Published May, 2010

Cropping Systems

Fossil Energy Use in Conventional and Low-External-Input Cropping Systems

Michael J. Cruse, Matt Liebman,* D. Raj Raman, and Mary H. Wiedenhoeft

ABSTRACT

Conventional agriculture production systems in developed countries rely heavily on fossil energy, but emerging uncertainties in energy supply indicate a need to better understand energy efficiency in conventional and alternative systems. We used 6 yr of data from a cropping systems experiment conducted in Iowa to compare energy use of a conventionally managed corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] system (a 2-yr rotation) with two low-external input (LEI) cropping systems that used more diverse rotations and manure, but substantially lower quantities of synthetic N fertilizer and herbicides. Depending on how fossil energy costs were assigned to manure, the two LEI systems (a 3-yr rotation of corn-soybean-small grain/red clover [*Trifolium pratense* L.], and a 4-yr rotation of corn-soybean-small grain/alfalfa-alfalfa, *Medicago sativa* L.) used between 23 and 56% less fossil energy than did the conventional system. In general, the primary category for fossil energy use in all systems was grain drying. The conventional 2-yr system used substantially more fossil energy embodied in synthetic fertilizers and pesticides than did the LEI systems. Economic return, harvested crop weight, and potential energy production of the conventional 2-yr and LEI 4-yr systems were similar. Efficiency ratios, including crop energy output and economic return per unit of fossil energy invested, were significantly higher in the LEI 4-yr rotation than in the conventional system. In coming years, if fossil energy prices rise significantly without concomitant increases in crop value, diversified LEI systems may become preferable to conventional cropping systems and used more widely.

Conventional agricultural production systems in developed countries rely heavily on fossil energy embodied in inputs such as N fertilizer, fuel for machinery operations and grain drying, and pesticides (Hill et al., 2006; Karlen et al., 1995; Kim and Dale, 2005; Miranowski, 2005; Rathke et al., 2007; Sijtsma et al., 1998). While the use of fossil fuels has increased yields and improved the consistency of agricultural production, heavy reliance on energy intensive inputs is also related to problems such as reductions in soil carbon stocks due to tillage (Franzluebbers, 2004; Reicosky et al., 2002), hypoxic conditions in surface waters due to the overapplication and subsequent off-site transport of nutrients (Shepard, 2000; U.S. Environmental Protection Agency, 2007), and environmental contamination and pest resistance due to overapplication and inappropriate use of pesticides (Gilliom et al., 2006; National Research Council, 2000).

Following the oil shocks of the 1970s, which involved sudden reductions in fossil fuel availability and rapid increases in price, a number of analysts examined agriculture's relationships with fossil energy (Pimentel and Pimentel, 1979; Steinhart and Steinhart, 1974). Attention to that topic faded during the subsequent three decades of relatively stable supplies and low fossil energy prices. However, current uncertainties regarding the availability and prices of fossil energy sources, and significant changes in agricultural practices since the 1970s, point toward a need to revisit the relationship between agricultural production and energy use. Additionally, though many individual agricultural management practices have been shown to reduce dependence on fossil energy inputs (Khakbazan et al., 2008; Lockeretz et al., 1981; Noble and Christmas, 2008), the impacts of whole production systems that incorporate multiple alternative practices over time have received relatively little attention. This is especially important as agricultural systems are being evaluated for their ability to provide multiple goods and services, including protection of environmental quality, generation of adequate income, and food security (Boody et al., 2005; Robertson and Swinton, 2005).

Here we report on fossil energy use and production efficiencies in a multi-year, 9-ha comparative cropping systems experiment conducted in Iowa, within the central U.S. Corn Belt (Liebman et al., 2008). The experimental treatments encompassed a conventionally managed 2-yr rotation system (corn-soybean), and a 3-yr rotation (corn-soybean-small grain + red clover) and a 4-yr rotation (corn-soybean-small grain + alfalfa-alfalfa) managed with substantially lower inputs of synthetic fertilizers and herbicides. The 2-yr rotation is typical of cash grain systems in the region, whereas the 3- and 4-yr rotations are representative of LEI cropping systems in the region that are integrated with cattle (*Bos taurus*) production through the feeding of crops to livestock and the application of manure to crop fields.

M.J. Cruse, Dep. of Agronomy, Iowa State Univ., Ames, IA 50011 (current address: Dep. of Agronomy, Univ. of Wisconsin, Madison, WI 53706); M. Liebman, Dep. of Agronomy, Iowa State Univ., Ames, IA 50011; D. Raj Raman, Dep. of Agricultural and Biosystems Engineering, Iowa State Univ., Ames, IA 50011; M.H. Wiedenhoeft, Dep. of Agronomy, Iowa State Univ., Ames, IA 50011. Received 5 Nov. 2009. *Corresponding author (mliebman@iastate.edu).

Published in Agron. J. 102:934–941 (2010)
Published online 24 Mar. 2010
doi:10.2134/agronj2009.0457

AJ AGRONOMY JOURNAL since 1908

Abbreviations: LEI, low-external input.

