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Millions of Acres for Dedicated Energy Crops: Farms, Ranches, or Plantations?

Francis M. Epplin[1]

Introduction

The Energy Independence and Security Act of 2007 contains a provision that by 2022, 21 billion gallons of ethanol will be produced in the U.S. from non-cornstarch products (e.g. sugar or cellulose) (Congressional Research Service, 2007). Perlack *et al*. (2005) have estimated that it is technically feasible for the U.S. to produce more than a billion tons annually of cellulosic biomass that could be used as biorefinery feedstock. If cellulosic biomass could be converted into ethanol at a rate of 90 gallons per dry ton, a billion tons could be used to produce ethanol containing approximately 26 percent of the BTUs of the 2005 U.S. net crude oil imports. Some biomass could be obtained from wood wastes. However, use of a billion tons annually can be expected to require a combination of crop residues (e.g. corn stover, wheat straw) and the development of dedicated energy crops such as miscanthus and switchgrass.

If and when an economically competitive cellulosic feedstock biorefinery system that depends on the use of dedicated perennial grasses is developed, a substantial quantity of traditional agricultural resources would be required to produce, harvest, store, and transport feedstock to biorefineries. From 33 to 78 million acres would be required to achieve the stated goal of 21 billion gallons, with a conversion rate of 90 gallons per dry ton, and a perennial grass yield of 3 to 7 dry tons per acre. In 2007, U.S. farmers planted 60 million acres to wheat, 64 million acres to soybeans, 94 million acres to corn, and 11 million acres to cotton. A dedicated energy crop could become a major competitor for agricultural lands.

U.S. farms come in many sizes; however, the size of farms that produce the bulk of food, feed, and fiber is largely determined by underlying economic factors. For most agricultural crops, seasonality of production, harvest window, and size economies specific to harvest have a big influence on the size of operation necessary to attain the low cost point on the long run average cost curve (Allen and Lueck, 1998; Cheung, 1969; Wright and Brown, 2007). In the absence of government policies that favor one size relative to another, size economies are likely to play a big role in the structure of firms that produce, harvest, and deliver dedicated energy crops.

Relative to grain, cellulosic biomass from mature perennial grasses is bulky and difficult to transport. In the U.S., feedstock acquisition logistics for grains such as wheat and corn are relatively simple. Users may post a competitive price and grain will be delivered by the existing marketing system. The infrastructure for production, harvest, storage, transportation, and price risk management of grain is well-developed. The structure of farms used to produce grain and the infrastructure required to harvest, store, and transport grain in the U.S. has evolved over time. Infrastructure required to deliver a steady flow of large quantities of cellulosic biomass from fields where it could be produced and harvested, to biorefineries where it would be processed, remains to be developed.

Figure 1 contains a chart of the estimated farm gate production costs for switchgrass. The relative share of harvest cost to total production costs is substantially greater for a perennial grass for biomass than for annuals such as corn and wheat for grain. Epplin *et al*. (2007) estimate that harvest costs (mowing, raking, baling, field stacking) will account for 45 to 65 percent of the total farm gate costs (including the cost of establishment, land, and fertilizer) to produce a ton of switchgrass. Perrin *et al*. (2008) found that over a five year period across ten farms in the Northern Plains, switchgrass harvest costs accounted for 24 percent of the total farm gate production costs. On the other hand, harvest costs account for less than 15 percent of the total farm gate cost of production for corn grain.

The most economical system for production of cellulosic biomass will depend on a number of factors and is likely to differ across feedstock source and regions. In February of 2007, the U.S. Department of Energy announced that six proposed scaled-up cellulosic ethanol plants had been selected to

[1] Epplin is a Charles A. Breedlove Professor of Agricultural Economics at Oklahoma State University, Stillwater, Oklahoma.

