The Visible, Sustainable Farm:
A Comprehensive Energy Analysis of a Midwestern Farm

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Abstract

The Sunshine Farm, in central Kansas, offers a unique data set detailing all the inputs and outputs of a farming project intended to be based, as much as possible, on solar energy. Such a complete and detailed data set, encompassing more than 1.25M data points for an 85 ha, 7 year project, has never before been compiled for any farm. The data show that important energy inputs that have thus far been left out of existing farm energy efficiency estimates, with implications for biofuels and other biomass for energy technologies. The SSF achieved energy efficiencies superior to conventional agriculture while maintaining soil health and delivering more nutritious, organic products. A first-ever analysis of the energy efficiency of horse traction shows that horses are significantly less energy-efficient and much less labor-efficient than tractors, although the horses in the study were clearly under-utilized. An analysis of the farm removing all inputs and outputs relevant to the horses shows that without horses the Sunshine Farm would have been competitive with conventional energy efficiencies even taking into account the farm's higher labor inputs and small size.

KEY WORDS: chemicals-free — draft horse — photovoltaics — livestock — organic —crop—rotation

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1 Introduction

How many people can be fed in a sustainable manner? Current chemical-based agriculture methods, while highly productive compared with traditional methods, require large fossil-fuel inputs and cause serious environmental impacts, such as topsoil erosion (Reganold et al., 1987; Green et al., 2005), organic matter loss (Khan et al., 2007), elimination of microbial biodiversity (Oehl et al., 2004), and pollution of air and water (Nations and Hallberg, 1992). As agriculture plays a major role in human-driven climate change, the depletion of fossil fuels, and environmental degradation, the need for low-energy, sustainable farming techniques is clear. The merely marginal improvements achieved by "best practices" within the conventional chemical-based system point to the need for a fundamental transformation (Dinnes et al., 2002; Randall et al., 1997). However, the energy and labor tradeoffs involved in switching to such methods have not been fully characterized, in part due to a lack of detailed data. Here we present the results from an unprecedentedly comprehensive accounting of the workings of a low-input, multi-output organic farm and compare its performance with existing studies of chemical-based and organic agriculture.

These results have implications beyond the feeding of people and animals. Although energy production from agriculture – i.e. biofuels and biomass – is currently being touted as a solution to fossil fuel depletion, the total energy inputs to agriculture are still poorly known. Such potentially large components of energy use as embodied energy of materials, buildings, labor, and commuting energy – have not yet been studied in sufficient detail to answer such basic questions as whether agriculture is a net energy source or sink. Previous studies investigating energy use in agriculture have been based on questionnaires and aggregate statistics from surveys, rather than on continuous, on-location monitoring and measurement (Sheehan et al., 1998a; Hill et al., 2006; Pimentel, 1980). Thus they have been limited to counting easy-to-quantify components such as direct electricity and fossil fuel use, energy embodied in fertilizer and agricultural chemicals, and in some case energy embodied in farming machinery (Farrell et al., 2006; Pimentel and Patzek, 2005; Patzek, 2004). Even these studies have cast significant doubt on the net energy content of many popular biofuels, but while the energy value of the output fuels (and to a lesser extent, the co-products) may be well known, many inputs have been poorly characterized. A complete picture of farming's energy requirements, including the embodied energy of the complex array of supplies and physical infrastructure used in agriculture, detailed fuel use in day-to-day operations, and the commuting costs of farm labor has not been possible due to a lack of data.

Beyond energy usage, agriculture's largest impact is the degradation of natural resources in and around the farm, such as erosion, depletion, and contamination of topsoil, pollution of water through runoff, loss of soil biodiversity, damage to wildlife and ecosystems, and pollution of the atmosphere. Some of these impacts affect the farm in the long term through reduced yields. All have a negative impact on the society in which the farm is embedded. These influences are not taken into account in conventional economic analyses, where they are termed "externalities". Including, and measuring the impacts of agriculture beyond the short-term economics of "fertilizer and fuel in, crops out" is essential to understanding the role of farming in a society, especially as global energy supplies tighten, populations rise, and the long-term impacts of damaging agricultural practices become plain. By examining the complete energy requirements for sustainable, productive farming, it becomes possible to see how farming can best integrate into a sustainable, well-nourished society of the future.

Here we present results from a multi-year, multi-output research farm (the "Sunshine Farm"), on which every operation involving energy or materials was recorded in detail. The design and operation of the farm were intended to illustrate how a sustainable farm might work in a future energy-limited economy; no artificial fertilizers, insecticides, fungicides, or herbicides were used, many synergies between animals and crops were employed, and the farm was managed to minimize topsoil loss. A broad spectrum of physical and chemical measurements was applied to the farm's soil throughout the project to monitor the system's impact. Analysis of this unique data set not only provides a picture of the energy footprint of almost-sustainable farming, but also gives an example of the importance of such detailed data in obtaining an accurate estimate of an agricultural system's energy input:output ratio. Results from the farm also show that more-sustainable farming can be energy efficient, indeed more so than current industrial farming techniques. This is especially relevant as biomass and biofuels from agriculture are increasingly being posed as future energy sources for industrialized economies, generally without reference to the sustainability of production methods.

As a public service, the full data from this study, as well as the MATLAB code used to generate the results, will be made generally available with the publishing of this study for further analysis and verification of these results.

2 Sustainability

The energy balance of an agricultural system is only truly meaningful when weighed against the sustainability of the system in question. Modern chemical-based agriculture relies heavily on subsidies from a wide range of non-renewable resources. Energy subsidies of industrial agriculture include the fossil fuels used to make chemical fertilizer, other agricultural chemicals (insecticides, fungicides, herbicides, etc.), direct fuel use by machinery, and energy used for irrigation. Less visible subsidies include the exploitation and disturbance of natural resources such as drainage systems, topsoil, aquifers, and stable climates.

The agricultural systems which sustained humanity for the last several thousand years were more or less sustainable by definition; however the populations supported by these systems were orders of magnitude smaller than at present. Since neither current nor historical agricultural systems are useful models of effective and sustainable agriculture, new systems must be devised and implemented (including distribution and consumption patterns) if all of humanity is to be fed in the future.

A sustainable agricultural system must use only renewable sources of energy, and must utilize natural resources no faster than they are replaced. As renewable energy sources are generally more expensive than fossil fuels are currently, it can be assumed that energy will be limited in a sustainable, long-term economy; as such, a detailed energy budget is necessary, and to reflect the farm's overall impact on the economy it serves, its energy budget must include indirect energy use as well as direct use, such as "embodied" energy – the energy required to manufacture and distribute goods and services. Labor commuting energy and food transport energy must also be taken into consideration to obtain a complete picture of a farming system's energy footprint.

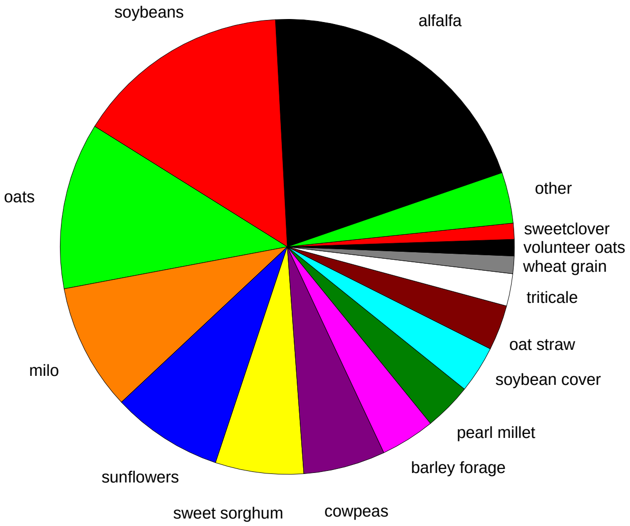

Figure 2: SSF crop areas, averaged over 6 years.

3 Sunshine Farm

The Sunshine Farm (Figure 1) was run from 1992-2001 in central Kansas. It included 20 ha of cropland, and 40 ha of pasture, which increased to 65 ha of pasture in the final two years of the project. The primary crops were a 5-year rotation of grain sorghum (*Sorghum vulgare*), soybeans (*Glycine max*), oats (*Avena sativa*), sunflowers (*Helicanthus annuus*), and soybean cover employed as a green manure. These crops were planted in narrow strips (4 rows with 40-inch spacing) with different entry points in the rotation, so that a diversity of crops was maintained at all times. Occasional substitutions of other crops were made as well, such as winter wheat (*Triticum aestivum*) for oats, pearl millet (*Pennisetum glaucum*) for sunflowers, and cowpeas (*Vigna sinensis*) or short-rotation alfalfa (*Medicago sativa*) for the soybean cover. Alfalfa and sweet sorghum (*Sorghum saccharum*) were grown in separate fields for animal feed. Other feed crops included grain sorghum, oats, pearl millet, and cowpeas, the last two being directly grazed on the crop strips by cattle. A summary of the acreage planted on the farm

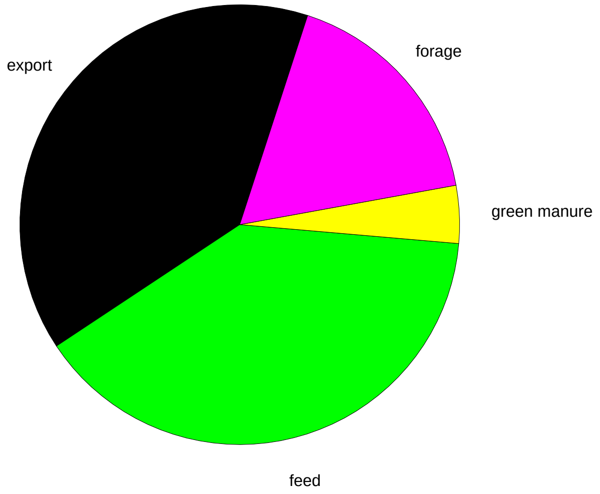

Figure 3: SSF crop uses by overall area, averaged over 6 years. Total crop area was 20 ha.

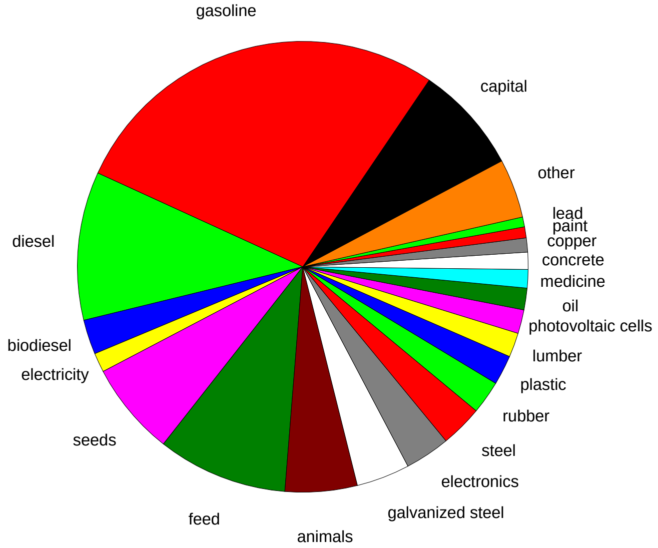

Figure 4: All inputs to the Sunshine Farm by total embodied energy, excluding labor. Total is 1602 GJ over 6 years.

over the project is shown in Figure 2. A summary of the uses of the crop acreage on the farm is shown in Figure 3. No irrigation was employed on the farm.

This study is based almost entirely on the data from years 1992-1998, during which the farm was worked by a combination of tractors and horses. In the years 1999-2001, the rows were widened to 20 meters to evaluate the efficiency and effectiveness of a reduced-tillage approach using larger equipment. The crop rotation was continued through this transition.

Animals on the farm included flocks of approximately 50 egg-laying hens and 75 broilers, as well as two draft horses and several cow-calf pairs (Texas Longhorns) on the pasture. The farm started with nine cow-calf pairs and expanded through on-farm births to 28 by the end of the project. The layers were mainly Barred Rock hens, with a small number of Rhode Island Red and White Leghorn during some years. The broilers were Cornish Cross.

A breakdown of the total energy used on the farm during the project is shown in Figure 4. A summary of the fuels and materials used on the farm is shown in Table 2, as well as the embodied energy assigned to each. The embodied energy factors for metal products were increased 25 percent to include energy used in fabrication (Smil, 1991; Ayres, 1994). A summary of capital equipment on the farm, including buildings and production machinery, is shown in Table 3. These contribute 7.7% to the overall energy budget of the farm, excluding labor.

All transactions on the farm involving energy or materials were individually recorded, with the exception of regularly repeated tasks, which were recorded weekly. Each record included the date, object (i.e. purpose of task), task type, transaction type, power source and instruments used, managerial and other labor hours, materials and animals involved, durable item lifetime, and the acreage affected.

