Environ. Sci. Technol. **2010,** *44,* 4006–4011

Energy Efficiency of Conventional, Organic, and Alternative Cropping Systems for Food and Fuel at a Site in the U.S. Midwest

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Received November 13, 2009. Revised manuscript received February 24, 2010. Accepted March 22, 2010.

The prospect of biofuel production on a large scale has focused attention on energy efficiencies associated with different agricultural systems and production goals. We used 17 years of detailed data on agricultural practices and yields to calculate an energy balance for different cropping systems under both food and fuel scenarios. We compared four grain and one forage systems in the U.S. Midwest: corn (*Zea mays*) - soybean (*Glycine max*) - wheat (*Triticum aestivum*) rotations managed with (1) conventional tillage, (2) no till, (3) low chemical input, and (4) biologically based (organic) practices, and (5) continuous alfalfa (*Medicago sativa*). We compared energy balances under two scenarios: all harvestable biomass used for food versus all harvestable biomass used for biofuel production. Among the annual grain crops, average energy costs of farming for the different systems ranged from 4.8 GJ ha^{-1} y^{-1} for the organic system to 7.1 GJ ha^{-1} y^{-1} for the conventional; the no-till system was also low at 4.9 GJ ha^{-1} y^{-1} and the low-chemical input system intermediate (5.2 GJ ha^{-1} y^{-1}). For each system, the average energy output for food was always greater than that for fuel. Overall energy efficiencies ranged from output:input ratios of 10 to 16 for conventional and no-till food production and from 7 to 11 for conventional and no-till fuel production, respectively. Alfalfa for fuel production had an efficiency similar to that of no-till grain production for fuel. Our analysis points to a more energetically efficient use of cropland for food than for fuel production and large differences in efficiencies attributable to management, which suggests multiple opportunities for improvement.

1. Introduction

Modern agriculture uses substantial amounts of fossil energy in the form of fertilizers, pesticides, and fuel for field operations. The environmental consequences of these agricultural practices include increased emissions of greenhouse gases (GHG) to the atmosphere, from sources both direct (e.g., fuel use during tillage and other field operations) and indirect (e.g., fuel used off-site to produce seeds and agricultural chemicals) (*1, 2*). Recently, the prospect of biofuel production on a large scale has focused attention on energy efficiencies associated with different agricultural systems and production goals.

Accurate estimates of agricultural efficiency can provide insights into how society can meet food and fuel security needs while minimizing fossil fuel impacts and can be calculated using energy balance tools (e.g. refs *3* and *4*). However, few empirical studies comparing whole-system, multiyear energy balances are available. Pimental et al. (*5*) compared organic and conventional farming systems with five to six rotational crops; Hoeppner et al. (*6*) examined two four-year rotational systems designed for grain (wheat-pea-wheat-flax) and forage-grain (wheat-alfalfa-alfalfa-flax) production; Ratheke et al. (*7*) examined different corn and soybean rotations; and Patzek and Pimentel (*8*) estimated the energy balance for woody biomass vs sugar cane. Finally, Baum et al. (*9*) estimated energy use efficiencies for an organic vs conventional farm. Insofar as we are aware, however, there are no studies that directly compare food vs fuel production efficiencies in long-term, well-equilibrated cropping systems with detailed descriptions of fossil energy use.

Common management systems for agricultural field crops today include intensive, high-energy input practices to prepare soil, plant, fertilize, manage weeds, and harvest. Organic farming is often assumed to have a lower impact on the environment due to the absence of synthetic chemicals and fertilizers (*10*), but efficiencies may in fact vary depending on management choices (*11*). Low chemical-input production systems and conservation tillage provide additional alternatives.

In this study we calculate energy balances for conventional, no-till, reduced input, and organic corn-soybean-wheat rotations as well as for an Alfalfa forage system, in order to compare energy efficiencies (output:input ratios) among different management practices. We also compare each system under separate food vs fuel production goals.