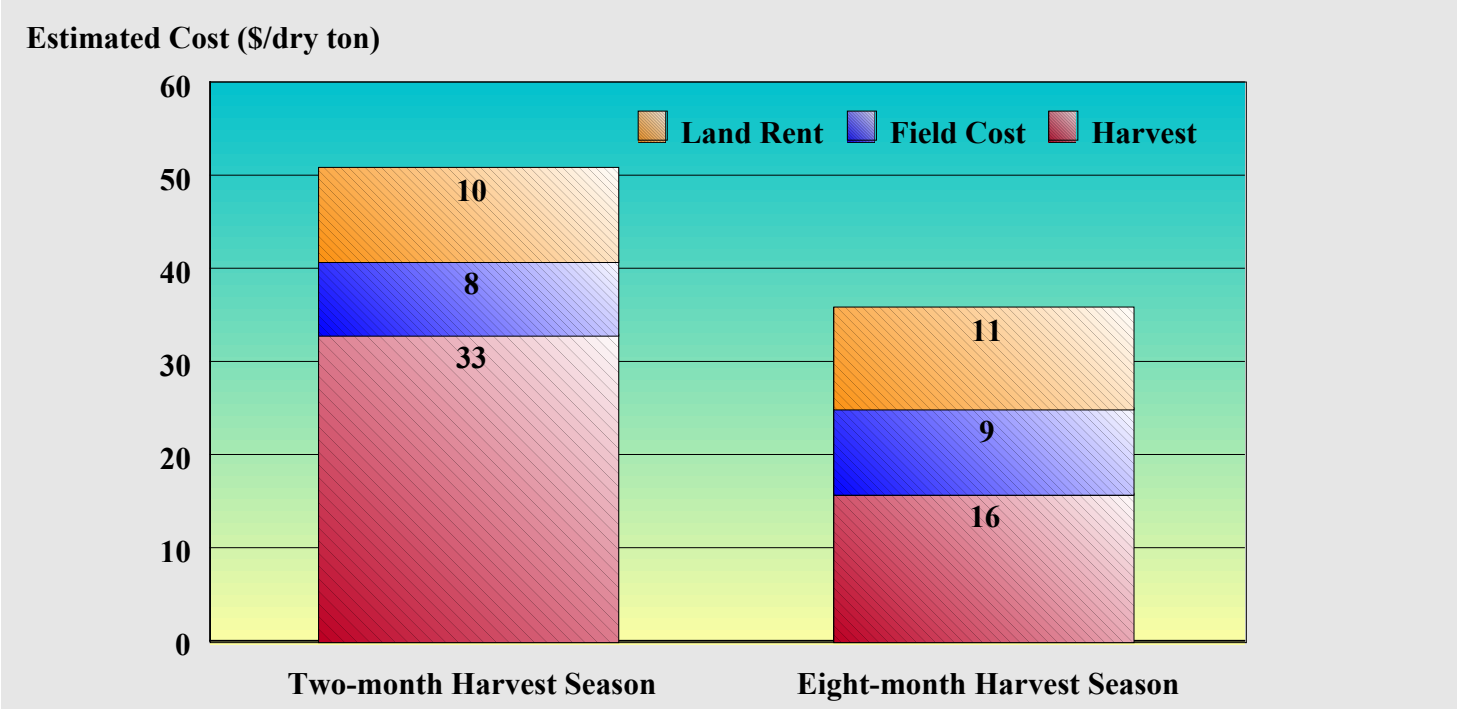

Figure 1. Estimated "Farm Gate" Cost to Produce a Ton of Cellulosic Biomass from Switchgrass (Epplin *et al*., 2007)

receive up to $385 million in federal investment funds (U.S. Department of Energy, 2007). Alico, one of the six companies, proposed to use feedstock produced exclusively on the more than 130,000 acres owned by the company. If existing companies with large land holdings manage cellulosic biomass as proposed by Alico, the consequences on farm structure may be minimal.

Another of the companies, BlueFire Ethanol, proposed to use 700 tons per day of sorted green waste and wood waste from landfills. Companies that follow the model proposed by BlueFire would also likely have little effect on conventional agriculture. A third company, Broin, proposed to use 842 tons per day of corn fiber, cobs, and stalks. If the feedstock is limited to residue and byproducts of an existing crop such as corn, the consequences on farm structure may be minimal. However, the most efficient method of crop residue acquisition, harvest, storage, and transportation remains to be determined.

Two of the companies, Abengoa and Iogen, proposed to use a combination of crop residues, switchgrass, and other feedstocks. Impacts on existing farm structure are more likely if perennial grasses such as switchgrass and miscanthus become the predominant feedstocks. And, based on the estimates produced by Perlack *et al*. (2005), a dedicated energy crop will be required to achieve a billion tons annually of cellulosic feedstock. Perlack *et al*. (2005) anticipate that 55 million acres of U.S. cropland, idle cropland, and cropland pasture could be seeded to a dedicated perennial energy crops with little economic consequences for food and fiber production. Similarly, English *et al*. (2006) conclude that with some economic incentives, switchgrass could be established on more than 100 million U.S. acres.

Based on small plot research, in years after switchgrass is established, in some environments, it requires very little annual maintenance (Fuentes and Taliaferro, 2002). Other than harvest, most stands can be maintained with one trip per year to broadcast fertilizer. If competition from weeds and pests is negligible, switchgrass production may require very little "farming". The structure is likely to be determined by the most cost efficient harvest, storage, and transportation system.

Objective

The purpose of the research reported in this paper is to identify factors that will ultimately determine the most efficient harvest system for a dedicated energy perennial grass such as switchgrass. The policy goal of 21 billion ethanol gallons per year from cellulose or sugar, may require 33 to 78 million acres. The harvest system that evolves is expected to have a large influence on the structure of farms that produce the feedstock.

Assumptions

For the purpose of discussion consider the following assumptions: (1) for the region of interest switchgrass is the most efficient dedicated energy crop; (2) the region has sufficient land to produce enough switchgrass biomass annually to support at least one cost efficient cellulosic biorefinery; (3)

the biorefinery can afford to pay a price for switchgrass feedstock that is sufficient to bid the quantity of required land in the region from current use to switchgrass production; (4) the biorefinery seeks to maximize returns above costs; (5) land owners seek to maximize returns to their scarce resource, land; (6) the biorefinery expects to require a continuous flow of switchgrass feedstock (24 hours per day, 7 days per week, throughout the year) perhaps 2,000 dry tons of biomass per day operating 350 days per year; (7) feedstock storage at the biorefinery is limited to no more than that required for one month; and (8) the number of acres required to support a 2,000 tons per day biorefinery would depend on the switchgrass yields which depend on climate and soils.

