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# Cost to produce and deliver cellulosic feedstock to a biorefinery: Switchgrass and forage sorghum

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## HIGHLIGHTS

- We model field-to-biorefinery dedicated energy crop production and delivery cost.
- We determine cost to produce and deliver switchgrass and forage sorghum biomass.
- Estimated costs of delivering a flow of switchgrass is less than for forage sorghum.
- The cost difference is primarily due to differences in harvest costs.
- Harvest cost are influenced by the length of the harvest window.

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## ABSTRACT

Switchgrass and forage sorghum have both been proposed as potential candidates for high yielding, dedicated energy crops. This research was conducted to determine and compare the costs to produce and deliver switchgrass and forage sorghum biomass under the assumptions that the biomass would be baled and transported by truck and that the biorefinery would use either switchgrass or forage sorghum but not both. A multi-region, multi-period, monthly time-step, mixed integer mathematical programming model is used to determine the costs to deliver a flow of biomass to a biorefinery. The model is designed to determine the optimal location of a biorefinery that requires 3630 Mg of biomass per day, the area and quantity of feedstock harvested in each county by land category, the number of harvest machines required, and the costs to produce, harvest, store, and transport a flow of biomass to a biorefinery. The estimated costs of land rent, establishment, maintenance, fertilizer, harvest, storage, and transportation is \$60 Mg$^{-1}$ for switchgrass and \$74 Mg$^{-1}$ for forage sorghum. The cost difference between the two crops is primarily due to harvest costs, which are estimated to be \$13 Mg$^{-1}$ greater for forage sorghum. Forage sorghum has a narrower harvest window, requires more time for field drying prior to safe baling and, as a consequence, requires significantly more harvest machines. Based on the assumptions used in this study for Oklahoma conditions, a switchgrass system with a nine-month harvest window can deliver baled biomass at a lower cost than a forage sorghum system with a five-month harvest window. However, the value of a Mg of switchgrass relative to a Mg of forage sorghum remains to be determined.


## 1. Introduction

The U.S. Energy Independence and Security Act of 2007 (EISA) mandates that U.S. retailers sell 136 billion L yr$^{-1}$ of biofuels by the year 2022 (if they are produced), with 79 billion L yr$^{-1}$ expected to be forthcoming from lignocellulosic feedstocks such as urban waste, forest biomass, and biomass from dedicated energy crops [1]. The U.S. Billion-Ton Update reported that 16–24 million ha of cropland and pasture could be converted to produce energy crops [2]. Switchgrass (*Panicum virgatum* L.) was evaluated as the model perennial grass energy crop species, and forage sorghum (*Sorghum bicolor* L. Moench) was considered as the model annual energy crop. Evaluating the logistics required to provide a flow of biomass produced by the energy crops throughout the year to a biorefinery was beyond the scope of the model used for the Billion-Ton Update [2].

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Switchgrass is considered a potential dedicated perennial energy crop in the U.S. Southern Great Plains because, in that region, it produces greater biomass yields than other warm season grasses such as Kleingrass (*Panicum coloratum* L.), Johnsongrass (*Sorghum halepense* L. Pers), and Bermudagrass (*Cynodon dactylon* L. Pers) [3]. Miscanthus (*Miscanthus x giganticus*) has been found to produce greater biomass yields than upland varieties of switchgrass in Illinois [4]. However, Aravindhakshan et al. [5] found that lowland switchgrass varieties produced 28% more annual biomass than miscanthus in a study conducted in the Southern Plains.

Forage sorghum has been proposed as an annual energy crop because it has broad genetic diversity that provides the opportunity to develop varieties adapted to diverse climates [6]. It has several desirable characteristics such as high yield potential, water-use efficiency, drought tolerance, established production systems, and the potential for genetic improvement using traditional and genomic approaches [7]. Hallam et al. [8] found that in Iowa, forage sorghum produced more biomass than alternatives that included reed canarygrass (*Phalaris arundinacea* L.), switchgrass, big bluestem (*Andropogon gerardii* Vitman), alfalfa (*Medicago sativa* L.), and corn (*Zea mays* L.).