2. Materials and Methods

To construct energy balances we analyzed data from a long-term agricultural ecosystem experiment in southern Michigan in the northeast portion of the U.S. Corn Belt. The experiment is part of the W. K. Kellogg Biological Station (KBS) Long-term Ecological Research (LTER) site (www.lter.kbs.msu.edu), at 42° 24′ N, 85° 24′ W at 288 m asl. Mean annual air temperature at KBS is 9.7 °C and annual precipitation is 920 mm, generally distributed evenly through the year. Soils are well-drained Typic Hapludalfs developed on glacial outwash (*1, 12*).

We studied four corn-soybean-wheat rotations managed (i) with conventional chemical inputs and tillage (CT), (ii) with conventional inputs and no tillage (NT), (iii) with low or reduced chemical inputs (LI), and (iv) organically with no chemical inputs (Org). The latter two treatments include a winter legume cover crop (red clover; *Trifolium pratense*), which is spring interseeded in wheat and planted late in the summer in the corn portions of the rotation. The red clover provides biologically fixed nitrogen. The LI system receives 1/3 of the chemicals applied to CT. Weed control in the LI and Org systems is provided by mechanical cultivation (for LI, combined with banded herbicide). No systems include compost or manure inputs. The fifth system, Alfalfa, is managed as a continuous forage crop, replanted every 5–6 years following a grain crop break year.

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10.1021/es903385g

TABLE 1. Estimates of Energy Associated with Production of Agricultural Chemicals and Seeds and Energy Content of Grains

	MJ kg^{-1}	source
agro-chemicals		
N	39.0	(*15,23*)
P	15.8	(*3*)
K	9.3	(*3*)
boron	4.7	(*4*)
lime	2.1	(*3*)
herbicide	288.0	(*3*)
insecticide	237.0	(*3*)
Seed		
wheat	5.6	(*2*)
soybean	12.9	(*2*)
corn	53.4	(*2*)
cover crop[a]	87.1	(*2*)
alfalfa	133.1	(*2*)
Grain Energy Content		
wheat	18.6	(*3*)
soybean	23.8	(*7*)
corn	15.5	(*15*)
alfalfa meal	16.2	(*24*)
Biofuel Energy Content[b,c]		
cellulosic biomass (ethanol)	21.1	(*25*)
soybean (biodiesel)[d]	34.5	(*26*)

[a] Energy use associated with red clover seeds. [b] Lower heating value (LHV; MJL^{-1}). [c] Conversion efficiency of the biomass to biofuel is 30% (*14*) for cellulosic biomass and 15% for biodiesel (*13*). [d] Average of reported LHV for biodiesel (33.3–35.7 MJ L^{-1}).

TABLE 2. Estimates of Energy Use Per Field Operations and Agricultural Machinery Maintenance[a]

field operation	L ha^{-1}	MJ ha^{-1}	source
Plowing[b]			
moldboard	21.8	792.8	(*2*)
chisel	10.1	367.7	(*27*)
soil finishing	7.4	243.9	(*27*)
fertilizer application	9.8	357.5	(*2*)
herbicide application	1.8	65.2	(*27*)
cultivation	5.1	186.2	(*27*)
rotary hoe	2.6	93.1	(*27*)
planting	4.9	179.5	(*2*)
Harvest			
baling (round)	7.4	269.9	(*27*)
mowing[c]	1.3	48.8	(*27*)
forage raking	2.2	79.1	(*27*)
alfalfa baling[c]	1.2	48.8	(*28*)
hay cut[d]	4.1	119.4	(*29*)
haylage[e]	13.1	426.2	(*29*)
soybean	11.1	405.5	(*2*)
wheat[f]	11.1	405.5	(*2*)
corn (grain)	12.8	465.5	(*27*)
forage	17.4	633.0	(*27*)
machinery		127.0	(*25*)

[a] Diesel energy content estimated to be 36.4 MJ L^{-1} (*30*). [b] Moldboard plowing was conducted in the years 1989–1997, and chisel plowing in the years 1997–2007. [c] Fuel usage depend on crop yield; values are per Mg yield. [d] 12 ft pull type pickup head. [e] 12 ft rotary mower-conditioner. [f] Wheat and soybean harvest operations were assumed to consume equivalent amounts of energy.

