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Farm-scale costs and returns for second generation bioenergy cropping systems in the US Corn Belt

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Abstract

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Keywords

Agronomy, Economics, bioenergy, biofuel, financial analysis, farm profitability, Landscape Biomass

Disciplines

Agricultural Economics | Agronomy and Crop Sciences | Natural Resources Management and Policy

Comments

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Farm-scale costs and returns for second generation bioenergy cropping systems in the US Corn Belt

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Abstract

While grain crops are meeting much of the initial need for biofuels in the US, cellulosic or second generation (2G) materials are mandated to provide a growing portion of biofuel feedstocks. We sought to inform development of a 2G crop portfolio by assessing the profitability of novel cropping systems that potentially mitigate the negative effects of grain-based biofuel crops on food supply and environmental quality. We analyzed farm-gate costs and returns of five systems from an ongoing experiment in central Iowa, USA. The continuous corn cropping system was most profitable under current market conditions, followed by a corn–soybean rotation that incorporated triticale as a 2G cover crop every third year, and a corn–switchgrass system. A novel triticale–hybrid aspen intercropping system had the highest yields over the long term, but could only surpass the profitability of the continuous corn system when biomass prices exceeded foreseeable market values. A triticale/sorghum double cropping system was deemed unviable. We perceive three ways 2G crops could become more cost competitive with grain crops: by (1) boosting yields through substantially greater investment in research and development, (2) increasing demand through substantially greater and sustained investment in new markets, and (3) developing new schemes to compensate farmers for environmental benefits associated with 2G crops.

Keywords: bioenergy, biofuel, financial analysis, farm profitability, Landscape Biomass Project

S Online supplementary data available from stacks.iop.org/ERL/8/035037/mmedia

1. Introduction

With the passage of the Energy Independence and Security Act (EISA) of 2007, the US established an aggressive agenda to reduce dependency on fossil fuels and foreign oil. Demand for liquid biofuel and biofuel feedstocks have grown in response (Sorda *et al* 2010). While EISA acknowledges that grain-derived ethanol will meet much of the initial need, cellulosic biomass (hereafter, second generation or 2G) feedstocks are mandated to provide a growing portion of the biofuel supply. The expanded Renewable Fuel Standard (RFS2) specifically states that no less than 16 billion gallons of biofuels must be produced from 2G sources by 2022 (USEPA 2010). Because such a mandate reduces the risk of investing capital, RFS2 should improve interest in building 2G biofuel production facilities (Schnepf and Yacobucci 2012).

2G feedstocks show numerous potential environmental advantages compared to grain-based systems, including reduced energy and nitrogen inputs, higher rates of energy return, improvements to soil quality, greater soil carbon sequestration, positive impacts on water quality, and reduced greenhouse-gas (GHG) emissions (Tilman *et al* 2009). 2G feedstocks also avoid potential competition between food and fuel systems (Tilman *et al* 2009). Yet, while the US has met established goals for grain-derived ethanol, the capacity to meet goals for producing 2G biofuels is lacking nationally and especially in the US Corn Belt, which otherwise affords substantial natural and infrastructural resources to support biofuel production (USDA 2010). Corn stover has dominated 2G research and development in the Corn Belt. Yet, it is unlikely that a single crop will meet all purposes in all agroecosystems, as crop performance can vary considerably with edaphic conditions (Thelemann *et al* 2010), and many other candidate biomass crops—especially perennial crops—are known to have a more positive impact on the environment (Asbjornsen *et al* 2013). A portfolio approach to 2G feedstocks is needed (Tilman *et al* 2009), in which potential feedstock, harvest–transport–storage, and conversion systems to be included in the biofuel portfolio are developed, tested, and compared to conventional systems prior to their implementation over field, landscape, and regional scales.

Agricultural residues and double, mixed, and perennial crops have been proposed as 2G crops because they do not compete with demand for food crops and because they can mitigate some environmental impacts associated with grain production (Tilman *et al* 2009). While research and investment in grain crops has been substantial, support for other sources of biomass has been comparatively modest. To meet mandated demand for 2G biofuel, all avenues toward the production of cellulose must be investigated and pursued.