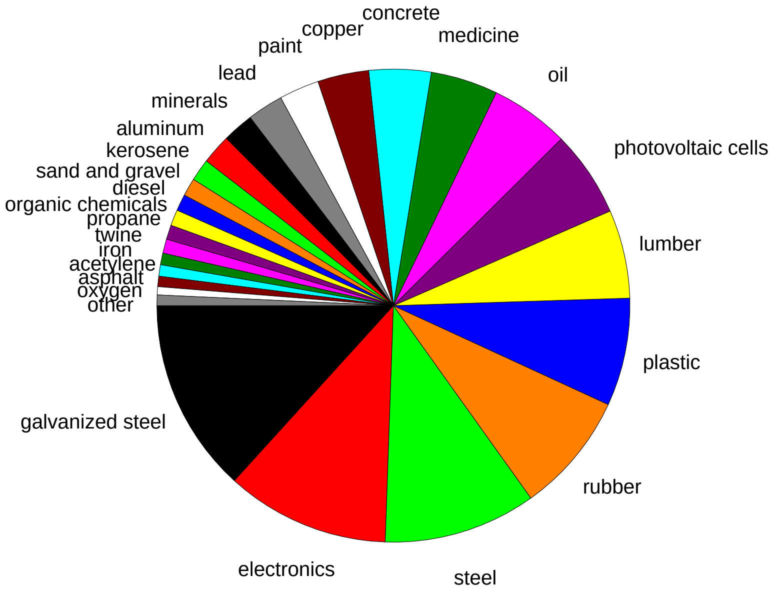

Figure 5: Miscellaneous materials used on the Sunshine Farm by total embodied energy. Excludes capital equipment, fuel, feed, and seeds.

3.1 Farm Inputs

Inputs to the Sunshine Farm are summarized in Figures 4 and 5. The farm took in a wide variety of feeds, seeds, fuels, and animals, in addition to a range of materials typical of midwestern farming (with the addition of solar cells). The main twenty-five material types shown in Figure 5 accounted for 99.2% of the materials used.

3.2 Farm Outputs

Outputs from the farm are summarized in Figures 6 and 7. Milo, soybeans, oats, sunflower seeds, and wheat grain were the primary crop exports of the farm. Animal outputs were calves, yearlings, one mature heifer, eggs, broilers, and culled hens. Alfalfa affected by mold was exported as a soil amendment but was not counted as part of the exports from the farm.

3.3 Input-Lowering Aspects of the Sunshine Farming System

The employment of multiple species of animals and plants on the farm created many opportunities to reduce the need for inputs. Animals which were sources of meat (cattle) and power

Table 1: Energy values used for fuels, feeds, seeds, and exports. Fuel energy values are HHV, before the 17% surcharge for refining, transportation, and distribution.

Material	Embodied Energy	Total Embodied Energy	Reference
Fuels			
petroleum gasoline	131 MJ/gal	378,000 MJ	(Patzek, 2007)
petroleum diesel	146 MJ/gal	147,000 MJ	(Patzek, 2007)
soy bio-diesel	125 MJ/gal	34,000 MJ	(Patzek, 2007)
propane	96.6 MJ/gal	174 MJ	(Patzek, 2007)
Purchased Feeds			
12-24% protein feed	5.60 MJ per kg	224,000 MJ	(Cook et al., 1980)
corn	5.20 MJ per kg	29,300 MJ	(Pimentel and Pimentel, 1979)
milo	3.40 MJ per kg	32,700 MJ	(Bukantis, 1980)
oats	5.40 MJ per kg	60,000 MJ	(Pimentel and Pimentel, 1979)
soybean meal	5.31 MJ per kg	1260 MJ	(Cook et al., 1980)
wheat	5.31 MJ per kg	1090 MJ	(Pimentel and Pimentel, 1979)
Purchased Seeds			
alfalfa	163 MJ per kg	56,600 MJ	(Heichel, 1980)
barley	8.00 MJ per kg	7,670 MJ	(Heichel, 1980)
cow peas	20.0 MJ per kg	9,840 MJ	(Heichel, 1980)
alfalfa inoculant	430 MJ per kg	2,560 MJ	(Heichel, 1980)
milo	38.0 MJ per kg	6,720 MJ	(Heichel, 1980)
oats	11.0 MJ per kg	58,000 MJ	(Heichel, 1980)
pearl millet	19.0 MJ per kg	3,120 MJ	(Heichel, 1980)
soybeans	20.0 MJ per kg	50,800 MJ	(Heichel, 1980)
sunflowers	109 MJ per kg	11,000 MJ	(Heichel, 1980)
sweet sorghum	25.0 MJ per kg	5470 MJ	(Heichel, 1980)
sweet clover	20.0 MJ per kg	272 MJ	(Heichel, 1980)
triticale	8.00 MJ per kg	3,090 MJ	(Heichel, 1980)
wheat grain	8.00 MJ per kg	1,420 MJ	(Heichel, 1980)
Animal Inputs			
bred cows	16000 MJ per animal	160,000 MJ	(Cook et al., 1980)
chick	4.4 MJ per animal	2248 MJ	(Ostrander, 1980)
hen	330 MJ per animal	8250 MJ	(Bender, 2006)
pullet	110 MJ per animal	4400 MJ	(Bender, 2006)
rented bull	1600 MJ per animal	8000 MJ	(Bender, 2006)
Crop Outputs			
milo	16.4 MJ per kg	704,000 MJ	(Crampton and Harris, 1969)
oats	17.5 MJ per kg	214,000 MJ	(Crampton and Harris, 1969)
soybeans	21.2 MJ per kg	717,000 MJ	(Crampton and Harris, 1969)
sunflowers	25.1 MJ per kg	119,000 MJ	(Salunkhe et al., 1991)
wheat grain	16.8 MJ per kg	31,100 MJ	(Crampton and Harris, 1969)
Animal Outputs			
beef carcass	14.5 MJ per kg	182,000 MJ	(Byerly, 1982)
broiler carcass	5.80 MJ per kg	9,950 MJ	(Byerly, 1982)
eggs	7.28 MJ per kg	33,100 MJ	(Byerly, 1982)

Table 2: List of materials used on the SSF

Material	Embodied Energy	Total Embodied Energy	Reference
galvanized steel	63 MJ per kg	61,257 MJ	(Boustead and Hancock, 1979)
electronics	24 MJ per $	51,666 MJ	(Casler and Hannon, 1989)
steel	31 MJ per kg	48,145 MJ	(Boustead and Hancock, 1979)
rubber	239 MJ per kg	38,145 MJ	(Stout, 1984)
plastic	100 MJ per kg	34,059 MJ	(Boustead and Hancock, 1979)
lumber	6 MJ per kg	27,911 MJ	(Boustead and Hancock, 1979)
photovoltaic cells	117 MJ per kg	27,217 MJ	(Knapp et al., 2000)
lubricating oil	52 MJ per kg	24,919 MJ	(Boustead and Hancock, 1979)
medicine	9 MJ per $	21,192 MJ	(Fluck et al., 1992)
concrete	2330 MJ per m^3	19,580 MJ	(Boustead and Hancock, 1979)
copper	163 MJ per kg	16,174 MJ	(Boustead and Hancock, 1979)
paint	200 MJ per kg	12,623 MJ	(Slesser, 1978)
lead	38 MJ per kg	11,325 MJ	(Boustead and Hancock, 1979)
minerals and salt	4 MJ per kg	9,886 MJ	(Craumer, 1977)
aluminum	325 MJ per lb	9,376 MJ	(Boustead and Hancock, 1979)
kerosene	47 MJ per kg	6,985 MJ	(Boustead and Hancock, 1979)
sand and gravel	0.1 MJ per kg	5,640 MJ	(Boustead and Hancock, 1979)
organic chemicals	46 MJ per kg	5,040 MJ	(McDuffie et al., 1980)
diesel	46 MJ per kg	4,468 MJ	(Boustead and Hancock, 1979)
twine	12 MJ per kg	4,453 MJ	(Craumer, 1977)
propane	50 MJ per kg	3,872 MJ	(Boustead and Hancock, 1979)
iron	23 MJ per kg	3,678 MJ	(Boustead and Hancock, 1979)
acetylene	237 MJ per kg	3,614 MJ	(Boustead and Hancock, 1979)
asphalt	25 MJ per kg	3,295 MJ	(Leary and Mack, 1980)
cloth	116 MJ per kg	790 MJ	(Bethel, 1976)
fiberglass	23 MJ per kg	775 MJ	(Hall et al., 1979)
sulfuric acid	2.6 MJ per kg	425 MJ	(Boustead and Hancock, 1979)
brass	200 MJ per kg	269 MJ	(Batty and Keller, 1980)
firewood	0.5 MJ per kg	247 MJ	(Tillman, 1978)
stainless steel	100 MJ per kg	224 MJ	(Boustead and Hancock, 1979)
oxygen	1.8 MJ per kg	206 MJ	(Nakamura, 1974)
cement	5 MJ per kg	195 MJ	(Chandler, 1985)
adhesive	78 MJ per kg	149 MJ	(Boustead and Hancock, 1979)
tin	250 MJ per kg	99 MJ	(Chapman and Roberts, 1983)
other		175 MJ	

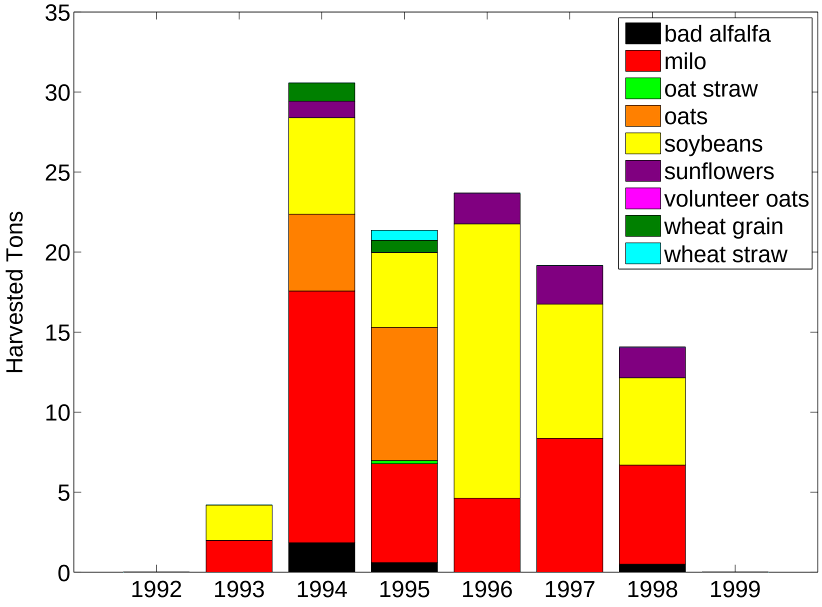

Figure 6: SSF crop output by year

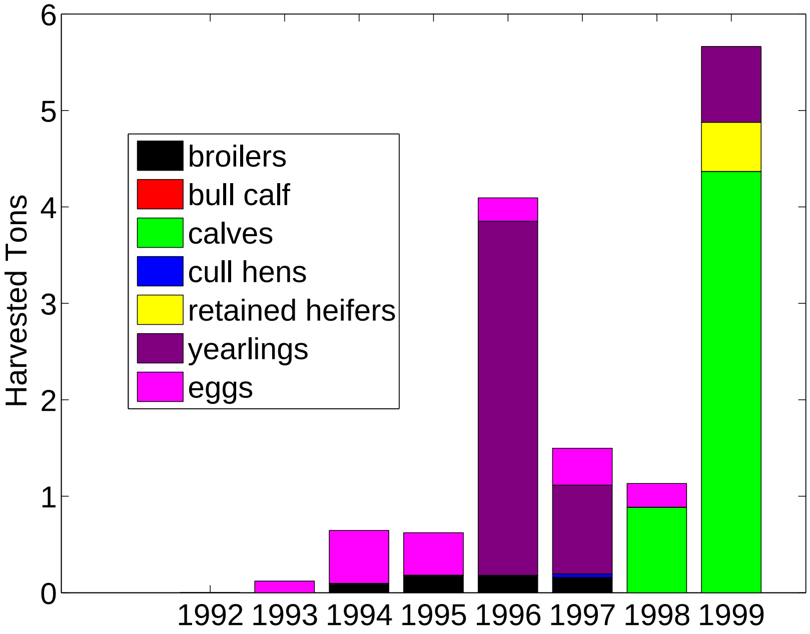

Figure 7: SSF animal output by year

(horses) were fed alfalfa, oats, rolled milo, soybean meal, sunflower seeds, and sweet sorghum, and were allowed to forage on barley, buckwheat, canola, cowpeas, pearl millet, triticale, and winter peas which were grown on the crop strips. Their manure, dropped on the cropland while foraging and working, deposited fixed nitrogen and minerals from their feed and pastures, improving yields and reducing the need for other fertilizers. Oat and wheat straw grown on the farm were used to provide bedding for the animals.

To eliminate the need for energy-intensive chemical fertilizers, approximately 40 percent of the crops grown were nitrogen-fixing legumes, of which one-fourth were green manure and three-fourths were forage and soybeans. The only elemental fertilizer inputs to the farm were phosphorus and potassium contained in purchased feed, which amounted to only a few kg per ha annually as grazing and foraging animals dropped their manure on the pasture and cropland.