A detailed experimental design and additional agronomic details are available at http://lter.kbs.msu.edu. Briefly, experimental treatments are arranged in a randomized complete block design with six replicate blocks, each containing a 1 ha treatment plot. All farming operations at the study plots were performed by commercial-size equipment, similar to that used by local farmers. The CT and NT treatments received 123 kg nitrogen (N) fertilizer ha^{-1} y^{-1} on corn and 56 kg N ha^{-1} y^{-1} on wheat portions of the rotation and pesticides as needed following Michigan State University (MSU) extension recommendations. The LI system was managed following organic system practices, with the exception that this system received N fertilizer and pesticides at a rate equivalent to 33% of the CT system (banded onto rows rather than broadcast). Herbicides are the only pesticides that have been required on a regular basis in the CT, NT, and LI systems.

For the first five years, the CT and NT systems followed a corn-soybean rotation, while the LI and Org systems followed a three-year rotation of corn-soybean-wheat. After the 1993 corn crop, all systems followed the three-year rotation. This resulted in an enhanced presence of wheat in LI and Org systems compared to CT and NT, which is consistent with biologically diverse farming systems such as Org, where a winter annual crop is required to establish an interseeded red clover crop prior to corn.

The data sets used for our calculations were based on detailed information documenting actual farming practices in these systems. Further, we developed calculations from measured biomass yields over the years 1989–2007 from each plot. For all systems, these data were used to estimate energy inputs and outputs (GJ ha^{-1} y^{-1}) based on standard values for the production costs of fertilizers and herbicides (Table 1) and fuel use (Table 2). Fuel use was calculated by field operation based on contract rates for farm operations - the hours per ha that is required to perform a given operation (such as tillage) by a specific piece of farm equipment with a known fuel consumption rate.

For output energy calculations, we used average rotational biomass yields, whereby crop-specific contributions to harvestable biomass by cropping system depend on the average yield and presence of the crop in the rotation. We converted biomass to biofuel using published conversion factors based on currently available technologies: 0.36 L ethanol kg^{-1} biomass for cellulosic and grain biomass and 0.17 L of biodiesel kg^{-1} soybean yield (*4, 13*).

We also evaluated energy efficiencies (energy output to input ratio) based on contrasting crop end-use, whether for biofuel or for food production. In our analysis, we did not account for byproducts of biofuel production (i.e., soybean or corn gluten meals). We restricted the "output energy" to the energy content of biofuel or grains only. That is, we compared energy budgets for two scenarios: a) harvested biomass of grain used for food production (Food) and b) all harvested biomass (grain for grain-based ethanol, soybeans for biodiesel, and all aboveground crop residue (90% harvest efficiency) for cellulosic ethanol) if used for biofuel production (Fuel).

3. Results and Discussion

An energy balance analysis of crop rotation performance faces a choice with respect to where one should draw system boundaries and on what basis to conduct a systems comparison (*3, 14, 15*). We base our analysis on a 17-year row crop ecology experiment, using actual energy investments for five crop sequences with different management intensity regimes. Our system boundary is the farm gate, except for fuel production for which we include a conservative factor for biomass to fuel conversion that excludes the costs of transportation to the biorefinery and biorefinery construction.

Table 3 presents the relative presence of each crop in our different cropping systems. The CT and NT systems were on

TABLE 3. Cropping System Characteristics for Our 17 Year Cropping System Experiment Located in Southwest Michigan[b]

	% presence over 17 years				
cropping system	alfalfa	corn	soybean	wheat	cover crop[a]
conventional tillage (CT)	-	41	35	24	-
no till (NT)	-	41	35	24	-
low input with cover (LI)	-	35	30	35	70
organic with cover (Org)	-	35	30	35	70
Alfalfa	82	-	-	-	18

[a] In LI and Org red clover was interseeded in wheat phases of rotation and crimson clover (*Trifolium incarnatum*) was interseeded into corn phases, whereas wheat was the cover crop interseeded between Alfalfa stands of 5 to 7 years duration in the long term Alfalfa system. [b] CT and NT rotations included a greater presence of corn and soybean over time and fewer wheat crops, compared to low input and organic management, which require rotation with wheat to facilitate integration of a frost-seeded legume cover crop.

