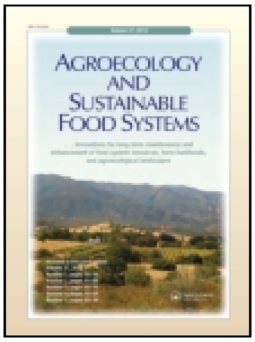

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Long-Term Ecological Assessment of Farming Systems (LEAFS): Comparing Human, Animal, and Small Machine Power for Fresh-Market Horticulture

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In order to assess the potential for human and animal power and related fertility management systems to reduce the demand for energy fossil fuels in agricultural production, we report findings from the first 2 years of the Long-Term Ecological Assessment of Farming Systems (LEAFS) at Green Mountain College in Poultney, VT, USA. LEAFS compares three small-scale, diverse vegetable production systems, one powered by human labor, one by draft animal power, and one by small engine power. Data was collected on all inputs including land usage, labor, and direct and indirect energy consumption. Yield of crops was measured and converted into energetic and economic output. This data was used to calculate efficiency statistics including energy and financial returns on land, labor, and energy invested. The draft animal and machine power systems were comparable in the financial returns to labor while the human system yielded approximately 25% less in this regard. The human and draft animal systems had equal energy returns to energy invested of 1.21, a high rate of efficiency for vegetable production. The machine system was net energy negative but efficient compared to conventional production. Data from all three systems suggests factor substitution of both labor and land for energy.

KEYWORDS energy efficiency, animal traction, manual production, cropping systems, vegetable farming

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1. INTRODUCTION

The energy intensity of the U.S. agricultural system is an area of growing concern. In 2002, food-related energy expenditures accounted for 14.4% of the U.S. energy budget (Canning 2010). Agriculture accounts for approximately 22% of this consumption, operating at a negative net energy balance (Heller and Keoleian 2000). Agriculture now consumes around 3% of global energy use, and energy use is increasing (Houghton et al. 2001). In the United States, there are indications that farming is becoming more energy efficient, partially in response to rising energy costs, but energy usage is still high relative to earlier times (Cleveland 1995).

Most of the energy inputs into developed world agriculture are fossil derived (Pimentel and Pimentel 2008) and, as a consequence, there is significant concern about the sustainability of agricultural production. Fossil fuel consumption is the primary driver of climate change, it is a source of many other environmental impacts, and the long-term stability of prices and supplies is uncertain (Pelletier et al. 2011). Already in the last 8 years there have been significant price disruptions in agricultural commodities linked to sharp rises in petroleum prices (Rosa and Vasciaveo 2012). The recent development of new hydrocarbon sources in North America may alleviate high energy prices, but at a significant environmental cost (Mulder and Hagens 2008; Woynillowicz and Severson-Baker 2009).

This has led to renewed interest in the role of energy in agriculture and increasing use of Life Cycle Analysis (LCA) methodologies to assess energy use in various agricultural products and systems (Heller and Keoleian 2000; Pelletier et al. 2011). These studies generally account for all of the direct and indirect energy inputs into a system, although they often ignore the energy costs associated with various externalities (Giampietro et al. 1997; Mulder and Hagens 2008). While the previous historical trend has been toward greater power production and fewer labor inputs at the cost of energy efficiency, there is the possibility that, in line with the seminal theories of Odum (1971) as energy becomes limiting there will be a move toward systems with greater diversity and higher energy efficiency. One possible component of this move toward more energy efficient systems could be the re-adoption of human- and animal-powered agricultural technologies.

2. LITERATURE REVIEW

Through energy analyses from various contexts, Pimentel and Pimentel (2008) have demonstrated a fairly consistent trend of higher energy efficiency in human- and animal-powered systems. Studies of bio-intensive mini farming (Jeavons 2001; Moore 2010) have demonstrated the ability of human-powered systems to provide energy returns significantly higher than U.S.

conventional agriculture, over 50 to the 1 in the case of onion production as reported by Moore (see also Ward et al. 1980). Most research on animal traction and to the authors knowledge, all published research on working cattle, is focused on agriculture in the developing world (Goe and McDowell 1980), but studies of horse-powered farming in the United States have demonstrated higher energy efficiency (Craumer 1979) and competitive economic performance (Bender 2001; James 2007) as well. When combined with an agroecological management approach, human- and animal-powered systems can also offer the potential for greater food and economic security (Altieri 1999).

