Bioenerg. Res.
DOI 10.1007/s12155-008-9002-1

Economics and Energy of Ethanol Production from Alfalfa, Corn, and Switchgrass in the Upper Midwest, USA

P. A. Vadas · K. H. Barnett · D. J. Undersander

Abstract In the USA, biomass crop systems will be needed to meet future ethanol production goals. We estimated production costs, profits, and energy budgets for three potential crop systems for the Upper Midwest: continuous corn with stover harvest, an alfalfa–corn rotation with stover harvest, and switchgrass. Production costs, profits, and on-farm energy use were greatest for continuous corn, less for alfalfa–corn, and least for switchgrass. Energy to transport crops was similar for all crop systems. Both energy used to produce ethanol and energy output in ethanol was greatest for continuous corn, less for alfalfa–corn, and least for switchgrass. Co-product energy output was 32% greater for alfalfa–corn than continuous corn and 42% greater than switchgrass. Net energy produced (outputs–inputs) was greatest for switchgrass, followed by continuous corn, and then alfalfa–corn. Efficiency of energy production (outputs/inputs) was greatest for switchgrass, followed by alfalfa–corn, and then continuous corn. Our analysis emphasizes tradeoffs among crop systems. Corn may produce high rates of ethanol and net energy, but will do so least efficiently and with the greatest erosion and N leaching. Corn may have the greatest production costs, but return the greatest profit. Comparatively, alfalfa–corn will produce less ethanol and net energy, but will do so more efficiently, and with less erosion and little N leaching. Production costs, but also profits, may be less for alfalfa–corn than continuous corn. Switchgrass may produce the most net energy and will do so most efficiently and with the least erosion, but will also yield the least ethanol. Nitrogen leaching will be less for switchgrass than corn, but greater than alfalfa–corn. Switchgrass may be the least expensive to produce, but may return a profit only if selling prices or yields are high.

Keywords Ethanol · Biomass · Crop systems · Alfalfa · Economics

Introduction

Production of biofuels as replacements for oil and gasoline is gaining attention around the world as issues of climate change, apparent declines in oil reserves, and insecure oil sources intensify. In the USA, corn-based ethanol leads biofuel production. In 2006, more than 45 billion kilograms of corn grain produced 18.5 billion liters of ethanol. However, corn grain alone cannot meet the US government's goal of replacing 30% of gasoline use by 2030 [30]. Corn also requires fairly heavy nitrogen (N) applications that can lead to N leaching and degradation of water resources [6]. Intensive soil tillage practices often used in corn production can lead to significant soil erosion and associated environmental impacts [16]. So while corn represents a significant biofuel source, it can also cause environmental deterioration.

Reducing the N fertilizer pollution and soil erosion of corn production would make it a more sustainable ethanol source. This can be accomplished by rotating a perennial

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legume like alfalfa into a continuous corn system. The ability of alfalfa to provide soil cover and develop deep roots reduces soil erosion [2], which maintains soil quality and productivity and reduces surface water pollution. Alfalfa does not require N fertilizer. Instead, alfalfa roots engage with soil bacteria to assimilate atmospheric N. When alfalfa is plowed down, residual N remains for crop production the next year. Alfalfa's very deep roots can also absorb water and N from as deep as 4 m. These unique N characteristics help alfalfa reduce agricultural N leaching and pollution of groundwater [6, 31, 45].

In an alfalfa–corn rotation, ethanol could also be produced from the cellulosic biomass of alfalfa and corn stover as well as the corn grain [14]. While switchgrass is a widely considered feedstock option for future cellulosic ethanol production [27], alfalfa has a number of characteristics that make it a strong candidate. Alfalfa can be grown in almost every part of the country and averages 7.8 Mg ha^{-1} of dry matter each year. The technology and machinery for cultivating, harvesting, and storing alfalfa is well established and widely available, and farmers are very familiar with alfalfa production. There is also a well-developed industry for alfalfa cultivar development and seed production, processing, and distribution.

We conducted an analysis to compare annual, farm-scale production costs, potential ethanol production, net energy balances, and environmental impacts of possible cropping systems for ethanol production in the Upper Midwest. Our objective was to assess the effect of rotating alfalfa with corn, and compare the rotation with other crop systems likely to be used to produce ethanol. To do this, we compared cropping systems of continuous corn, an alfalfa–corn rotation, and continuous switchgrass in Wisconsin.

Methods

Crop System Descriptions

We evaluated four, 4-year cropping systems that could be grown in Wisconsin: continuous corn without stover harvest, continuous corn with stover harvest, an alfalfa–corn rotation with stover harvest, and continuous switchgrass. Continuous switchgrass and corn were four years of each crop. While perennial stands of switchgrass will likely be grown for ten years of more, we used a 4-year assessment to be consistent with the other systems. The alfalfa–corn rotation had one establishment and one production year of alfalfa, followed by 2 years of corn. While alfalfa–corn rotations may typically have three or more years of alfalfa, we chose only 2 years to take advantage of greater ethanol yield from corn than alfalfa, while still gaining 2 years of N credits from alfalfa for corn production.

