Optimal Switchgrass Harvest Strategies Accounting for

Yield and Nitrogen Requirement Differences by Month of Harvest

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Abstract

Extending switchgrass harvest over many months would require a smaller investment in harvest machines, but would result in a lower average harvestable yield per acre and would require more nitrogen fertilizer, less land for storage, and more land for growing switchgrass. A model was constructed and solved to determine the optimal strategy.

Keywords: biofuel, cellulosic, harvest, mathematical programming, nitrogen, switchgrass

Introduction

The U.S. Energy Independence and Security Act of 2007 (EISA) included a provision that by 2022, 36 billion gallons of biofuel be produced annually including 16 billion gallons of cellulosic biofuels. Biomass from dedicated energy crops such as switchgrass and crop residues is expected to provide most of the feedstock requirements to fulfill the EISA cellulosic biofuels goal. Given a switchgrass yield of three tons per acre, a 50 million gallons per year biorefinery would require the production from 190,000 acres. If the average yield was seven tons per acre, 80,000 acres would be required.

Switchgrass may be harvested in mid-season as early as July. Biomass yield is lower from stands harvested in mid-season and protein (nitrogen) levels are relatively high in grasses cut in mid-season (Haque, Epplin, and Taliaferro, 2009). Late in the growing season, nitrogen translocates from the above ground foliage to the plant's crown and rhizomes. If harvest is delayed until after the first frost and the initiation of senescence, biomass yield will be maximized and nitrogen will have translocated, which reduces the quantity of nitrogen fertilizer needed for biomass production in subsequent years (Adler et al., 2006; Kering et al., 2009; Madakadze et al., 1999; Reynolds, Walker, and Kirchner, 2000; Sanderson, Read, and Reed, 1999; Vogel et al., 2002).

Year-round operation of a biorefinery will require year-round delivery of feedstock but switchgrass cannot be harvested in every month. One alternative would be to harvest switchgrass during a relatively narrow window (September and October) and store it until needed as with conventional grain crops such as corn. This system might result in the largest harvestable yield per acre and minimal requirements for nitrogen fertilizer, but would require a relatively large investment in harvest machines and a large investment in storage. Another alternative would be to extend the harvest season over as many months as possible (July through March). This system would require a smaller investment in harvest machines since they could be used over many months. However, this system would result in a lower average harvestable yield per acre and would require more nitrogen fertilizer, less land for storage, and more land for growing switchgrass.

Previous studies have estimated switchgrass production, fertilization, harvest, storage, and transportation strategies that maximize the net present worth of a cellulosic biorefinery system or that minimize the cost to deliver feedstock to an optimally located biorefinery (Tembo, Epplin, and Huhnke, 2003; Epplin et al., 2007; Mapemba et al., 2007; Mapemba et al., 2008). They find that feedstock harvest cost is a key cost component and that the length of the harvest season matters.

Rather than assume a narrow harvest window, Tembo, Epplin, and Huhnke (2003), Mapemba et al. (2007), and Mapemba et al. (2008) assume that switchgrass could be harvested in Oklahoma from July through February. They did not have precise information about switchgrass yield differences across months of harvest and assume that the quantity of nitrogen fertilizer required would not differ across harvest months. Results of more recent field trials enable estimates of yield differences and nitrogen requirement differences across months of harvest (Haque, Epplin, and Taliaferro, 2009). This information could be used to determine if a strategy of extending the harvest over many months is economically preferable to a strategy of harvesting only in peak harvest months. Optimization of a cellulosic biorefinery system that uses switchgrass feedstock requires an understanding of the many tradeoffs encountered when the length of the harvest window is changed.

Objective

The objective of this research is to determine the switchgrass production, fertilization, harvest, storage, and transportation strategy that would provide the least-cost flow of switchgrass biomass to a biorefinery that operates continuously throughout the year. Results from a model that permits a harvest window from July through March will be compared with results from a model that restricts harvest to September and October. The model accounts for differences in yield and nitrogen fertilizer requirements across harvest months.