Despite these possible advantages, human and animal-power face significant constraints. Power output by workers using hand tools or animals is greatly reduced, as a person works at an effective rate of 50 W, while an animal may work at a sustained pace of 745 W (1 HP), and even the small walking tractor used in our research has a maximum power output of 8 kW. Harnessing less power, and thus decreasing labor efficiency, is a necessary component of reducing traction energy by using these technologies.

Draft animal power also faces the constraint of low gross energy efficiency (Dube and Mulder in review): Work energy output as a fraction of feed energy input is often equal to or less than 5% (Ward et al. 1980; Bender 2001). The heating value of the manure may be much greater than the work energy output (Ward et al. 1980). The low energy conversion efficiency by draft animals is reflected by large cropland requirements—feed production alone for draft animals can require as much as one fifth of the cultivated land they are used on (Bender 2001) as well as further non-arable land in pasture. In spite of these disadvantages, economically successful horse-powered produce farms operate in the American Northeast (Nordell and Nordell 2012), and Amish farms using horse-power are profitable and expanding (Bender 2001).

Power production (traction) on farms, however, only accounts for about one fifth of on-farm energy use while nutrient amendments account for one third or more (Giampietro et al. 1994). Synthetic nitrogen production is the single largest energy input in many cropping systems and the energy required to mine and process phosphorous and potassium can also be significant (Pimentel and Pimentel 2008). Significant energy is also required to stabilize organic wastes through composting. Animal power can be used to not only spread amendments, but nutrient transfers through manure provide an important benefit of the system. Human power does not offer an equivalent benefit, but the light footprint of a worker gives human power a soil-health advantage, particularly when combined with permanent bed systems. Human powered biointensive systems have demonstrated high soil quality (Jeavons 2001; Moore 2010). Farmers, no matter their power source, may use green manure crops for building soil and reducing energy inputs for fertility, although power source will influence how these crops are managed.

Most evidence suggests that this will have the negative impact of requiring additional land, although some researchers suggest otherwise (Badgley et al. 2007).

3. METHODS

To test the potential trade-offs associated with low-energy, human- and animal-powered production systems, the Long-Term Ecological Assessment of Farming Systems (LEAFS) research trial was established at Green Mountain College in Poultney, VT, USA, in 2011. The project is comprised of three vegetable production systems that vary in their use of labor, external inputs, and land: a land-extensive, low-input system powered by oxen; a land- and labor-intensive system using only human power; and a higher external-input system utilizing an 11-hp walking tractor. For all three systems, all labor, land, and energy inputs are tracked in order to determine the relative efficiencies of the systems with regard to these production inputs and thereby the potential tradeoffs between these inputs.

3.1. Study Site

The study site is 0.41 ha in size, located on Hamlin Silt Loam, a Coarse-silty, mixed, active, mesic Dystric Fluventic Eutrudept. Mean historical annual temperature is 8°C, and mean annual precipitation is 99 cm. The site had been in organic vegetable production for 2 years prior to initiation of the study and was in alfalfa-grass hay for at least 11 years previous to that.

3.2. Cropping Systems and Cultural Practices

LEAFS encompasses three vegetable production systems, all of which simulate small farms growing vegetables for direct market. The oxen system is land extensive, substituting land in the form of forage land for oxen and periodic intensive fallow for fossil energy and human labor. The tractor system utilizes small machine power and a range of commonly used outside inputs, such as compost and commercial organic fertilizer, to increase efficiency of labor and land use. The human system utilizes permanent beds, intensive cover cropping, tight plant spacing, waste organic mulches, and high labor use to utilize land efficiently without excessive outside energy use. A summary of cultural practices used by each system is found in Table 1.