For each crop system, we assessed both "normal" and "high" crop yield scenarios (Table 1). Normal yields were based on 2000 to 2005 mean yields for Wisconsin (Wisconsin Agricultural Statistics Service 2001–2006), which were 8.47 Mg ha^{-1} for corn grain and 8.06 Mg ha^{-1} for full alfalfa production. Based on results of long-term cropping systems trials, we assumed corn yield the first year following alfalfa was increased by 15% [25]. The high yield scenario for corn represented optimal growing conditions in south-central Wisconsin. High alfalfa yields represented crops selected and managed for maximum biomass yield [23, 24]. We assumed switchgrass yields based on data from large field plots in southern Wisconsin [42].

Table 2 details fertilizer, lime, and pesticides inputs for the three crop systems. Table 3 details tillage, planting, and harvest machinery used. For switchgrass, we followed data from Vogel et al. [49] for N fertilizer rates that would promote the yields used in our analysis and still maintain soil N concentrations. For alfalfa–corn, we assumed two cuttings of alfalfa. We assumed the alfalfa crop provided 132 kg ha^{-1} of N for the first year corn crop, and 55 kg ha^{-1} of N for the second year corn crop [21]. For all corn crops, we estimated stover yield using a harvest index of 45. In this calculation, megagram per hectare of grain yield divided by 0.45 equaled total above-ground plant weight. This product times 0.55 equaled total corn stover yield. We assumed 50% of the stover produced was harvested (baled) from the field to keep wind and rainfall erosion at acceptable levels [14]. We assumed one cutting for switchgrass in late summer.

Table 1 Harvested yields of crops and corn stover in the normal and high yield scenarios of the three crop systems

	Crop yield[a]	
Crop system	Normal (Mg ha^{-1})	High (Mg ha^{-1})
Alfalfa–corn		
Alfalfa establishment	4.48	6.72
Alfalfa production	8.96	13.44
Corn grain—year 1	9.73	12.54
Corn grain—year 2	8.47	10.98
Corn stover—year 1	5.94	7.67
Corn stover—year 2	5.17	6.71
Corn		
Grain	8.47	10.98
Stover	5.17	6.71
Switchgrass	8.96	13.00

[a] Yields are on a dry weight basis

Table 2 Seed, fertilizer, pesticides, and lime inputs for the three crop systems

Product	Quantity per hectare	Alfalfa–corn rotation								Continuous corn		Switchgrass		
		Alfalfa establishment		Alfalfa production		Year 1 corn		Year 2 corn						
		Normal	High	Normal	High	Normal	High	Normal	High	Normal	High	Establishment	Normal	High
Seed	kg	5.4	5.4	–	–	22.4	22.4	22.4	22.4	22.4	22.4	11.2	–	–
Fertilizer														
0–0–60	kg K	112.1	168.10	224.1	336.19	–	–	–	–	–	5.6	80.7	100.9	201.7
0–46–0	kg P	28.02	39.22	56.03	84.05	28.0	28.0	28.0	28.0	22.4	39.2	17.9	22.4	44.8
28% N solution	kg	–	–	–	–	–	–	–	–	123.3	123.3			
Urea 46–0–0	kg N	–	–	–	–	–	–	43.7	74.5	67.2	130.0	–	112.1	168.1
9–23–30	kg	–	–	–	–	168.1	168.1	168.1	168.1					
Lime	Mg	–	–	–	–	5.6	5.6	–	–					
Pesticides														
Chlorpyrifos	l	–	–	1.2	1.2	–	–	–	–					
Acetochlor/Atrazine	l	–	–	–	–	2.1	2.1	2.1	2.1	2.1	2.1			
Clopyralid/Flumetsulam	kg	–	–	–	–	0.3	0.3	0.3	0.3	0.3	0.3			
Terbufos	kg									7.3	7.3			

Table 3 Implements and accompanying tractors used for field operations for the three crop systems

Operation and crop system	Implement	Tractor
Tillage		
Alfalfa, corn, switchgrass	6.3 m tandem disk	160 HP MFWD
	4.5 m disc-chisel plow	160 HP MFWD
Planting		
Alfalfa, switchgrass	3 m double disk drill	75 HP
Continuous corn	6–30 min-till planter	75 HP
Fertilization		
Alfalfa, corn, switchgrass	12 m fertilizer spreader	60 HP
Pesticides		
Alfalfa, corn	9 m sprayer and tank	40 HP
Harvest		
Alfalfa, switchgrass	4.5 m mower conditioner	100 HP
	3 m hydraulic rake	40 HP
	Large rectangular baler	130 HP MFWD
Continuous corn	6–30 corn grain head	220 HP Combine
Corn stover	6 m flail chopper	75 HP
	Large rectangular baler	130 HP MFWD

HP Horse power, *MFWD* mechanical front wheel drive

Crop System Economics

Annual Production Costs

We used the Agriculture Budget Calculation Software (ABCS) to calculate annual production costs for all crop systems [11]. ABCS uses an engineering approach to calculate whole-farm costs based on enterprise budgets. Table 4 details costs of fertilizer, lime, and pesticide inputs, as well as other financial assumptions. For corn grain drying, we assumed grain moisture content would be reduced by six percentage points at a cost of \$0.028 per percentage point. We estimated switchgrass establishment costs at \$28.37 ha^{-1} per year assuming a 10-year stand life. For annual land charges (cash rent equivalent), we assumed high crop yields would be produced on better quality cropland that would command a greater land charge than average quality cropland producing normal yields. Therefore, we used an annual land charge of \$242.16 ha^{-1} for high yield and \$150.73 ha^{-1} for normal yield scenarios. These prices were based on 2005 cropland values in southern WI [4].