Our energy analyses focus on what Gopalakrishnan (1994) considered to be "economic energy," or "forms of energy that command a price." This reduces the scope of energy sources to those that can be controlled directly by an individual's management decisions. For example, solar energy inputs are not included in our analyses, whereas fuel usage is. Energy measurements in our study were made on components that flowed across field boundaries (Fig. 1). Our study also takes a reductionist point of view in that it considers only in-field management of the cropping systems, which is a departure from past studies of agricultural energy use that have used wide system boundaries to attempt to quantify energy use in agriculture more holistically (Karlen et al., 1995; Hoeppner et al., 2006). While our approach reduces the scope of energy inputs and outputs, it focuses on key aspects of contrasting production systems, providing a clearer picture of differences among systems. Finally, it should be noted that agricultural energy analyses are often limited in their comparability across studies because boundaries of each individual study rarely match perfectly with the boundaries of another. In our work, the presence of both conventional and alternative production systems within the same experiment has allowed for the consistent use of energy values and the same system boundary design, giving power to comparisons made across the production strategies.

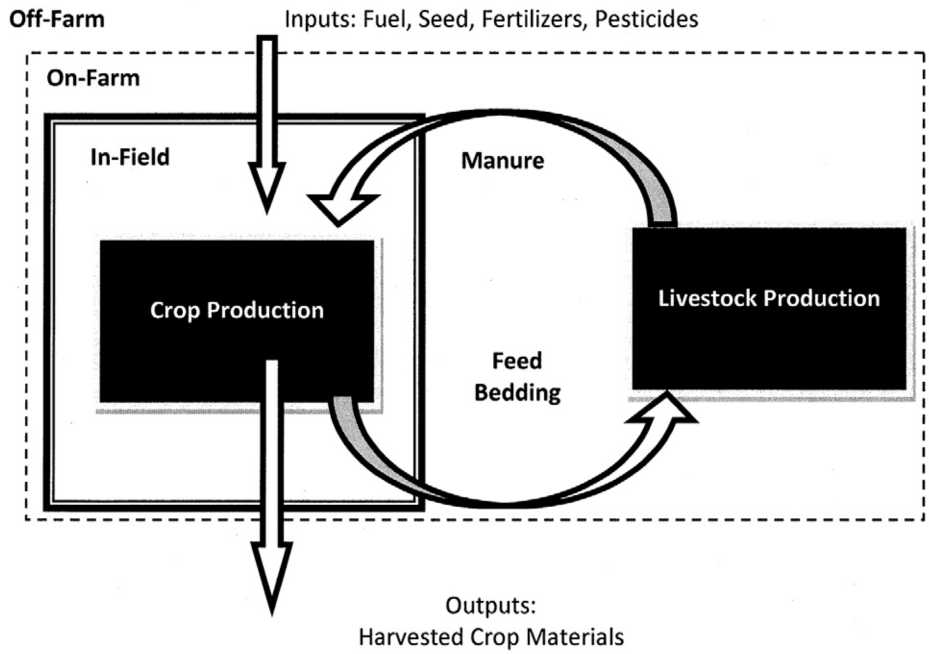

Fig. 1. Depiction of the system of interest. Inputs and outputs that cross the field boundary are the focus of our analyses.

MATERIALS AND METHODS

Research Site and Crop Management Practices

The cropping systems experiment from which we generated the data was conducted at the Iowa State University Marsden Farm, in Boone County, Iowa (42°01′ N, 93°47′ W; 333 m above sea level), on Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludolls), Nicollet loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), and Webster silty clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) soils. The 2-, 3-, and 4-yr rotation systems were compared during 2003 to 2008, a period encompassing large fluctuations in input costs and crop prices. The study was implemented using a randomized complete block design, with each crop phase of each rotation system present every year in the four replicate blocks. Plot size was 18 by 85 m. In the 3- and 4-yr systems, triticale was used as the small grain crop in 2003 to 2005, whereas oat (*Avena sativa* L.) was used in 2006 to 2008. Manure was applied in the 3- and 4-yr rotations before corn production at a mean dry matter rate of 10 Mg ha^{-1}, representing,

Table 1. Crop identities, planting and harvest dates, seeding rates, and row spacings used in 2007–2008. Data for 2003–2006 can be found in Liebman et al. (2008).

Year	Crop	Rotation system	Hybrid or cultivar	Planting date	Harvest date(s)	Seed density	Seed mass	Inter-row spacing
						seeds ha^{-1}	kg ha^{-1}	cm
2007	corn	all	Agrigold 6395	16 May	26 Oct.	79,534	–	76
2008	corn	all	Agrigold 6395	19 May	3 Nov.	79,534	–	76
2007	soybean	2-yr	Kruger 287RR	18 May	10 Oct.	400,140	–	76
2007	soybean	3-yr and 4-yr	Kruger K-2918	18 May	10 Oct.	400,140	–	76
2008	soybean	2-yr	Kruger 287RR	21 May	6 Oct.	382,850	–	76
2008	soybean	3-yr and 4-yr	Kruger K-2918	21 May	6 Oct.	382,850	–	76
2007	oat	3-yr and 4-yr	IN09201	9 Apr.	17 July	–	61	20
2008	oat	3-yr and 4-yr	IN09201	16 Apr.	8 Aug.	–	65	20
2007	red clover	3-yr	Duration	9 Apr.	–	–	13	20
2008	red clover	3-yr	Duration	16 Apr.	–	–	13	20
2006	alfalfa	4-yr	Farm Science Genetics 400LH	6 & 10 Apr.	2007: 6 June, 5 July, 9 Aug., 14 Sept.	–	17	20
2007	alfalfa	4-yr	Farm Science Genetics 400LH	9 Apr.	2007: 14 Sept.; 2008: 6 June, 1 Aug., 17 Sept.	–	17	20
2008	alfalfa	4-yr	Farm Science Genetics 400LH	16 Apr.	2008: 17 Sept.	–	17	20

Table 2. Synthetic and organic soil fertility amendments for crops grown in contrasting rotation systems in 2007–2008. Data for 2003–2006 can be found in Liebman et al. (2008).