The three systems were laid out in nine plots. Four plots measuring 7.6-×-30.5 m were assigned to each of the Tractor and Human treatments and one plot measuring 15.2-×-121.9 m was assigned to the Oxen treatment. A mix of 19 vegetable crops was grown in these plots in the summers of

TABLE 1 Summary of cropping system treatments

	Common to all	Oxen	Tractor	Human
Power sources	Human labor with hand tools	Oxen pair, approximately 1000 kg each	11 HP BCS walking tractor	Human labor only
Fertility inputs	Cover crops, potting soil, wood ash (pH)	Manure refuged from hayfields	Compost, mixed organic fertilizer	Hardwood leaf mulch
Pest mgmt	manual controls	floating row cover	floating row cover	
Tillage type		Moldboard plow and disc, crops grown on temporary ridges	Rotary tillage	Surface cultivation, permanent beds
Cropping intensity*		Low, 2:1, plus native meadow for pasture/hay	High 1:0; all areas cropped every year.	Medium 4:1
Row spacing		Single rows, 1.17 m centers	Single or double rows, .76–.95 m	Beds 1.07 m wide; 1–4 rows/bed, permanent walkways, .46 m wide

*Ratio of cash–crop years to years devoted fully to cover crops.

2011 and 2012 with the intention that this study continue for at least 10 years. The crop allocation was such that each crop rotation phase of the Human and Tractor systems was present once in each year (4-year rotation), while in the Oxen system each crop rotation phase was present once every 3 years. The oxen treatment was assigned a larger plot to accurately assess the efficiencies of the animals for fieldwork; work efficiency would be dramatically decreased by frequent turning in small plots. The need for a large plot made it not feasible to replicate the oxen treatment.

3.3. Data Collection

Crop yields, field labor, tools used, and input amounts were recorded each day as work was done in each system. Ancillary labor inputs, including crop processing, transportation, and transplant production, were estimated based on a sampling of measurements.

3.4. Estimation of Energy Inputs

Farm systems were charged for human metabolic energy, on-site fossil fuel consumption (Tractor) and the energy embodied in farm tools and purchased inputs. Estimates were also produced for embodied energy in the farm greenhouse used for transplant production and the energy used for refrigeration

TABLE 2 Energy values used for important inputs

Input	MJ Units	Reference*
Oats	16.68/kg	1, 2, 3
Pea seed	28.81/kg	2, 4
Vetch seed	231.51/kg	2
Clover seed	72.20/kg	2, 5
Rye seed[a]	10.52/kg	1, 3, 5
Potato seed	4.31/kg	1
Floating row cover[b]	$/2.92m^2$	3
Organic fertilizer[c]	5.39/kg	5
Gasoline	33.18/liter	
Water	4.60/Kliter	1
Potting soil[d]	1.06/kg	
Compost	0.59/kg	6
Brassica seeds	16.88/kg	1
Other vegetable seeds	46/kg	1, 2, 4, 7
Farm tools and equipment	80/kg	3, 8

[a]Data for wheat and barley used.
[b]Polyester fabric.
[c]Conventional values for NPK, fertilizer analysis was 5-3-4.
[d]Weighted average of compost (7), granite dust (9), vermiculite (from perlite, 9), peat (10), and fertilizer (5, c).
*1 = Pimentel and Pimentel 2008; 2 = Pimentel 1980; 3 = Baum et al. 2009; 4 = Burgess 2012; 5 = The Farm Energy Analysis Tool 2011; 6 = Sharma and Campbell 2003; 7 = Mortimer et al. 2004; 8 = Kitani 1999; 9 = Jones and Hammond, 2008; 10 = Cleary et al. 2005.

and storage of produce. These were prorated based on number of transplants required and crop harvest amounts respectively. Values used and their sources and derivation are provided in Table 2.

Human energy was assessed based on data for various farming tasks from Vaz et al. (2005). Metabolic output above maintenance, as used by Moore (2010) was based on the reported physical activity ratios and a basal metabolism calculated from average height, weight, and age for farm workers in 2011.