We sought to inform the development of the 2G crop portfolio by assessing the profitability of novel biomass cropping systems that potentially mitigate negative effects of grain-based biofuel crops on food supply and/or environmental quality. To this end, we analyzed farm-gate costs and returns of five 2G systems associated with an ongoing experiment in central Iowa, USA. The five 2G systems include (1) *continuous corn*, in which agricultural residue in the form of stover serves as a 2G feedstock, (2) *soybean–triticale/soybean–corn (hereafter, 'modified rotation')*, which supplements the conventional corn–soybean rotation with triticale as a winter cover and 2G crop, (3) *corn–switchgrass*, a mixed cropping system using corn as a harvestable nurse crop as the 2G switchgrass establishes, (4) *triticale/sorghum*, a double cropping system in which triticale serves as a winter cover and 2G crop followed by a 2G sorghum crop, and (5) *triticale–aspen*, a mixed cropping system in which triticale is planted between rows of trees and serves as a cover and 2G crop in the first three years that the high-yielding 2G woody crop is establishing. Because of differences among systems in the length of the production cycle, our economic analysis is based on long-term enterprise budgets. To inform farm-level financial planning and the development of a more diversified bioenergy industry, we also present breakeven prices at fixed yields and breakeven yields at fixed prices. To our knowledge, a profitability analysis has never been previously published on any of the systems addressed here. Although similar work has been conducted on corn–soy, full-season sorghum, switchgrass, and other systems (Hallam *et al* 2001, James *et al* 2010, Turhollow and Epplin 2012), our analysis is new in that the novel systems are compared to one another.

2. Methods

Our analysis considers the costs of production to the field edge. Costs associated with transporting biomass are ignored in this analysis, as these costs could vary significantly depending on the proximity of individual farms to the nearest biomass collection or processing facility. Yield and management data for the five 2G cropping systems were derived from an ongoing experiment, referred to as the 'Landscape Biomass Project' (www.nrem.iastate.edu/landscape/content/landscape-biomass-project-agronomic-economic-and-environmental-performance-biomass-cropping), established in fall 2008 on an Iowa State University Research and Demonstration Farm in central Iowa, USA (41°55′53″N, 93°45′45″W) (figure 1). Yield data were collected from 2009 to 2011 and projected to a 12-year planning horizon except the triticale–aspen intercrop system, which was projected to a 20-year planning horizon due to the longer life of hybrid aspen stands relative to the other systems. The assumed lifespan of the switchgrass and hybrid aspen stands is equal to the number of years in their respective planning horizons. Enterprise budgets were constructed using standard practices for agronomic cost and return estimates (CIMMYT 1988, AAEA 2000). Production costs were not allocated across multiple revenue streams within individual systems; instead, each system was considered as a single entity producing multiple outputs. We used a 3% real rate when discounting future costs and returns. Because the cropping systems are analyzed over multiple years, we computed an annual annuity with the same net present value as the 12- or 20-year system, as a means to compare profitability, using the following equation:

$$A = \mathrm{PV}\left[\frac{r(1+r)^T}{(1+r)^T - 1}\right], \qquad (1)$$

where PV is the net present value of the system for the entire planning horizon, r is the discount rate (0.03 in this case), and T is the number of years over which the payments are received (12 or 20 in this case).

Crop cultivars used in this experiment were selected based on appropriateness for the local climate, high yield potential, and availability. We used Pioneer 34A20 corn (*Zea mays* L.) seed in all years. The two switchgrass (*Panicum virgatum* L.) cultivars used were Kanlow (hereafter, KAN) and Cave-in-Rock (hereafter, CIR). The hybrid aspen clone used in this experiment was Crandon (*P. alba* x *P.*

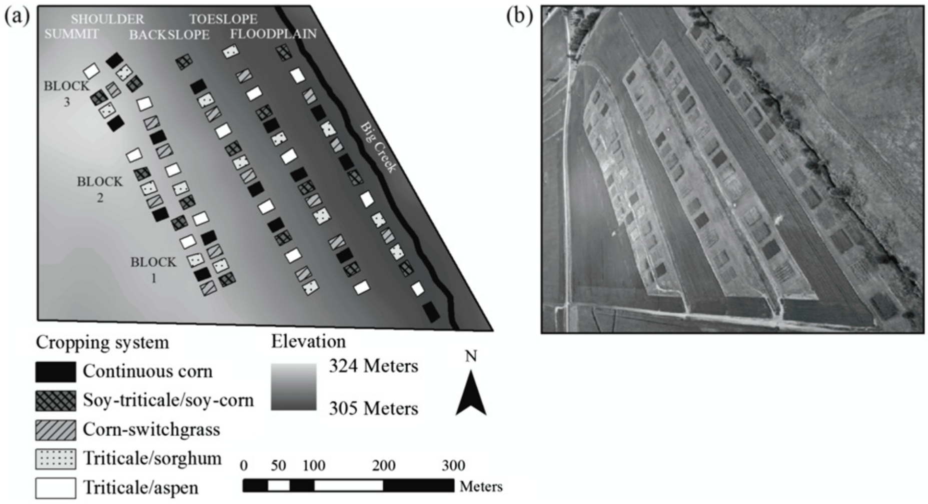

Figure 1. (a) Diagram detailing Landscape Biomass Project plot locations from an overhead perspective and (b) an aerial photo of the site from the same perspective as the diagram (photo credit: Tom Schultz).

Table 1. Unit prices for land rent, planting materials, fertilizers, and herbicides.

