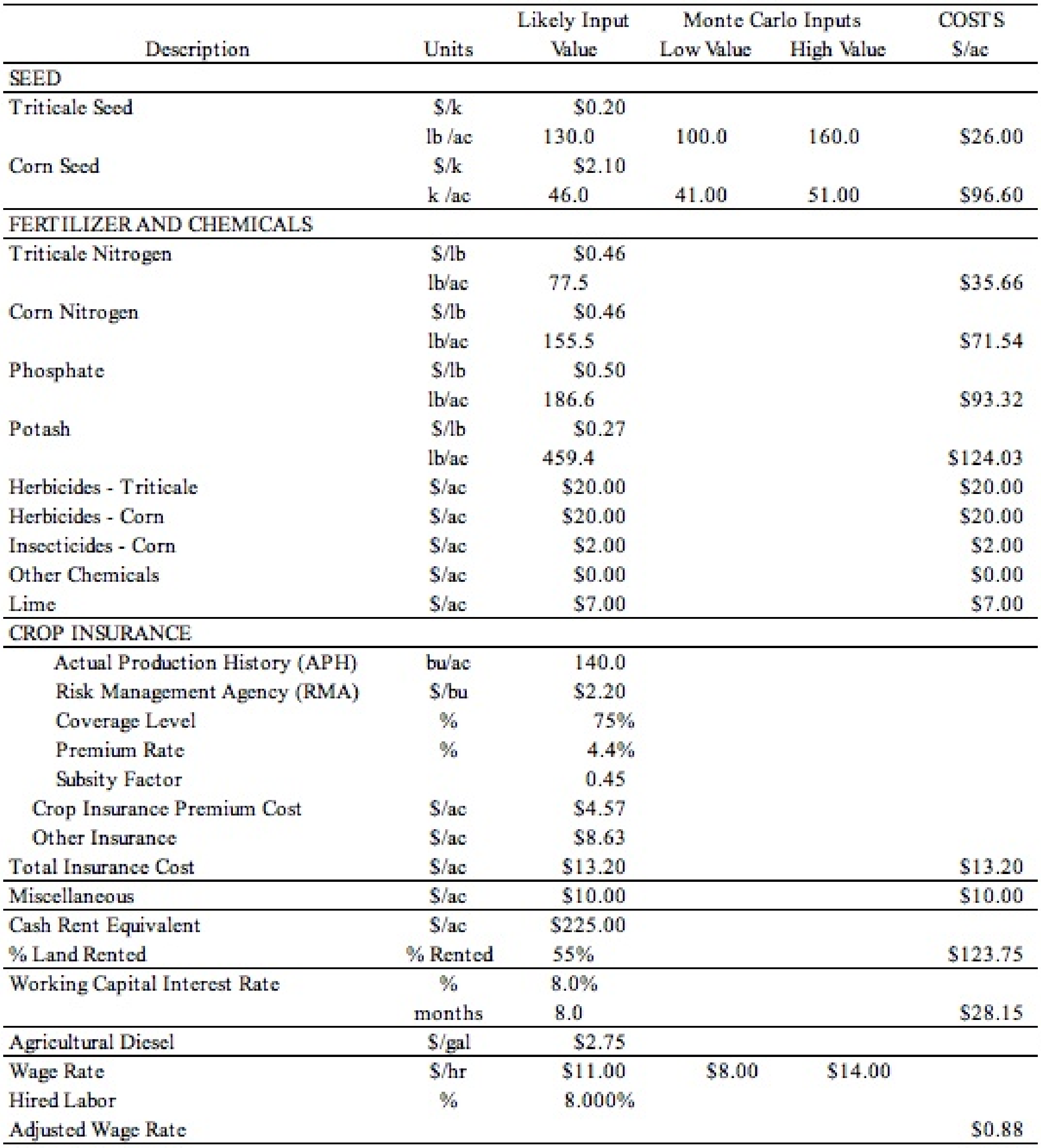
Table A-6. Crop production inputs and income