TABLE 4. Number of Farming Operations Per Practice in the Five Systems Examined for the 1989–2007 Period

system	plowing	disking	finishing	planting	fertilization[a]	cultivation[b]	harvest (combining)[c]	pest control	mowing	baling
Conventional tillage (CT)	17	10	17	17	25	17	17	17	3	3
no till (NT)	-	-	-	17	41	-	17	25	3	3
Low Input with cover (LI)	17	11	17	30	18	47	17	16	10	5
Organic with cover (Org)	17	6	17	30	-	50	17	-	10	5
Alfalfa	-	-	-	9	21	-	30	6	13	23

[a] Includes applications of N, P, K, boron, and lime. [b] Includes rotary hoeing. [c] Includes hay cutting, and hay silage.

TABLE 5. Energy Balance of Studied Systems, Evaluating the Energy Efficiency for Use of Harvestable Biomass for Food Production and Fuel[c]

system	farming (GJ ha^{-1} y^{-1})	output food[a] (GJ ha^{-1} y^{-1})	output fuel[a] (GJ ha^{-1} y^{-1})	output:input ratio for food	output:input ratio for biofuel	net energy gain for food (GJ ha^{-1} y^{-1})	net energy gain for biofuel (GJ ha^{-1} y^{-1})	food vs biofuel ratio
Conventional tillage (CT)	7.1	72.7 (8.5)	54.5 (2.1)	10	7	65.6	47.4	1.38
no till (NT)	4.9	78.5 (3.4)	57.3 (0.6)	16	11	73.6	52.4	1.41
Low Input with cover (LI)	5.2	66.9 (3.2)	53.2 (0.9)	13	9	61.7	48.0	1.29
Organic with cover (Org)	4.8	53.1 (5.6)	40.5 (1.2)	11	7	48.3	35.7	1.35
Alfalfa	5.5	26.1 (3.2)[b]	58.4 (5.1)	5	11	20.6	52.9	0.39

[a] Output energy based on net harvested biomass. [b] For alfalfa, output assumes harvested biomass is used as ruminant livestock feed; harvested biomass energy content is 101.1 ± 2.8 GJ ha^{-1} y^{-1} (energy content of alfalfa meal (*24*)). [c] Values averaged over 17 years (±s.e., $n = 6$ replicate blocks).

a corn-soybean rotation in the beginning of the experiment and then were converted to a corn-soybean-wheat rotation in 1993, while LI and Org systems were under a corn-soybean-wheat rotation from the start. The Alfalfa system was replanted three times during the studied period (Table 3).

In some cropping system energy assessments the unit of analysis is the crop, i.e., energy output:input efficiencies are associated with each crop within a rotation (*5*). Alternatively, the entire rotational system can be used as the unit of analysis (*6*). The latter takes into account the intensity of crop presence within a rotation and has particular bearing for evaluating energy efficiencies in rotational systems that vary in biodiversity. We take this latter approach.

3.1. Energy Inputs. We calculated energy input, based on actual agricultural practices (Table 4) combined with published energy costs of farm equipment use and agricultural chemical and seed production (Tables 1 and 2). Studied systems differ in number of farming operations due to different management regimes. For example, the CT and NT systems had standard chemical inputs, while LI and Org systems had more intensive planting and cultivation inputs, and the Alfalfa system was more intensively harvested (2–3 harvests per year) (Table 4).

Overall, fossil energy inputs in the studied systems varied from 4.8 to 7.1 GJ ha^{-1} y^{-1} (Table 5). Among grain crops, energy inputs were lowest in the NT and Org systems. Inputs were slightly higher for the LI system, and ~40% higher in the CT system (Table 5), largely on account of the high energy cost of plowing and agricultural chemical applications (Table 2). Energy costs in the Alfalfa system were intermediate to the NT and CT system at 5.5 GJ ha^{-1} y^{-1} (Table 5).