Rotation system	Crop	2007	2008
2-yr	corn	112 kg N ha^{-1} as urea, at planting	78 kg P + 104 kg K ha^{-1}, before planting; 112 kg N ha^{-1} as urea, at planting; 101 kg N ha^{-1} as urea, side-dressed
2-yr	soybean	none	78 kg P + 104 kg K ha^{-1}, before planting
3-yr	corn	121 kg N + 70 kg P + 94 kg K ha^{-1} as composted manure, before planting	123 kg N + 52 kg P + 114 kg K ha^{-1} as composted manure, before planting; 101 kg N ha^{-1} as urea, side-dressed
3-yr	soybean	none	none
3-yr	small grain	none	none
4-yr	corn	121 kg N + 70 kg P + 94 kg K ha^{-1} as composted manure, before planting	78 kg P + 104 kg K ha^{-1}, before planting; 123 kg N + 52 kg P + 114 kg K ha^{-1} as composted manure, before planting; 101 kg N ha^{-1} as urea, side-dressed
4-yr	soybean	nnone	78 kg P + 104 kg K ha^{-1}, before planting
4-yr	small grain	none	78 kg P + 104 kg K ha^{-1}, before planting
4-yr	alfalfa	none	78 kg P + 104 kg K ha^{-1}, before planting

for the 4-yr system, about 70% of the manure that would be available on a farm where cattle were raised on the quantities of corn and forage obtained from our experimental plots. Soil samples were collected annually from all plots and subsequent applications of commercial fertilizers, based on test results, were tailored for each rotation system to achieve high crop yields. All crops were managed with standard farm machinery. Details of the farming practices and inputs used in the contrasting systems are provided by Liebman et al. (2008) and in Tables 1, 2, and 3.

Energy Inputs and Outputs

We used data from field logs concerning machinery operations, materials consumed, and crop production to determine energy inputs and outputs, and classified these data by year, rotation system, and individual crop. We considered five categories of energy inputs: field operations, seed, fertilizer, pesticides, and grain handling. Grain handling included both hauling harvested material out of the field and drying the material to standard storage conditions. Energy costs of grain storage were not included in our analyses, as they are part of grain marketing, not production. Grain drying energy costs were only applied to the corn crop, so as to imitate a standard Iowa production system, and were based on actual moisture concentrations of harvested corn and on a high temperature system with air circulation (Hellevang, 1994). Values for fuel usage associated with various field operations were taken from Hanna (2001). Hauling distances were set in our analyses to 0.8 km, one-way. Energy values for fuel, fertilizers, grain drying, and pesticides were taken from the Oak Ridge National Laboratory (2009) and Shapouri et al. (2004) and are shown in Table 4. All seeds used for planting were assumed to be produced with 1.5

Table 3. Mechanical and chemical weed management practices, and insecticides used for crops grown in contrasting rotation systems in 2007–2008. Dosages of active ingredients (kg ha^{-1}) are shown in parentheses. Data for 2003–2006 can be found in Liebman et al. (2008).

Rotation system	Crop	2007	2008
2-yr	corn	PRE†, broadcast: S-metolachlor‡ (1.14), isoxaflutole§ (0.088)	PRE, broadcast: S-metolachlor (1.14), isoxaflutole (0.088)
2-yr	soybean	POST¶, broadcast: glyphosate as isopropylamine salt# (2.25); lambda-cyhalothrin†† (0.035)	POST, broadcast: glyphosate as isopropylamine salt (2.25); lambda-cyhalothrin (0.014)
3-yr	corn	Interrow cultivation (1x); POST, banded: nicosulfuron‡‡ (0.013), rimsulfuron§§ (0.007), mesotrione¶¶ (0.053)	Interrow cultivation (1x); POST, banded: nicosulfuron (0.013), rimsulfuron (0.007), mesotrione (0.053)
3-yr	soybean	Interrow cultivation (2x); POST, banded: flumiclorac pentyl ester## (0.015), clethodim††† (0.051), lactofen‡‡‡ (0.053); lambda-cyhalothrin (0.035)	Interrow cultivation (2x); POST, banded: flumiclorac pentyl ester (0.015), clethodim (0.051), lactofen (0.053); lambda-cyhalothrin (0.014)
3-yr	triticale/clover or oat/clover	Stubble mowing (1x)	Stubble mowing (1x)
4-yr	corn	Interrow cultivation (1x); POST, banded: nicosulfuron (0.013), rimsulfuron (0.007), mesotrione (0.053)	Interrow cultivation (1x); POST, banded: nicosulfuron (0.013), rimsulfuron (0.007), mesotrione (0.053)
4-yr	soybean	Interrow cultivation (2x); POST, banded: flumiclorac pentyl ester (0.015), clethodim (0.051), lactofen (0.053); lambda-cyhalothrin (0.035)	Interrow cultivation (2x); POST, banded: flumiclorac pentyl ester (0.015), clethodim (0.051), lactofen (0.053); lambda-cyhalothrin (0.014)
4-yr	triticale/alfalfa or oat/alfalfa	Stubble mowing (1x), hay removal (1x)	Stubble mowing (1x), hay removal (1x)
4-yr	alfalfa	Hay removal (4x)	Hay removal (3x)

† PRE: preemergence application.