Description	Units	Likely Input Value	Monte Carlo Inputs Low Value	High Value	INCOME $/ac
CROP PRODUCTION AND INCOME					
Triticale	ton/ac	3.400	2.400	4.200	
Triticale Feed Price	$/ton	$80.00			$272.00
Grain Yield (@15.5% MC wet basis)	bu/ac	152.16	109.89	181.74	
Grain Yield	lb/ac	8,521			
Grain Moisture Content at harvest (wb)	%	15.5%			
Grain Yield	dry ton/ac	3.600			
Grain Price	$/bu	$5.00			$760.80
Harvest Ratio - Grain : DM Stover	ratio	100%			
Percent Stover Recovery	%	100%			
Stover Yield	dry ton/ac	3.600			
Biomass Price	$/ton	$70.00			$252.01
GOVERNMENT SUDSIDIES AND INSURANCE PAYMENTS					
Base Acres	ac	400			
Base Yield	bu/ac	140			
DP Payment Rate	$/bu	$0.28			
CCP Target Price	$/bu	$2.63			
CCP Loan Rate	$/bu	$1.95			
LDP Loan Rate	$/bu	$1.95			
CCP Payment Rate	$/bu	$0.00			
DP Grain Subsidy	$/ac	$33.32			
CCP Grain Subsidy	$/ac	$0.00			
LDP Grain Subsidy	$/ac	$0.00			
Indemnity Payment	$/ac	$0.00			$33.32
TOTAL INCOME					$1,284.81

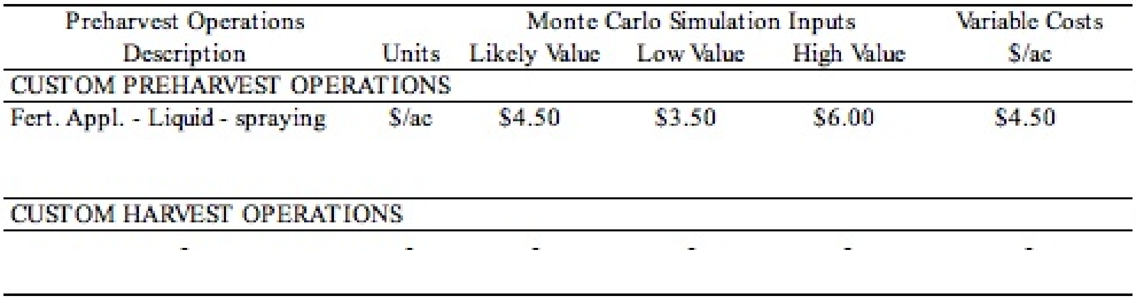
Table A-8 shows inputs that represent custom farm operations, including preharvest and harvest operation and associated low, high and likely values necessary to run Monte Carlo simulations. Table A-9 lists Monte Carlo multiplier factors used to simulate farm machinery list price, purchase price, annual hours operation and repair and maintenance costs.

Table A-7. Cost inputs: Seed, fertilizers, chemicals, insurance, land rent, labor, working capital interest and diesel