Potential Farm Profits

To estimate potential farm profits across entire crop systems, we considered low, medium, and high commodity

Table 4 Costs of input items used to produce the three crop systems

Crop input	Unit	Price (\$ unit^{-1})
Seed		
Alfalfa	kg	8.82
Corn	kg	8.27
Switchgrass		13.23
Fertilizer		
0–0–60	kg K	0.51
0–46–0	kg P	0.86
28% N Solution	kg	0.31
Urea 46–0–0	kg N	0.93
9–23–30	kg	0.35
Lime	Mg	28.64
Pesticides		
Lorsban 4E	L	9.78
Harness	L	30.12
Hornet WDG	kg	158.76
Counter 15G	kg	3.75
Fuel		
Gasoline	L	0.69
Diesel	L	0.69
Electricity	kWh	0.10
Lubrication	L	0.69
Miscellaneous		
Corn Drying	Mg	7.09
Labor	h	20.00
Land charge normal yield	ha	150.73
Land charge high yield	ha	242.16
Short-term interest	%	7.35
Long-term interest	%	7.15

price scenarios. For corn grain, prices were \$78.75, \$118.13, and \$157.50 Mg^{-1} (\$2, \$3, and \$4 per bushel) to reflect price fluctuations over the past several years. For corn stover, we assumed a farmer would be responsible for all costs up until delivery of stover to an ethanol facility. This includes stover harvest and baling costs, and a cost of \$12.00 Mg^{-1} [8] to move bales to the field edge, load bales on a flatbed trailer, and transport bales 81 km. We then assumed three delivered price scenarios of \$22, \$33, and \$44 Mg^{-1} stover to reflect a range of prices similar to those paid in the Harlan, Iowa project [13].

For ethanol production, we assumed harvested alfalfa would be sold to a facility that would separate leaves from stems, then sell alfalfa leaf meal as an animal feed and alfalfa stems to an ethanol facility. We assumed a farmer would pay to transport alfalfa hay to a separation facility at the same cost as corn stover above. To estimate a price paid to farmers by the separation facility for delivered alfalfa, we assumed the separation facility would sell stems to an ethanol facility for about \$44 Mg^{-1} [50] and alfalfa leaf meal for \$143 Mg^{-1}. We estimated the alfalfa leaf meal price from the current value of distillers grains, given both will be used as protein sources in cattle diets. We assumed a current price of \$121 Mg^{-1} for distillers grains with 24% protein, and thus an equivalent price of \$143 Mg^{-1} for alfalfa leaf meal with 28% protein. Therefore, an alfalfa separation facility could afford to pay about \$93 Mg^{-1} for alfalfa hay, which is the average of their selling prices for alfalfa leaf meal and alfalfa stems. We thus used \$66, \$88, and \$121 Mg^{-1} for our three price scenarios to reflect a range of possible selling prices to an alfalfa separation facility.

We also estimated potential farmer profit if alfalfa hay was produced for direct sale for animal feed instead of separation for ethanol and leaf meal. For direct hay as feed sale, we assumed all the same crop systems details as outlined above for the alfalfa–corn rotation, except that alfalfa would be cut four times instead of two and the seeding rate would be 2.5 times greater [23]. Average selling prices for alfalfa hay in WI from 2005 to 2006 were \$120 Mg^{-1}. We thus used alfalfa hay prices of \$88, \$121, and \$154 Mg^{-1} to reflect the range of possible prices alfalfa hay crops of various quality.

For switchgrass, we assumed a farmer would pay to transport bales to an ethanol facility at the same cost as corn stover and alfalfa hay above. We then assumed three possible delivered prices of \$33, \$66, and \$99 Mg^{-1}. These prices reflect a range around current estimates of feedstock prices able to be paid by an ethanol facility [50] and prices a farmer may need to produce switchgrass for a profit (see switchgrass production cost estimate discussion below).

Crop System Energy Budgets

We intended our energy budget to be an extensive but not fully exhaustive representation of all possible energy inputs and outputs associated with either crop or ethanol production. Other studies consider this issue more rigorously [20, 29, 39]. Instead, we intended our energy budget to be a balanced comparison across crop systems that considers similar inputs and outputs.