Texas Longhorns were chosen for their relative independence, especially their nearly 100% successful birthing in the absence of human assistance, as there were no family or other full-time residents on the farm. Longhorns have been successful in North America for over 500 years, and their ability to live with minimal human assistance also helped to reduce inputs to the farm.

The egg-laying hens were raised free-range, including some fenced production to compost old straw for return to cropland. The roughly 75 broilers were produced in a portable pen moved daily over the alfalfa field in which they foraged for insects and plants. Both these techniques reduced the amount of feed required to sustain the poultry, and reduced the levels of insect pests and weeds on the farm.

Short-duration grazing management of the cattle was employed to maximize productivity and sustainability while keeping inputs low. Electric polywire fencing and numerous paddocks with piped water were used to move the cattle every 1-6 days, depending on the condition of each paddock, with each paddock given 30-60 days to recover before another grazing period. In this way the per-area productivity of the beef production was maximized, both by reducing shading of new growth and by preventing damage caused by overgrazing. The paddocks were monitored annually by cover class analysis of the plant species composition. The use of a subsurface automatic waterer for the livestock eliminated the need for an energy-intensive stock tank heater in the winter. In some years, beef yearlings were market-finished using electric polywire fence to confine their grazing to appropriate crops and residues within the crop strips. This eliminated any energy costs for harvesting, transporting, storing, and feeding the crops to the animals, as well as any manure-handling costs.

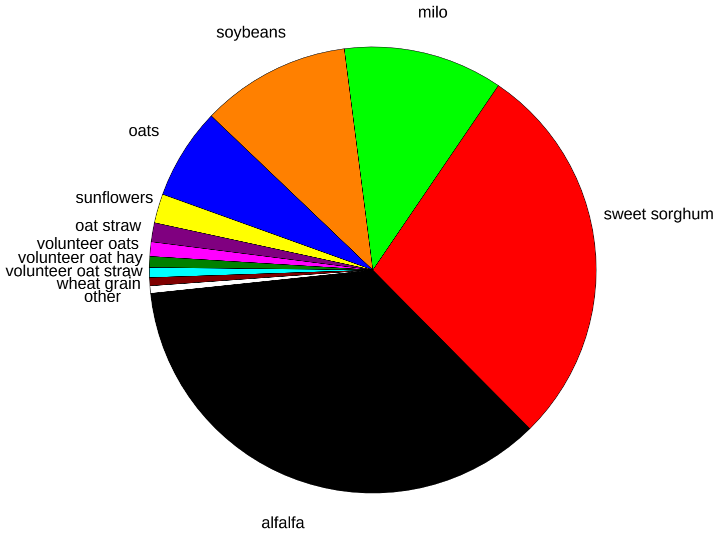

Figure 8: SSF total crop yields

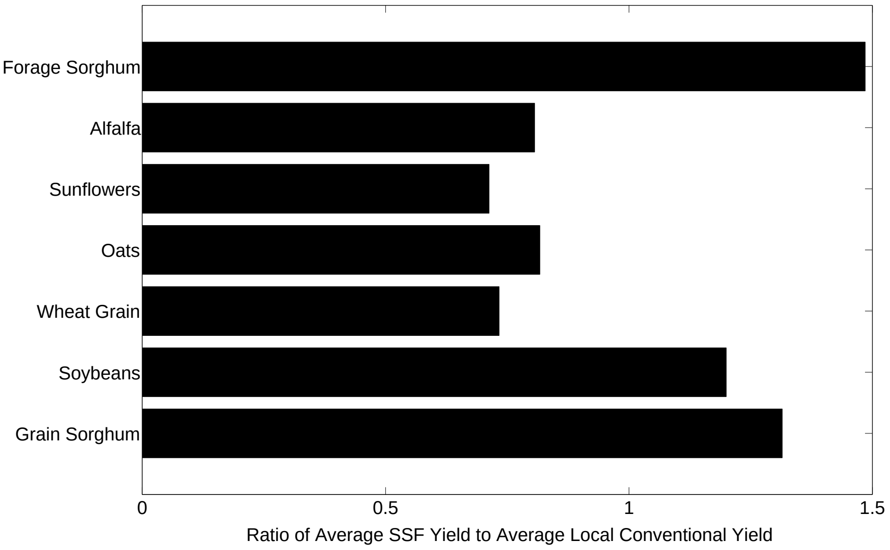

Figure 9: SSF crop yields compared to local conventional farms

3.4 Crop Yields

Total crop yields for the farm are shown in Figure 8. Yearly averages of crop yields are shown in Figure 9, relative to those of neighboring farms also in Salina County. Crop yields for the Sunshine Farm's major export crops, soybeans (30 bu/acre) and milo (53 bu/acre), were somewhat higher than those of the local conventional farms; yields for forage sorghum (5.1 tons/acre) were almost 50% higher. Yields for the other crops were lower – 22 bu/acre for wheat, 38 bu/acre for oats, 710 lbs/acre for sunflowers, and 2.6 tons/acre for alfalfa – but overall the farm performed very well considering its lower inputs, lessened impact on its soils (see Section 5), and the presumed higher nutritional content of its exports (see Section 11 below).

Table 3: Weight and depreciation rate of farm capital goods by type, before adjustments detailed in Section 3.5. An embodied energy of 46.5 MJ/kg is assumed.

Equipment Class	kg	GJ/yr
Balers and Rakes	3391	4.81
Harvesters	6011	14.20
Seed Planters	1525	2.10
Primary Tillage	1639	1.53
Secondary Tillage	3378	9.93
Small Equipment	8136	11.89
Tractors and Vehicles	22350	54.54
Horse Equipment	2070	2.17
Building	4540	4.23
TOTAL	53040	105.39

3.5 Sunshine Farm Capital Equipment

A summary of the capital goods used on the Sunshine Farm is shown in Table 3. Despite being almost 15 times smaller than the average Kansas farm (20 ha versus 294 ha), the Sunshine Farm had a generous assortment of equipment, especially tractors. In fact, according to interviews with local farmers, the capital goods of the Sunshine Farm could have comfortably served a farm of 60 ha (Renich, 2008). In the specific case of traction, the Sunshine Farm had, in addition to the horses, three tractors weighing 8037 kg, 2880 kg, and 1692 kg, when just two of the 2880 kg (diesel) tractors would have provided more than sufficient traction for a 60 ha farm (Renich, 2008). Applying this estimate to the SSF capital data set – i.e. by replacing the weight of the three tractors by the weight of two 2880 kg tractors, then dividing the whole capital energy budget by three – presents a more accurate picture of the capital needs of the farming system, if it were implemented efficiently for a farm of at least 60 ha size. With this adjustment, capital equipment represented 7.7% of the total non-labor inputs. The maintenance costs of the entire equipment suite are not changed, as if these costs would scale linearly with the size of the farm, a conservative assumption. These assumptions result in a capital equipment charge 1.5x that of other studies (Hill et al., 2006). The unitary nature of many of the farming implements also suggests that farms below approximately 60 ha are likely to under-employ capital equipment, resulting in significantly lower energy efficiency. This effect would be in addition to the significant fuel saving associated with using larger, multi-row equipment, discussed below.

Figure 10: The Sunshine Farm solar array, with battery-storage and electronics shed.

4 Farm Solar Array

The farm incorporated a 4.5 kW photovoltaic array of standard polycrystalline silicon wafers for the study of farm-scale energy generation. The array contributed energy beyond that required to run the farm's water pumps, grain auger, and single outbuilding to the local utility grid. In fact, the array generated more than 5 times the total on-farm usage, so this export was the array's primary function.

In our analysis, the solar array is treated as a separate entity, rather than as an integral part of the farm. This separation is precise, and does not affect the analysis of the remainder of the farm, due to the detailed metering and the lack of synergistic interactions between the array and the other element of the farm. This is in contrast to the crops and the animals of the farm, which contributed to each others' performance in ways that are difficult to quantify (i.e. manuring, foraging, etc.).

The solar array generated 116 GJ of electricity during its six years of operation; using this performance as an average, the array would be projected to produce 385 GJ over a 20-year lifetime (not counting the slight degradation that such arrays experience, or the likelihood of a significantly longer service life). Such electrical energy generation could replace approximately $116/0.35 = 330$ GJ and 1100 GJ, respectively, of fossil fuel energy, based on a representative coal plant electrical generation efficiency of .35. The panels' energy production compares favorably to the 90.7 GJ embodied in the panels themselves. However, the total embodied energy of the materials used to construct the array and the lead-acid battery storage system totals 344 GJ, in addition to the 13.5 GJ of fuel used to transport the components to the farm. This includes 30.3 GJ of copper, 28.8 GJ of lead, 12.6 GJ of plastic, 6.8 GJ of lumber, 13.1 GJ of steel, and 132 GJ for electronics. Much of the copper, and a significant fraction of the fuel expended in the construction, went into tying the system to the local power grid.

The authors believe this last figure (for battery charger and inverter systems) to be greatly overstated, as the energy intensity of electronics (24 MJ/$) has almost certainly decreased since the most recent estimation of this statistic (1989) (Casler and Hannon, 1989) due to miniaturization, single-chip implementations, and the maturity of the industry. Furthermore, manufacturing of such electronics has expanded greatly both since 1989 and since the Sunshine Farm project, leading to economies of scale that would reduce the embodied energy of such systems. (The only other significant use of electronics on the farm was 35.6 GJ for cattle production.) Finally, the use of PV panels in an exclusively utility-grid-tied system would not only eliminate the battery embodied energy but also the battery charger electronics. Large-scale application of intermittent sources such as solar does, however, require the presence on the grid of load-balancing energy sources – e.g. hydroelectricity or gas-fired power plants.

The solar array accounted for 277 hours of labor on the farm; 223 were for construction, 51 for transport. If these are budgeted at 75 MJ/hr (see Section 10), the labor hours amount to 20.6 GJ. Adding this to the other solar array inputs results in an output of 1.02 GJ/ GJ input for the whole system, assuming a 20-year lifetime; however this is probably an overestimate due to the batteries having a service lifetime shorter than 20 years. Taking into account the relative inefficiency of fossil fuel power generation as mentioned above, the system could have replaced almost 3 times as much energy as was invested in its manufacture, installation, and operation.

Because of the relatively small size of the array, and the ad-hoc nature of its design and implementation, this result should not be considered a comment on solar power in general, but perhaps it should be considered a note of caution regarding the energy balance of "one-off" small-scale installations, especially those employing both battery storage and a long grid tie connection. Other studies (Fthenakis et al., 2008; Knapp et al., 2000) suggest that it is possible to construct effective PV solar systems with highly favorable energy ratios.

5 Sunshine Farm Soil

The Sunshine Farm soil is an alluvial silt loam soil with 2.3% organic content typical of central Kansas, classified as an ustic mollisol. This relatively low organic content is typical of long-term conventional farming in midwestern soil (Glover, 2008). It is dark-colored and organic-rich down to several feet depth and is dry many months of the year, but contains some moisture in summer (USDA-SCS, 1992). The cropland of the farm was farmed conventionally in wheat, soybeans, and grain sorghum (milo) for many years, but was farmed in winter wheat without commercial fertilizer or pesticides during 1987-1992, the south 10 hectares (planted to the 5-year rotation strips in the SSF project) replaced with alfalfa during 1990-1992. Precipitation there averages 75 cm annually, and 46 cm during the May-September growing season.

Erosion rates on the farm were reduced through the use of narrow strips that minimized the width of open areas, and the extensive use of cover crops, which maintained some ground cover after harvest. The strip system was chosen in part to facilitate ridge tillage, which would have reduced erosion by up to 3x, but more standard tillage was chosen due to a lack of ridge-tillage equipment. Topsoil loss was estimated using the standard USLE equation to be 2.0

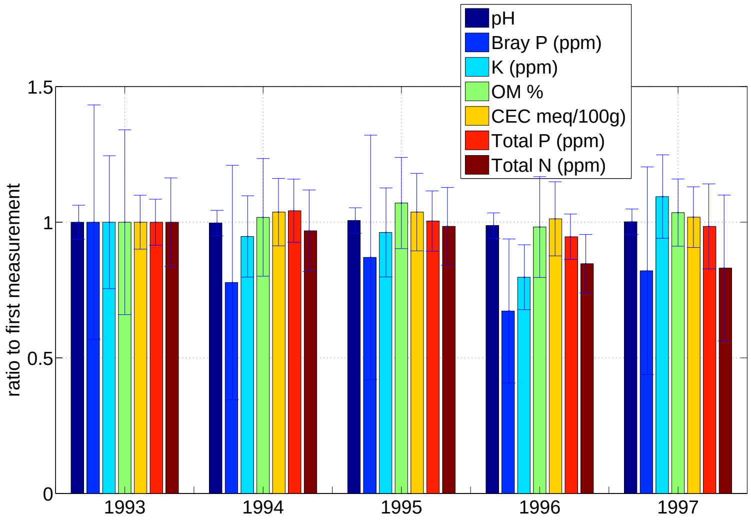

Figure 11: Evolution of SSF soil chemistry

tons/acre/yr for water and 1-4 tons/acre/yr for wind, due to variability in wind exposure over the area of the farm. Average water erosion loss for Kansas farm land in 1992 (excluding CRP land) was 2.6 tons/acre (Sheehan et al., 1998a). However, erosion rates vary in a log-normal distribution, with a standard deviation was 4.55 tons/acre, so much higher erosion rates are fairly common. Erosion is much higher for low-cover, shallow-root crops such as soybeans (averaging 5.4 tons/acre with a 7.99 tons/acre standard deviation), which was one of the primary crops of the farm. Average wind erosion for 1992 Kansas farmland was 1.9 tons/acre with a 4.55 tons/acre standard deviation. A study of perennial crop farming is planned for the site, which is likely to reduce erosion. Eliminating tilling might also have reduced erosion, but the extensive pesticide applications generally required for this approach (organic no-till techniques were not considered) are incompatible with the organic farming practiced on the farm. Subsequent work on the farm has shown the feasibility of reduced-till methods that can cut fuel usage by approximately 2.5x while reducing erosion.