This study differs from prior studies in several respects. First, data produced in a designed multiyear field trial are used to estimate switchgrass harvestable yield response to nitrogen fertilizer for alternative harvest months. Second, this study is the first attempt to account for differences in nitrogen requirements dependent on months of harvest for switchgrass. These data enable a comparison of the economic tradeoffs between a relatively narrow harvest window versus an extended harvest season. A narrow harvest window would result in the largest harvestable yield per acre and minimal requirements for nitrogen fertilizer. An extended harvest season would result in a lower average harvestable yield per acre and would require more nitrogen fertilizer, less land for storage, and more land for growing switchgrass.

Data Descriptions and Assumptions

Data were obtained from a switchgrass biomass yield response to nitrogen study conducted at Stillwater, Oklahoma (Haque, Epplin, and Taliaferro, 2009). Switchgrass biomass yield response to nitrogen fertilizer was estimated for July as well as October harvests. These yield estimates were combined with other data (Graham, Allison and Becker, 1996) and expert opinion (Taliaferro, 2000) to produce yield estimates for each of 55 counties for each of nine harvest months. Table 1 includes estimates of the proportion of potential switchgrass expected yield by harvest months. In Oklahoma, the harvest season may begin in July and extend through March. However, harvests during April, May, or June are not expected since it is anticipated that harvest during these months would damage plant growth for subsequent years. Maximum expected yield is obtained by harvesting in either September or October. Expected yield from harvest in July is 80 percent of maximum. If switchgrass is left to stand in the field, dry matter losses of five percent per month are expected from November through March. This result is consistent with field loses from delayed harvests reported by Vogel et al. (2002).

Table 2 includes estimates of the level of nitrogen (pounds per acre) applied in the spring required to achieve plateau yield depending on harvest months. For modeling purposes the price of nitrogen relative to the price of switchgrass is assumed to be optimal at the plateau point on the production surface. Fields that are harvested in July are expected to require 80 pounds per acre of nitrogen to achieve the plateau yield, whereas fields harvested during and between October and March are expected to require only 58 pounds per acre.

The study is based on the assumption that a biorefinery would depend entirely on switchgrass as a single feedstock. The model includes 55 Oklahoma counties as production regions because tall grasses such as switchgrass are not common in the native prairies of the westernmost 22 counties of Oklahoma. Field trials would be required to determine if pure stands of switchgrass would persist on the soils and in the climate of these counties (Wu, 2009; Gopal, 2009). Eleven potential biorefinery locations are included in the model. These locations are selected considering biomass relative density, proximity to the potential biomass producing counties, and availability of road infrastructure.

In the model, switchgrass production is restricted to two land classes: cropland and improved pasture land. Data from the census of agriculture are used to determine existing acres of cropland and improved pasture (USDA, 2002). The expected switchgrass yields are assumed to be the same on improved pasture land as on cropland (Wu, 2009; Gopal, 2009). This assumption follows from the finding that switchgrass yield is limited more by available moisture and the length of the growing season than by soil quality (Wu, 2009; Gopal, 2009).

Restrictions are included in the model to limit switchgrass production in each county to no more than ten percent of the county's cropland and no more than ten percent of the county's improved pasture land. Another assumption is that the use of this cropland and improved pasture land can be acquired at a long-term lease rate of $60 and $40 per acre per year, respectively. The average 2005-09 cropland cash rental for Oklahoma non-irrigated cropland ranged from $28-$31 per acre, and the average 2005-09 pasture land cash rental for Oklahoma ranged from $8.50-$10.50 per acre (USDA, 2009). The assumptions of $60 and $40 per acre for cropland and pasture land lease rates used in the study are made to account for the need to entice land owners to enter into a long-term lease that would be necessary for the perennial grass and to recognize that land lease rates in the vicinity of a biorefinery would increase in response to the plant's existence. Switchgrass production cost estimates are based on establishment and maintenance budgets prepared by Haque, Epplin, and Taliaferro (2009). The estimated establishment costs for switchgrass grown on cropland and improved pasture land of $178 and $158 per acre respectively are amortized at a rate of seven percent over ten years.