To facilitate the analysis several additional assumptions were employed. Research and development is ongoing in an attempt to develop economically competitive methods to produce ethanol from cellulose (Aden *et al*., 2002; McKendry, 2002; Mosier *et al*., 2005; Service, 2007; Wyman, 1994). Examples include enzymatic hydrolysis, acid hydrolysis, gasification, gasification-fermentation, liquefaction, and mixalco. The optimal feedstock characteristics may depend on whether the processing system that "wins" requires dry versus wet and/or loose versus dense biomass. For purposes of discussion it is assumed that an economically competitive gasification-biofermentation system will be developed. Several private and public research entities are attempting to develop gasification-biofermentation technology (Klasson *et al*., 1990; Rajagopalan, Datar, and Lewis, 2002). However, the technology remains to be proven economically viable at a commercial scale.

It is anticipated that a gasification-biofermentation biorefinery could process a variety (switchgrass, miscanthus, corn stover, wheat straw, sugarcane bagasse) of dry and dense or loose feedstock. Current commercially available forage harvest systems include those that produce (1) small bales; (2) large cylindrical solid bales; (3) large rectangular solid bales; (4) loosely chopped material; (5) pressed modules based on cotton module systems; and (6) chopped relatively wet material for ensilage systems (Cundiff, 1996; Cundiff and Marsh, 1996; Gallagher *et al*., 2003; Kumara and Sokhansan, 2007; Sokhansanj and Turhollow, 2002; Worley and Cundiff, 1996). For large volume, and current forage harvest technologies, to collect for field storage and transport substantial distances, large rectangular (approximately 4 feet by 4 feet by 8 feet) solid bales is the least-cost system for harvesting biomass from perennial grasses in the Southern Plains (Thorsell *et al*., 2004).

One advantage of establishing switchgrass as a bioenergy crop in the Southern Plains is that it could be harvested once per year anytime between July and February of the following year (Epplin *et al*., 2007). This extended harvest season is likely to result in the development of harvest units that include an economically efficient set of machines and workers. Harvest units could develop in a manner similar to custom grain harvesting firms that harvest a substantial quantity of the grain produced in the Great Plains. The cost economies are such that it is difficult for a moderate sized wheat producer to justify combine ownership. For many farms in the region hiring a custom harvester is more economical than either combine ownership or leasing.

Custom grain harvest firms exploit the economies of size associated with ownership and operation of grain harvest machines. Kastens and Dhuyvetter (2006) found that a typical custom grain harvest company harvests 28,049 acres per year, with 4.1 combines, 6.3 trucks, and 10.3 workers. These harvest companies may begin their season in regions where the crops mature first and migrate as the harvest season progresses. For example, some harvest firms begin harvesting wheat in Texas in May and travel north as the crop matures.

Modeling

In the absence of government policies that place restrictions on land ownership and resource use, structure will be largely determined by the underlying economics. Economic models have been constructed to estimate production costs and identify potential bottlenecks and constraints (Hess, Wright, and Kenney, 2007; Mapemba *et al*., 2007; Petrolia, 2006; Tembo, Epplin, and Huhnke, 2003).

Thorsell *et al*. (2004) introduced the concept of an economically efficient harvest unit for switchgrass. Figure 2 contains a chart of the estimated costs to harvest a ton of biomass with Thorsell's (2001) defined harvest unit as a function of the number annually harvested acres. This is the long run average cost of machine ownership and operation. The chart shows the magnitude of the potential economies of size that could be expected to result from a coordinated harvest system. For a relatively low yielding feedstock, such as two tons per acre, the lowest costs per ton were achieved at a harvest unit capacity of 27,420 acres per year. Thorsell's harvest unit includes nine tractors, three balers that produce large rectangular (approximately 4 feet by 4 feet by 8 feet) solid bales, three sets of tandem mowers, three sets of tandem rakes, one bale transporter, and ten workers to maintain and operate the machines. For a relatively high yielding feedstock such as five tons per acre, the lowest costs per ton were achieved at an annual harvest unit capacity of approximately 11,000 acres. Few U.S. farms could independently take advantage of these harvest cost economies.

Because of differences in weather requirements between mowing and baling, Hwang (2007) modified Thorsell's (2001) harvest unit concept by separating the mowing unit from the raking-baling-stacking unit. Hwang (2007) incorporated the modified harvest unit system into a multi-region, multi-period, mixed integer mathematical programming model simi-