The similarity between the NT and Org systems was mainly due to cost offsets: the high energy cost of intense cultivation in the Org system was offset by lower chemical costs, and the high energy cost of chemical use in the NT system was offset by the absence of plowing and cultivation (Table 4). Although

TABLE 6. Average Agricultural Yield by Crop and Management Intensity System, in Rotational Cropping Sequences Used for Calculation of Energy Output for "Food" Scenario[c]

	Mg ha^{-1} y^{-1}					
	individual crop			rotation yield[a]		
system	corn	wheat	soybean	corn	wheat	soybean
conventional tillage (CT)	5.90 (0.37)	3.54 (0.09)	2.33 (0.07)	2.43 (0.15)	0.83 (0.02)	0.82 (0.02)
no till (NT)	6.25 (0.12)	3.74 (0.08)	2.65 (0.01)	2.57 (0.05)	0.88 (0.02)	0.93 (0.01)
low input with cover (LI)	5.23 (0.12)	3.09 (0.03)	2.57 (0.04)	1.85 (0.04)	1.09 (0.01)	0.76 (0.01)
organic with cover (Org)	4.08 (0.22)	2.05 (0.05)	2.48 (0.06)	1.44 (0.08)	0.72 (0.02)	0.73 (0.02)
Alfalfa	6.85 (0.85) [b]					

[a] Rotation yield based on crop yield and percentage of crop presence within each rotation between 1989 and 2007. [b] Include wheat straw biomass produced during reestablishment years, calculated from average yields of CT, NT, and LI cropping systems and percentage of crop presence (0.62 ± 0.06 Mg ha^{-1} y^{-1}). [c] Includes only grain yields except biomass yield is reported for alfalfa. Values averaged over 17 years (±s.e., $n = 6$ replicate blocks).

TABLE 7. Averaged Agricultural Yields Used in Calculation of Energy Output from Cropping Systems for Fuel Production[c]

	Mg ha^{-1} y^{-1}	
system	biomass yield for cellulosic ethanol production[a]	biomass yield for biodiesel production
conventional tillage (CT)	6.20 (0.13)	0.82 (0.02)
no till (NT)	6.46 (0.05)	0.93 (0.00)
low input with cover (LI)	6.07 (0.04)	0.76 (0.01)
organic with cover (Org)	4.52 (0.07)	0.73 (0.02)
Alfalfa	6.85 (0.85)[b]	

[a] Assumes 90% harvest efficiency for corn and wheat biomass. [b] Includes wheat biomass produced during re-establishment years, calculated from average yields of CT, NT, and LI cropping systems and percentage of crop presence (0.62 ± 0.06 Mg ha^{-1} y^{-1}). [c] Yields are averages of total harvested biomass (grain and stover or straw) during the studied years (relative sum of yields for corn, wheat, soybeans, corn stover, straw per rotation; mean ± s.e., $n = 6$ replicate blocks), stover and straw biomass are calculated based on harvest index, $HI = (grain)/(grain + stover)$.

the Org system had no fertilizer and pesticide applications relative to CT and NT, there were high energy inputs associated with cover crop management. Put another way, the NT system had no energy inputs associated with tillage but had relatively high agricultural chemical use (Table 4), including more lime applications than the CT system. The Alfalfa system had a relatively high energy cost of herbicide application and seed production as well as high energy inputs associated with multiple harvests per year.

Large energy inputs in the CT system were mainly due to the high tillage intensity, the use of agricultural chemicals, and fertilizer inputs (~60 kg N ha^{-1} y^{-1} rotational average). Overall, input energy showed clear trade-offs among different practices, e.g. reduction of tillage (NT) required more agricultural chemical use (as compared to CT), and reduced agricultural chemical use (LI and Org) required more mechanical tillage.

Importantly, the use of cover crops in the LI and Org systems contributed significantly to energy inputs into these systems. In each system about 50% of energy inputs (42% and 53%, respectively) were associated with cover crop establishment and management.