Harvest days per month by county are obtained from Hwang et al. (2009). Harvest costs are estimated based on the harvest unit concept described by Thorsell et al. (2004) and modified by Hwang (2007). Machinery (windrowers, tractors, rakes, balers, bale stackers) prices, diesel prices, and interest rates are updated to 2009 levels. Annual ownership and the operating cost of a mowing unit for a nine-month harvest season are estimated to be $82,516. This figure includes the cost of depreciation, interest on average investment, taxes, insurance, fuel, oil, lubricants, repairs for a tractor, mower, and driver. If the unit is only used two months per year, the annual ownership and operating cost of the mowing unit is estimated to be $23,531.

The annual cost of a raking-baling-stacking harvest unit used nine months per year is estimated to be $492,446. This unit includes three 95 horsepower tractors, three 20-foot wheel rakes, three 150 horsepower tractors, three balers (that produce four feet by four feet by eight feet bales), one bale collector-stacker, and seven drivers. If the unit is only used for two months, the annual ownership and operating cost is estimated to be $131,925.

Transportation costs depend on the distance the feedstock will be shipped from the fields to the biorefinery. The distance between any biomass supplying county and any plant location is estimated by the distance from the county's central point to the plant location. A transportation cost equation is estimated from data provided by Wang (2009 who estimates the costs to transport switchgrass from fields in Tennessee to a biorefinery located in Tennessee. Wang

(2009) assumes that a semi-tractor trailer could transport 16 dry tons of rectangular solid bales per load. The equation used to calculate biomass transportation costs for a 16 dry ton truck load is:

(1) $TRC_{ij} = 12.78 + 1.72d_{ij}$,

where TRC_{ij} is the estimated transportation cost in dollar per 16 dry ton truck load for transporting biomass from the supplying county *i* to the biorefinery plant location j; d_{ij} is the round-trip distance in miles. Feedstock transportation costs per ton are calculated by dividing TRC_{ij} by the truck capacity of 16 dry tons.

The biorefinery is assumed to operate 350 days per year and require 2,000 dry tons of feedstock per operating day. Storage losses at the biorefinery and in the field are assumed to be one percent per month. Another assumption is that bales stored in the field would be covered with a plastic tarp. The cost of field storage is estimated to be $2 per ton regardless of the number of months the material is in storage.

Procedure/Method

The data are incorporated into a multi-region, multi-period, mixed mixed integer mathematical programming model similar to the models described by Tembo, Epplin, and Huhnke (2003), Epplin, Mapemba, and Tembo (2005), Mapemba et al. (2007), and Mapemba et al. (2008). The model is designed and solved to determine the area and quantity of switchgrass harvested by county, the number of harvest machines, and the cost to procure, harvest, store, and transport a flow of switchgrass biomass to an optimally located 2,000 tons per day biorefinery for both an extended harvest window (July through March) and a restricted harvest window (September and October). The plant locations are treated in the model as binary variables. The model determines the most economical site for plant location. Biomass yield and nitrogen requirements differ across harvest months and production regions (counties). Integer variables are used to endogenously determine the optimal number of harvest units. The model accounts for storage losses as a function of months stored.

Six different systems are modeled to capture the differences in cost per ton of delivered switchgrass feedstock. In four models, the harvest season is permitted to extend from July to March (nine-month (9m) system). In two models, the harvest season is restricted to September and October (two-month (2m) system). Model 1 accounts for differences in expected yield (Ym) and nitrogen requirements (Nm) depending on months of harvest and permits switchgrass establishment on both cropland (Crop) and improved pasture land (Past) (9mYmNmCropPast); Model 2 restricts land used to only cropland (9mYmNmCrop); Model 3 assumes a fixed level of nitrogen fertilizer of 80 pounds per acre per year independent of harvest months (9mYmN80CropPast); Model 4 assumes switchgrass yields would be the same independent of harvest months (9mYmaxNmCropPast). Model 5 uses the assumptions of Model 1 regarding expected yield and nitrogen requirements, but limits harvest to September and October (2mYmNmCropPast). Model 6 uses the assumptions of Model 2, but limits harvest to September and October (2mYmNmCrop).