‡ S-metolachlor: acetamide, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)-,(S).

§ Isoxaflutole: 5-cyclopropyl-4-(2-methylsulfonyl-4-trifl uoromethylbenzoyl) isoxazole.

¶ POST: postemergence application.

Glyphosate: N-(phosphonomethyl) glycine in the form of its isopropylamine salt.

†† Lambda-cyhalothrin: (RS)-alpha-cyano-3-phenoxybenzyl 3-(2-chloro-3,3,3-trifluoropropenyl)-2,2,-dimethylcyclopropanecarboxylate.

‡‡ Nicosulfuron: 2-((4,6-dimethoxypyrimidin-2-yl)aminocarbonyl) aminosulfonyl-N,N-dimethyl-3-pyridinecarboxamide.

§§ Rimsulfuron: N((4,6- dimethoxypyrimidin-2-yl)amino]carbonyl)-3-(ethylsulfonyl)-2-pyridine sulfonamide.

¶¶ Mesotrione: (2-(4-methylsulfonyl)-2-nitrobenzoyl)-1,3-cyclohexanedione.

Flumiclorac pentyl ester: (pentyl(2-chloro-4-fl uoro-5-(1,3,4,5,6,7-hexahydro-1,3-dioxo2H-isoindol-2-yl)phenoxy)acetate.

††† Clethodim: (E)-2-(1-(((3-chloro-2-propenyl)oxy)imino)propyl)-5-(2-(ethylthio)propyl)-3-hydroxy-2–2cyclohenen-1-one.

‡‡‡ Lactofen: ethyl O{5-(2-chloro-a,a,a-trifluoro-p-toluoxy)-2-nitrobenzoyl}-DL-lactate.

Table 4. Fossil energy values for fuel, fertilizers, grain drying, and pesticides.

Input	Energy value	Units	Source
Diesel fuel	36.40	MJ L^{-1}	Oak Ridge National Laboratory (2009)
Nitrogen	56.97	MJ kg^{-1}	Shapouri et al. (2004)
Phosphorus	9.30	MJ kg^{-1}	Shapouri et al. (2004)
Potassium	6.97	MJ kg^{-1}	Shapouri et al. (2004)
Grain drying	4.65	MJ kg^{-1} of H_2O	Hellevang (1994)
Pesticides (active ingredient)	358.10	MJ kg^{-1}	Shapouri et al. (2004)

times the fossil energy used for regular harvested grain except for corn, for which a factor of 4.7 was used (Shapouri et al., 2004).

The appropriate energy value of manure is a topic subject to substantial debate, so we conducted two types of energy analyses. In the first analysis, manure was considered a waste product of a livestock operation and its only energy cost was energy used for application. We termed this analysis the "low-energy manure" analysis. A second energy analysis was conducted by adding the energy cost of application to the energy costs of the manure nutrients assessed as commercial fertilizers. The second analysis thus created considerably higher energy costs for manure, and was termed the "high-energy manure" analysis.

Weight outputs of crop materials were based on dry weights of recorded harvests. To determine energy outputs in crop materials, random samples of all harvested material were collected in 2008 from individual plots at each crop's harvest date. Samples were then dried at 60°C for 48 h, ground, and processed to determine their caloric values at the Central Analytical Laboratory, University of Arkansas Division of Agriculture. Samples from a single year were accepted as representative across all years because similar crop varieties were grown throughout the study and fertilizer rates did not vary widely throughout the study, which has been shown to influence seed composition (Miao et al., 2006). Higher heating values of crop materials are shown in Table 5.

Economics

Data sources for economic inputs were taken from Duffy and Smith (2003–2008). Crop prices for 2003–2007 were from USDA statistics (NASS, 2009b); prices for the 2008 marketing year are estimates from Iowa State University Extension specialists (Table 6). Crop prices represent the average price for the entire year after harvest in the state of Iowa. Crop subsidies were not included in our analyses. Labor costs are accounted for in our economic analyses at a rate of $10 per hour, but since energy input from labor was so small, labor energy was omitted.

Table 6. Prices for grain crops, straw and forage (National Agricultural Statistics Service, 2009a; Iowa State University Extension specialists).

Crop	Year					
	2003	2004	2005	2006	2007	2008
	U.S. $ kg^{-1}					
Corn	$0.09	$0.08	$0.08	$0.12	$0.17	$0.14
Soybean	$0.28	$0.21	$0.20	$0.24	$0.39	$0.32
Small grain†	$0.09	$0.08	$0.08	$0.13	$0.18	$0.19
Straw	$0.07	$0.07	$0.07	$0.07	$0.09	$0.09
Alfalfa hay	$0.09	$0.09	$0.09	$0.10	$0.13	$0.15

† Small grain crop was triticale during 2003–2005 and oat during 2006–2008.