Direct comparison of our values with previously reported values is difficult, mainly due to a lack of studies with similar rotation × management regimes. However, Rathke et al. (*7*) reported very similar values of 5.4 GJ ha^{-1} y^{-1} for energy inputs to a no-till continuous soybean system and somewhat higher values than ours of 7.3 GJ ha^{-1} y^{-1} for a no-till corn-soybean rotation. Pimentel et al. (*5*) reported almost twice higher values for an organic system with a legume cover crop but under a complex rotation involving 5 or more crops plus intensive manure application. Hoeppner et al. (*6*) reported energy inputs similar to ours for conventional and organic grain wheat-pea-flax and wheat-alfalfa-flax rotations, between 2.2 to 6.9 GJ ha^{-1} y^{-1}. Finally, Deike et al. (*11*) reported inputs of 8.1 GJ ha^{-1} y^{-1} to an organically managed wheat-potato-rye-barley cropping system.

The largest energy input we found, 7.1 GJ ha^{-1} y^{-1} for managing the CT system, was also lower than reported energy inputs in a winter wheat-potatoes-sugar beets-corn rotations in central Germany (8.9−36.9 GJ ha^{-1} y^{-1}) (*3*), mainly due to our less intensive use of fuel, lower fertilizer input rates, and the absence of manure application.

3.2. Energy Outputs. The output energy of our agricultural systems we determined by the amount and quality of harvestable biomass. The NT system had the highest yields, and this translated into the largest amount of output energy among the row crop systems under both scenarios: 78.5 GJ ha^{-1} y^{-1} for Food and 57.3 GJ ha^{-1} y^{-1} for Fuel scenarios (Tables 6 and 7). The CT system was the next most productive food-production system, while the Alfalfa system was the most productive fuel-production system. Energy production overall for the Food scenario was NT > CT > LI > org$\gg$Alfalfa, and for the Fuel scenario Alfalfa = NT > CT = LI $\gg$ Org (Table 5). Differences in energy production originated from a) differences in biomass production and b) assumed end-use of the biomass. Differences in biomass yields between the systems were considerable, with average yields in the NT system 5−35% higher than in other grain crops (Tables 6 and 7).

Unlike in the grain systems, in the Alfalfa system energy yield was higher under the Fuel scenario than under the Food scenario (Table 5). This is because under the Food scenario alfalfa biomass can be used only as ruminant livestock feed and conversion efficiency of forage energy to weight gain by livestock is 9:1 (*6*). Were we to assume that corn, soybean, and wheat were to be used for livestock production rather than direct human consumption (*16*), similar energy conversion efficiencies by livestock would apply. This would result in about 87% lower energy output from the grain systems, similar to Alfalfa energy yields.

3.3. Energy Efficiencies. Overall energy efficiencies, based on output:input ratios for the food scenario are NT > LI > Org > CT > Alfalfa, and for the fuel scenario are NT = Alfalfa > LI > Org = CT. Under both scenarios the CT system was associated with relatively large energy outputs - substantially higher than in the Org system (Table 5). However, high energy inputs, required for CT management, result in slightly lower overall energy efficiency of the CT system for both food and fuel as compared to Org (Table 5).

The differences in energy efficiencies for Org vs CT systems stand in contrast to the high energy efficiency reported for organic systems in some earlier reports (*5, 10*). This is probably because organic row crop systems in other trials involve manure inputs (concentrating nutrients from a larger area) or are on fine-textured soils of high nutrient content.

The energy efficiency of the NT system was the highest among the systems we studied, 16 and 11 for both food and fuel scenarios, respectively (Table 5). Reduced tillage systems have been adopted broadly for row crop production in the U.S., and at more moderate levels in Asia and Europe (*17*). The results presented here support NT as a recommended agricultural practice for optimizing energy efficiency for cropping systems in Midwest climatic and soil conditions. However, it is worth noting that our system is permanent NT, whereas most NT soils in the U.S. are periodically cultivated. The LI system also exhibited high energy efficiency but in this case mainly due to low energy inputs relative to modest crop yields (Table 6).