A number of studies have evaluated the farm gate costs of producing switchgrass [8–10] and forage sorghum [11–13]. For the most part, these studies have ignored the logistics of transporting a continuous flow of feedstock throughout the year from fields or storage to a biorefinery. The costs incurred to move biomass from the farm gate to provide a daily flow of feedstock to the biorefinery, may differ substantially across feedstocks. In Oklahoma, switchgrass harvest may begin in July and extend though March. During the nine-month harvest window, switchgrass biomass could be harvested and delivered "just-in-time" (JIT). Preliminary estimates are that the harvest window for forage sorghum in Oklahoma could only extend for five months, from October through February. More storage would be required for forage sorghum. A JIT system has several advantages in that it could substantially reduce the investment required in harvest machines and reduce the amount of space required for storage. However, a JIT system also has several potential disadvantages. Expected switchgrass and forage sorghum harvestable yields and expected fertilizer requirements differ depending on the month of harvest [14] (Table 1). Harvesting switchgrass prior to full maturity is expected to result in lower harvestable yields and greater fertilizer requirements. A comprehensive evaluation of a JIT system is needed to compare the tradeoffs among yield, fertilizer, harvest machinery, storage, and other factors.

This research attempts to compare the economic competitiveness of the proposed annual energy crop, forage sorghum, relative to the proposed perennial crop, switchgrass. Separate models are built for switchgrass and forage sorghum. The most economical commercial scale system for converting lignocellulosic biomass to economically competitive biobased products has not been determined. Some studies model an enzymatic hydrolysis process. Others model thermochemical processes such as gasification or pyrolysis. It remains to be determined which of these several competing technologies will ultimately prevail, and if a biorefinery can use multiple feedstocks. Since the harvest windows for forage sorghum and switchgrass overlap, potential economies from using both feedstocks are not evident. Differences in the value of a delivered dry unit of switchgrass biomass relative to a dry unit of forage sorghum also remain to be determined. However, the profitability of a biorefinery will depend in part on the cost of delivered feedstock. The objective of this research is to determine and compare the costs to deliver a year round flow of baled biomass to a biorefinery for both a system that uses forage sorghum exclusively and a system that uses switchgrass exclusively. This type of information will be essential to determine the potential economic viability of biorefineries that plan to use either forage sorghum or switchgrass biomass feedstock.

## 2. Methods

Since an infrastructure for producing and marketing biomass feedstock does not exist, and since biomass feedstock has few alternative uses, the risk would be very high for a biorefinery to rely on spot markets for feedstock. To overcome some of these risks, a biorefinery could develop a vertically integrated system similar to that used by several U.S. wood products companies that, through either ownership or leases, have rights to thousands of hectares of timber land [15]. These companies manage timber production, harvest, transportation, processing, and sales of produced products. A biorefinery that requires year round delivery of biomass could also be efficiently organized with a vertically integrated business plan [16,17].

Similar to integrated timber companies, production, harvest, storage, and delivery of feedstock could be centrally managed and coordinated. Land could be leased and seeded to energy crops in a manner similar to what occurred when millions of U.S. ha were enrolled in the Conservation Reserve Program (CRP) and seeded to perennial grasses. The difference being that the biorefinery, rather than the government, would be the lessee and would be responsible for paying the leasing costs. This system has the potential to quickly identify and reduce bottlenecks and achieve cost efficiencies by managing quality throughout the field-to-products chain.

The optimal size of a cellulosic biorefinery is not known, but economies of scale suggest the industry will "be characterized by regionally dominant, large capacity biorefineries" [18]. Kazi et al. [19] and Wright et al. [20] budgeted for 2000 dry Mg per day. Wright and Brown [21] find that for some conversion technologies optimally sized lignocellulosic biorefineries would require more than 12,000 Mg per day. Regardless of the average feedstock yield, a substantial quantity of land would be necessary to fulfill the

**Table 1**
Switchgrass and forage sorghum yield proportion and fertilizer requirements by harvest month.

| | January | February | March | April | May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Proportion of potential yield by harvest month*[a] | | | | | | | | | | | |
| Switchgrass | 0.80 | 0.75 | 0.70 | | | | 0.79 | 0.86 | 1.00 | 1.00 | 0.90 | 0.85 |
| Forage sorghum | 0.80 | 0.75 | | | | | | | | 1.00 | 0.90 | 0.85 |
| | *Level of nitrogen (kg N $ha^{-1}$) by harvest month* | | | | | | | | | | | |
| Switchgrass | 71 | 71 | 71 | | | | 90 | 83 | 77 | 71 | 71 | 71 |
| Forage sorghum | 101 | 101 | | | | | | | | 101 | 101 | 101 |
| | *Level of phosphorus (kg $P_2O_5$ $ha^{-1}$) by harvest month* | | | | | | | | | | | |
| Switchgrass | 0 | 0 | 0 | | | | 11 | 11 | 11 | 0 | 0 | 0 |
| Forage sorghum | 50 | 50 | | | | | | | | 50 | 50 | 50 |

[a] Switchgrass harvest is not permitted in April, May, and June. Forage sorghum harvest is not permitted from March through September.