Table 5. Higher heating values of harvested crop materials. Means and their standard errors are shown.

Crop	kJ g^{-1}
Corn grain	17.57 ± 0.21
Soybean grain	22.25 ± 0.13
Oat grain	18.18 ± 0.06
Oat straw	16.60 ± 0.25
Triticale (grain and straw)	16.47 ± 0.24
Alfalfa	15.46 ± 0.39

Similar to the two approaches used for energy analyses, we conducted two types of economic analyses. In the first type of analysis, representing a low-cost scenario, manure was considered a waste product of a livestock operation and was thus regarded as being free except for the application costs, consistent with the analysis pattern used by Liebman et al. (2008). A second economic analysis, representing a high-cost scenario, was conducted assigning commercial fertilizer prices to the nutrients within the manure so as to present a higher potential value of manure. Costs of fertilizer nutrients during 2003 to 2008 are shown in Table 7.

Statistics

Statistical analyses were conducted using SAS version 9.1.3 (Statistical Analysis Systems, Cary, NC) and the PROC MIXED function. Block and year were treated as random factors; cropping system (i.e., rotation) and crop were treated as fixed factors. Means were separated using Tukey's multiple comparison test with significance determined at the $\alpha = 0.05$ level.

RESULTS

Fossil Energy Inputs and Distribution

For both energy analyses, all cropping systems differed significantly in fossil energy inputs. The 2-yr rotation had the largest annual energy investment (Table 8); the low-energy manure analysis and high-energy manure analysis showed that the 3-yr rotation annually required 59 and 77%, respectively, and 4-yr rotation annually required 44 and 58%, respectively, of the energy invested in the 2-yr rotation. In Table 9, each rotation system is divided into five categories of fossil energy inputs: fertilizers, pesticides, field operations, seed, and grain handling. Grain handling, which includes drying, was the largest input category for both energy analyses and in all three rotations with the exception of the energy-valued manure analysis of the 4-yr rotation, where fertilizer inputs were the largest. Moisture concentrations of harvested corn in our study ranged from 170 to 221 g H_2O kg^{-1}. Compared to the 2-yr rotation, the 3- and 4-yr rotations had greater fossil energy requirements for field operations, but lower energy requirements for fertilizers and pesticides (Table 9). For all rotations and both energy analyses, corn was

Table 7. Commercial fertilizer prices on an elemental basis (adapted from Duffy and Smith, 2003–2008).

Year	N	P	K
	$ kg^{-1}		
2003	$0.44	$1.25	$0.31
2004	$0.55	$1.41	$0.40
2005	$0.66	$1.66	$0.48
2006	$0.77	$1.86	$0.61
2007	$0.68	$1.86	$0.61
2008	$1.01	$2.50	$0.72

Table 8. Fossil energy inputs and labor requirements for the three contrasting crop rotation systems, averaged across years (2003–2008). Within columns, means not marked with the same letter are significantly different ($p < 0.05$).

Rotation system	Low-energy manure scenario†	High-energy manure scenario‡	Labor input
	GJ ha^{-1} yr^{-1}		hr ha^{-1} yr^{-1}
2-yr	16.1 a	16.1 a	1.7 c
3-yr	9.5 b	12.4 b	2.7 b
4-yr	7.1 c	9.3 c	3.4 a

† Manure considered to have no fossil energy cost other than the energy used for its application.

‡ Fossil energy costs of manure considered to be equal to the energy costs of application plus the energy costs of nutrients within the manure assessed as commercial fertilizers.

Table 9. Fossil energy inputs separated into five selected categories for the three crop rotation systems, averaged across years (2003–2008).

Fossil energy inputs	Rotation system		
	2-yr	3-yr	4-yr
	GJ ha^{-1} yr^{-1}		
Low-energy manure scenario†			
Fertilizers	4.63	1.62	1.38
Pesticides	1.64	0.63	0.48
Field operations	1.26	1.53	1.58
Seed	0.32	0.24	0.18
Grain handling	8.29	5.47	3.47
High-energy manure scenario‡			
Fertilizers	4.63	4.56	3.58
Pesticides	1.64	0.63	0.48
Field operations	1.26	1.53	1.58
Seed	0.32	0.24	0.18
Grain handling	8.29	5.47	3.47

† Manure considered to have no fossil energy cost other than the energy used for its application.

‡ Fossil energy costs of manure considered to be equal to the energy costs of application plus the energy costs of nutrients within the manure assessed as commercial fertilizers

Table 10. Fossil energy inputs by crop for the three contrasting cropping systems during 2003–2008. Within each energy scenario, means within columns not marked with the same lowercase letter are significantly different ($p < 0.05$), and means within rows not marked with the same uppercase letters are significantly different ($p < 0.05$).

Fossil energy inputs	Rotation system		
	2-yr	3-yr	4-yr
	GJ ha^{-1} yr^{-1}		
Low-energy manure scenario†			
Corn	27.5 A a	22.4 B a	19.0 B a
Soybean	4.8 A b	3.9 B b	4.3 AB b
Small grain	–	2.2 A b	2.8 A b
Alfalfa	–	–	2.3 b
High-energy manure scenario‡			
Corn	27.5 A a	31.2 A a	27.8 A a
Soybean	4.8 A b	3.9 B b	4.3 AB b
Small grain	–	2.2 A b	2.8 A b
Alfalfa	–	–	2.3 b

† Manure considered to have no fossil energy cost other than the energy used for its application.