Input	Unit	Unit price (US$)	Source
Land rent	ha	568.33	ISU (2012b)
Aspen bare root stock	Seedling	0.37	Iowa DNR state tree nursery
Corn seed	1000k	3.81	Survey of local suppliers
Sorghum seed	kg	5.27	Survey of local suppliers
Soybean seed	1000k	0.43	Survey of local suppliers
Switchgrass seed	kg	19.27	Survey of local suppliers
Triticale seed	kg	0.88	Survey of local suppliers
Nitrogen (N)	kg N	1.39	Survey of local suppliers
Phosphorus (P)	kg P	1.39	Survey of local suppliers
Potassium (K)	kg K	1.21	Survey of local suppliers
2, 4D	l	6.76	Survey of local suppliers
Atrazine	kg	8.13	Survey of local suppliers
Hornet WDG	l	156.90	Survey of local suppliers
Roundup	l	7.78	Survey of local suppliers
Volley	l	14.88	Survey of local suppliers

grandidentata). For the rest of the crops, the cultivar varied over the three years. In 2009 we planted Pioneer 92M61 soybeans (*Glycine max* L.), but in 2010 we used Pioneer 92Y30. There were no soybeans planted in 2011. In 2009 and 2010, half of each sorghum (*Sorghum bicolor* L.) plot was planted with Sugar T, while the other half was planted with TX09024. In 2011, all sorghum plots were entirely planted with M-81E. In 2009 and 2010, we used NE422T triticale (x *Triticosecale rimpaui* Wittm.), but in 2011 we planted a variety called Pika due to availability.

Table 2. Pre-harvest machinery costs and labor hours required. All values are presented on a per-hectare basis. Total cost excludes wages.

Operation/equipment	Total cost (US$)	Labor hours	Source
Boom sprayer	9.88	0.217	ISU (2009a)
Bulk fertilizer spreader	8.65	0.151	ISU (2009a)
Chisel plow	21.25	0.272	ISU (2009a)
Conventional drill	21.74	0.304	ISU (2009a)
Conventional planter	28.17	0.168	ISU (2009a)
No-till drill	32.37	0.405	ISU (2009a)
No-till planter	31.63	0.262	ISU (2009a)
Tree planting (custom hire)	481.85	N/A	ISU (2009b)

Costs of production are based on data collected from informal surveys of local agriculture supply companies, Iowa State University Agricultural Extension Service publications (ISU 2008, 2009b, 2009a, 2012b) and estimates from existing peer-reviewed literature (James *et al* 2010, Klepac and Rummer 2009, Langholtz *et al* 2011). Pre-harvest costs include land rent, machinery operations and associated labor, planting material, fertilizer, and herbicides (tables 1 and 2). The land rental rate was calculated by multiplying the average rental charge per bushel of corn produced in the surrounding area (\$1.59 bu^{-1}) (ISU 2012b) by our average corn yield (146 bu/ac). As these systems are being compared relative to one another, land rent is included in the budgets for all of the systems in every year. Harvest costs include machinery operations and associated labor (table 3). In all cases, 'staging' refers to the action of moving bales of material to a central location on the farm in preparation for transport. The assumed

Table 3. Harvest machinery costs and labor hours required. Total costs are presented on a per-hectare basis and exclude wages, unless otherwise noted.

Operation/equipment	Total cost (US$)	Labor hours	Source
Biobaler harvesting system[a,b]	44.10 dry Mg^{-1}	0.000	Klepac and Rummer (2009), Langholtz *et al* (2011)
Combine corn	79.07	0.516	ISU (2009a)
Combine soybeans	62.52	0.447	ISU (2009a)
Dry grain[a]	9.45 Mg^{-1}	0.000	ISU (2009a)
Feller buncher/forwarder[a,c]	28.67 dry Mg^{-1}	0.000	James *et al* (2010)
Grain cart	22.24	0.514	ISU (2009a)
Handle grain (auger)[a]	1.97 Mg^{-1}	0.385	ISU (2009a)
Haul grain on-farm[a]	3.14 Mg^{-1}	0.773	ISU (2009a)
Large square baler	48.18	0.378	ISU (2009a)
Mower-conditioner	24.96	0.366	ISU (2009a)
Rake	15.81	0.378	ISU (2009a)
Staging[a,c]	6.72 Mg^{-1}	0.000	ISU (2008)
Wood chipper[a,c]	13.23 dry Mg^{-1}	0.000	James *et al* (2010)

[a] Total cost per ha depends on yield.

[b] Wages included in total cost at \$11.70 h^{-1}.

[c] Custom hired service.

Table 4. Per-hectare inputs for each cropping system for years 1–3 based on experimental research logs.