Results

Table 3 includes a summary of the results of estimated costs, number of harvest units, harvested acres, and tons harvested to provide a flow of switchgrass feedstock to an optimally located biorefinery for each of the six models.

Comparison of results of Model 1 (9mYmNmCropPast) with Model 5(2mYmNmCropPast)

Restricting harvest to two months (Model 5) increases the costs of delivering feedstock by about $11 per ton over the costs for the nine-month harvest system. The estimated costs for land rent, establishment, maintenance, harvest, storage, and transportation for the nine-month harvest window is \$53 per ton versus \$64 for the two-month window. Most of this cost difference can be attributed to the difference in harvest costs which are estimated to be \$13 per ton more for the two-month harvest system. The two-month harvest system requires substantially more harvest machines which increases the “fixed” machinery costs. The optimal number of harvest units for mowing increases from 44 for the nine-month harvest window to 244 for the two-month harvest window, and the optimal number of raking-baling-stacking harvest units increases from 17 for the nine-month harvest window to 116 for the two-month harvest window. The increase in harvest machines is not proportional since the months do not contain the same number of harvest days. Based on historical weather data, in most years, October is expected to have relatively few days during which switchgrass may be safely baled (Hwang et al., 2009).

The 2,000 tons per day biorefinery requires 700,000 tons per year (assuming 350 days of operation per year). The total biomass harvested for the nine-month and two-month systems is 711,129 and 737,920 tons, respectively (Table 3). More biomass must be harvested with the two-month harvest system to compensate for the additional storage losses, which are modeled as a function of the time in storage. For a nine-month harvest system, only 74,664 tons and 33,966 tons are scheduled for harvest in September and October, respectively. But when the harvest window is restricted to September and October, 509,472 and 228,449 tons are scheduled for harvest in September and October, respectively. The chart in Figure 1 illustrates the number of tons harvested per month for both systems.

Figure 2 illustrates total harvested acres of cropland and improved pasture land for both the nine-month and two-month harvest systems (Model 1 and 5). As noted in Table 1, one disadvantage of an extended harvest season is that harvestable yield per acre declines if harvest is extended beyond October. As a result, fewer acres are required for the two-month harvest system (122,545) than for the nine-month harvest system (143,822). The model enables a holistic comparison of the economic tradeoffs between the increased harvestable yield per acre from the two-month harvest system versus the rather substantial decrease in harvest costs per ton for the nine-month system. Leasing an additional 21,000 acres and establishing switchgrass on it is more economical than investing in and maintaining an additional 200 mowing units and 99 baling units. Details of the economic tradeoffs are provided in Table 3. The nine-month harvest season optimally requires more acres, which results in greater land rent, establishment and maintenance costs, and nitrogen costs per ton of delivered switchgrass. However, these costs are substantially less than the additional harvest and storage costs of the two-month harvest system.

Comparison of results of Model 1 with Model 2, 3, and 4 and Model 5 with Model 6

As noted for Model 1, land available for switchgrass production for each county is restricted to no more than 10 percent of the total cropland and no more than 10 percent of the total improved pasture land. Even though the county yield is assumed to be the same for both land types, and the lease rate is assumed to be $20 per acre more for cropland, Model 1 optimally selects a combination of cropland and improved pasture. Leasing more costly cropland close to a biorefinery is more economical than leasing less costly land at a greater distance, transporting the feedstock, and incurring the additional transportation cost.