3.5. Measurements and Estimates Unique to the Oxen System

In the analysis of the oxen system, the oxen and the land needed for their maintenance were treated as within the system boundary. As such, the energy flows of feed consumed or effort exerted were not charged to the oxen system. Rather, the oxen system was charged for the land, labor and human and equipment energy required to maintain a team of oxen as an available source of traction. Several measurements of the labor required to harvest hay were used to produce a data set of labor and equipment usage required per ton of hay (Dube and Mulder in review). The oxen treatment was additionally charged for the estimated embodied energy of the equipment used to harvest the using the same methodology as for other equipment usage. Similarly, daily labor required to care for the animals, during both the grazing season and winter months was averaged from several measurements. The oxen were also charged for the estimated labor and energy needed to train and raise a replacement team, and for a 6 m^2 of barn space at 90 MJ/m^2/yr (Sainz 2003). These values were prorated to a per minute rate based on a usage level of 549 h/animal/yr. This number is inferred from Nordell and Nordell (2012) who reported 196–443 h/horse/yr for farm work at three horse-powered direct-market vegetable farms in the northeast, cultivating 1–3 ha, with a mean value of 313 h/yr. Animals were assumed to work a similar number of hours per week in the off season, as work animals may be used in forestry, agro-tourism and other functions as well as for farm work. Based on an estimated 30-week growing season, vegetable work would represent 57% of total utilization for a total of 549 h/yr.

Our estimate is lower than numbers reported by early 20th-century agronomists—Morrison (1936) and Warren and Bailey (1918) who reported 690–740 and 870–1470 h/horse/yr, respectively. Numbers from horse-powered market vegetable farms were chosen as more representative, as animal utilization in farming systems is limited mostly by the needs pattern and acreage of the cropping system rather than the intrinsic capacity of the animals. Perhaps the most dramatic evidence of this is the 10- to 30-fold difference in h/buffalo/yr between buffaloes (*Bubalus bubalis bubalis)* used in low-input rice-cropping systems versus haulage of goods in Indonesia (Chantalakhana and Bunyavejchewin 1994).

3.6. Crop Outputs

Weights of crop yield were used to estimate energy and economic outputs of the systems. Energy contents for the 19 crops grown in the study were drawn from the Norwegian Food Composition Database (Rimestad et al. 2000), while economic values were based on averages from Maine Organic Farming and Gardening Association's organic price report ("Organic price reports" 2012) and the University of Vermont direct-market price report ("Vermont direct market produce price reports" 2012).

4. ANALYSIS

Systems were evaluated for comparative efficiency in the use of land, labor and energy inputs, relative to their outputs. Labor use was calculated as the sum of field labor for each treatment added to derived numbers for transplant production, postharvest transportation to the processing area, and processing for direct-market sale. This sum was multiplied by a field efficiency factor of 1.2 to account for transition periods, water breaks, routine tool maintenance, and other labor inputs not directly recorded as field labor. Energy input was

TABLE 3 Means of calculating productivity and efficiency indicators

Input	Tractor and human	Oxen
Land	$A_V = A_T$	$A_V + (A_O * O_V/(O_C - O_M) = A_T$
Labor	$\dfrac{L_V + L_G + L_H + L_P}{e} = L_T$	$\dfrac{L_V + L_G + L_H + L_P + (O_V{}^*L_{OM}/(O_C - O_M))}{e} = L_T$
Energy	$E_H + E_I + E_E + E_G + E_S = E_T$	$E_H + E_I + E_E + E_G + E_S + (E_{OM}{}^*O_V/O_C) = E_T$

A_V Land used to grow crops.
A_O Area needed to support Oxen.
e Labor utilization efficiency, set at .83.
L_V Total hours used directly in vegetable production.
L_{MO} Labor required for maintenance of oxen.
L_G Labor in greenhouse for transplant production.
L_P- Labor used for packaging and processing vegetables for sale.
E_E Depreciation of energy embodied in equipment.
E_H- Human Metabolic Energy burned while doing work.
E_I- The energy embodied in consumable inputs- ex: seeds and potting soil, remay, soil amendments and organic agrichemicals, and fuel.
E_G Per-transplant greenhouse embodied energy depreciation charge.
E_{OM} Human and equipment energy required to maintain the oxen through a year.
E_S Estimated energy used by on-farm walk in cooler.
O_V Total oxen-hours used in research plot.
O_M Total number of oxen-hours required for maintenance of team (haying and grassland management).
O_C Oxen work capacity on a farm that utilizes them to a moderate degree. Estimated at 549 h per animal/per year.

calculated as the sum of all energy inputs described in the methods (see Table 3).