Crop Production Energy

For each crop system, we estimated energy contained in inputs (Tables 2 and 3) required to produce crops using the average of energy values reported in the literature (Table 5). For fertilizers, seed, and agrochemicals, energy input values considered energy required to produce the items, energy contained in the items, and energy used to transport the items. We used ABCS to estimate fuel use for farm operations, while accounting for increased harvest fuel use as a function of yield. We also assumed corn drying used

Table 5 Equivalent energy contained in crop production inputs and ethanol

Item	Energy	Reference
Seed production	104.0 MJ kg^{-1}	Patzek [29]
N fertilizer	46.9 MJ kg^{-1}	Kim and Dale [20], Patzek [29], Shapouri et al. [39]
P fertilizer	11.9 MJ kg^{-1}	Kim and Dale [20], Patzek [29]
K fertilizer	7.9 MJ kg^{-1}	Kim and Dale [20], Patzek [29]
Lime	1.5 MJ kg^{-1}	Kim and Dale [20], Patzek [29]
Herbicide	315.5 MJ kg^{-1}	Kim and Dale [20], Patzek [29], Shapouri et al. [39]
Insecticide	321 MJ kg^{-1}	Kim and Dale [20], Patzek [29], Shapouri et al. [39]
Gasoline	38.7 MJ l^{-1}	Patzek [29], Shapouri et al. [39]
Diesel	40.0 MJ l^{-1}	Patzek [29], Shapouri et al. [39]
Electricity	9.1 MJ kWh^{-1}	Shapouri et al. [39]
Lube oil	41.9 MJ kg^{-1}	Patzek [29]
LPG	49.95 MJ kg^{-1}	Patzek [29]
Ethanol	21.3 MJ l^{-1}	Patzek [29]

0.01 kWh of electricity and 2.98 l of propane (LPG) per megagram of grain per moisture point. We did not consider energy used by farm labor for non-farm activities, energy used to transport labor to the farm, or energy embodied in farm machinery.

Potential Ethanol and Co-Product Energy

For potential ethanol production, we assumed alfalfa would be separated into leaves and stems, with half the yield as leaves and half as stems. There is no industry for separating alfalfa leaves and stems, so we estimated the energy required to do so at 29.2 MJ Mg^{-1} of alfalfa hay [32]. We assumed all harvested alfalfa stems, switchgrass, corn grain, and corn stover would be used to produce ethanol. We estimated the theoretical ethanol yield for each feedstock using the US Department of Energy theoretical ethanol yield calculator [47], which predicts ethanol yield based on feedstock composition assuming 100% conversion efficiency. While 100% conversion efficiency is not likely and is not achieved in current corn-grain ethanol production, it provides a fair comparison across different feedstock materials. This is necessary when considering future cellulosic ethanol feedstocks where actual industry conversion efficiencies do not yet exist. We thus assumed ethanol yields of 326.0 l Mg^{-1} for alfalfa stems [24], 416.7 l Mg^{-1} for switchgrass [47], 519.1 l Mg^{-1} for corn grain [47], and 469.8 l Mg^{-1} for corn stover [47].

We assumed separated alfalfa leaves would be processed to produce alfalfa leaf meal for animal feed. We also assumed corn-grain ethanol production would yield distillers grains that would be used for animal feed. Several methods appear in the literature for assigning an energy value to animal feed co-products. We used the replacement method [19], which credits the co-product with the energy required to produce the item in the animal diet that the co-product replaces. We assumed distillers grains would replace soybean meal in cattle diets as a protein source and have an energy value of 4.1 MJ for every liter of ethanol produced from corn grain [9]. This equates to 7,094.4 MJ Mg^{-1} of distillers grains, assuming that 0.3 kg of distillers grains is produced per kilogram of corn grain. We assumed distillers grains contains 24% protein [35] and alfalfa leaf meal contains 28% protein [5, 40]. We thus assumed alfalfa leaf meal could replace more soybean meal in animal diets and thus gave alfalfa leaf meal an energy value 17% greater than distillers grains.

We assumed a facility producing ethanol from corn grain requires 14.41 MJ of fossil fuel energy per liter of ethanol produced [39]. We assumed that a facility producing ethanol from cellulosic feedstocks would use fermentation waste products to generate its own required energy and would also generate excess electricity at a rate of 350 kWh Mg^{-1} of biomass used to generate ethanol [53].

Transportation Energy

We assumed energy required to transport switchgrass and corn stover to an ethanol facility was 0.2 MJ of diesel fuel per kilogram of material for an 81 km distance from the farm to the facility [20]. This assumption is similar to that of Shapouri et al. [39]. We assumed an alfalfa separation facility would be half the distance from the farm as the ethanol facility and alfalfa hay would be transported from the farm to the separation facility, alfalfa stems from the separation facility to the ethanol facility, and alfalfa leaf meal from the separation facility to the farm. Transportation of all alfalfa materials would thus be equivalent to transport of bulk hay to the ethanol facility. Finally, we assumed transport of corn grain and distillers grains between the farm and ethanol facility each required 0.075 MJ of diesel fuel per kilogram of material for an 81 km one-way trip [20].

Energy Comparison of Crop Systems

For each crop system, energy inputs included energy required to grow and harvest crops; to transport harvested crops, alfalfa leaf meal and stems, and distillers grains; to separate alfalfa leaves and stems; and to produce ethanol at a conversion facility. Energy outputs included energy contained in ethanol, alfalfa leaf meal, distillers grains, and excess electricity. Net energy generated was thus total energy generated in outputs minus total energy in inputs.

Efficiency of energy generation was outputs divided by inputs.