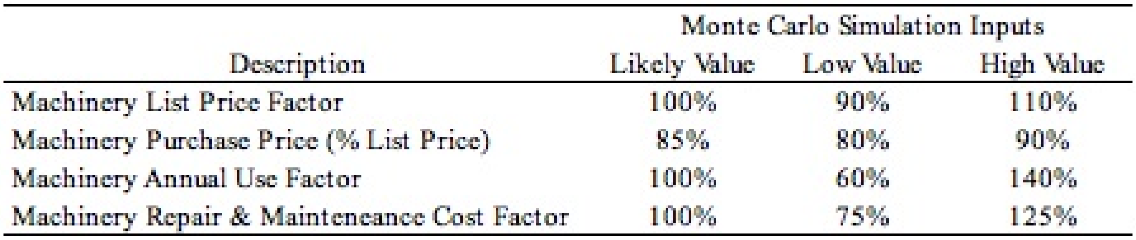
Description	Units	Likely Input Value	Monte Carlo Inputs Low Value	Monte Carlo Inputs High Value	COSTS $/ac
SEED					
Triticale Seed	$/k	$0.20			
	lb /ac	130.0	100.0	160.0	$26.00
Corn Seed	$/k	$2.10			
	k /ac	46.0	41.00	51.00	$96.60
FERTILIZER AND CHEMICALS					
Triticale Nitrogen	$/lb	$0.46			
	lb/ac	77.5			$35.66
Corn Nitrogen	$/lb	$0.46			
	lb/ac	155.5			$71.54
Phosphate	$/lb	$0.50			
	lb/ac	186.6			$93.32
Potash	$/lb	$0.27			
	lb/ac	459.4			$124.03
Herbicides - Triticale	$/ac	$20.00			$20.00
Herbicides - Corn	$/ac	$20.00			$20.00
Insecticides - Corn	$/ac	$2.00			$2.00
Other Chemicals	$/ac	$0.00			$0.00
Lime	$/ac	$7.00			$7.00
CROP INSURANCE					
Actual Production History (APH)	bu/ac	140.0			
Risk Management Agency (RMA)	$/bu	$2.20			
Coverage Level	%	75%			
Premium Rate	%	4.4%			
Subsity Factor		0.45			
Crop Insurance Premium Cost	$/ac	$4.57			
Other Insurance	$/ac	$8.63			
Total Insurance Cost	$/ac	$13.20			$13.20
Miscellaneous	$/ac	$10.00			$10.00
Cash Rent Equivalent	$/ac	$225.00			
% Land Rented	% Rented	55%			$123.75
Working Capital Interest Rate	%	8.0%			
	months	8.0			$28.15
Agricultural Diesel	$/gal	$2.75			
Wage Rate	$/hr	$11.00	$8.00	$14.00	
Hired Labor	%	8.000%			
Adjusted Wage Rate					$0.88

Table A-8. Custom preharvest and harvest inputs



Preharvest Operations Description	Units	Monte Carlo Simulation Inputs Likely Value	Low Value	High Value	Variable Costs $/ac
CUSTOM PREHARVEST OPERATIONS					
Fert. Appl. - Liquid - spraying	$/ac	$4.50	$3.50	$6.00	$4.50
CUSTOM HARVEST OPERATIONS					
-	-	-	-	-	-

Table A-9. Farm machinery Monte Carlo inputs



	Monte Carlo Simulation Inputs		
Description	Likely Value	Low Value	High Value
Machinery List Price Factor	100%	90%	110%
Machinery Purchase Price (% List Price)	85%	80%	90%
Machinery Annual Use Factor	100%	60%	140%
Machinery Repair & Mainteneance Cost Factor	100%	75%	125%

Each model allows the user to select the appropriate farm machinery necessary to model a given crop production scenario. Per selected implements and power units, the model estimates salvage values, depreciation, interest, taxes, shelter costs, fuel and lubrication costs, repair costs and operator labor costs. Tables A-10 and A-11 show sample estimates for implements and power units.

Table A-12 shows a summary of sweet sorghum farm-gate production costs. Included are preharvest and harvest costs on biomass and FC basis. Net FC costs are also calculated assuming sweet sorghum residuals are combusted for a fuel credit.