The energy efficiency of the Alfalfa system depended on the assumed end use of harvested biomass. That Alfalfa had low energy efficiency when biomass is used for forage expresses a physiological limitation of ruminant livestock and not forage quality per se (*18*). The alternative use of alfalfa biomass for cellulosic biofuel feedstock more than doubles its energy efficiency (Table 5). These results, together with recent reports on potentially high energy efficiency and productivity of plants grown for cellulosic biofuels feedstock production (*19*), emphasize the importance of further research on purposefully grown cellulosic energy crops.

3.4. Synthesis. Energy efficiencies for all food-production systems followed the order NT > LI > Org > CT > Alfalfa. The use of grain crops for biofuel production resulted in 30−40% lower net energy gain than when the crops were used for food production. Alfalfa, on the other hand, yielded more energy when used as a fuel than as food owing to a lower livestock than fuel conversion factor: before alfalfa energy is available for food it must be converted to livestock energy.

The lower energy efficiencies for crops used for fuel than for food would be lower still if a more sustainable harvest efficiency were used. We conservatively assumed that 90% of crop biomass could be used for fuel. This is a theoretical maximum, not taking into account soil carbon maintenance and conservation needs (*20*). A more realistic harvest efficiency (*21*) will reveal larger differences between the two scenarios.

Biorefinery conversion efficiency is the main reason for relatively low net energy gains for biofuel use. We used a conservative fuel yield of 0.36 L ethanol kg^{-1} cellulosic and grain biomass (*14*) and 0.17 L biodiesel kg^{-1} soybean yield (*13*), which represents between 40% and 75% energy loss upon biomass conversion to fuel. This is an inherent limitation of biofuel conversion. More efficient refining would lessen the difference between the food and fuel scenarios.

Energy efficiency of agronomic systems for food and fuel production could be increased by use of a hybrid or combination system. Using 100% of harvested grain for food and 50% of residuals for fuel will increase the net energy output from the systems in the food scenario by 37% to 48% for NT and Org systems, respectively. Similarly, the use of coproduct (dried distillers' grains and solubles; DDGS) for livestock feed in the fuel scenario will increase net energy output from the systems by 23% to 31% for LI and CT systems, respectively. In this case, 922 g of DDGS per kg of ethanol is produced; DDGS contains 30% more digestible energy than corn if used as livestock food (*31, 32*).

The low net energy gains from the LI and Org systems were partially due to the use of cover crops (LI and Org) and partially due to low biomass production (particularly Org). Cover crop management added to the high energy cost of LI and Org due to the energy costs of cover crop seeds and the additional energy used to plant them (Tables 1 and 4). However, cover crops also provided indirect energy efficiency. The incorporation of nitrogen-fixing cover crops into the soil prior to summer crop planting allowed for less nitrogen fertilizer use, thus saving the energy costs associated with its manufacture and application.

On average, the CT system used 3.1 GJ ha^{-1} y^{-1} of energy associated with agricultural chemical use, while the Org system used none (data not shown). Future energy limitations may lead to a preference for biological nitrogen fixation rather than nitrogen fertilizer use. Moreover, the use of cover crops resulted in larger soil organic carbon accumulation in the Org system (*1*) and less hydrologic nitrogen export from both the LI and Org systems as compared to the CT system (*22*). And interestingly, plowing and herbicide use for weed control in the CT system required 9% more energy input than energy requirements for plowing and mechancial weed control in the Org system (data not shown).

Overall, our results suggest a more energetically efficient use of cropland for food than for fuel production and large differences in energy efficiencies attributable to different management practices. These differences provide many opportunities for improving the energy efficiencies of both food and fuel systems.

Acknowledgments

We thank S. Bohm and S. Vanderwulp for help with assembling the data for this analysis. This research was supported by the U.S. National Science Foundation (LTER program), DOE Great Lakes Bioenergy Research Center (DOE BER Office of Science DE-FC02-07ER64494), and the Michigan Agricultural Experiment Station.

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ES903385G