The evolution of soil characteristics on the farm from 1993 to 1997 are summarized in Figure 11. These were measured in 60 sites on the farm over a sample depth of 0-30 cm. Acidity, potassium, total phosphorus, and CEC (cation exchange capacity) stayed essentially constant during the farm's operation. While ammonium ion levels declined by almost 50% from initial levels (5.8 ± 1.0 ppm to 3.25 ± 0.63 ppm), NO_3 levels rose (2.6 ± 1.5 ppm to 7.2 ± 3.2 ppm), so total nitrogen declined only slightly from 1993 to 1997. Subsequent measurements of total N through 2000 using the same methodology showed a rise over the next three years erasing 3/4 of this loss; in addition, samples extending to 60 cm depth over the whole project period showed no net N loss. Earthworm numbers were also measured several times during the project; their populations showed no decline or increase within the error margin.

These results suggest that the soil chemistry impact of the farm was sustainable, in contrast to current industrial farming practices. Long-term studies of heavily-fertilized plots in the American Midwest have shown consistent loss of soil organic matter, amounting to .05%/yr or more – even when crop residue is returned to the soil – due to fertilizer-driven acceleration of microbial activity (Khan et al., 2007). Such a rate of SOM loss would have been clearly detectable in this study. The long term soil quality benefits of the use of manure and compost on the farm are clear, as are the synergistic benefits of closing the nutrient cycle using animals which also generate products and traction for the farm. The 9.5 GJ/ha embodied energy of just the NPK-Ca fertilizer applied to a typical U.S. corn field (Patzek, 2004) stands in stark contrast to the average *total* energy inputs of 4.3 or 8.1 GJ/ha for milo and soybeans on the SSF respectively. The data clearly show that the fertilizer system of the SSF sustains the soil, minimizes energy inputs, and promotes diverse farm outputs (e.g. animal products). The energy data show that this superior stewardship of the land was in fact associated with improvements in energy efficiency as well.

6 Analysis of the Sunshine Farm Data

6.1 Previous Studies of the Sunshine Farm Data

The Sunshine Farm data were analyzed previously by Bender (Bender, 2003; Bender, 2006). The present study represents an entirely fresh analysis of these data, with new tools (implemented in MATLAB) and a considerably different approach. Bender's analysis focused on the ability of the farm to function as a self-sufficient entity, and only secondarily on the farm as an energy producer/consumer in a larger economy.

This study does not attempt to evaluate the farm's performance as an independent entity but as a part of an overall energy economy. As such, this study focuses on the energy efficiency of the exports of the farm, rather than on means by which the farm could satisfy its own energy needs (e.g., biofuels). The solar array is treated as a stand-alone entity (c.f. Section 4). This approach makes possible direct comparisons to previous studies of the particular exports of the farm, presenting a more complete evaluation of the successes and failures of the project. This study also looks more deeply into the efficiency of particular elements of the farm, e.g. the horses.

6.2 Forms of Energy Accounting Used

Inputs and outputs from the farm are reported here in three different ways, reflecting their societal energy impact. For easily-exchanged energy resources such as fuels, caloric content, expressed as high-heating value, or actual meter readings for electricity, reflect their value and exchangeability with similar resources such as biofuels, natural gas, and electricity (although relative efficiency of conversion to shaft work must be take into account, i.e. gasoline vs. diesel, internal combustion vs. electrical motors, and the efficiency of electrical generation). Energy for refining, transportation, and distribution were added to all fossil fuels and biofuels as a 17% energy surcharge based on estimates of this cost for petroleum-based liquid fuels (Patzek, 2004). The petroleum-based charge was used for biodiesel bought for the farm (in effect, treating the biodiesel as ordinary diesel on energy-equivalent basis) due to the highly variable energy costs of biofuel production, and their currently limited availability. No biofuels were made on the farm. The energy content of materials and capital goods is expressed as embodied energy, or the total energy expended in acquiring and processing the basic materials, manufacturing, assembling, transporting and distributing the finished goods to dealers, in accordance with the standard practices of the field of Energy Analysis (Costanza, 1981a). Transportation from dealers to the farm is included explicitly in the farm's energy accounting. Thirdly, the energy embodied in labor can be accounted for in a number of different ways; this issue is dealt with in Section 10.

6.3 Sunshine Farm Accounting Versus Previous Farm Energy Accounting Methods

To the authors' knowledge, the Sunshine Farm database represents the first truly comprehensive energy accounting of a functioning farm. The profound differences between the exhaustively thorough accounting of the Sunshine Farm and the estimates employed in previous studies mean that the SSF study represents a new standard for farm energy accounting, and a resource for identifying uses of energy in farming that have not been taken into account previously. Having a completely disaggregated energy picture of the farm also makes it possible to separate out all the components of the farm in spite of their proximity, and to assess the possible energy impacts of modifications to the farming system (for example, what the farm's energy and labor efficiencies would have been without the horses – see Section 8).

Table 4: Distribution proportions between elements of the Sunshine Farm used to build Input-Output Matrix

Type of Object	Method for Assigning to Exports and Other Objects
Animal export	To corresponding animal export
Animal-related tools	Split among animals by entry fuel use
Feed and export crop	To animals and crop export by weights fed and exported
Electrical export	To electrical export
Feed	To animals by weight fed
Field power source or field tool	To crops by acreage treated
Non-field power source	To objects based on fuel usage
Forage	To animals by average animal mass during season
Green manure	To crops grown next season in same strips
Compost and general field prep	Split among all crops by planted acreage
Infrastructure	Uniform surcharge to all inputs
Farm management and planning	Uniform surcharge to all inputs
Outside services	To object, pro-rate maintenance and materials

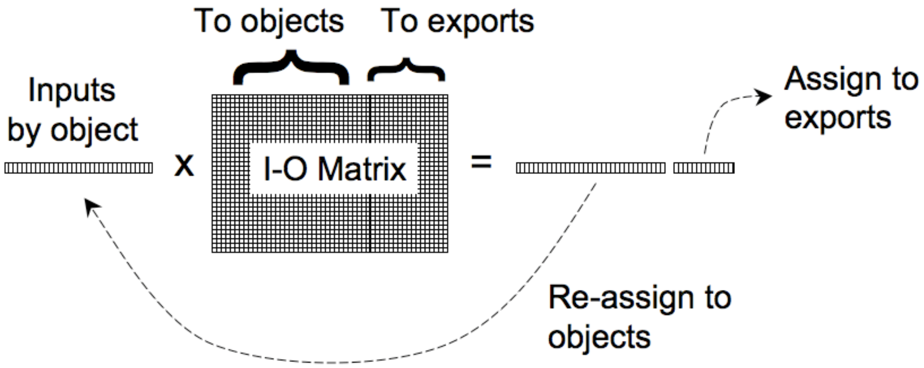

Figure 12: Illustration of the use of the input-output matrix to assign farm inputs to farm exports

6.4 Input-Output Matrix

To deal with the complexities of the inter-relationships between the many parts of the farm, the matrix methods of economic input-output analysis were adapted for this study. For this purpose, the farm was expressed as consisting of 70 components called objects – each capturing a portion of the farm's activity, including animals (horses, cattle, broilers, and layers), crop species, power sources, vehicles, and tools. Each entry into the farm's database included a specification of the object to which the activity was devoted, e.g. feeding the broilers, fixing a tractor, sowing seeds for a crop, etc. To calculate the ultimate assignment of energy inputs to exports from the farm, inputs to objects – consisting of combinations of direct fuel and electrical energy, material embodied energy, and labor hours – were assigned to other objects and exports as shown in Table 4. For example, energy expended on care of the horses was distributed to the crops which were worked by horse labor on the basis of acres worked.

This system of distribution of inputs among objects and exports reflects the internal workings of the farm as detailed in the 1.25 million record database. These relationships were used to build a matrix distributing input energies as shown in individual entries to other objects and exports. This matrix was applied repeatedly, as in many cases objects contributed to each other; through these repeated operations the inputs moved through the farm's network of energetic relationships, until all the input energy was assigned to exports in a way that reflected the inter-relationships of the components of the farm. For example, energy assigned to the maintenance of a plow might be assigned to a green manure crop for which it had prepared the soil, which would in turn be applied to the following crop on that acreage, which in turn would feed horses and other animals (with possible export of these animals and partial export of the crop); the horses would then work on other crops, contributing to their exports and feed for other animals, including the horses themselves. As energy assigned to exports was removed from these cycles of distributions, by repeated application of these distribution rules (whose parameters were precisely set to conserve energy), eventually all inputs could be assigned to outputs. This process is illustrated in Figure 12. The final results are shown in Figure 20.

To illustrate how these calculations were carried out take for example an extremely simplified version of the farm, consisting of four objects – (1) an export and feed crop, (2) a green manure crop, (3) a tractor, and (4) an animal production system, and the two exports from the export crop (5) and the animal production (6). Each object has one unit of energy going into it, represented by the following vector:

$$\begin{pmatrix} 1 & 1 & 1 & 1 \end{pmatrix};$$

this represents direct inputs to each object, such as seeds for the two crops, oil for the tractor, and bought feed for the animals. To distribute these inputs to other objects and to exports the matrix is constructed, based on relationships between the objects. These relationships are represented by the rows that show the fractions of an object's inputs to assign to objects and exports, in the order specified above. To accurately account for all the input energy, the vector's coefficients must add up to 1.0 to conserve total energy.

For example, say that the farm's database shows that half of the feed and export crop harvest went to feed, and the other half to export, so its row reads

$$\begin{pmatrix} 0 & 0 & 0 & .5 & .5 & 0 \end{pmatrix}.$$

The green manure crop provides fertility to the feed and export crop, and does not contribute to the other objects or exports, its corresponding row of the matrix is

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

The tractor works the two crops, so its row reads

$$\begin{pmatrix} .5 & .5 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

The animal production contributes only to its own export, so its row is

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix},$$

resulting in the following matrix:

$$\begin{pmatrix} 0 & 0 & 0 & .5 & .5 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ .5 & .5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

To distribute the inputs to the objects and exports, multiply the input vector by the matrix, to obtain a vector of energy going into objects and exports:

$$\begin{pmatrix} 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & .5 & .5 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ .5 & .5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1.5 & .5 & 0 & .5 & .5 & 1 \end{pmatrix}$$

Note that the sum of the elements of the result equals the sum of the inputs, satisfying energy conservation. The last two elements of the resulting 6-element vector represent energy passing into exports; the first four represent energy passing into objects. As the goal is to distribute the input energy to exports, we set aside the last two elements and distribute the first four elements again:

$$\begin{pmatrix} 1.5 & .5 & 0 & .5 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & .5 & .5 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ .5 & .5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} .5 & 0 & 0 & .75 & .75 & .5 \end{pmatrix}$$

The last two elements are added to the previous iteration's export elements to obtain 1.25 for the crop and 1.5 for the animal export; the remaining energy in the first four elements now totals 1.25, substantially down from the 4.0 originally fed into the system. These inputs can then be cycled in this way until the energy being redistributed back into objects is small enough to be neglected. In this simple case, two more cycles suffice to distribute all the inputs to exports, resulting in a final result of 1.5 units of input to the crop export, and 2.5 units of input to the animal export.