‡ Fossil energy costs of manure considered to be equal to the energy costs of application plus the energy costs of nutrients within the manure assessed as commercial fertilizers.

consistently the crop with the largest energy input levels and the crop that was significantly different from all others (Table 10).

Weight Output of Crop Materials

During the period 2003 to 2008, synthetic N fertilizer inputs were reduced 66% in the 3-yr rotation system and 78% in the 4-yr rotation system compared with the 2-yr system (Liebman et al., 2008; Table 2); similarly, herbicide use was reduced by an average of 80% in the 3-yr system and 85% in the 4-yr system (Liebman et al., 2008; Table 3). Despite these reductions in inputs, corn and soybean yields in the LEI 3- and 4-yr systems matched or exceeded levels obtained from the conventionally managed 2-yr system (Liebman et al., 2008; Table 11). Crop yields in all of the experimental systems were similar to, or greater than, mean yields of commercial farms in the surrounding county (NASS, 2009a) in all years of the experiment.

Mean weight output of crop materials for the 3-yr rotation was 96% of the output for the 2-yr rotation, whereas weight output from the 4-yr rotation was 7% higher when compared to the 2-yr rotation (Table 12). The only significant difference in weight output was found between the 3-yr and 4-yr rotations (Table 12). Ratios of crop weight/fossil energy input, using the energy-free manure analysis, increased with rotation length, with significant differences among all rotation systems (Table 13). Using the energy-valued manure analysis, the crop weight/fossil energy input ratios also increased with rotation length, but the only rotation that was significantly different from the others was the 4-yr rotation. In the 2-yr rotation, the corn crop weight/fossil energy input was lower and significantly different than the soybean ratio. For both energy analyses, in the 3- and 4-yr rotations, the corn and soybean crop weight/fossil energy input ratios were statistically similar and smaller than the other crops and the largest crop weight/fossil energy input ratio was realized in the 4-yr alfalfa crop (Table 14).

Energy Output

Potential energy outputs from each rotation were computed using the energy content values presented in Table 5. As shown in Table 12, the conventional 2-yr rotation system and the LEI 4-yr rotation system produced more energy than the LEI 3-yr rotation system, but did not differ from each other. For the low-energy manure scenario, the energy gain ratio (crop energy out/fossil energy in) was greatest for the 4-yr rotation, least for the 2-yr rotation, and intermediate for the 3-yr rotation; for the high-energy manure scenario, the energy gain ratio was still greatest for the 4-yr rotation, but the 2- and 3-yr rotations were smaller and statistically similar (Table 13). For both energy analyses, corn had the smallest energy gain ratio in all rotations, but was statistically similar to soybean in the 3- and 4-yr rotations. Alfalfa had the greatest energy gain ratio of all crops (Table 14).

Economic Return

Under the assumption that manure was an economically free input to cropping systems (other than labor and machinery costs for its application), Liebman et al. (2008) found that monetary return to land and management for the period of 2003 to 2006 was greatest in the 4-yr rotation, lowest in the 3-yr rotation, and intermediate for the 2-yr rotation. As shown in Table 12, using a similar assumption for the period of 2003 to 2008 led to a similar trend, although the differences among the rotation systems

Table 11. Yields of corn, soybean, oat, and alfalfa hay (at moisture concentrations of 155, 130, 140, and 150 g H_2O kg^{-1}, respectively) in contrasting crop rotation systems, in 2007 and 2008. Within rows, means not marked with the same letter are significantly different ($p < 0.05$). Data for 2003–2006 can be found in Liebman et al. (2008).

Crop	Year	Rotation system 2-yr	3-yr	4-yr
		Mg ha^{-1}		
Corn	2007	11.30 b	11.81 ab	12.28 a
Corn	2008	12.14 a	12.65 a	12.43 a
Soybean	2007	3.55 b	4.19 a	4.24 a
Soybean	2008	3.61 a	3.58 a	3.98 a
Oat†	2007	—	3.12 a	3.19 a
Oat†	2008	—	3.12 a	3.19 a
Alfalfa‡	2007	—	—	5.69
Alfalfa‡	2008	—	—	9.74

† Mean yield of harvested oat straw in the 3- and 4-yr rotations was 2.22 Mg ha^{-1} in 2007 and 2.70 Mg ha^{-1} in 2008.

‡ Total alfalfa hay yield for second-year stands. Mean first-year yield was 1.68 Mg ha^{-1} in 2007 and 1.00 Mg ha^{-1} in 2008.

were not significant. For the low-energy manure scenario, revenue returned to land and management per unit of fossil energy input was significantly lower for the 2-yr rotation than both the 3- and 4-yr rotations, which were not statistically significantly different from one another. However, for the high-energy manure scenario, the ratio for the 4-yr rotation was significantly higher than ratios for both the 2- and 3-yr rotations, which were not significantly different than each other (Table 13).