Table A-10. Implement list price, purchase price, salvage value, depreciation, interest, taxes, insurance, shelter, repairs, annual use, fuel, lube and field capacity

Field Operations IMPLEMENT Description	List Price	Salvage Value	Deprec.& Interest	Taxes, Insurance Shelter	Purchase Price	Pwr Unit Fixed $ $/ac	Implement Fixed $ $/ac	Pwr Unit Repair $ $/ac	Annual Use - hrs	Implement Repair $ $/ac	Fuel & Lube $ $/ac	Labor $ $/ac	Field Capacity ac/hr	Variable Costs per Ac	Fixed Costs per Ac	Total Cost per Ac	Repair Costs
PREHARVEST FIELD OPERATIONS																	
17 FT. TANDEM DISK	$18,300	$3,385	$1,449	$95	$15,555	$1.66	$1.25	$0.43	120	$0.48	$1.14	$0.11	10.26	$2.16	$2.91	$5.07	$596
FLD. CULT., 21 FT.	$14,700	$2,719	$1,164	$76	$12,495	$1.13	$0.68	$0.29	120	$0.33	$1.16	$0.07	15.15	$1.85	$1.81	$3.66	$603
PLANTER, 8 row narrow	$26,400	$7,582	$1,974	$150	$22,440	$2.16	$2.70	$0.56	100	$1.67	$1.48	$0.14	7.88	$3.86	$4.86	$8.72	$1,320
CULTIVATOR, 8 row narrow	$8,000	$1,480	$634	$41	$6,800	$1.67	$0.55	$0.43	120	$0.27	$1.15	$0.11	10.18	$1.96	$2.23	$4.19	$330
SPRAYER, 45 FT.	$6,500	$1,867	$486	$37	$5,525	$0.40	$0.25	$0.10	100	$0.14	$0.20	$0.05	21.27	$0.49	$0.64	$1.14	$301
HARVEST FIELD OPERATIONS																	
TP Forage Harvester, 2ROW	$33,100	$5,411	$2,652	$168	$28,135	$49.54	$24.18	$5.40	200	$17.56	$35.32	$1.89	0.58	$60.16	$73.72	$133.88	$2,048
TP Hi-dump Forage Box	$27,600	$4,512	$2,211	$140	$23,460	$29.22	$20.16	$7.56	200	$12.50	$20.05	$1.89	0.58	$42.00	$49.39	$91.38	$1,458

Table A-11. Power unit list price, purchase price, salvage value, depreciation, interest, taxes, insurance, shelter, repairs, annual use, fuel, lube and labor

Field Operations TRACTOR	IMPLEMENT	List Price	Salvage Value	Deprec.& Interest	Taxes, Insurance Shelter	Purchase Price	Total Fixed Costs	Fuel Costs	Lube Costs	Annual Use - hrs	Labor Costs	Total Variable Costs	Total Costs	Fixed Costs per Hr.	Variable Costs per Hr.	Fuel Costs per Hr.	Repair Costs
PREHARVEST FIELD OPERATIONS																	
105 HP	TANDEM DISK	$78,700	$18,150	$6,332	$484	$66,895	$6,816	$4,066	$610	400	$352	$6,790	$13,606	$17.04	$16.98	$10.16	$1,763
105 HP	FLD. CULT.	$78,700	$18,150	$6,332	$484	$66,895	$6,816	$4,066	$610	400	$352	$6,790	$13,606	$17.04	$16.98	$10.16	$1,763
105 HP	PLANTER	$78,700	$18,150	$6,332	$484	$66,895	$6,816	$4,066	$610	400	$352	$6,790	$13,606	$17.04	$16.98	$10.16	$1,763
105 HP	CULTIVATOR	$78,700	$18,150	$6,332	$484	$66,895	$6,816	$4,066	$610	400	$352	$6,790	$13,606	$17.04	$16.98	$10.16	$1,763
75 HP	SPRAYER	$38,800	$7,760	$3,154	$233	$32,980	$3,387	$2,904	$436	400	$352	$4,561	$7,948	$8.47	$11.40	$7.26	$869
HARVEST FIELD OPERATIONS																	
185 HP	TP Forage Harvester	$131,200	$21,707	$10,790	$765	$111,520	$11,554	$7,163	$1,074	400	$352	$9,849	$21,403	$28.89	$24.62	$17.91	$1,260
105 HP	TP Hi-dump Forage Box	$78,700	$18,150	$6,332	$484	$66,895	$6,816	$4,066	$610	400	$352	$6,790	$13,606	$17.04	$16.98	$10.16	$1,763