	Continuous corn			Soy–triticale/ soy–corn			Corn–switchgrass			Triticale/sorghum			Triticale–aspen		
Inputs (units)	Y1	Y2	Y3	Y1	Y2	Y3	Y1	Y2	Y3	Y1	Y2	Y3	Y1	Y2	Y3
Planting material															
Corn seed (1000 kernels)	82	82	79			79	82								
Soybean seed (1000 kernels)				329	329										
Triticale seed (kg)					106					121	106	112	121	106	56
Switchgrass seed (kg)							6.72								
Sorghum seed (kg)										11.9	12.2	11.2			
Bare root stock (seedlings)													890		
Fertilizer															
Nitrogen (kg)	168	150	168			123	168		134	168	142	142	34	34	34
Phosphorus (kg)		65	61		56	56		63	56		56	56		56	56
Potassium (kg)		152	133		112	112		143	112		112	112		112	112
Herbicide															
2, 4D (l)			1.75			1.75	1.75	2.34	2.34	1.75					
Atrazine (kg)							2.24	2.24		2.24					
Hornet WDG (l)			0.22			0.22									
RoundUp (l)	1.75	2.12	1.9	3.5	3.8	1.9					1.9				
Volley (l)			2.34			2.34									

wage for machinery operation was \$11.70 h^{-1}. Based on these costs, budgets were constructed for each individual year for all of the treatments analyzed.

The inputs for years 1–3 all reflect our experimental protocol based on management logs and field data, with the exception of altered phosphorus and potassium application rates in years following corn production (table 4). In systems where corn stover is a revenue source, nutrient replacement was accounted for in the year following the harvest at rates of 2.9 kg P and 12.5 kgK/Mg of stover removed (ISU 2002). Unless stated otherwise, we used average input levels from the first three years to construct the budgets for subsequent years. The modified rotation was treated differently because it consists of a three-year rotation and we only had one year of data for each crop in the rotation. As such, we assumed that the exact same protocol would continue throughout subsequent years for each crop in the rotation. For the triticale–aspen treatment, we based our protocol and yield expectations beyond the third year on a combination of experimental data from our and other nearby research sites (Goerndt and Mize 2008, Zalesny *et al* 2011, Hall 2012). In the corn–switchgrass system, separate economic analyses were conducted to reflect differences in yield between the KAN and CIR varieties. We also tested two different harvest rotation lengths for the trees in the triticale–aspen system. In one scenario, we looked at revenues from harvests that begin in year 4 and then occur every two years through year 20 (hereafter, 2YR). In the other scenario, harvests are carried out in years 10 and 20, and thinning is conducted between the rows in years 11 and 13 (hereafter, 10YR). Conducting separate analyses for the switchgrass varieties and aspen rotations brought the total number of cropping systems evaluated in the economic analysis to seven. Additional changes to the experimental protocol included the incorporation of tillage every fourth year for the continuous corn, modified rotation, and triticale/sorghum treatments and up-scaling of machinery to reflect typical central-Iowa farming operations. 'Up-scaling' refers to scaling up from the equipment used to conduct plot-level farm management to corresponding equipment of the size necessary to operate a typical Iowa row-crop farm. We accomplished this by assuming the use of a 165 horsepower tractor to pull all implements and a 275 horsepower combine for all grain harvests. Specific information about the inputs and operations included in the budget for each system is provided in the supplementary materials (supplementary data S1–S7 available at stacks.iop.org/ERL/8/035037/mmedia). Typical corn and soybean input costs for the region, determined by the USDA's Economic Research Service, are provided as supplementary material (supplementary data S8 available at stacks.iop.org/ERL/8/035037/mmedia).

Revenues for the first three years were calculated using our experimental yields. For the continuous corn, modified rotation, and triticale/sorghum systems, we used the average yield from the first three years as the yield for years 4–12. County-wide average yield data for corn grain and soybeans is provided in the supplementary materials (supplementary data S9 available at stacks.iop.org/ERL/8/035037/mmedia). For the corn–switchgrass and triticale–aspen systems, the yields beyond year 3 were projected based on data from our and other trials, making some adjustments for alternative fertilization rates. In systems where corn stover was collected, we assumed a 30% removal rate in the economic analysis. The marketed yields for all of the systems are provided as supplementary materials (supplementary data S10 available at stacks.iop.org/ERL/8/035037/mmedia). Methods for assigning unit prices for harvested crops varied depending on the market for each crop. Since there are abundant data on corn and soybean grain prices, these values were generated based on the average price paid to Iowa farmers from 2009 to 2011 (ISU 2012a). Thus, we evaluated the expected prices for corn and soybean grain at \$197.97 and \$445.73 Mg^{-1} (\$5.03 and \$11.32 bu^{-1}), respectively, for all years in the analysis. There are no such values available for evaluating the expected prices for biomass, as fully functioning markets for such material have yet to emerge. To develop an assumed unit price for biomass, we assessed current prices for similar baled crops and values assumed in previous studies (James *et al* 2010, Kou and Zhao 2011, USDOE 2011). Accordingly, we evaluated three different possible prices for biomass (\$40, \$80, and \$120 Mg^{-1}) and assumed that all feedstocks would provide equal returns per unit biomass. Operational markets might eventually result in variable prices depending on the energy value per unit biomass, ash content, and conversion costs associated with individual feedstocks, but we ignored this potential variability, as price expectations are only speculative at present.