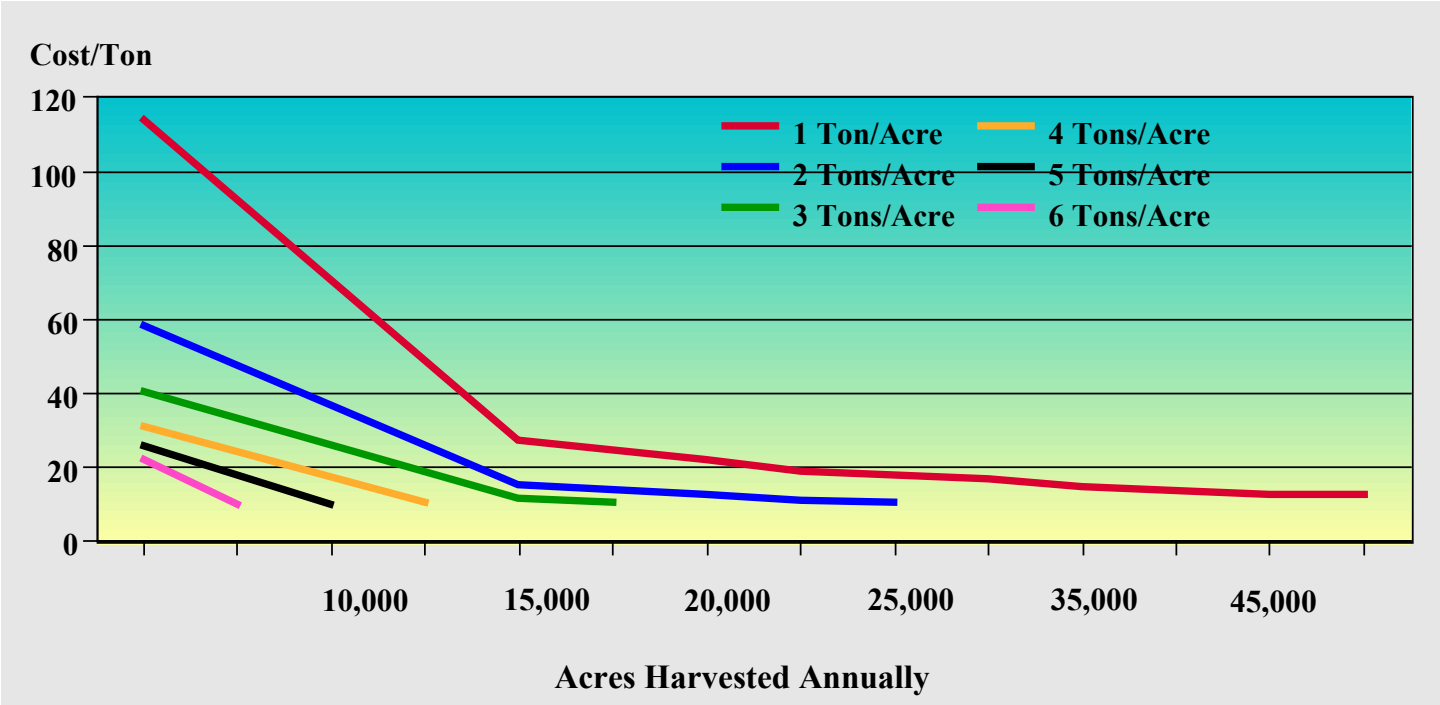

Figure 2. Total Cost to Mow, Rake, Bale, and Field Stack Switchgrass Biomass for Alternative Switchgrass Yields and Acres Harvested Annually ($/dry ton) (Thorsell, 2001)

lar to that described by Tembo, Epplin, and Huhnke (2003) and Mapemba *et al*. (2007). The model was formulated and solved to determine the cost to produce, harvest, store, and transport a flow of switchgrass biomass to a biorefinery and identify the optimal biorefinery location from among several potential sites.

Expected yields used in the model were obtained from Graham, Allison, and Becker (1996) and Fuentes and Taliaferro (2002). Fuentes and Taliaferro (2002) reported switchgrass yields from two Oklahoma locations over seven years. The best yielding plots at both locations included a blend of the cultivars Alamo and Summer. Over the seven years, mean yields from this blend at Chickasha (average annual precipitation of 35 inches) were 6.0 tons per acre but ranged from 4.0 tons per acre in 1998 to 9.8 tons per acre in 1995. At Haskell (44 inches of average annual precipitation) the annual yield over the seven years averaged 8.5 tons per acre, ranging from a low of 5.4 tons per acre in 1999 to 11.5 tons per acre in 1994 (Fuentes and Taliaferro, p. 278).

Expected biomass yields differ across months of the year due to stage of growth and field losses that occur after plant maturation (Figure 3). Biorefinery size was based on biomass feedstock requirements of 2,000 dry tons per day (Epplin *et al*., 2007). The model endogenously determines the number of harvest machines. Shipment and processing of biomass can be done in any of 12 discrete periods (months of the year). In months when biomass is harvested, it may be placed in storage or transported directly from the field to the biorefinery. Two harvest seasons were modeled. The first harvest season extended from July through February of the following year (eight-month system), while the second was restricted to July and August (two-month system). This restriction was imposed to determine how the length of the harvest season affects the number of required harvest machines and fixed and variable costs of operating them (Epplin *et al*., 2007).

Results

Figure 4 illustrates the number of tons harvested per month for the eight-month and two-month harvest systems. Harvested tons differ across months because the number of harvest hours per day varies with average day length, and the number of harvest days varies with expected weather. If harvest is restricted to July and August, more than 390,000 tons would be scheduled for harvest in July and an additional 345,000 tons in August. If harvest could be spread over eight months, only 135,000 tons would be scheduled for harvest in July. Relatively few tons are harvested in October because of weather-related constraints on the number of harvest days. The expected October harvest is 40,000 tons. As reported in Figure 5, the optimal number of harvest units for raking-baling-stacking required to harvest feedstock for the 2,000 tons per day biorefinery increases from 19 for the eight-month harvest system to 56 for the two-month harvest system. The average investment in harvest machines increases from $10.8 to $26.7 million as the length of the harvest season declines from eight to two months (Figure 6).