Table A-12. Farm-gate production cost summary

Description	Units	Variable	Fixed	TOTAL
Preharvest Costs	$/ac	$141.38	$111.45	$252.83
	$/ha	$349.35	$275.40	$624.74
	$/wet ton	$4.58	$3.61	$8.19
	$/wet Mg	$5.05	$3.98	$9.03
	$/dry ton	$41.57	$32.77	$74.34
	$/dry Mg	$37.71	$29.73	$67.44
Preharvest $/Mg recovered FC	$/ Mg	$50.47	$39.78	$90.25
Harvest Costs	$/ac	$117.16	$147.28	$264.44
	$/ha	$289.49	$363.94	$653.43
	$/wet ton	$3.80	$4.77	$8.57
	$/wet Mg	$4.18	$5.26	$9.44
	$/dry ton	$34.45	$43.30	$77.75
	$/dry Mg	$31.25	$39.29	$70.53
Harvest $/Mg recovered FC	$/ Mg	$41.82	$52.57	$94.39
Total Operational Costs	$/ac	$258.54	$258.74	$517.27
	$/ha	$638.84	$639.34	$1,278.18
	$/wet ton	$8.37	$8.38	$16.76
	$/wet Mg	$9.23	$9.24	$18.47
	$/dry ton	$76.01	$76.07	$152.09
	$/dry Mg	$68.96	$69.01	$137.97
Production $/Mg recovered FC	$/ Mg	$92.29	$92.36	$184.64
Net Farm-gate Fermentable Carbohydrate Cost				
Net FC $/Mg at $4.00 /GJ	$/ Mg			$106.69
Net FC $/Mg at $6.00 /GJ	$/ Mg			$67.71
Net FC $/Mg at $8.00 /GJ	$/ Mg			$28.73

References

ASABE. 2003a. Agricultural machinery management data. American Society of Agricultural and Biological Engineers. *ASABE Standard* D497.4 FEB03.

ASABE. 2003b. Agricultural machinery management. American Society of Agricultural and Biological Engineers. *ASAE Standard* EP496.2 FEB03.

Edwards, W. 2007. Personal communication and unpublished 2007 machinery cost spreadsheet. Iowa State University Extension Service. Ames, IA.

Edwards, W. and D. Smith. 2006. Iowa farm custom rate survey. ISU Extension Service Publication FM 1698, Iowa State University Extension Service, Ames, IA.

Hanna, M. 2006. Personal communication. Iowa State University Extension Service.

ACKNOWLEDEMENTS

I would like to acknowledge my major professor, Dr. Robert P. Anex for his support, patience and intellect. His valued guidance and encouragement is greatly appreciated. I thank my co-major professor Dr. Robert C. Brown for his suggestions, comments and for the inspiration to get into the gasification business. I owe sincere gratitude to committee members Dr. Carl J. Bern, Dr. Thomas J. Brumm and Dr. Gregory M. Maxwell for being great teachers, and for their support, encouragement and helpful suggestions. I would like to sincerely thank Dr. Tom L. Richard for taking a chance and giving me the opportunity to chase my quest for higher learning after quite a few years of working far from academia and having not-so-great GRE scores from the early 80's. I also want to thank the Iowa Energy Center for supporting much of this work (grant number 05-02).

Finally, I would like to thank my wife Gina and to my daughters Melissa, Stephanie and Michelle. Their support throughout this effort has been invaluable and without it I would not have been able to complete this work. I would also like to thank my friends and family for their guidance and assistance during the writing of this work. I especially want to thank my mother, Helga, my sister Kathy and my brother, Mike for their support and financial assistance.