Pricing manure nutrients at levels commensurate with synthetic fertilizer reduced annual return to the 3- and 4-yr rotations by \$93 and \$69 ha^{-1}, respectively (Table 12). Under this high-cost manure scenario, a significant difference was found in economic returns between the 2- and 3-yr rotations, whereas the 2- and 4-yr rotations were not significantly different. Combined with the low-energy manure scenario, the economic return per unit of fossil energy input was significantly greater for the 4-yr system than for the 2-yr system; the 3-yr system was intermediate. Combined with the high-energy manure scenario, the economic return per unit of fossil energy input was also significantly greater for the 4-yr rotation, whereas the 2- and 3-yr rotations were statistically similar (Table 13).

On an individual crop basis, corn had the smallest economic return per fossil energy input for all crops regardless of rotation, economic analysis, or energy analysis; alfalfa had the largest ratio for economic return per fossil energy input (Table 15).

DISCUSSION

On a fossil energy input basis, the LEI 3- and 4-yr rotation systems required lower inputs than did the conventional 2-yr rotation. Results of this study also indicate that management at harvest time has a large potential impact on fossil energy use, as grain handling and more specifically grain drying accounted for proportionally the largest or second largest fossil energy input for all system analyses. Reducing consumption of energy for grain drying is challenging in northern latitudes where both farm size and length of growing season reduce the amount of time farmers can leave corn plants in the field to dry grain with solar energy. However, growing corn less frequently within a rotation sequence can decrease requirements for fossil energy for drying grain.

Table 12. Economic return and weight and energy outputs from the three contrasting crop rotation systems during 2003–2008. Within columns, means not marked with the same letter are significantly different ($p < 0.05$).

Rotation system	Economic return: Low-cost manure scenario†	Economic return: High-cost manure scenario‡	Weight output	Energy output
	— US \$ return ha^{-1} yr^{-1} —		kg crop material ha^{-1} yr^{-1}	GJ crop energy ha^{-1} yr^{-1}
2-yr	\$614 a	\$614 a	6680 ab	124 a
3-yr	\$605 a	\$512 b	6380 b	116 b
4-yr	\$624 a	\$555 ab	7170 a	126 a

† Manure considered to be a free input other than labor and machinery costs for application.

‡ Manure cost considered to be equal to labor and machinery costs for application plus costs of nutrients in manure assessed as commercial fertilizers.

For the low-energy manure scenario, much of the energy savings that was observed between the conventional 2-yr system and the LEI systems was due to reduced use of N fertilizer, which is consistent with the results of past research (Hoeppner et al., 2006). For the efficiency ratios presented, both LEI systems were more efficient than the conventional system. Most of the variability observed among systems in energy use efficiency ratios was due to differences in fossil energy input values, not in outputs from the systems. For the high-energy manure scenario, the difference between the conventional and LEI systems in fossil fuel energy input was reduced and consequently the differences in efficiency ratios were also reduced. The energy values for manure presented here are likely the two extreme values, with the real value being dependent on the configuration and management of the livestock operation.

Table 13. Energy use efficiency ratios for the three contrasting crop rotation systems during 2003–2008. Within rows, means not marked with the same letter are significantly different ($p < 0.05$).

Scenarios	Rotation system 2-yr	3-yr	4-yr
	Economic return/energy ratio		
Low-energy manure scenario†	— US \$ return GJ^{-1} fossil energy —		
Low-cost manure scenario§	\$47 b	\$84 a	\$107 a
High-cost manure scenario¶	\$47 b	\$73 ab	\$97 a
High-energy manure scenario‡			
Low-cost manure scenario	\$47 b	\$59 b	\$78 a
High-cost manure scenario	\$47 b	\$51 b	\$70 a
	Weight/energy ratio		
	— kg crop material GJ^{-1} fossil energy —		
Low-energy manure scenario	450 c	767 b	1122 a
High-energy manure scenario	450 b	555 b	827 a
	Energy gain ratio		
	— GJ crop energy GJ^{-1} fossil energy —		
Low-energy manure scenario	8.4 c	14.0 b	19.8 a
High-energy manure scenario	8.4 b	10.1 b	14.7 a

† Manure considered to have no fossil energy cost other than the energy used for its application.

‡ Fossil energy costs of manure considered being equal to the energy costs of application plus the energy costs of nutrients within the manure assessed as commercial fertilizers.

§ Manure considered to be a free input other than labor and machinery costs for application.

¶ Manure cost considered to be equal to labor and machinery costs for application plus costs of nutrients in manure assessed as commercial fertilizers.

Table 14. Energy use efficiency ratios, by crop, for the three contrasting crop rotation systems during 2003–2008. Within each energy scenario, means within columns not marked with the same lowercase letter are significantly different ($p < 0.05$), and means within rows not marked with the same uppercase letter are significantly different ($p < 0.05$).

Scenarios	Rotation system		
	2-yr	3-yr	4-yr
	Weight/energy ratio		
	— kg crop material GJ^{-1} fossil energy —		
Low-energy manure scenario†			
Corn	418 B b	587 AB b	695 A c
Soybean	677 B a	893 A b	809 A c
Small grain	—	2962 A a	2393 A b
Alfalfa	—	—	4037 a
High-energy manure scenario‡			
Corn	418 A b	381 A b	441 A c
Soybean	677 B a	893 A b	809 AB c
Small grain	—	2962 A a	2393 A b
Alfalfa	—	—	4037 a
	Energy gain ratio		
	— GJ crop energy GJ^{-1} fossil energy —		
Low-energy manure scenario†			
Corn	7.3 B b	10.3 AB b	12.2 A c
Soybean	15.1 C a	19.9 A b	18.0 B c
Small grain	—	50.9 A a	40.6 B b
Alfalfa	—	—	65.9 a
High-energy manure scenario‡			
Corn	7.3 A b	6.7 A b	7.8 A c
Soybean	15.1 C a	19.9 A b	18.0 B c
Small grain	—	50.9 A a	40.6 B b
Alfalfa	—	—	65.9 a

† Manure considered to have no fossil energy cost other than the energy used for its application.