Model 2 differs from Model 1 in that switchgrass production is limited to cropland. As reported in Table 3 a major finding is that if production is limited to ten percent of the cropland in any county, the optimal plant location shifts from Pontotoc to Canadian County. The region including Canadian and surrounding counties has a higher percentage of cropland relative to total land. The optimal plant location differs as a result of the interactions between transportation cost and available land area, and the estimated total cost of delivered feedstock increases from $53 to $59 per ton when the model is not permitted to lease improved pasture land. As reported in Table 3 more acres are required for Model 2 because the expected switchgrass yield is lower in the Canadian County region than in the Pontotoc County region.

Models 5 and 6 enable a similar comparison of limiting production to cropland versus both cropland and improved pasture land for a two-month harvest window. Production is limited to no more than ten percent of a county's cropland acres for Model 6. In this case, the optimal plant location shifts from Pontotoc to Garfield County (Table 3). The cost to deliver feedstock increases from $64 to $66 per ton with the reduction in access to improved pasture land. When the harvest window is reduced from nine to two months, the restriction to use only cropland is not as costly. When the plant location is moved from Pontotoc to Garfield County, switchgrass production moves to a region with substantially more September and October harvest days, which requires a smaller investment in harvest machines.

In Model 3, the variable nitrogen rate by harvest months assumption (Model 1) is replaced with an assumption that 80 pounds per acre per year of actual nitrogen would be applied to the established stands of switchgrass for all harvest months. (Eighty pounds per acre would be required to achieve the plateau yield if the biomass is harvested in July.) This change increases the estimated cost of nitrogen by $1.20 per ton of switchgrass delivered, but results in few other changes.

For Model 4, switchgrass yield is assumed to be at the highest level independent of the harvest months Relative to Model 1, in which the harvestable yield is a function of harvest months as reflected in Table 1, assuming the same yield per month reduces the estimated cost to deliver a ton of feedstock by $4.00 per ton.

Discussion

Based on the assumptions included in the model that consider many of the tradeoffs encountered when the length of the harvest window is changed, the strategy of extending harvest over many months is economically preferable to a strategy of harvesting only in peak yield harvest months. Based on the model results, a two-month harvest season would increase the cost to deliver feedstock by 21 percent. This finding has a number of potentially important implications.

A number of discussions have occurred regarding what has become to be known as the "chicken and egg" problem with switchgrass and cellulosic biorefineries. That is, a rational land owner would not establish switchgrass until a biorefinery is built and long term contracts are offered. However, rational investors would be reluctant to invest in a biorefinery that did not have a reasonably certain supply of feedstock for the life of the plant. Results of the model suggest that the structure of a mature switchgrass feedstock based cellulosic biorefinery system is not likely to resemble the atomistic structure that we observe for U.S. grain production and consequently is not likely to resemble the corn based ethanol system. A corn ethanol biorefinery may simply post a price and have feedstock delivered by the existing grain marketing infrastructure. No such infrastructure exists for perennial grasses. The results of the modeling exercise suggest that a cost efficient switchgrass feedstock biorefinery system would most likely engage in long term contracts with land owners prior to, or simultaneously with, construction of a biorefinery.

Given the long stand life and wide harvest window for switchgrass, market forces are likely to drive the structure toward vertical integration. For a cost efficient mature industry, land leasing, feedstock production, harvest, and transportation are likely to be centrally managed and coordinated (Epplin, 2009).

Similar to the Conservation Reserve Program (CRP), switchgrass production in post establishment years, is not expected to require many farming activities. One potential role for government that could facilitate the policy goal of establishing dedicated energy crops on millions of acres would be to guarantee or insure payment over the expected life of the crop. Perhaps the most cost efficient way to entice land owners to establish dedicated perennial energy crops would be to use the existing CRP infrastructure to manage land leases. In addition the average cost to lease an acre is likely to be reduced if the government agrees to convert the land into the CRP and continue payments for the life of a contract in the event of a biorefinery bankruptcy.