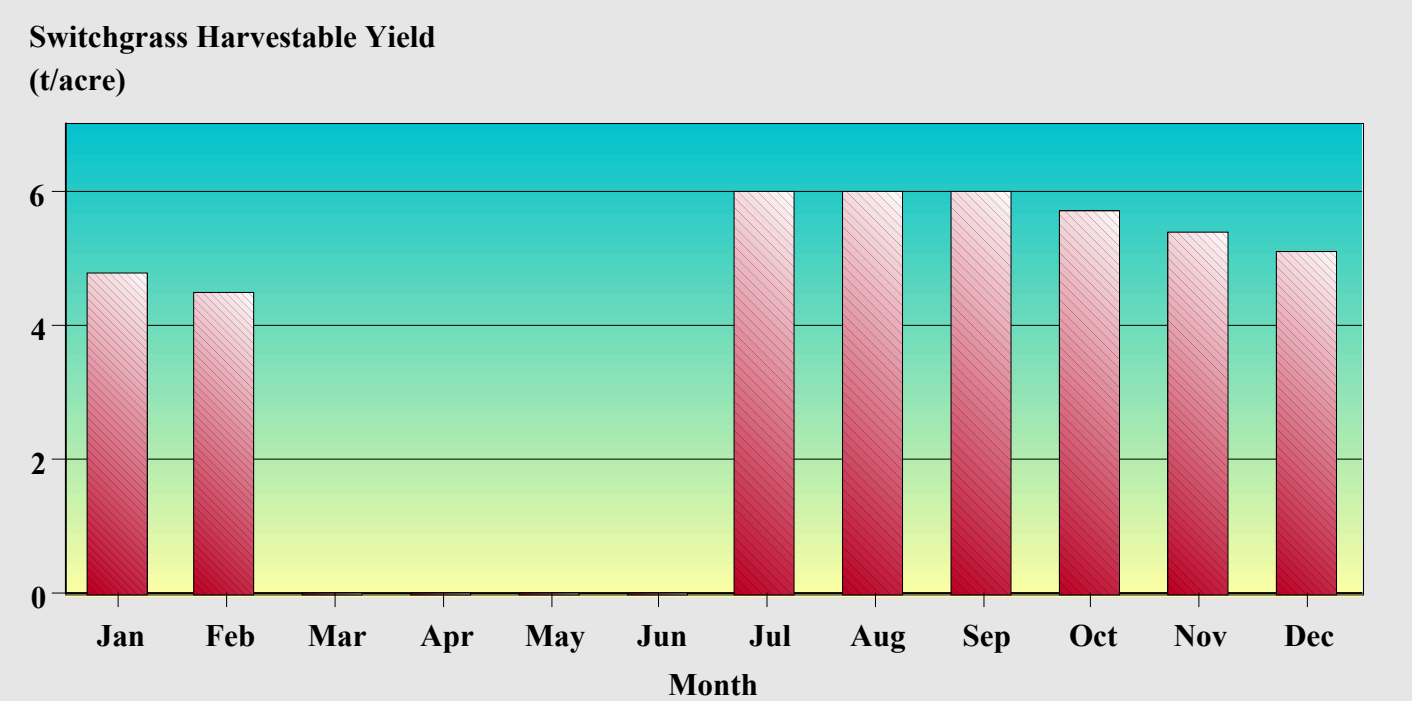

Figure 3. Switchgrass Expected Harvestable Yield (Dry Tons Per Acre) Ranges from 3.75 to 6.50 Dry Tons Per Acre Depending on Oklahoma County and Month of Harvest