Crop System Environmental Impacts

We used the Integrated Farm Systems Model [33] to estimate N leaching and denitrification and erosion for the three cropping systems. IFSM is a whole-farm simulation model that predicts the long-term performance, environmental impact, and economics of dairy, beef, and crop farms over multiple years of weather. IFSM has been shown to successfully predict both N leaching [34] and erosion [37]. In IFSM, N movement and transformation in soils is modeled with functions from the Nitrate Leaching and Economic Analysis Package [38]. Erosion sediment loss is predicted using the modified universal soil loss equation [37]. For the IFSM simulations, we used the same crop systems inputs as described above and 25 years of weather data from Madison, WI.

Results

Crop System Economics

Annual Production Costs

Table 6 shows annual direct, fixed, and total on-farm crop production costs in dollar per hectare. Direct costs included fertilizers, pesticides, fuels and electricity, equipment repairs and maintenance, and input interest expenses. Fixed costs included land charges, labor, and interest, insurance, and depreciation expenses on equipment and structures. Total costs were greater for continuous corn than alfalfa–corn, primarily due to greater direct costs in inputs. Total switchgrass costs were 30 to 50% less than total costs for continuous corn and alfalfa–corn. Low switchgrass costs were due to lesser costs in all categories except land charges.

Continuous corn production costs without stover harvest were \$108 Mg^{-1} grain for high yields and \$118 Mg^{-1} grain for normal yields (\$2.75 and \$2.99 per bushel; Table 6). Including stover harvest increased production costs by about 4%. Corn stover harvest costs ranged from \$5.50 to \$7.70 Mg^{-1}, which includes depreciation, interest, labor, and energy required to own and operate a flail chopper and rectangular baler. Sokhansanj and Turhollow [44] estimated corn stover shredding and baling costs at about \$13 Mg^{-1}, which is greater than our estimates. A corn stover collection project was conducted in Harlan, Iowa from 1996 to 1998 [13]. In that project, a corn stover collection facility contracted with farmers and custom harvesters to perform baling. Bales were picked up in the field as left by the baler, and balers were paid \$16 Mg^{-1}, which equates to about \$19 in 2006. This payment amount and our cost estimates, even if somewhat low, suggest farmers could certainly profit from collecting corn stover as a cellulosic ethanol feedstock.

Incorporating alfalfa into the continuous corn with stover harvest system increased some corn production costs (e.g., lime for alfalfa needs applied to corn crop), but it also decreased other costs (e.g., N fertilizer). The net effect of incorporating alfalfa decreased corn production costs by 3.4 to 11% (Table 6). When averaged over establishment and full production years, production costs for alfalfa were \$77 Mg^{-1} for high and \$90 Mg^{-1} for normal yields. In Iowa, Hallam et al. [15] estimated production costs from \$60 to \$66 Mg^{-1} for a two-cut alfalfa system yielding 6.3 Mg ha^{-1} during the establishment year and 9.4 Mg ha^{-1} for four to five full production years. These Iowa costs are less than ours mostly because costs were spread out over greater yields of more production years. If we spread our production costs out over 4 years of full production at the same Iowa yields, they would be about \$69 Mg^{-1}, which compares well to the Iowa costs. This analysis shows that while limiting alfalfa to 2 years in rotation with corn will benefit from greater ethanol and energy production from corn, it will also considerably increase alfalfa production costs per megagram of yield.

Annual production costs for switchgrass were \$56 Mg^{-1} for high and \$60 Mg^{-1} for normal yields (Table 6). These costs include an annualized stand establishment cost of \$28.37 ha^{-1}. These estimates agreed well with other model results and field data from the literature (Fig. 1), showing ABCS estimated production costs in a manner consistent with other reported methods. Assuming transportation costs of \$12 Mg^{-1} [8], the cost to produce, harvest, and deliver switchgrass to an ethanol facility may be about \$70 Mg^{-1}. These costs are much greater than the USDA and USDOE estimates of \$44 Mg^{-1} that an ethanol facility could afford to pay for a biomass feedstock to ensure profitable ethanol production.

Potential Farm Profits

Potential farm profits (dollars per hectare) for entire crop systems depended on yield and price scenarios (Table 7). For normal yields, continuous corn with stover harvest and alfalfa–corn for ethanol and leaf meal systems were generally the most profitable as averaged across price scenarios. The alfalfa–corn for hay system was on average slightly less profitable, followed by the continuous corn without stover system. Switchgrass was the least profitable.