We conducted a sensitivity analysis to develop understanding of how potential yield increases may affect cropping system profitability. In this analysis, we tested how yield increases of 10%, 25%, and 50% would affect the profitability of the systems at \$40, \$80, and \$120 Mg^{-1} biomass. In addition, we conducted an analysis to determine the precise biomass price (at current yields) and yield increase necessary for each of the systems to break even (i.e., annualized revenues equal to annualized costs) at the three aforementioned possible biomass prices. We only tested yield improvements associated with triticale, switchgrass, sorghum, and aspen biomass. Because corn stover yields are directly correlated with corn grain yields, the continuous corn system was not included in these analyses.

3. Results

3.1. Profitability analysis

At \$40 Mg^{-1} for biomass, only two of the seven treatments produced positive net revenue as represented by the annuity (figure 2(a)). At this biomass price, continuous corn is the most profitable system, with an annuity valued at \$260.91 ha^{-1}. The only other system with positive revenue was the modified rotation, which produced an annuity of \$180.66 ha^{-1}. The remaining systems produced annual net losses exceeding \$500 ha^{-1} at current yields. The net present value for each system is provided in the supplementary materials (supplementary data S11 available at stacks.iop.org/ERL/8/035037/mmedia).

At \$80 Mg^{-1} for biomass, continuous corn and the modified rotation remained the most profitable systems (figure 2(a)). However, the triticale–aspen 10YR system also became profitable at this biomass price, netting \$80.16 ha^{-1} annually. The other four treatments produced net losses that ranged from—\$202.27 ha^{-1} (corn–switchgrass KAN) to—\$605.09 ha^{-1} (triticale–aspen 2YR).

All but three of the treatments produced positive returns when biomass was valued at \$120 Mg^{-1} (figure 2(a)). Due to the greater disparity between harvest costs and revenues at this price, the triticale–aspen 10YR system was the most profitable, producing an annualized return of \$902.27 ha^{-1}. The next most profitable systems were continuous corn and the modified rotation at \$459.88 ha^{-1} and \$340.86 ha^{-1}, respectively. The corn–switchgrass system produced positive revenue with the KAN variety, netting \$159.37 ha^{-1}, but the CIR variety fell short of breaking even, with a net loss of \$6.71 ha^{-1}. The other two systems remained unprofitable at \$120 Mg^{-1}, having annual net losses of \$29.42 ha^{-1} for triticale/sorghum and \$494.40 ha^{-1} for triticale–aspen 2YR.

3.2. Market price and yield sensitivity analysis

Sensitivity analysis conducted on yield shows that potential yield increases of either 10% or 25% had little impact on the overall result: only the continuous corn and modified rotation were profitable at \$40 Mg^{-1} biomass (figures 2(b) and (c)). Given those same yield increases at \$80 Mg^{-1} biomass,