The Conservation Reserve Program (CRP) was established in 1985. USDA provided CRP participants with an annual per acre rent and half the cost of establishing a permanent land cover (usually grass or trees) in exchange for retiring land for 10 years. During the first three enrollment periods in March, May, and August of 1986, more than 8 million acres were enrolled. An additional 13.9 million acres were enrolled in February and July of 1987. More than 22 million acres were enrolled in the two years after the 1985 legislation (Osborn, Llacuna, and Linsenbigler, 1995). This suggests that public policy could be used to solve the “chicken and egg” problem.

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Table 1. Proportion of Potential Switchgrass Expected Yield by Harvest Months in Study Region

Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0.80	0.75	0.70				0.80	0.86	1.00	1.00	0.90	0.85

Note: Maximum expected yield is obtained by harvesting in either September or October. The expected yield from harvest in July is 80 percent of maximum. In Oklahoma, the harvest season may begin in July and extend through March. However, harvests during April, May, or June are not permitted since it would damage plant growth for subsequent years.

Table 2. Level of Nitrogen (pounds per acre) Applied in the Spring Required to Achieve Plateau Yield Depending on Harvest Months

Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
58	58	58				80	66	66	58	58	58

Note: Fields that are harvested in July are expected to require 80 pounds per acre of nitrogen to achieve the plateau yield. The price of nitrogen relative to the price of switchgrass is assumed to be optimal at the plateau point on the production surface.

Table 3. Comparison of Results of Five Models for Estimated Costs, Number of Harvest Units, Harvested Acres, and Tons Harvested to Provide a Flow of Switchgrass Feedstock to a 2,000 Dry Tons per Day Biorefinery

	Model Comparison					
	Nine-month harvest window				Two-month harvest window	
	Model 1 (Cropland & Improved Pasture)	Model 2 (Only Cropland)	Model 3 (Nitrogen level fixed at 80 lb/ac for all harvest months)	Model 4 (Yield fixed at maximum level for all harvest months)	Model 5 (Cropland & Improved Pasture)	Model 6 (Only Cropland)
Category	9mYmNmCropPast	9mYmNmCrop	9mYmN80CropPast	9mYmaxNmCropPast	2mYmNmCropPast	2mYmNmCrop
Plant location (county)	Pontotoc	Canadian	Pontotoc	Pontotoc	Pontotoc	Garfield
Land rent ($/ton)	9.24	13.96	9.24	7.71	7.97	12.62
Establishment & maintenance cost ($/ton)	5.53	6.76	5.52	4.58	4.73	6.11
Cost of Nitrogen ($/ton)	4.53	5.12	5.73	3.75	3.90	4.66
Harvest cost ($/ton)	17.15	16.32	17.15	17.03	30.06	26.70
Field storage cost ($/ton)	0.41	0.41	0.41	0.41	1.66	1.65
Transportation cost ($/ton)	15.91	16.39	15.94	15.29	15.49	14.10
Total cost of delivered feedstock ($ /ton)	52.76	58.96	53.98	48.77	63.80	65.84
Harvest units for mowing (no.)	44	43	44	43	244	201
Harvest units for baling (no.)	17	16	17	17	116	106
Biomass harvested from cropland (tons)	193,530	710,540	193,647	197,080	209,525	737,733
Biomass harvested from improved pasture land (tons)	517,599		517,555	514,321	528,395	
Total Biomass Harvested (dry tons)	711,129	710,540	711,702	711,402	737,920	737,733
Cropland harvested (acres)	35,777	162,827	36,592	31,866	33,781	147,192
Improved pasture harvested (acres)	108,045		106,763	87,121	88,764	
Total land harvested (acres)	143,822	162,827	143,355	141,780	122,545	147,192