5. RESULTS

Estimates of land, labor, and energy efficiency for the first 2 years of LEAFs are shown in Table 4. The human and tractor areas have measures of economic land efficiency comparable to other diversified vegetable systems in New England where gross sales from $20,000 to over $100,000 per hectare

TABLE 4 Indicators of resource-use efficiency in LEAFS systems

	Land efficiency		Labor efficiency		Energy efficiency	
Treatment	$/ha	Kg/ha	$/ hr	Kg/hr	$/MJ	EROEI*
Human	77,097 a	13,290 a	24.78 a	4.29 a	5.18 a	1.21 a
Oxen	17,161 b	3,600 b	31.44 a	6.60 a	4.39 ab	1.21 a
Tractor	86,951 a	16,150 a	32.74 a	6.18 a	2.76 b	0.74 a

Note. Numbers with different letters are statistically different at the 0.05 level. Statistical significance for energy and labor efficiency was calculated with the Mann-Whitney U test, while land efficiency was calculated using one-way ANOVA.
*Energy return on energy invested.

TABLE 5 Five largest energy inputs for LEAFS treatments, 2012

Human	Portion of total energy input	Oxen	Portion of total energy input	Tractor	Portion of total energy input
Cover crop seed	27.21%	Cover crop seed	28.96%	Compost	20.10%
Potting soil	22.60%	Equipment	16.05%	Gasoline	15.81%
Materials	12.08%	Potting soil	11.24%	Cover crop seed	14.59%
Vegetable seed	11.47%	Vegetable seed	11.18%	Vegetable seed	10.03%
Human metabolism	10.58%	Storage	11.14%	Potting soil	8.22%

are often achieved (Stoner et al. 2008; Chan 2012). The oxen system was significantly lower due to land demands for forage production, intensive fallow and cover crop periods, as well as the wider row spacing necessary for cultivation. The human area had approximately 25% lower returns to labor suggesting that some sort of premium might be necessary for human power to be economically competitive. Finally, both the human and oxen systems were net energy positive which was not the case for the tractor system, although the difference between the three treatments was not statistically significant ($P > 0.1$). Three eighths of the human plot-years, one eighth of the tractor, and one half of the oxen were calculated as net-energy positive. Further, the human system had statistically higher economic returns per unit energy than the tractor system, implying a higher level of energy efficiency.

Table 5 provides a broader comparison of the three systems relative to each other. Some results were contrary to our initial hypotheses. While the human system was originally conceived of as a low-input system, using literature values for the nutrient content of hardwood leaf litter (Heckman and Kluchinski 1996) we estimated that deep mulching just 10% of the human plots annually was equivalent to 85% of the nutrients imported into the tractor treatment where purchased compost and organic fertilizer were applied. Additionally, despite the significant human energy investments in managing and feeding oxen, the oxen system was nearly equivalent to the human system in overall energy efficiency, a testament to the energy efficiency of the oxen forage production system.

We also anticipated yields in the human system to be lower than the tractor system since the human system has no purchased amendments for fertility or pest control. In the first year, yields were slightly higher in the human treatment, despite having 20% of area being dedicated to cover crops. In the second year of the study, crop yields in the human treatment fell by 31% compared to the first year while yields in the tractor treatment increased by 11%. Because of this, the tractor treatment outperformed the human by a substantial degree in land productivity (55%, $p < 0.1$) and labor productivity (48%, $p < 0.05$) in 2012. These results are consistent with a possible decrease in soil fertility due to lack of inputs; data from the next few years is needed to determine a trend.

Figure 1 displays the energy values of different inputs into each system; Table 6 shows the five greatest for each system in 2012. Cover crop seed was a high input for all three systems reflecting the high estimated value of the embodied energy in conventional cover crop seed, especially legumes. Similarly, potting soil and compost both had very high-input values, again related to the high energy inputs of a mechanized production system. Gasoline was predictably a significant energy input in the tractor system, while human metabolic energy was a notable but not significant energy input due to the relatively low power output of the human body.