For high yields, the alfalfa–corn for hay system was on average the most profitable, followed closely by the continuous corn with stover and alfalfa–corn for ethanol

Table 6 Annual production costs ($ ha^{-1}) for the four crop systems

	Direct costs				Fixed costs				
	Inputs	Energy	Input interest	Repair and maintenance	Land charge	Labor	Interest and insurance	Depreciation	Total costs
	Normal yields								
Cont. corn no stover	568.48	49.15	26.86	23.38	150.73	47.52	67.71	66.62	1,000.43
Cont. corn with stover	568.48	59.60	28.59	23.65	150.73	57.35	77.12	77.44	1,042.96
Alfalfa–corn									
Alfalfa establish	232.32	50.04	20.83	11.02	150.73	96.69	74.11	82.73	718.47
Alfalfa production	174.82	34.47	15.12	7.93	150.73	68.72	57.99	64.27	574.06
First year corn	630.11	60.54	28.96	25.92	150.73	59.87	79.07	79.81	1,115.01
Second Year Corn	489.85	59.63	28.54	20.73	150.73	57.35	76.85	77.22	960.90
Switchgrass[a]	207.00	18.63	9.98	8.45	150.73	32.74	40.33	43.22	511.08
	High yields								
Cont. corn no stover	660.94	52.51	26.86	26.76	242.16	47.52	67.71	66.62	1,191.07
Cont. corn with stover	660.94	63.90	28.59	27.03	242.16	57.35	77.12	77.44	1,234.54
Alfalfa–corn									
Alfalfa establish	270.38	55.08	20.83	12.40	242.16	96.69	74.11	82.73	854.37
Alfalfa production	288.54	39.17	14.63	12.08	242.16	66.10	56.93	62.89	782.49
First year corn	662.87	65.65	28.96	27.13	242.16	59.87	79.07	79.81	1,245.53
Second year corn	537.20	64.74	28.54	22.46	242.16	57.35	76.85	77.22	1,106.51
Switchgrass[a]	329.31	19.94	9.98	12.95	242.16	32.74	40.33	43.22	730.63

[a] Annual switchgrass costs do not include annualized establishment costs of $28.37 ha^{-1}

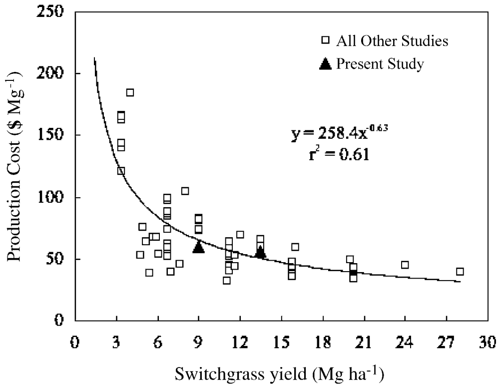

Fig. 1 Switchgrass production costs as estimated by the present study and in published studies of Schmer et al. [36], Walsh [51], Duffy and Nanhou [7], Hallam et al. [15] and Bransby et al. [3]. Dollar values are adjusted to 2006 dollars

and leaf meal systems, which were on average equally profitable. The continuous corn without stover system was less profitable than these three aforementioned systems, while switchgrass was the least profitable.

Our farm profit analysis highlights several considerations. First, switchgrass production may be profitable to farmers only if both prices and yields are high. High yields may initially be difficult to consistently achieve given the inexperience farmers have in growing and managing switchgrass [36]. Second, harvesting stover can increase farm profits compared to a corn system without stover harvest. Third, rotating alfalfa into continuous corn may increase or decrease profits depending on yield and commodity prices. Finally, producing alfalfa for ethanol and leaf meal can be more or less profitable as producing alfalfa hay for direct sale as animal feed, depending on yields. Overall, our data demonstrate that farmers may choose which crops to actually grow for future cellulosic ethanol production based not on energy balances or ethanol yields but rather on personal profit. However, profit will depend on future commodity prices, especially concerning the ability of ethanol production facilities to pay more for biomass feedstocks than is currently estimated [50], and the existence of public incentive programs that encourage farmers to grow specific crops.

Table 7 Potential annual farmer profits for the crop systems and three commodity price scenarios

Crop system and yield level	Profits per price scenario		
	Low ($ ha^{-1})	Med ($ ha^{-1})	High ($ ha^{-1})
	Normal yields		
Continuous corn no stover	($333.24)	$0.35	$333.93
Continuous corn with stover	($323.85)	$66.82	$457.48
Alfalfa–corn	($255.48)	$28.44	$349.42
Alfalfa–corn for hay	($305.36)	5.62	$336.61
Switchgrass	($350.66)	($54.14)	$242.38
	High yields		
Continuous corn no stover	($326.22)	06.20	$538.63
Continuous corn with stover	($302.48)	$203.83	$710.14
Alfalfa–corn	($206.40)	76.11	$614.22
Alfalfa–corn for hay	($225.49)	$212.62	$650.73
Switchgrass	($475.81)	($31.03)	$413.75

Crop System Energy Balances

Table 8 details energy balances of each crop system. Energy use on farms was by far greatest for the continuous corn systems. On-farm energy use was 6% to 44% greater for alfalfa–corn than switchgrass. The main on-farm energy inputs varied among crop systems. For continuous corn, the greatest energy inputs were N fertilizer, corn drying, diesel fuel, and seed. For switchgrass, the greatest inputs were N fertilizer, K fertilizer, and diesel fuel. For alfalfa–corn, the greatest inputs were diesel fuel, corn drying, lime, and seed. Energy used to transport harvested crops was similar for all systems, while energy used to convert crops to ethanol was greatest for continuous corn, less for alfalfa–corn, and zero for switchgrass. Overall, total energy inputs were by far greatest for continuous corn, much less for alfalfa–corn, and quite low for switchgrass.