‡ Fossil energy costs of manure considered being equal to the energy costs of application plus the energy costs of nutrients within the manure assessed as commercial fertilizers.

Table 15. Economic return to fossil fuel energy investment, by crop, for the three contrasting crop rotation systems during 2003–2008. Within each scenario, means within columns not marked with the same lowercase letter are significantly different ($p < 0.05$), and means within rows not marked with the same uppercase letter are significantly different ($p < 0.05$).

	Rotation system		
Scenarios	2-yr	3-yr	4-yr
	— US $ Return GJ^{-1} fossil energy —		
	Low-energy manure scenario†		
Low-cost manure scenario§			
Corn	$31 B b	$53 AB b	$59 A b
Soybean	$134 B a	$195 A ab	$167 AB b
Small grain	—	$242 A a	$141 A b
Alfalfa	—	—	$351 a
High-cost manure scenario¶			
Corn	$31 A b	$37 A b	$42 A c
Soybean	$134 B a	$195 A a	$167 AB b
Small grain	—	$242 A a	$141 A bc
Alfalfa	—	—	$351 a
	High-energy manure scenario‡		
Low-cost manure scenario			
Corn	$31 A b	$32 A b	$36 A c
Soybean	$134 B a	$195 A a	$167 AB b
Small grain	—	$242 A a	$141 A bc
Alfalfa	—	—	$351 a
High-cost manure scenario			
Corn	$31 A b	$22 B b	$25 AB c
Soybean	$134 B a	$195 A a	$167 AB b
Small grain	—	$242 A a	$141 A bc
Alfalfa	—	—	$351 a

† Manure considered to have no fossil energy cost other than the energy used for its application.

‡ Fossil energy costs of manure considered being equal to the energy costs of application plus the energy costs of nutrients within the manure assessed as commercial fertilizers.

§ Manure considered to be a free input other than labor and machinery costs for application.

¶ Manure cost considered to be equal to labor and machinery costs for application plus costs of nutrients in manure assessed as commercial fertilizers.

When considering manure as low-cost economic input, the monetary return to land and management was similar for all systems, whereas the use of commercial fertilizer prices for manure nutrients reduced returns for the LEI systems. The true economic value (price) of manure is dependent on local market conditions, but probably lies between the low and high costs examined in this study. The incorporation of alfalfa into the 4-yr rotation was important: in all economic analyses, the 4-yr rotation was significantly more efficient in energy use than the 2-yr rotation, whereas the 3-yr rotation was not (Table 13). Previous research has shown that the diversification of corn-based cropping systems through the addition of small grains and forage legumes can provide higher, more stable net returns (Meyer-Aurich et al., 2006).

Fossil energy use is not the only factor to be considered when choosing a cropping system. Labor and management requirements are also important factors influencing farmers' decisions. In our study, labor inputs followed an opposite trend to that seen for fossil energy inputs, with the 4-yr rotation having the largest input and the 2-yr rotation having the smallest input (Table 8). As compared with the 2-yr rotation, the 3-yr rotation required 54% more labor, whereas the 4-yr rotation required 91% more labor. All differences among systems were significant. It should be noted, however, that incorporation of small grain crops (triticale and oat) and alfalfa into the 3- and 4-yr rotation systems would place much of the extra time investment into parts of the year that do not overlap with peak activities associated with corn and soybean production.

For the management practices and economic conditions used for this study, our analysis shows that a conventional 2-yr rotation system widely used in the central U.S. Corn Belt (corn-soybean) relies on fossil energy to reduce labor requirements while allowing net economic returns to remain constant, effectively allowing greater wage rates for the producer. In this light, the energy intensiveness of industrial agriculture can be seen as an example of industrial processes permitting increased wages through the injection of fossil fuel and capital. Historically low energy prices during the 20th century, along with relatively high wages in the United States, have contributed to widespread adoption of energy-intensive farming practices. Nonetheless, our results show that diversified LEI systems can provide greater returns per unit of fossil energy invested, even though overall returns to land are similar to the conventional system.

In coming years, if demands from ethanol plants or overseas markets increase the price of corn grain faster than input costs rise (USDA, 2008), or if commercial-scale production of biofuels from corn stover becomes economically viable (Perlack et al., 2005), Midwestern cropping systems might become less diverse and more focused on corn. Alternatively, if fossil energy prices rise significantly without concomitant increases in crop value, diversified LEI cropping systems, such as those described in this study, may become preferable to conventional cropping systems and used more widely.

ACKNOWLEDGMENTS

We express our sincere thanks to David N. Sundberg for assistance with field operations and to Craig A. Chase for assistance with economic analyses. Funding for this study was provided by the USDA National Research Initiative (Projects 2002-35320-12175 and 2006-35320-16548) and the Leopold Center for Sustainable Agriculture (Projects 2004-E06 and 2007-E09).

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