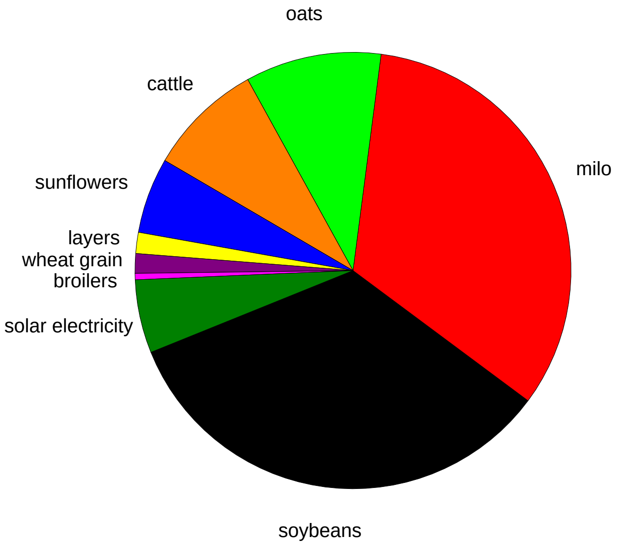

Figure 13: All exports from the Sunshine Farm by their total embodied energy. Total: 2127 GJ.

6.5 Breakdown of Inputs to Exports by Type

A breakdown of the proportions of the inputs into the farm exports by type – fuel (including electricity), feed, seed, animal, capital, and supply (all other materials, as described below) is shown in Figure 15. The proportions of these types for the major crops of the farm – milo, soybeans, oats, and wheat grain – are roughly similar, with oats and soy showing higher

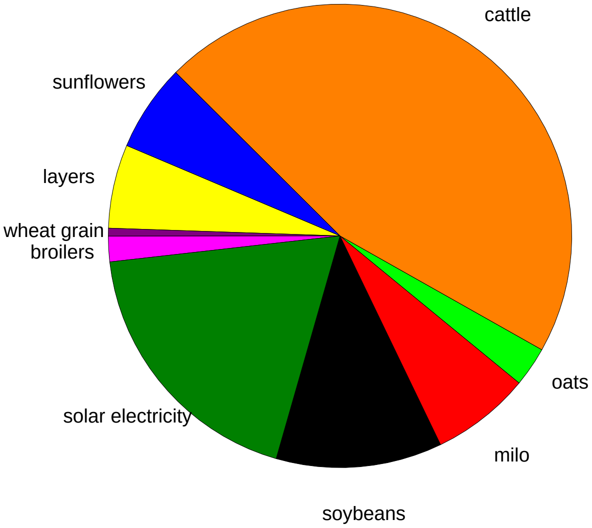

Figure 14: SSF input energy going to each export, excluding labor.

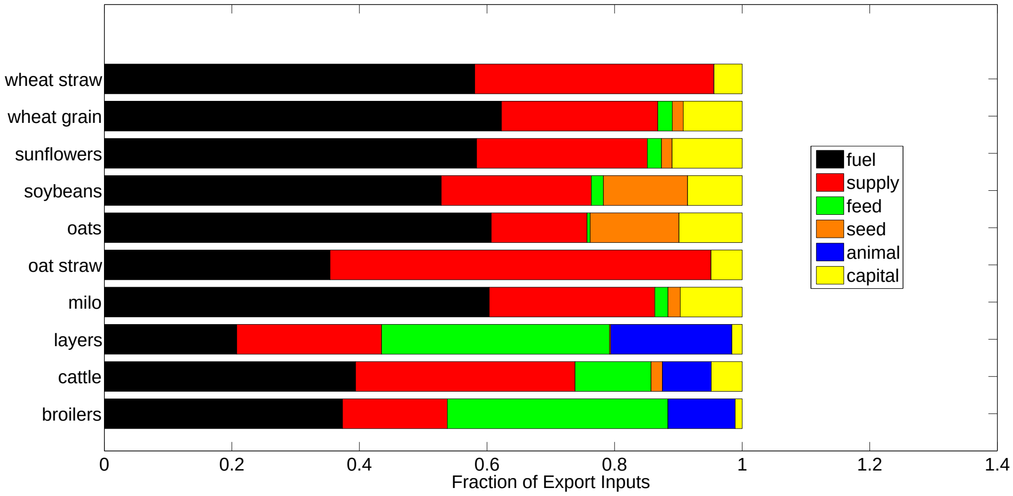

Figure 15: Energy use fractions by type for major exports.

seed input energy due to higher per area seed application rates. The "supply" category of miscellaneous materials, unaccounted for in previous studies, is substantial, 15% and higher, for every export. Capital equipment inputs for the crops is relatively small but significant, amounting to 11-13% for the major crops. For the animal exports, feed is a major input, although it is smaller for the cattle, due to their ability to feed themselves by grazing on the farm's pastureland.

Remark 1 The relatively high fraction of the "Supplies" portion of the SSF energy inputs – representing energy inputs relating to other material inputs – can be seen clearly in the diagram, and demonstrates a significant flaw in all previous farming energy studies. This category represents all of the materials – from galvanized steel to rubber and lumber – that were used on the farm, and which are not accounted for in previous studies. □

Although there are no data on the subject, it is obvious that such materials are also used on other farms, in spite of the fact that such use is not tracked, and in spite of the differences between the production techniques of the Sunshine Farm and conventional farms there is no particular reason to believe that ratios between supplies and other forms of energy consumption would be radically different.

Remark 2 If these ratios are assumed to be similar then this would have profound implications for policy decisions regarding biomass and biofuels, as the energy ratios of these products would become significantly worse, limiting their usefulness in the overall economy. In the case of corn ethanol, taking account of these materials could eliminate the energy surplus calculated in the most recent studies (Farrell et al., 2006) (Shapouri et al., 2003) (Shapouri and McAloon, 2004) (Graboski, 2002), even without taking into account the adverse environmental impacts of conventional corn farming. □

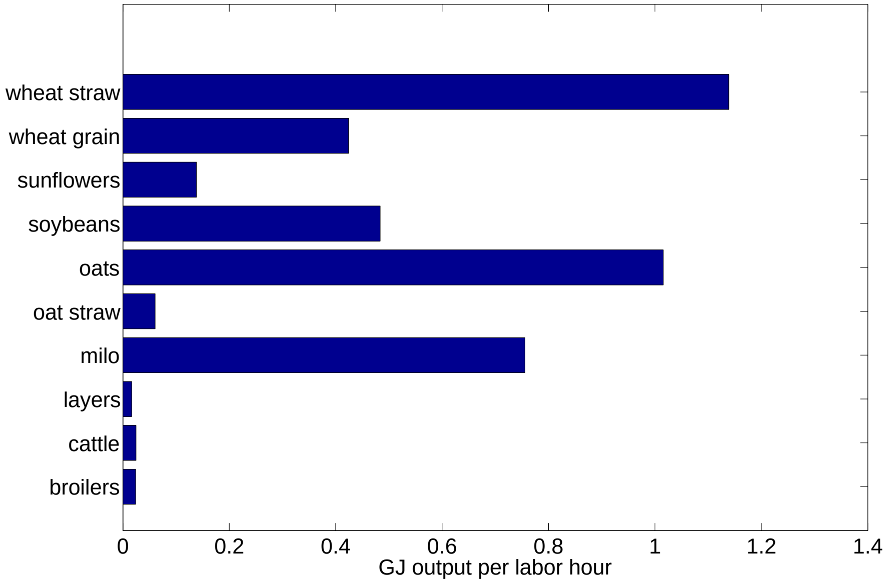

Figure 16: Labor efficiency of SSF major exports

7 Labor Usage on The Sunshine Farm

Labor efficiency – GJ of exported goods per labor hour – is shown for each major export in Figure 16. These ratios are calculated using the same methods used to allocate energy inputs to exports, so that all recorded labor on the farm is allocated to one or more exports through the input-output matrix discussed in the section above. This means that in addition to the obvious labor costs such as animal feeding, plowing, seeding, watering, harvesting, etc. accounted for in previous studies, indirect labor costs such as management, equipment repair and maintenance, trips to local merchants, construction, etc. can be taken into account and properly allocated using the details of their database entries. Furthermore, labor on crops used in part as feed can be accurately allocated to animals fed by these crops, with any exported portion receiving its own portion of the labor. As in the energy case, the result is a picture of on-farm labor usage far more detailed and accurate than ever before available.

Labor hours per gigajoule of exported product follows similar trends to the energy ratios. Animal products are far less efficient than the crops, owing to the large amounts of daily labor involved in feeding and caring for animals as well as growing the crops they ate. Beef production is more labor-efficient than either the layers or broilers, as the cattle required less feeding and other care in proportion to their output. Oats are particularly efficient due in part to a single crop of volunteer (not intentionally seeded or plowed) oats which required very little labor to produce.

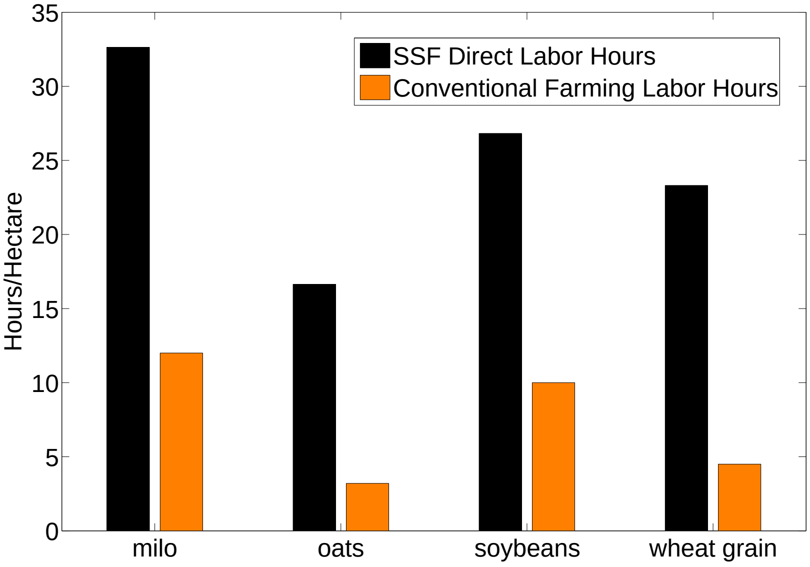

Figure 17: Labor per hectare for exported crops

Figure 17 compares labor hours per hectare of cropland on the SSF to labor hours in conventional agriculture. This figure shows labor directly attributable to the crops – only work done explicitly for the purpose of growing crops. This is for direct comparison to the previous studies.

Per-hectare labor rates are much higher than in conventional agriculture, at 2.7x for milo, 2.7x for soybeans, 5.2x for oats, and 5.2x for wheat. The Sunshine Farm labor statistics include both field operations and transport of the harvested crops to local buyers. It is not known if the other labor estimates include this transportation charge; however this amounts to only 3-5% percent of labor hours for the important crops of the farm. The small size of the tractors (and the horse-drawn implements) used on the farm contributed to higher labor hours, as did the small size of the farm and the use of several different crop types, leading to inefficiencies due to setup times for a larger number of separate tasks on the farm. Horses require 1.6x and 2.3x more direct field labor per treated hectare than the two main tractors of the farm; however this has little impact as the horse only treated 6.4% of the total area worked on the farm. Horse care and management entailed 13.7% of all labor on the farm. The complete energy impact of the horses on the farm is addressed in the next section.

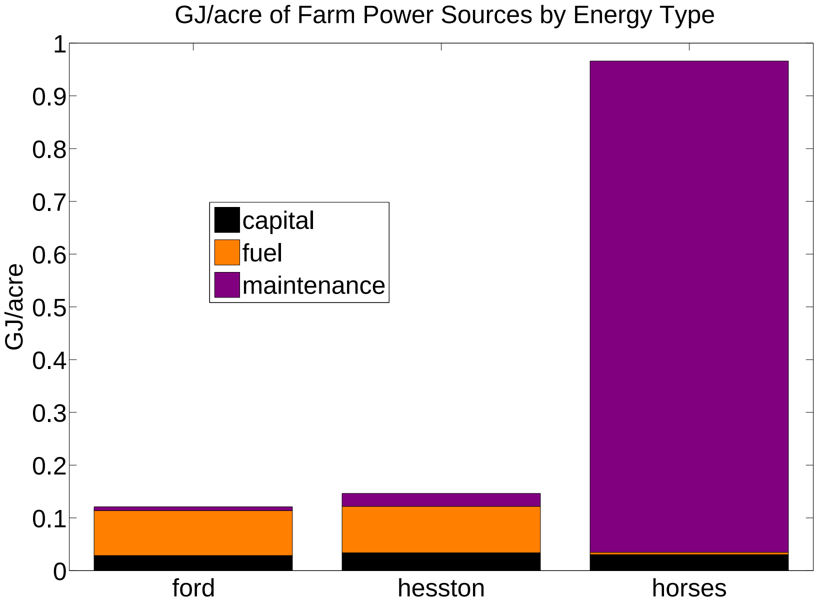

Figure 18: GJ/acre of Power Sources on SSF, with input breakdown by type

8 Horses Versus Tractors

The energy efficiency of the two horses used on the farm versus the various tractors is shown in Figure 18. The energy efficiency of each power source was considered taking into account embodied energy in capital equipment and supplies for maintenance as well as fuel use. For the horses, this included apportioned energy inputs for forage crops as well as feed and feed crops. Some 36% of the alfalfa and 42.5% of sweet sorghum grown on the farm was fed to the horses; this was a major contribution (47%) to the energy attributable to the horses. 96% of the horses' feed was grown on-farm. An average of 24% of the total farm crop area was dedicated to feed and forage for the horses.