Finally, Figure 2 displays our results with regard to factor substitution between the three main resources—energy, land, and labor. First to note is the significant range in overall efficiency between plots and years within a given system especially within the human system. This suggests that more data will be required to determine whether factor substitution is occurring. However, the top chart seems to suggest a tradeoff between energy and labor with the oxen system lying between the human and tractor systems. Similarly, the bottom picture seems to suggest a clear tradeoff between the tractor and human systems with regard to energy and land efficiency. There

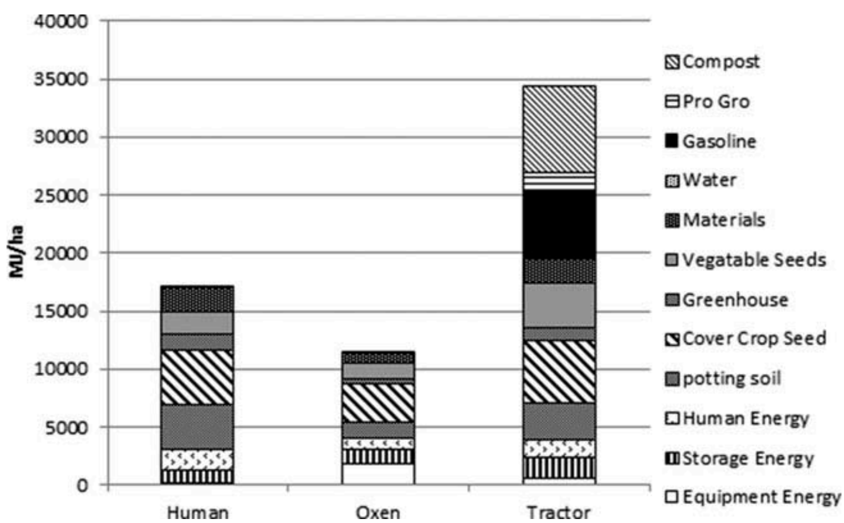

FIGURE 1 Energy Inputs by type, LEAFS 2012.

TABLE 6 Relative inputs to LEAFS production systems

Input type	Human powered	Animal powered	Tractor powered
Direct fossil fuel usage	0	0	100
Indirect fossil fuel usage	51	37	100
Imported nutrients	85	5	100