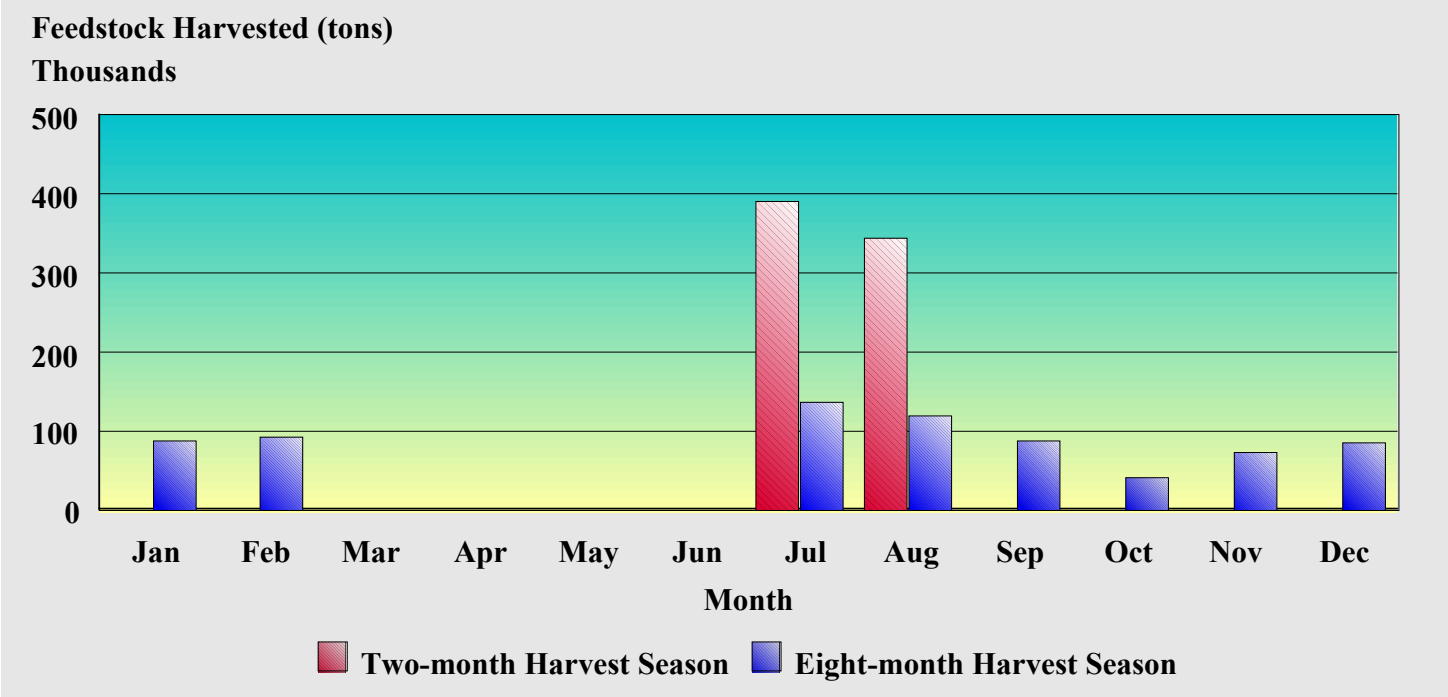

Figure 4. Switchgrass Harvested Per Month for Both a Two- and Eight-Month Harvest Season to Provide a Flow of Feedstock to a 2,000 Dry Tons Per Day Biorefinery in Oklahoma (Epplin *et al*., 2007)

Figure 7 includes a chart of the estimated number of acres harvested per year per raking- baling-stacking harvest unit for both the two- and eight-month harvest season to provide a flow of 2,000 dry tons per day. Estimated "farm gate" costs for producing, harvesting, and field stacking switchgrass is included in the chart in Figure 1. The chart includes the total costs for land rent, establishment amortized over 10 years, an annual application of fertilizer, and a single harvest per year. Land rental costs and other non-harvest costs per ton are slightly greater for the 8-month harvest system. This re-

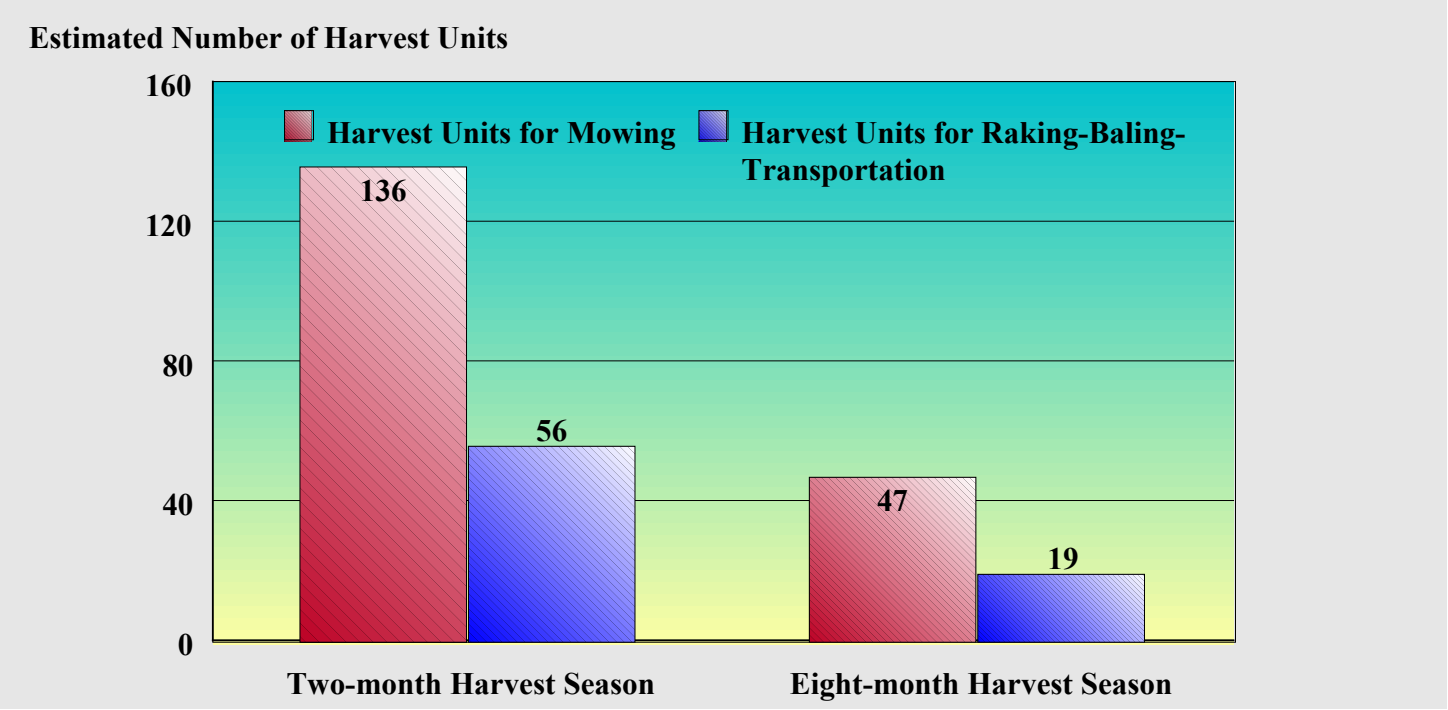

Figure 5. Estimated Number of Harvest Units for Two- and Eight-Month Harvest Season to Provide a Flow of 2,000 Dry Tons Per Day (Hwang, 2007)