For the two small tractors employed on the farm, 27% and 29% of their energy use can be attributed to depreciation of the embodied energy of the tractors themselves, 5% and 15% to maintenance supplies (engine oil, tires, etc.), and 68% and 56% to actual fuel use.

As can be seen in the figure, horses were considerably less efficient than the tractors used on Sunshine Farm. As these tractors are less efficient than larger tractors (as suggested by follow-on studies performed on the study farm using larger equipment), this difference would seem to be decisive. However horses are likely to be far more efficient than indicated by this measurement, and deliver several unique advantages as well.

Horses are more energy-efficient than tractors when pulling loads – and can run on crops with low embodied energy. However, they use feed and maintenance energy at a rate that is only weakly dependent on the amount of work they do, unlike tractors; this means that their efficiency is heavily dependent on their being fully utilized – i.e. used for work as much as possible. The Sunshine Farm horses were clearly under-utilized. Over 5.5 years of heavy farming, assuming a 50-week work year, the horses worked an average of 2.36 hours per week. In a farm sized to match such horses, work weeks of an order of magnitude greater or more would not be unusual, although the seasonality of the work would reduce the overall average. Horses performed only 6.4% of field operations over the lifetime of the farm on an acreage basis, so their relative inefficiency had a limited effect on the farm's overall energy efficiency. Their

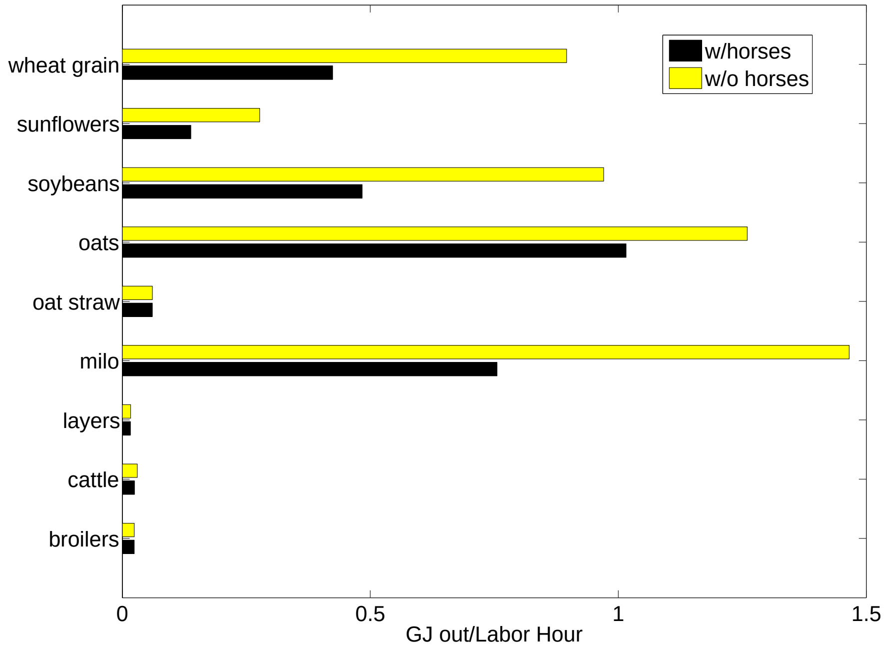

Figure 19: Comparison of labor hours per GJ for exports, for horse and no-horse cases.

impact on the labor efficiency of the farm was much more pronounced. Once the labor involved in their care and growing their feed was taken into account, the horses required 492x and 187x more total labor input per acre treated than the two main tractors of the farm.

Horses do supply unique advantages over tractors, however. By dropping their manure on the crop area as they worked, they deliver valuable minerals and fixed nitrogen from the pasture area. It is also worth pointing out that horses can provide transportation as well as traction; in this sense they were doubly under-utilized. With carriages and buggies, horse power could have been used to transport supplies, which was one of the largest energy uses on the farm, totaling 146 GJ, or 25% of all fuel and electricity energy use; using horses for half of this would almost completely offset all their care and maintenance energy costs (76.5 GJ), including feed, fuel, and supplies. There remains much room for further research into the energy effectiveness of substituting horse power for internal combustion power.

The SSF horses consumed a considerable amount of resources on the farm, and were employed relatively inefficiently, as noted above. The detailed nature of the database allows an analysis of how the farm might have performed without the horses. To analyze the no-horse scenario, all fractions of labor, fuel, supplies, and feed for the care and maintenance of the horses was eliminated, as well as horse-related capital equipment. Acres worked using horse power were assumed to have been worked by the other field traction sources on the farm, proportionally to the acreage which they worked over the lifetime of the SSF. Fuel and materials usage per acre worked was calculated for each non-horse field power source, and these assumed fuel and maintenance costs were assigned to the crops worked by the horses. Crops grown to feed the horses, including a an animal mass-weighted fraction of the forage crops, were assumed to have never been planted.

Even without taking labor into account, the energy efficiency of the no-horse farm scenario is significantly better overall, particularly for three of the four major crops of the farm. The no-horse energy efficiency improves on the with-horse efficiency by 1.42x for milo, 1.31x for soy, and 1.48x for wheat. Oats is mostly unchanged, as it was largely unworked by the horses. Figure 19 shows the even larger labor savings. The labor efficiency (GJ of output per labor hour) of the major crops improves in the no-horse case by 1.94x for milo, 2.0x for soy, 2.0x for wheat, and 1.24x for oats. Animal labor efficiencies are mostly unchanged. Furthermore, a high proportion of the labor saved in the no-horse case is higher-skilled, "manager" labor; although manager labor is charged at the same rate as other labor types in the above analysis, this type of labor is economically more valuable. Because of possible unaccounted-for side benefits of having the horses on the farm (discussed above), this assessment may overestimate the savings of a horse-free farm.

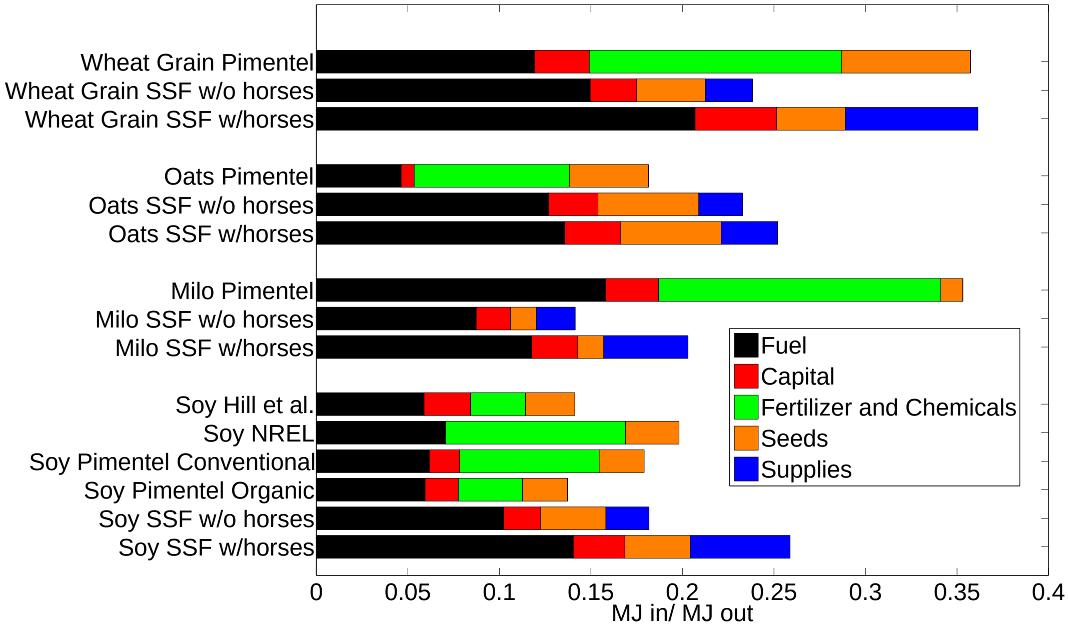

Figure 20: Energy efficiency of SSF compared to previous studies of conventional agriculture

9 Comparison to Previous Studies of Agricultural Energy Efficiency

The exhaustive and extremely detailed accounting employed at the Sunshine Farm stands in distinct contrast to the estimations employed by previous workers in the field, which are generally based on unverified voluntary reporting of a small number of easily-measured farm parameters. The near-microscopic granularity of the SSF data (including every labor hour, nut and bolt, etc. as described above) reveals many aspects of energy use in farming not apparent in previous studies. Because the higher level of detail, many energy inputs were identified that were missed in previous studies. Some of these can be clearly accounted for, such as the "supplies" category of miscellaneous materials; these amount to a significant fraction of the inputs and point to a higher energy use in farming generally than has previously been assumed. Others are almost certain to exist (as discussed below) but cannot be easily separated. As such, directly comparing the energy ratios of the Sunshine Farm to previous studies is not entirely fair. In spite of this, the Sunshine Farm performed well in terms of energy efficiency.

A comparison to previously-reported crop energy efficiencies is shown in Figure 20. Because previous studies have not taken into account all energy inputs into farming, the energy inputs of the SSF were broken into categories for direct comparison. Even so, it is likely that due to more extensive accounting the SSF data are more accurate, and take into account more uses of fuel and capital equipment than previous studies. These ratios take into account all fuel inputs to the crops, including indirect fuel inputs for items such as trips to local vendors, outside service vehicles, compost and green manure, fuel and capital inputs to draft animals, tools, and other capital objects such as buildings. The two Sunshine Farm (SSF) cases are for the actual farm and the projection of the farm's performance without horses, detailed below.

To ensure that differences in energy ratios are based on reported resource use and not on the different embodied energy factors used by various researchers, energy inputs for each of the studies were re-calculated based in the quantities of substances reported by the author(s), multiplied by uniform embodied energy factors (Hill et al., 2006; Sheehan et al., 1998b; Pimentel, 2006; Pimentel, 1980). For materials used in this study, the values from Tables 2 and 1 were used; for agricultural chemicals, embodied energy factors were taken from Pimentel (Pimentel, 1980). Fertilizer and chemical inputs for the Sunshine Farm are counted as zero; all energy expenditures related to crop fertility are included in the allocated fuel, capital, and supply figures for the crops. These inputs – for fixed nitrogen, phosphorus, potassium, herbicides, pesticides, and lime – constitute a large part of the energy balance for industrial agricultural systems, ranging from 24-47% of total estimated inputs. None of the previous studies took into account the full range of inputs to farming; only fuel, fertilizer, chemicals, seeds, and in some cases capital equipment were included. This difference is shown in the "Supplies" portion of the energy inputs shown in the figure, and amounts to a substantial fraction of the inputs, 15-27%. The studies by Pimentel (Pimentel, 2006) (Pimentel, 1980) do not take farm buildings into account. One major study (Sheehan et al., 1998b) neglects capital equipment inputs entirely; these amount to 7.7% of non-labor inputs to the SSF.

As can be seen, the energy efficiency of the Sunshine Farm was competitive with conventional agriculture. Discounting the "Supplies" category to make the comparison fair, the non-horse SSF attained a superior energy ratio to conventional farming in 4 of 6 cases, coming within 15% of the conventional energy ratios in the other two cases. In all cases except milo, the SSF fuel use is markedly higher; this is likely due to both the more complete accounting and the relative inefficiency of the SSF tractors (sized for horse-compatible rows). Use of larger equipment with the SSF's sustainable techniques would result in efficiency markedly superior to conventional techniques in all cases. Use of electric tractors in place of internal combustion tractors would reduce traction energy use by a factor of approximately 4x, although for full accounting the source of the electricity would have to be taken into account. Tractors may be run on a farm-scale grid to eliminate the need for large, expensive batteries.

These estimates do not take into account the energy costs of cleaning up the environmental degradation caused by current industrial agriculture production. These costs are difficult to quantify, but are likely to be much larger than the whole direct energy cost (Patzek, 2004), which would overwhelm the small energy differences calculated here.

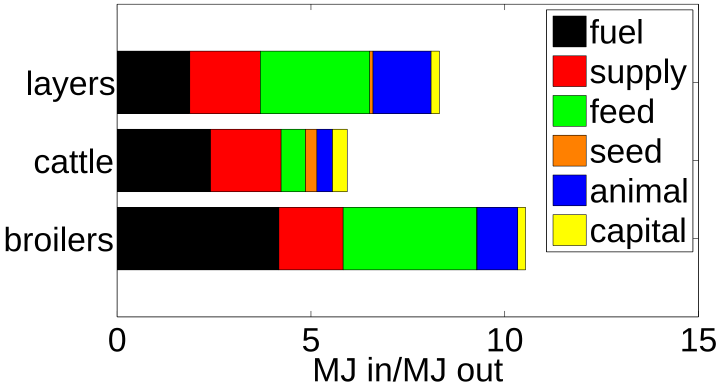

Figure 21: Energy efficiency of SSF animal production

9.1 Animal Production Energy Efficiency

Figure 21 shows the energy efficiency of animal production on the farm. Animal export calories required 14-34x more energy input than export crop calories. Beef production on the farm was markedly more efficient than broiler or egg production, largely due to the fact that the cattle fed themselves mainly on forage, consuming significant amounts of feed only during December, January, and February. As with the crop production, the “supplies” category, unaccounted for in previous studies, is significant, ranging from 34% for beef production to 16% for the broilers.