Theoretical ethanol yield, and thus energy output from ethanol, was greatest for continuous corn with stover harvest; and harvesting stover increased ethanol yield by 56% (Table 8). For any corn crop, ethanol yield from grain was about 1.8 times greater than that from stover. Rotating alfalfa into continuous corn decreased ethanol yield by about 35%. For alfalfa–corn, about 82% of the ethanol yield was from corn grain and stover. Ethanol yield was always least for switchgrass. Energy outputs in animal feed co-products and excess electricity was about 1.3 times greater from alfalfa–corn than continuous corn with stover harvest and 1.4 times greater than switchgrass. In the alfalfa–corn rotation, alfalfa leaf-meal accounted for 37%, distillers grains for 20%, and excess electricity for 43% of total energy output in co-products.

Our analysis showed a positive energy balance for all crop systems. Ethanol production from continuous corn without stover harvest had the least net energy ratio (outputs/inputs) at 1.4, which is similar to other estimates in the literature [17, 39]. Switchgrass had the greatest net energy ratio at about 11, which is greater than an estimate by Mclaughlin and Walsh [26] at 4.43. Mclaughlin and Walsh [26] estimated greater energy for crop production because they considered energy inputs that we did not, including energy embodied in the manufacture and transport of machinery, machinery repairs, and transport of fuels. Our net energy ratios for continuous corn with stover

Table 8 On-farm energy use in crop production inputs; energy inputs in farm use, transportation, plant separation and bioconversion; energy outputs in ethanol and feed co-products; and efficiency of energy production, net energy production, and theoretical ethanol yield for the three crop systems

	Corn no stover		Corn with stover		Alfalfa–corn		Switch	
	High	Normal	High	Normal	High	Normal	High	Normal
On-farm inputs	% of total on-farm energy use							
N fertilizer	39	33	37	32	9	8	63	67
P fertilizer	4	4	4	4	6	5	4	3
K fertilizer	2	2	2	2	9	8	13	10
Seed	11	12	10	11	9	10	0	0
Lime	0	0	0	0	16	19	0	0
Herbicide	3	3	3	3	2	3	0	0
Insecticide	2	2	2	2	0	0	0	0
Boron	0	0	0	0	0	0	0	0
Gasoline	1	1	1	1	2	2	2	3
Diesel	12	14	14	17	21	21	15	13
Lube oil	2	2	2	2	3	3	2	2
Farm electricity	0	0	0	0	1	1	1	1
Corn drying electricity	1	1	1	1	1	1	0	0
Corn drying LPG	25	25	24	24	22	20	0	0
	Energy inputs (MJ ha^{-1})							
Total on-farm	21,733	16,747	22,433	17,353	13,220	11,298	12,483	7,855
Transportation	1,124	866	2,466	1,901	2,638	1,970	2,988	1,962
Plant separation	0	0	0	0	1,961	1,307	0	0
Bioconversion	80,613	62,187	80,613	62,187	43,185	33,397	0	0
Total	103,470	79,799	105,512	81,441	61,005	47,971	15,471	9,817
	Energy outputs (MJ ha^{-1})							
Ethanol	121,163	93,469	188,422	145,354	118,405	89,703	119,263	79,508
Co-products[a]	23,704	18,286	47,271	36,466	65,016	46,045	47,221	31,481
Total	144,867	111,755	235,692	181,820	189,242	139,630	166,484	110,989
	Net energy or ethanol production							
Efficiency (out/in)	1.40	1.40	2.23	2.23	3.05	2.87	10.76	11.31
Net (out–in)	41,397	31,955	130,180	100,378	127,248	90,998	151,013	101,172
Ethanol yield (l ha^{-1})	5,701	4,398	8,866	6,839	5,571	4,221	5,612	3,741

[a] Co-products include distillers grains, alfalfa leaf meal, and excess electricity

harvest and alfalfa–corn fell in between the extremes of our continuous corn without stover harvest and switchgrass systems. Our net energy ratio for continuous corn with stover harvest at 2.23 was similar to that of Sheehan et al. [41] at 2.38. In our analysis, net energy produced (outputs–inputs) per hectare was greatest for switchgrass, followed by continuous corn with stover harvest, and finally alfalfa–corn (Table 8). Continuous corn without stover harvest always generated the least net energy.

Crop System Environmental Impacts

IFSM simulations estimated the alfalfa–corn rotation to have 2.0 to 4.8 times less N leaching and 1.3 to 4.7 times less denitrification than either the continuous corn or switchgrass systems (Table 9). This is due to the greatly reduced N fertilizer requirements of the alfalfa–corn rotation. IFSM estimated that continuous corn would have about 60% more erosion than alfalfa–corn. This reduction is due to reduced soil tillage and greater soil cover provided by the perennial alfalfa crop. Because of its excellent soil cover and absence of tillage, switchgrass had very little soil erosion.