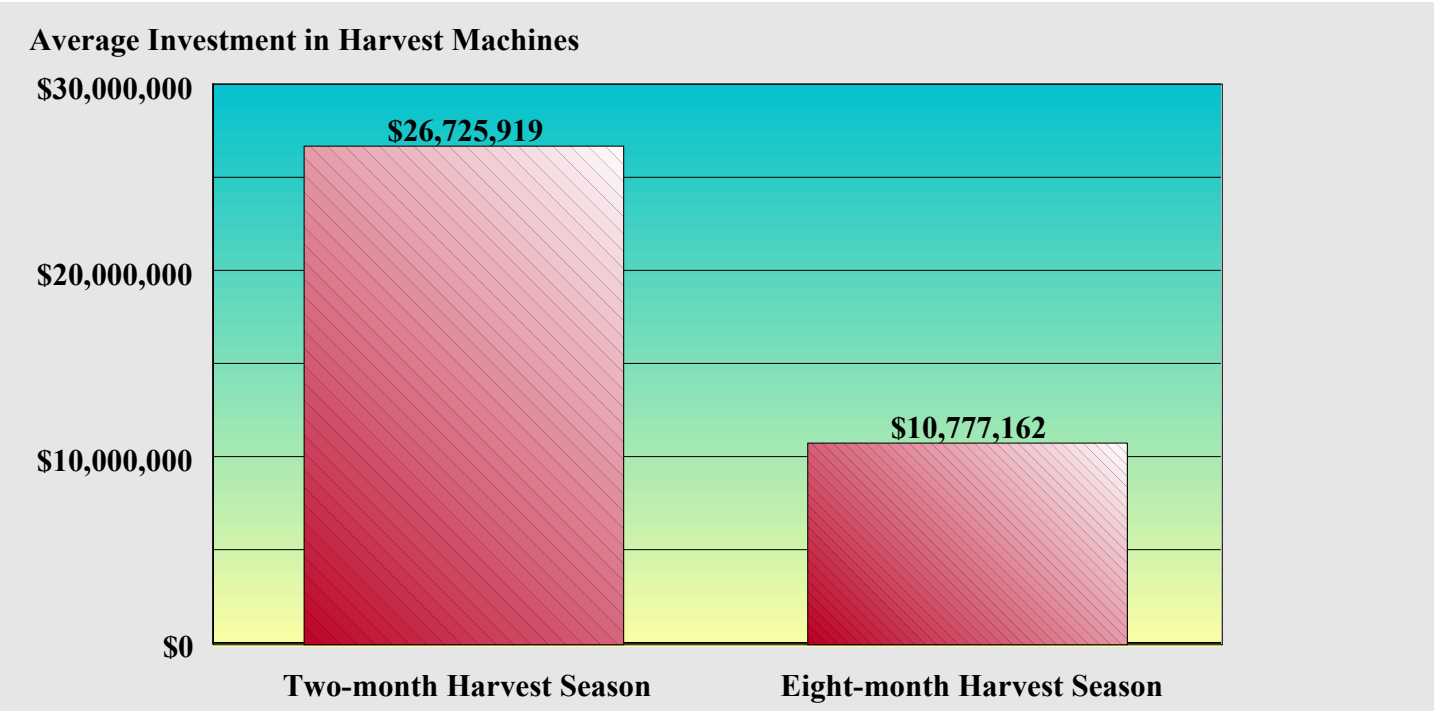

Figure 6. Average Investment in Harvest Machines for Two- and Eight-Month Harvest Season to Provide a Flow of 2,000 Dry Tons Per Day (Hwang, 2007)

sults because harvestable yield per acre declines as harvest is delayed past peak yield (Figure 3). However, the estimated harvest cost per ton is substantially greater for the two-month harvest system. Since fewer machines are required, the investment required and hence the fixed cost of harvest machines is substantially greater if the harvest window is limited to two months per year.