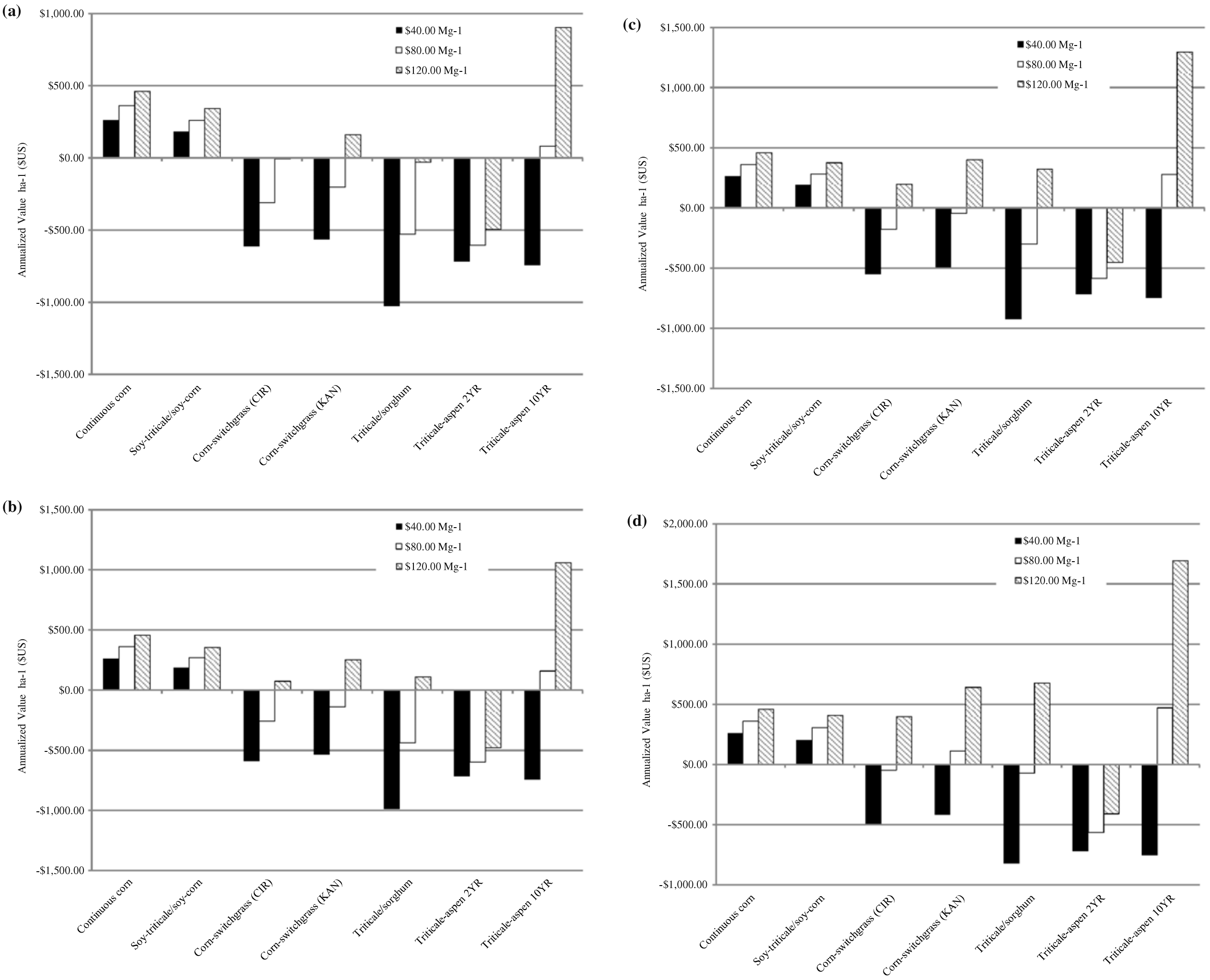

Figure 2. Annualized per-hectare value of all cropping systems (a) at current yield and with (b) 10%, (c) 25%, and (d) 50% yield increases for biomass crops, assuming biomass prices of \$40 Mg^{-1}, \$80 Mg^{-1}, and \$120 Mg^{-1}. Only yields of triticale, switchgrass, sorghum, and/or aspen biomass were altered in the yield increase scenarios. CIR = Cave-In-Rock seed variety, KAN = Kanlow seed variety, 2YR = trees harvested every 2 years (beginning in year 4), 10YR = trees harvested every 10 years.

triticale–aspen 10YR became profitable, and when the price of biomass was set at \$120 Mg^{-1}, all of the systems became profitable with a 10% yield increase with the exception of triticale–aspen 2YR.

With a 50% yield increase, the continuous corn and modified rotation were again the only profitable systems at \$40 Mg^{-1} biomass (figure 2(d)). However, the triticale/aspen 10YR and corn–switchgrass KAN systems also produced positive returns with a 50% yield increase when the biomass price was set at \$80 Mg^{-1}. When biomass was valued at \$120 Mg^{-1}, the only system that was not profitable was triticale–aspen 2YR.

3.3. Breakeven yield analysis

At current yields, breakeven prices for biomass in these 2G cropping systems, in descending order, are as follows: \$298.66 Mg^{-1} for triticale–aspen 2YR, \$122.36 Mg^{-1} for triticale/sorghum, \$120.89 Mg^{-1} for corn–switchgrass CIR, \$102.38 Mg^{-1} for corn–switchgrass KAN, and \$76.10 Mg^{-1} for triticale–aspen 10YR. Because the net returns from the grain harvest exceed the costs incurred during the stover harvest, the continuous corn and the modified rotation systems are profitable even if the value of the stover biomass is zero and so these systems were not considered in the status-quo breakeven price analysis.

At \$40 Mg^{-1}, relatively large yield increases would be required to make systems other than continuous corn and the modified rotation profitable (table 5). To break even at this price, the corn–switchgrass system would have to achieve switchgrass yields just over 24.5 Mg ha^{-1}, which equates to 252% and 194% yield increases for the CIR and KAN varieties, respectively. Similarly, the triticale/sorghum system would need a 248% yield increase to break even, from an average of 12.4 to 43 Mg ha^{-1}. Because the cost per dry Mg to harvest trees exceeds the price of biomass in this scenario, neither of the triticale–aspen systems would be able to break even at \$40 Mg^{-1} for biomass.

When biomass is priced at \$80 Mg^{-1}, the triticale–aspen 10YR system becomes profitable at current yields

Table 5. Yield increase (%) in triticale, switchgrass, sorghum, and/or aspen biomass necessary for each system to break even. CIR = Cave-In-Rock seed variety, KAN = Kanlow seed variety, 2YR = trees harvested every 2 years (beginning in year 4), 10YR = trees harvested every 10 years.