Table 5: Total Energy Input Versus Protein Energy Output for SSF versus conventional production. Conventional beef production numbers are for feedlot and grass-fed production respectively. Source: Pimentel, 2006

Output	SSF	Conventional
Beef	20.6:1	40:1/20:1
Eggs	20.4:1	39:1
Broilers	18.9:1	4:1

Heitschmidt (Heitschmidt et al., 1996) reported energy ratios for a range of grass-fed and feedlot scenarios. The closest match to the production practices of the Sunshine Farm was an interpolation between Heitschmidt’s calf and yearling scenarios with 84 feedlot days. Weighting by the proportions of calves and yearlings exported by the SSF, and pro-rating for the calf loss experienced on the SSF (4%) results in an expected energy ratio of 3.17:1, almost twice the SSF’s 5.95:1. This difference may be due to Heitschmidt’s much larger herds (250+ head for pasture, 1000+ for feedlot production), and to the more complete Sunshine Farm accounting.

Comparison with Pimentel’s energy input to protein energy output ratios (based on national USDA data) (Pimentel, 2006) yields a distinctly different result (see Table 5). The farm’s beef protein production efficiency is almost twice that of feedlot beef, and essentially equal to that for grass-fed beef. Egg production is almost twice the efficiency of conventional production. Chicken meat (“broiler”) production is 4.7x less efficient than the spectacularly efficient conventional caged production. However broiler production was only a very small part of the farm’s activities, representing less than 0.5% of exports. Broiler chickens were fed bought feed almost exclusively (very little farm-grown), which contributed to their relatively high energy inputs, as bought feed had higher embodied energy and transportation costs.

In summary, the Sunshine Farm achieved a high level of energy efficiency even while producing organically and maintaining the fertility of the soil (see Sections 11 and 5. This is remarkable in view of the relatively small size of SSF (the average size of a farm in Kansas from 1993-1998 was 294 ha, versus the SSF’s 20 ha cropland and 40-65 ha pasture), the use of horses for traction (see Section 8), and the relative novelty of the rotation and multi-species production methods employed. Labor usage on the farm is treated in a separate section below.

10 Labor and Commuting Energy

The Sunshine Farm used less energy of combined fuel, materials, feed, seed, and capital equipment than conventional industrial agriculture, but used more labor. To obtain a full picture of how an agricultural system impacts a society’s energy economy, it is necessary to assign some energy cost to the labor. How much to assign is a matter of some controversy in the energy analysis literature (Sollner, 1997). A minimum charge, applicable to subsistence agriculture, would be for the additional food calories needed to sustain the physical work on the farm; for the purposes of this analysis this would be far to small a charge (approximately 0.36MJ/hr) to consider, and differences between labor usage in conventional agriculture and the SSF system would not impact the energy savings of the SSF methods. Humans in an industrial society use far more energy than needed to sustain their metabolism, however, and so many authors have attempted to include some fraction of workers' total energy usage into the scope of energy inputs considered.

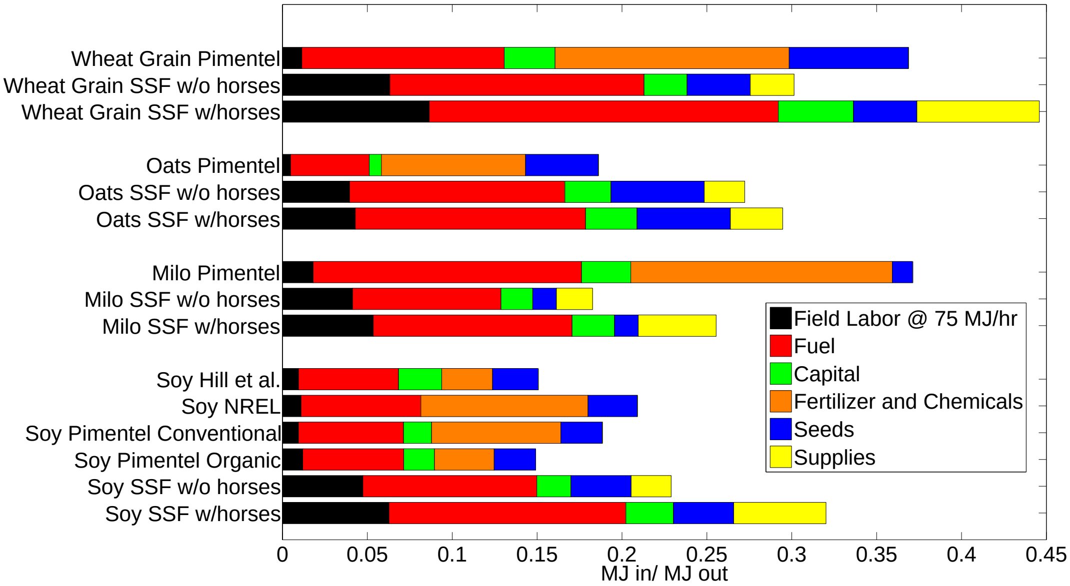

Figure 22: Comparison to previous studies including field labor charged at 75 MJ/hr

In the approach of Costanza and Herendeen (Costanza and Herendeen, 1984), labor is treated as an internal part of an economy (one of a number of sectors represented by an input-output matrix), consuming internal flows of embodied energy originating from external energy inputs. This approach to labor contrasts traditional economic theory treating labor, land, and capital as external inputs, as if human labor was not dependent on energy in the form of goods and services (Costanza, 1981a) (Costanza, 1981b). Following this approach, Fluck (Fluck, 1992) disaggregated the US gross national product into 50-some economic sectors, applied dollar-based energy intensities to each sector (from Bullard (Bullard et al., 1976)) to get energy consumption for each sector, and then subjectively assigned a portion of each sectors energy consumption to labor. The sum of the assigned energy portions for labor represented 22 percent of US energy consumption. Fluck then applied two factors relating the expenditures and earnings of rural workers to urban workers. This procedure yielded a value of 594 MJ/day, or 75 MJ/hour, for average US rural labor. This value is comparable to other studies (Williams et al., 1975) (USDA, 1974) (De Wit and Van Heemst, 1976) using other methods.

Figure 22 shows the results of charging labor energy at this rate. It should be noted that for comparison, the labor charged to the Sunshine Farm exports in this figure consists only of field operations, including field preparation, hauling, and other direct crop-related labor costs (this includes labor to grow green manure crops). A full accounting of the labor for each export, including horse husbandry, transportation, repair and maintenance of equipment, farm management and planning, and other miscellaneous jobs is shown in Figure 16; these costs were presumably not included in the compared studies. Although the increased labor use on the SSF has a significant impact on the energy ratio of the farm, the farm remains competitive with conventional agriculture with labor charged at this rate. It is worth noting that a large fraction of the farm's labor was performed by relatively inexperienced volunteers; with experienced hands the hours might have been significantly reduced.

Conscious decisions about farm design can affect the labor's energy usage, e.g. energy-efficient on-farm housing. Also, some types of farm labor now widely employed (e.g. migrant labor) clearly use less energy than typical industrial workers. While it is important for whole societies to evaluate the impacts of net per-person energy use, it is not clear that labor-saving on a farm saves energy in the economy as a whole. Pivotal to the question of the energy cost of labor is how the total population of a society (and its per-person energy usage) might vary with the amount of labor employed in agriculture, and how much energy the actual agricultural workers use in their day-to-day existence. These important questions have not been significantly addressed beyond the work outlined above, so there is much room for further research. It is also worth noting that the average American uses approximately five times the energy of an average human; in less-energy-intensive societies the benefits of such energy-for-labor tradeoffs would be even better.

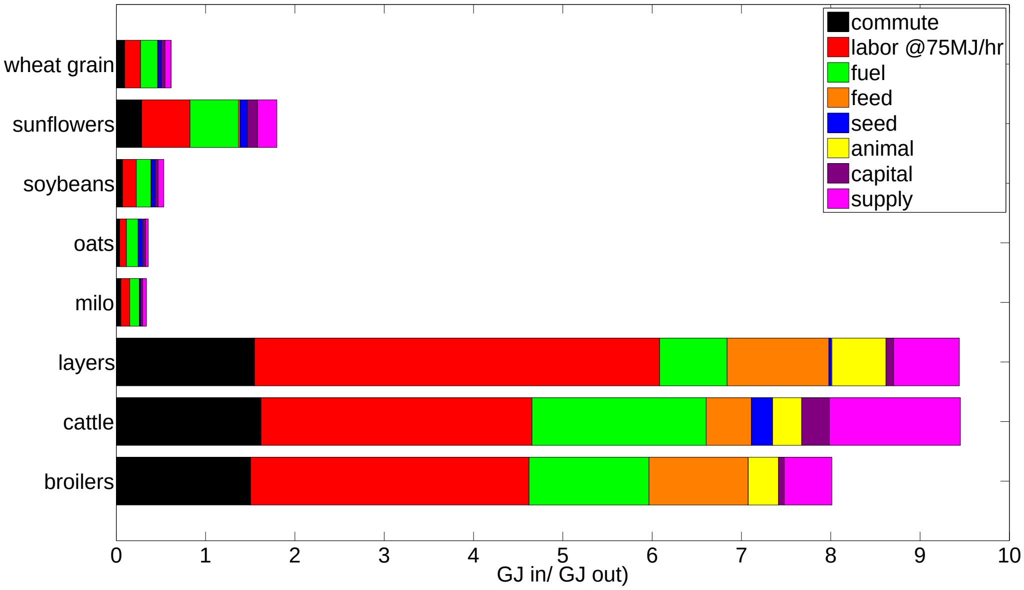

Figure 23: SSF MJ inputs per MJ output including commute and labor charged at 75 MJ/hr

10.1 Commuting Energy

One of the unique aspects of the SSF data was the availability of an hour-by-hour picture of activities on the farm, allowing the estimate of the number of commuting trips required for farming operations. None of the workers on the farm lived on-farm, or within walking distance. The lowest possible number of commutes possible to perform the work on the farm was estimated for manager and non-manager labor, the two categories of labor on the farm, by assuming one commute for each category of labor when any number of hours were logged in a day in that category. The number of days on which more than 9 hours of labor in any category were recorded – implying more than one category worker on the farm – was small enough to not significantly affect the results. Furthermore, some labor entries are known to consist of multiple, repetitive tasks – such as feeding – accumulated into one entry for simplicity. Due to the methodology these results are clearly a lower limit on commuting energy.

Only two authors attempt to include commuting energy in estimates of energy consumption in agriculture. Hill (Hill et al., 2006) used the same formula employed by Patzek (Patzek, 2004) to estimate the commuting energy consumed by an agricultural system. This formula obtains the number of round-trip commutes by dividing the number of labor hours by 9. This means that the resulting estimate is based on an assumption that that laborers work 9-hour days exclusively. The SSF database suggests that at least for the SSF system this assumption would lead to a substantial underestimate of the number of commutes, as the day-by-day entries show that workers frequently came to the farm for smaller periods of time.

The consequences of including commute costs are shown in Figure 23. Commute energy costs, as figured by using the above methodology and the per-trip energy costs assumed by Hill and Patzek (6 liters of gasoline per commute, i.e. 208 MJ), amount to 34-54% of the 75 MJ/hr labor costs for the major exports of the farm, and to 16-46% the total non-labor inputs. This significant expense, as explained above, is clearly a lower limit. The commuting cost could be reduced by using better-mileage vehicles for commuting, but low-mileage pickup trucks are currently frequently employed for this purpose.

Remark 3 These results point to large energy savings for family farms, and any farm where the workers reside on the farm. □

11 Nutritional Quality of Food Produced by the Sunshine Farm

In addition to improving care for the soils on the farm, the SSF production methods are also likely to produce superior-quality produce. In addition to a lack of pesticide residues, the crops produced may have been more nutritious. Although the nutritional content of the Sunshine Farm products was not evaluated directly, a recent meta-study combining the data of 97 studies closely matching production conditions showed that organically-produced crops are generally higher in important nutrients (Benbrook et al., 2008). For example, organic produce was an average of 24% higher in total antioxidants, and 10% higher in total phenolics. Although conventional produce was slightly higher in protein (presumably due to higher available nitrogen), harmful nitrates were also higher by an average factor of 1.8.

The animal products of the farm are also likely to be of higher quality than current conventional animal production systems. In particular, analyses of poultry and livestock produced using organic feed and pastures show moderately higher protein, more of some vitamins and minerals, and increased levels of healthful omega-3 fatty acids and conjugated linoleic acid (CLA) fats (Huber, 2007; Clancy, 2007).