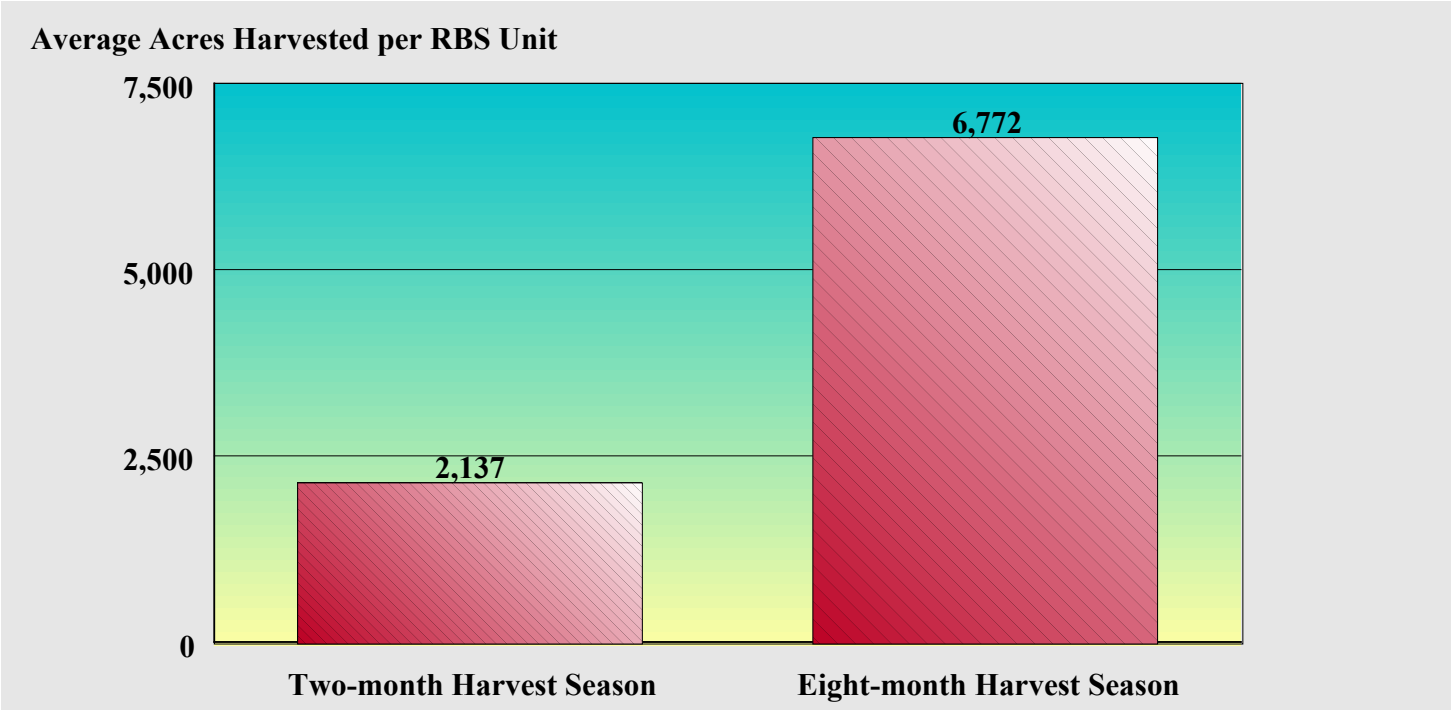

Figure 7. Estimated Number of Acres Harvested Per Year Per Raking-Baling-Stacking Harvest Unit for Two- and Eight-Month Harvest Season to Provide Flow of 2,000 Dry Tons Per Day

Discussion

Harvest would extend over as many months as permitted by weather, feedstock sources, and policy. Given the quantity of biomass required, and the lack of an existing infrastructure to harvest a continuous flow of massive quantities of biomass, it is likely that a system of harvest would develop that exploits the economies of size associated with harvest machines. It remains to be seen if independent companies, such as those that exist for grain harvest in Great Plains, develop. Alternatively, harvest crews and harvest machines could be managed as wholly owned subsidiaries of biorefineries.

Given the rather substantial cost economies associated with harvest machines, and given that the costs of harvest may account for 45 to 65 percent of the total farm gate costs of production, and given that a biorefinery is expected to require a continuous flow of feedstock, if switchgrass or some other perennial grass, is established on millions of acres, it is likely that a highly coordinated harvest system will develop. Established stands of an indigenous perennial grass such as switchgrass are expected to require little management, perhaps one trip across the field for fertilization per year, followed later in the year by harvest. Except for the activities associated with harvest, established stands of switchgrass are not likely to require much activity.

The incentive structure required to bid 33 to 78 million acres from current use, to establish switchgrass, or some other dedicated energy crop, remains to be determined. It would be very risky for a biorefinery to depend on spot markets for feedstock. In the absence of spot markets, obtaining a reliable flow of feedstock from a dedicated energy crop such as switchgrass could involve: (1) contracts with individual growers; (2) contracts with a group of growers through a cooperative arrangement; (3) long-term land leases similar to Conservation Reserve Program (CRP) leases; and/or (4) land acquisition. The most cost efficient from among these systems remains to be determined. However, land owners have experience with engaging in long term (10-15 year) CRP contracts. More than 30 million acres have been under CRP contract. These contracts may provide a blueprint for biorefineries that need to insure a reliable flow of feedstock and for landowners that desire a reliable rent and little risk.

The structure of a mature cellulosic feedstock production and delivery system remains to be determined. However, production characteristics and harvest cost economies could result in a structure for perennial grass production for use as a dedicated energy crop that more nearly resembles the structure of U.S. timber production rather than the atomistic system that we observe for U.S. grain, oilseed, and fiber production. If the low-cost feedstock is a perennial with a long stand life and wide harvest window such as miscanthus or switchgrass, market forces may drive the structure toward vertical integration. For a mature industry, feedstock production, harvest, and transportation may be centrally managed and coordinated.

A number of additional issues remain. A system to manage the risk associated with feedstock yield variability and the risk of fire of standing and stored switchgrass will be required. It is not clear how a biorefinery would respond to short crops. In years of above average yields, not all acres would have to be harvested. However, in years of below average yields, the biorefinery may not have sufficient feedstock to operate throughout the year.

The grain-ethanol program has increased the cost of inputs (land, fertilizer, machinery) required to produce switchgrass and thus the cost to produce switchgrass. Finally, the ultimate challenge is to discover, develop, design, and demonstrate an economically competitive biorefinery technology necessary for a profitable business model.

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