	Yield increase (%) to break even						
Biomass price (US$) ($Mg^{-1}$)	Continuous corn	Soy–triticale/ soy–corn	Corn–switchgrass (CIR) (%)	Corn–switchgrass (KAN) (%)	Triticale/ sorghum (%)	Triticale–aspen 2YR (%)	Triticale–aspen 10YR
$40.00	[a]	[a]	252	194	248	[b]	[b]
$80.00	[a]	[a]	59	33	58	759	[a]
$120.00	[a]	[a]	1	[a]	3	294	[a]

[a] System breaks even at current yield.

[b] System unable to break even at specified biomass price because harvest cost per dry Mg exceeds the assumed biomass price.

(table 5). Breakeven yield for corn–switchgrass would be 11.1 Mg ha^{-1}, which represents boosts of 59% and 33% for the CIR and KAN varieties, respectively. The breakeven yield for the triticale/sorghum system at this biomass price was 19.5 Mg ha^{-1}, an increase of 58%. The triticale–aspen 2YR system would require a yield increase of 759% to break even in this scenario.

When biomass is priced at $120 Mg^{-1}, the triticale–aspen 10YR system is the most profitable system and the corn–switchgrass KAN system becomes profitable at current yields (table 5). The corn–switchgrass CIR system and the triticale/sorghum system nearly break even at this biomass price, but would require 1% and 3% yield increases, respectively. The triticale–aspen 2YR system would require a 294% yield increase to break even in this scenario.

4. Discussion

The costs and returns evaluated in this study support the continued dominance of grain crops in the US Corn Belt based on current market economics. Even in the unlikely circumstances of $120 Mg^{-1} for biomass, most of the 2G crops evaluated failed to match the large economic returns associated with corn and soybean systems. However, our analysis also showed that rotations of annual grain crops can remain profitable when incorporating a 2G crop as a winter cover crop, which offers one potential solution for improving the environmental performance of corn production (Heggenstaller *et al* 2008). Comparatively, the triticale/sorghum double cropping system was never profitable under the market scenarios tested. Allowing that our yields were somewhat compromised by weather-induced delays of some field operations, it is unlikely that improved management alone would result in a large enough revenue boost to overcome production costs unless biomass prices are far in excess of what we believe to be feasible.

Switchgrass is being widely pursued as a 2G crop and provides moderate biomass productivity and some environmental benefits, such as improved soil quality, soil stabilization, and water filtration. Although generally not as productive as corn, it requires fewer nutrient inputs, and McLaughlin and Walsh (1998) estimate that the efficiency of energy production from switchgrass could exceed that of corn by as much as 15-fold. While its production can be economically competitive (McLaughlin and Kszos 2005) and high-yielding in Iowa (Lemus *et al* 2002), a major constraint to switchgrass as a 2G crop is the time required to establish stands and obtain maximum production. A more economically competitive option is to establish switchgrass beneath a companion crop of corn (Hintz *et al* 1998), which was the case we evaluated. We found, however, that substantial yield boosts would be required for either of the varieties assessed to be profitable under reasonable market scenarios. We expect that some gains in yield are achievable through improved management; however, even if biomass prices were $80 Mg^{-1}, switchgrass yields would have to improve by over 30% to break even. With management for higher yields, net returns may be higher depending on the costs of achieving them. For instance, achieving higher yields through increasing fertilization rates may be less cost effective than altering the timing of management actions. Regardless, the environmental benefits associated with this crop may make it a viable alternative on some portions (including, but not exclusively, marginal lands) of the agricultural landscape (Tilman *et al* 2009, Gelfand *et al* 2013).

We further found the triticale–hybrid aspen intercropping system to have the highest average yield when conducting harvests on a 10-year rotation, but the profitability of the continuous corn system was only surpassed when biomass prices exceeded foreseeable market values. Woody 2G crops offer numerous additional advantages that recommend them as a critical component of the overall feedstock portfolio: an average of over 18.1 Mg ha^{-1} yr^{-1} can be grown on a variety of soils and landscape positions (Zan *et al* 2001, Goerndt and Mize 2008, Zalesny *et al* 2009), on-demand harvest that reduces storage needs, high energy output:input ratios of up to 55:1 (Keoleian and Volk 2005), and associated environmental benefits that can be significant (Kort *et al* 1998, Udawatta *et al* 2002, Schultz *et al* 2004, Righelato and Spracklen 2007). Of the bioenergy cropping systems we evaluated, NO_3–N concentrations in soil water were lowest under the triticale–aspen system (Welsh 2011) and the concentration of this pollutant never exceeded levels set by the US Environmental Protection Agency for concentration in surface waters used as a source for drinking water (USEPA 1986). Pollutant concentrations in soil water also remained below recommended total N levels for streams and rivers to prevent potential damage to aquatic ecosystems in the region (USEPA 2000). Despite the many benefits of woody 2G crops, a key drawback to their use is the lag time in bringing a new planting to full production (~10 yr). We proposed an intercropping system using winter triticale to overcome this constraint. Theoretically, incorporating a winter annual between rows of trees could allow near-term 2G biomass during the establishment of the more productive woody system. We found, however, that the cost of managing the annual crop outweighed the benefits under existing market and harvest scenarios. Our aspen system would be more cost effective if the second 2G crop were eliminated and a low-cost perennial were established beneath the trees to provide weed control and other environmental benefits.