Table 6: Summary of Sunshine Farm energy efficiency ratios versus previous studies. Labor, and materials not counted in previous studies ("Supplies" category), not included.

Crop	Study	Method	MJ Out per MJ In
Soybeans	SSF w/Horses	Organic	4.9:1
Soybeans	SSF w/o Horses	Organic	6.3:1
Soybeans	Pimentel	Organic	7.3:1
Soybeans	Pimentel	Conventional	5.6:1
Soybeans	Sheehan, et al.	Conventional	5.0:1
Soybeans	Hill, et al.	Conventional	7.1:1
Milo	SSF w/Horses	Organic	6.4:1
Milo	SSF w/o Horses	Organic	8.3:1
Milo	Pimentel	Conventional	2.8:1
Oats	SSF w/Horses	Organic	4.5:1
Oats	SSF w/o Horses	Organic	4.8:1
Oats	Pimentel	Conventional	5.5:1
Wheat	SSF w/Horses	Organic	3.5:1
Wheat	SSF w/o Horses	Organic	4.7:1
Wheat	Pimentel	Conventional	2.8:1

12 Conclusion

The database of the Sunshine Farm is a valuable record of the entire mechanism of an organic, sustainable farm. Its high level of detail gives insights into the hidden components of energy consumption on farms. In particular, few if any previous studies take into account the full range of materials used on the farm, which has a significant impact on the SSF's energy budget, and should be considered in any future consideration of farm energy budgets. The use of horses on the farm reduced its energy efficiency, mostly due to their underutilization; however, the detail of the database allows analysis of the farm with the horses' influence removed. With this adjustment, the energy efficiency of crop and animal production methods of the SSF are seen to be competitive and in most cases superior to those of conventional agriculture (as summarized in Table 6), in spite of the more detailed accounting. The higher labor hours employed on the farm do not reverse this result, even when energy intensive American labor is factored in. As the SSF also eliminates the problems of loss of soil quality, water pollution, and air pollution, as well as providing superior quality, organic meat, legumes, and grains, the methods of the SSF represent a significant advance over current, conventional farming methods.

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References

Ayres, R. U. 1994, *Information, Entropy, and Progress: A New Evolutionary Paradigm*, American Institute of Physics Press, New York.

Batty, J. C. and Keller, J. 1980, in D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp 35–44, CRC Press, Boca Raton, Florida.

Benbrook, C., Zhao, X., Yáñez, J., Davies, N., and Andrews, P. 2008, *New Evidence Confirms the Nutritional Superiority of Plant-Based Organic Foods*, Technical report, The Organic Center.

Bender, M. H. 2003, Energy budget of an energy-integrated organic farm, in *Changing Sciences for a Changing World: Building a Broader Vision, 2003 ASA-CSSA-SSSA Annual Meetings.*

Bender, M. H. 2006, *The Sunshine Farm Book*, The Land Institute, Salina, Kansas.

Bethel, J. 1976, *Renewable Resources for Industrial Material: Reference Materials Systems: A Source for Renewable Materials Assessment*, National Academy Press, Washington D.C..

Boustead, I. and Hancock, G. F. 1979, *Handbook of Industrial Energy Analysis*, John wiley & Sons, Inc..

Bukantis, R. 1980, in D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp 103–108, CRC Press, Boca Raton, Florida.

Bullard, C. W., Penner, P. S., and Pilati, D. A. 1976, *Energy Analysis Handbook. CAC Document No. 214*, Center for Advanced Computation, University of Illinois, Urbana.

Byerly, T. C. 1982, in *CRC Handbook of Agricultural Productivity, Vol. II, Animal Productivity*, pp 265–304, CRC Press, Boca Raton, Florida.

Casler, S. and Hannon, B. 1989, Readjusted potentials in industrial energy efficiency and structure, *Journal of Environmental Economics and Management* **17**: 93–108.

Chandler, W. U. 1985, *Energy Productivity: Key to Environmental Protection and Economic Progress. Worldwatch Paper No. 63.*, Technical report, Worldwatch Institute, Washington, DC..

Chapman, P. F. and Roberts, F. 1983, *Metal Resources and Energy*, Butterworths, London.

Clancy, K. 2007, *Greener Pastures: How Grass-fed Beef and Milk Contributes to Healthy Eating*, Technical report, Union of Concerned Scientists, Washington, D.C..

Cook, C., Combs, J., and Ward, G. 1980, in *Handbook of Energy Utilization in Agriculture*, pp 405–418, CRC Press, Boca Raton, Florida.

Costanza, R. 1981a, in H. E. Daly and A. F. Umaña (eds.), *Energy, Economics, and the Environment: Conflicting Views of an Essential Interrelationship*, pp 119–145, Westview Press, Boulder, Colorado.

Costanza, R. 1981b, in H. Daly and A. Umaña (eds.), *Energy, Economics, and the Environment: Conflicting Views of an Essential Interrelationship*, pp 187–192, Westview Press, Boulder, Colorado.

Costanza, R. and Herendeen, R. 1984, Embodied energy and economic value in the united states economy: 1963, 1967 and 1972., *Resources and Energy* **6**: 129–163.

Crampton, E. W. and Harris, L. E. 1969, *Applied Animal Nutrition: The Use of Feedstuffs in the Formulation of Livestock Rations. 2nd edition*, W.H. Freeman and Co., San Francisco.

Craumer, P. R. 1977, *Master's thesis*, University of Wisconsin, Madison.

De Wit, C. T. and Van Heemst, H. D. J. 1976, in W. T. Koetsier (ed.), *Chemical Engineering in a Changing World*, pp 125–145, Elsevier, Amsterdam.

Dinnes, D., Karlen, D., Jaynes, D., Kaspar, T., Hatfield, J., Colvin, T., and Cambardella, C. 2002, Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils, *Agronomy Journal* **94**: 153–171.

Farrell, A. E., Plevin, R. J., Turner, B. T., Jones, A. D., O'Hare, M., and Kammen, D. 2006, Ethanol can contribute to energy and environmental goals, *Science.*

Fluck, R. C. (ed.) 1992, *Energy in farm production*, Elsevier Publishers, Amsterdam.

Fluck, R. C., S., P. B., and Baird, C. D. 1992, *Florida Agricultural Energy Consumption Model. Final Report.*, Technical report, Florida Energy Extension Service, Gainesville, Florida.

Fthenakis, V. M., Kim, H. C., and Alsema, E. 2008, Emissions from photovoltaic life cycles, *Environmental Science & Technology* **42(6)**: 2168–2174.

Glover, J. 2008, *Private communication.*

Graboski, M. S. 2002, *Fossil Energy Use in the Manufacture of Corn Ethanol*, Report prepared for the National Corn Growers Association, Colorado School of Mines.

Green, V. S., Cavigelli, M. A., Dao, T. H., and Flanagan, D. 2005, Soil physical properties and aggregate associated c, n, and p distributions in organic and conventional cropping systems, *Soil Sci.* **170**: 822–831.

Hall, C. A. S., Kaufman, E., Walker, S., and Yen, D. 1979, Efficiency of energy delivery systems: Ii. estimating energy costs of capital equipment, *Environmental Management* **3**: 505–510.

Heichel, G. H. 1980, in D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp 27–33, CRC Press, Boca Raton, Florida.

Heitschmidt, R. K., Short, R. E., and Grings, E. E. 1996, Ecosystems, sustainability, and animal agriculture, *J. Anim. Sci.* **74**: 1395–1405.

Hill, J., Nelson, E., Tilman, D., Polasky, S., and Tiffany, D. 2006, Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels and benefits of biodiesel and ethanol biofuels, *PNAS* **103**: 11206–11210.

Huber, M. (ed.) 2007, *Organic, more healthy? – A search for biomarkers of potential health effects induced by organic products, investigated in a chicken model*, Louis Bolk Institute and FQH (Organic Food Quality and Health).

Khan, S. A., Mulvaney, R. L., Ellsworth, T. R., and Boast, C. W. 2007, The myth of nitrogen fertilization for soil carbon sequestration, *J. Environ. Qual.* **36**: 1821–1832.

Knapp, K. E., Jester, T. L., and Mihalik, G. B. 2000, Energy balances for photovoltaic modules: status and prospects, in *Photovoltaic Specialists Conference, 2000. Conference Record of the Twenty-Eighth IEEE*, pp 1450–1455.

Leary, R. and Mack, R. S. 1980, in R. Mack, H. Leff, S. Bell, S. Nestor, and H. McDuffie (eds.), *Industrial Energy Use Data Book*, Chapt. 9, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

McDuffie, H. F., Warren, K., and Leff, H. S. 1980, in R. Mack, H. Leff, S. Bell, S. Nestor, and H. McDuffie (eds.), *Industrial Energy Use Data Book*, Chapt. 8, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

Nakamura, L. 1974, in *Energy consumption in manufacturing*, pp 205–217, Ballinger Publishers, Cambridge, Massachusetts.

Nations, B. K. and Hallberg, G. 1992, Pesticides in iowa precipitation, *Journal of Environmental Quality* **21**: 486–492.

Oehl, F., Sieverding, E., Mäder, P., Dubois, D., Ineichen, K., Boller, T., and Wiemken, A. 2004, Impact of long-term conventional and organic farming on the diversity of arbuscular mycorrhizal fungi, *Oecologia* **138(4)**: 574–583.

Ostrander, C. E. 1980, in D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp 379–392, CRC Press, Boca Raton, Florida.

Patzek, T. W. 2004, Thermodynamics of the corn-ethanol biofuel cycle, *Critical Reviews in Plant Sciences* **23(6)**: 519–567.

Patzek, T. W. 2007, *Energy, Earth, and Humans: CE 170 Course Reader*, University of California.

Pimentel, D. 1980, *Handbook of energy utilization in agriculture*, CRC Press, Inc.,Boca Raton, FL.

Pimentel, D. 2006, *Impacts of Organic Farming on the Efficiency of Energy Use in Agriculture*, Technical report, The Organic Center.

Pimentel, D. and Patzek, T. W. 2005, Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower, *Natural Resources Research* **14(1)**: 65–76.

Pimentel, D. and Pimentel, M. 1979, *Energy, Food and Society*, John Wiley and Sons, New York.

Randall, G., Huggins, D., Russell, M., Fuchs, D., Nelson, W., and Anderson, J. 1997, Nitrate losses through subsurface tile drainage in conservation reserve program, alfalfa, and row crop systems, *Journal of Environmental Quality* **26**: 1240–1247.

Reganold, J., Elliot, L., and Unger, Y. 1987, Long-term effects of organic and conventional farming on soil erosion, *Nature* **330**: 370–372.

Renich, X. Y. 2008, *Private communication with local farmers Glenn Laubhaun, Charles Melander, and Steve Renich.*

Salunkhe, D. K., Chavan, J. K., Adsule, R. N., and Kadam, S. S. 1991, *World Oilseeds: Chemistry, Technology, and Utilization*, Van Nostrand Reinhold, New York.

Shapouri, H., Duffield, J. A., and Wang, M. 2003, The energy balance of corn ethanol revisited, *Trans. ASAE* **46(4)**: 959–968.

Shapouri, H. and McAloon, A. 2004, *The 2001 net energy balance of corn ethanol*, Report, USDA, Washington, D.C., Also presented as a conference paper by H. Shapouri, A. McAloon, and M. Wang, Corn Utilization and Technology Conference, June 7–9, 2004, Indianapolis, IN, www.usda.gov/oce/reports/energy/index.htm.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., and Shapouri, H. 1998a, *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*, Final Report NREL/SR-580-24089, National Renewable Energy Laboratory, Golden, Colorado 80401, www.nrel.gov/docs/legosti/fy98/24089.pdf.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., and Shapouri, H. 1998b, *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*, Technical report, National Renewable Energy Laboratory.

Slesser, M. 1978, *Energy in the economy*, St. Martin's Press, New York.

Smil, V. 1991, *General Energetics: Energy in the Biosphere and Civilization*, John Wiley and Sons, New York..

Sollner, F. 1997, A reexamination of the role of thermodynamics for environmental economics, *Ecological Economics* **22**: 175–201.

Stout, B. A. 1984, *Energy Use and Management in Agriculture*, Breton Publishers, North Scituate, Massachusetts.

Tillman, D. A. 1978, *Wood as an energy resource*, Academic Press, New York.

USDA 1974, *The US Food and Fiber Sector: Energy Use and Outlook*, Technical report, Economic Research Service, U.S. Department of Agriculture, Washington, DC.

USDA-SCS 1992, *Soil Survey of Saline County, Kansas*, Technical report, Soil Conservation Service, U.S. Department of Agriculture, Washington, DC.

Williams, K. F., McCarty, T. R., Gunkle, W. W., Price, D. R., and Jewell, W. J. 1975, in W. Jewell (ed.), *Agriculture and Waste Management*, pp 29–47, Ann Arbor Science Publishers, Ann Arbor, Michigan.