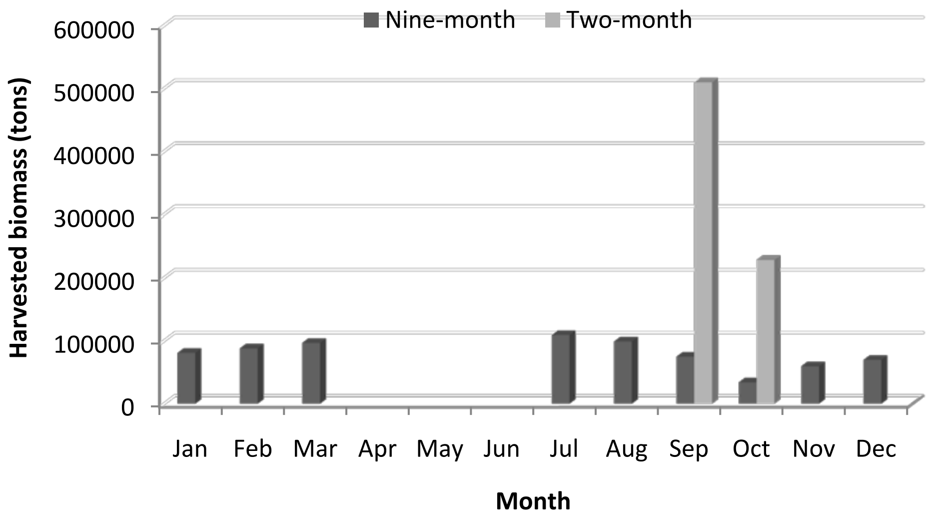

Figure 1. Switchgrass harvested per month for the nine-month and two-month harvest systems to provide a flow of feedstock to a 2,000 dry tons per day biorefinery with variable yield and variable nitrogen requirements by harvest months considering both cropland and improved pasture (results from Models 1 (9mYmNmCropPast) and 5 (2mYmNmCropPast))

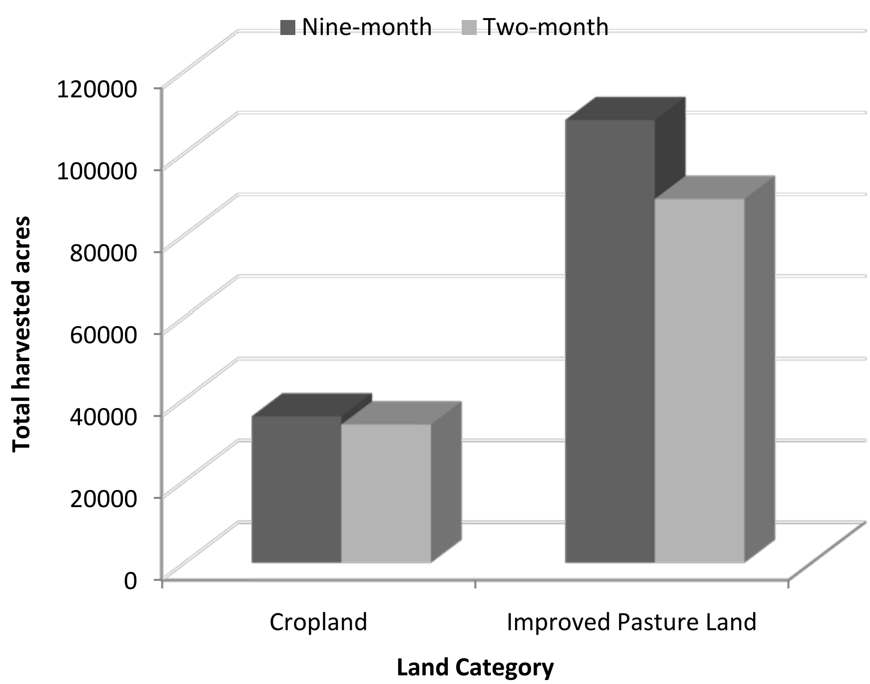

Figure 2. Total harvested acres of cropland and improved pasture land for the nine-month and two-month harvest systems (results from Model 1 (9mYmNmCropPast) and Model 5 (2mYmNmCropPast))