Table 9 Annual N leaching and denitrification and erosion for the three crop systems as estimated by the IFSM model

	Continuous corn		Alfalfa–corn		Switchgrass	
	High	Normal	High	Normal	High	Normal
Leaching (kg N ha^{-1})	16.1	8.5	3.4	3.1	8.1	6.3
Denitrification (kg N ha^{-1})	39.1	24.3	8.3	6.9	13.8	9.1
Erosion (kg ha^{-1})	2,307	2,307	1,471	1,473	78	78

Discussion

Our analysis of production costs, farm profits, and energy balances for potential biofuel crop systems in the Upper Midwest shows why there is a focus on using corn to produce ethanol. For our scenarios, the continuous corn with stover harvest system could potentially produce the most ethanol yield and net energy per hectare, while potentially returning a good profit to farmers. This is an important energy asset when considering the sheer volume of ethanol that will need to be produced if it is expected to be a realistic replacement for gasoline and oil. However, continuous corn was also the least efficient producer of energy, generating only about 2.0 times the amount of energy that it consumes during crop production, crop and co-product transportation, and ethanol production. Continuous corn also suffers from relatively great soil erosion [12] and fertilizer N requirements, which often translates into N loss to the environment. Both erosion and N loss lead to environmental degradation [1, 22] and raise concerns about the sustainability of continuous corn for biofuel generation. Finally, our analysis indicates that when cellulosic ethanol technologies begin to mature, producing ethanol from corn grain alone (i.e., without stover harvest or instead of switchgrass or an alfalfa–corn rotation) will not make much sense.

Our analysis shows that rotating alfalfa into a continuous corn system could increase the efficiency of energy production by about 33%, and decrease on-farm energy requirements by about 38%. However, it would also decrease ethanol yield per hectare by about 35%, but net energy yield per hectare by about only 6%. Future alternative management practices for alfalfa, such as a single cut system, in-field separation of stems and leaves [43], and establishment of alfalfa within the final year of a corn crop to increase first-year alfalfa yields [10], could all help improve the energy and ethanol yield of an alfalfa–corn rotation. For example, a one-cut alfalfa production system where alfalfa is interseeded with the last year of corn to make first-year alfalfa yields equal to typical production years would increase ethanol yield by 4%, net energy production per acre by 13% (making it nearly equal to continuous corn with stover harvest), and efficiency of net energy production by 6%. Such a system would also reduce alfalfa production costs per hectare by 19% and production costs per hectare across the entire alfalfa–corn rotation by 7%, and would increase potential income per hectare for the entire rotation by $170 to $240, depending on commodity prices.

Our economic analysis indicates farmers could certainly profit from an alfalfa–corn rotation, and sometimes more than if alfalfa hay was produced directly as an animal feed rather than for ethanol and leaf-meal production. However, rotating alfalfa into corn will greatly reduce the need for N fertilizer use and the risk of N loss from farms to the environment [6, 31]. Rotating alfalfa with corn should also reduce soil erosion [2]. These environmental benefits of alfalfa should increase the sustainability of biofuel crop systems, but are unfortunately benefits that do not easily manifest themselves in energy balance and farm economic analyses such as ours.

Compared to continuous corn or alfalfa–corn crop systems, switchgrass was by far the most efficient producer of net energy, generating about 11 times the energy consumed. Switchgrass also produced the greatest amount of net energy per hectare, but the least amount of ethanol. Switchgrass may not return the potential income to farmers that alfalfa and corn could unless both switchgrass prices to farmers were at least \$83 Mg^{-1} and yields were at least 11 Mg ha^{-1}. Both of these conditions may not be readily achieved given present economic forecasts for cellulosic ethanol production [50] and yields in commercial production environments [36]. If switchgrass yields can someday approach 16 to 18 Mg ha^{-1}, switchgrass can efficiently produce high volumes of ethanol and net energy at a good profit for farmers. However, switchgrass yields are often low the first year or two after establishment, and may not reach optimal yields until the third year [36]. Switchgrass may also require significant annual N fertilizer to produce high yields [28, 49], which may pose an N leaching risk, but likely less than that for corn. Given it is a perennial crop that will likely by grown for at least 10 years, switchgrass may also limit the potential of agricultural lands producers may need for shorter crop rotations. Instead, switchgrass may be better suited to marginal or erosion-prone agricultural lands already set aside from traditional crop rotations, such as in the Conservation Reserve Program [48, 52] or in riparian buffer strips [46]. Farmers may also benefit financially from CRP payments or buffer programs when using switchgrass in such scenarios, although the CRP regulations would have to change to allow harvest. Given switchgrass is a fairly new crop for farmers with a variety of economic and agronomic unknowns, its production as a bioenergy feedstock could be more complex than for corn or alfalfa, which already have well-established production systems [18].

Clearly, our analysis of production costs, energy balances, and environmental impacts of potential biofuel crop systems demonstrates that different systems will have both advantages and disadvantages. Production of one system over another will likely depend on a variety of factors, including the ability and need to produce a given volume of ethanol, the desire to protect environmental quality and natural resources, the promotion of rural economic growth and stability, and current and future farm production strategies and goals. It is thus likely, and perhaps most desirable, that cellulosic ethanol feedstock production will consist of a variety of crop systems that meet the needs and abilities of different regions and individual producers within those regions. For example, highly erodible lands may be best suited to permanent switchgrass production, while areas with environments sensitive to non-point source N pollution may be best served by alfalfa–corn rotations.

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