We perceive several barriers impeding the viability of the 2G crops we evaluated for the US Corn Belt. With high corn prices due to demand for feed and ethanol, the prices of agricultural inputs such as land and fertilizer are high enough to make most cropping systems focused on 2G crops unprofitable. For example, high land rental rates are currently the norm in this region due to historic high prices being garnered by corn and soybean. As others have suggested, biomass crops may be more economically competitive on less fertile lands (Gelfand *et al* 2013), which are less suitable for corn and soybeans and also carry lower rental rates. A second barrier has been the comparatively lower investment in the genetics and optimal management of alternative crops (NRC 2011). For example, traditional breeding techniques have led to increased switchgrass yields of 20–30% (McLaughlin and Kszos 2005); greater increases are expected through further investments in genetics and improved management (Schmer *et al* 2008). Lastly, high cost associated with harvest operations poses a third barrier to the adoption of 2G crops. In this study, as well as that of James *et al* (2010), harvest operations were responsible for a large portion of the total production cost for systems tested. Not including the cost of staging, the harvest costs for sorghum, triticale, and switchgrass total nearly \$90 ha^{-1}. In the triticale–aspen 10YR system, we assumed the farmer would hire a timber harvesting contractor to extract the biomass with a feller buncher and forwarder and then grind the material into chips. We adapted figures from James *et al* (2010) to estimate the cost of these contracted services at \$41.90 dry Mg^{-1}. For the triticale–aspen 2YR system, we assumed that the harvests would be conducted using a BioBaler, which is an implement capable of cutting and baling stems with diameters as large as 10 cm. By adapting data from other studies (Klepac and Rummer 2009, Langholtz *et al* 2011), we estimated the cost to the field edge for a BioBaler harvesting system to be \$44.10 dry Mg^{-1}. However, the highest price cited for woody biomass in Iowa is approximately \$99 dry Mg^{-1} (Randall 2012). Since harvest costs are currently consuming nearly half of this prospective revenue, little incentive exists for farmers to enter into the currently risky woody biomass market until the harvest costs are significantly reduced.

Regardless of the potential to improve productivity and reduce costs associated with the production of 2G crops, robust markets for the biomass do not currently exist in the US Corn Belt. The prices used in our analysis were based on literature review because market-based data do not exist, and may or may not turn out to be reasonable once robust markets develop. Indeed, while our analysis assumes that all biomass will be equally valued, future markets for biomass may develop such that feedstocks with higher energy output:input ratios or improved environmental performance draw higher prices. For example, recent studies are attempting to quantify the external costs associated with bioenergy production (Kusiima and Powers 2010) and to develop payments for ecosystem services for bioenergy producers that take advantage of more environmentally friendly options, such as switchgrass (Chamberlain and Miller 2012). Our findings suggest that substantial investments will be required and must be sustained to initiate market development surrounding 2G biomass, as the development of a sophisticated market is contingent upon investment in an infrastructure network to store and process large feedstock quantities. Should these factors become reality, 2G feedstocks could become competitive with grain crops. On the other hand, some of the crops used in our experiment could also be sold for uses unrelated to bioenergy production—including forage, fiber, or solid wood products—thus giving farmers an opportunity to capitalize on higher prices in alternative markets when biomass prices are low.

5. Conclusions

Our analysis underscores the fact that there are few incentives at present for farmers to adopt 2G feedstock production beyond agricultural residues in the US Corn Belt. In the near term, bioenergy production is likely to be dominated by corn-based systems due to high prices garnered by grain, large investments in seed technology and crop management, and well developed existing infrastructure. While alternative crops could be more competitive on land that does not produce high corn yields (Gelfand *et al* 2013), markets for biomass are not mature enough to encourage large-scale adoption.

We perceive three ways 2G crops could become more cost competitive by: (1) boosting yields through significantly greater investment in research and development, (2) creating more demand through substantially greater and sustained investment in new markets, and (3) developing schemes to compensate farmers for environmental benefits associated with second generation biomass crops. It is likely that all three pathways will need to be pursued simultaneously for the ideals inspiring mandates for 2G biofuels to be realized. In the absence of such conditions, there is little reason to believe 2G biofuel mandates will be met. Substantial and consistent public and private investment is needed to establish mature 2G bioenergy markets.

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