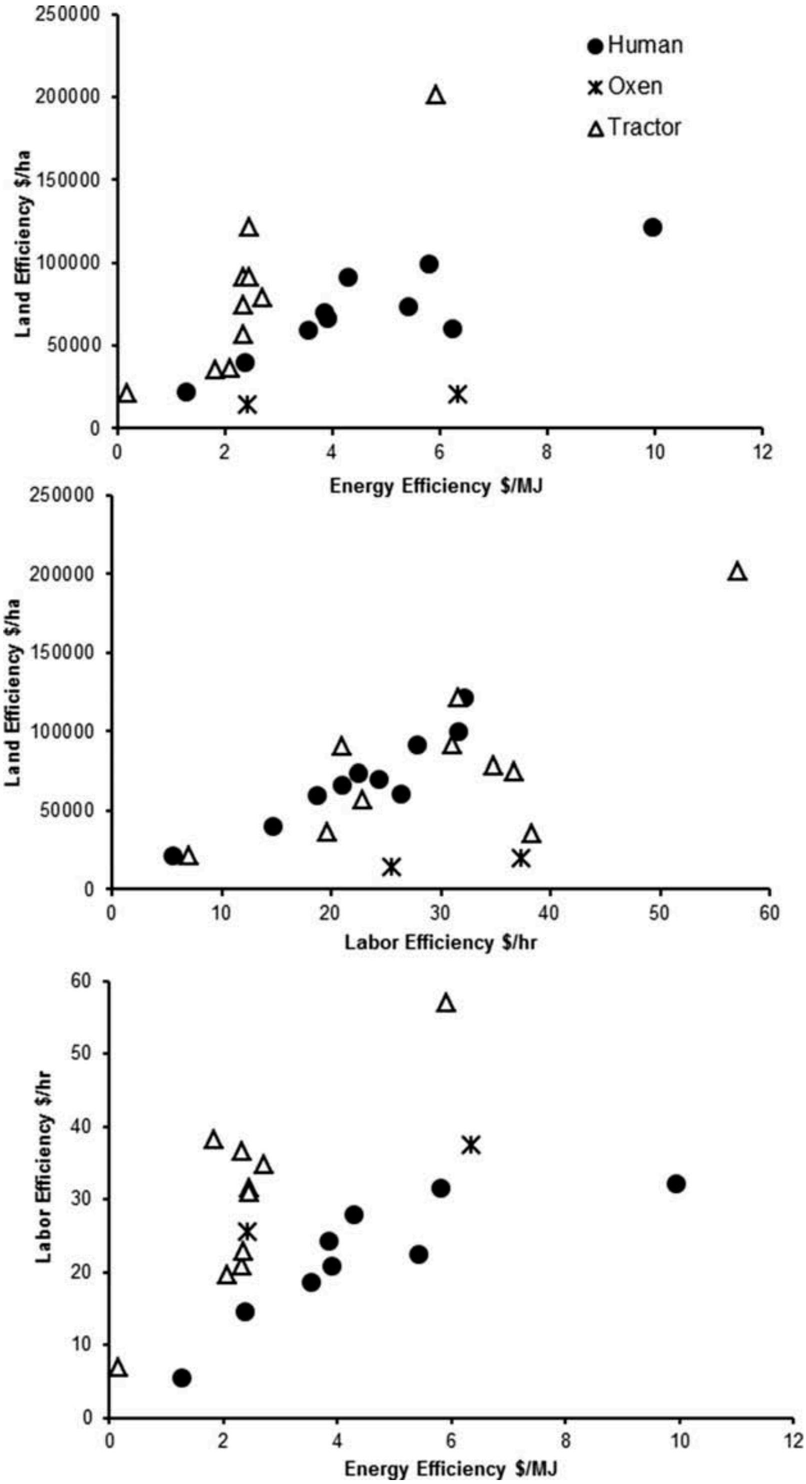

FIGURE 2 Energy, land, and labor efficiency of 9 plots, 3 treatments over 2 years.

is perhaps a similar tradeoff for the oxen system, but it is not clear from only two data points. There does not appear to be a clear tradeoff between labor and land.

6. DISCUSSION

6.1. Economic Efficiency

Our experiment examines systems not previously assessed in academic research. The preliminary results appear to be promising and surprising. In spite of the low relative power output of the oxen system, economic yield per unit of labor was not significantly less than the tractor system, and our data suggests that both human power and draft animal power can be economically viable on a wider scale than currently adopted Part of the reason that human power did not have lower returns to labor relative to the other systems is that all three systems utilized a large amount of human labor for harvesting and hand cultivation, something typical of diversified direct-market vegetable production. Harvesting produce was the single largest labor use in all systems. 80% of labor in the oxen vegetable area did not involve the oxen at all, 19% of the labor was driving the oxen, and 1% of labor was used when an extra worker was needed to steer oxen equipment. Operating the walking tractor accounted for only 8% of field labor in the tractor system, and gasoline represented 16% of energy use.

The economic efficiency of the systems is dependent on direct marketing of produce. We used direct-market prices in New England to estimate total economic yield after subtracting for estimated marketing costs and losses (Chan 2012). This still yielded values in excess of wholesale organic prices. The scale and diversity of the systems are highly appropriate for high-value direct-market channels such as community supported agriculture, farm stand, or farmers market.

To compare power output and other factors with conventional U.S. vegetable production, we used data from Pimentel and Pimentel (2008) to estimate inputs and outputs for a representative U.S. vegetable farm producing the same types of crops in equivalent proportions (root crop, fruit crop, leaf crop, and *Brassica*). These numbers were used to develop a first order comparison with larger-scale, conventional production. Based on this analysis, conventional production had approximately 60% higher yields per unit land and over 20 times the yield per unit of labor versus our best performing systems. This was achieved in part by a significantly higher power output—23–25 times the energy throughput per unit of labor versus the LEAFS systems as well as higher energy inputs per unit of land, 1.5–6 times higher than in the LEAFS systems. The high level of mechanization is evident both in high labor efficiency as well as four times greater fuel use per hectare than in the walking-tractor system. Thesimulated conventional vegetable farm operated at a net energy loss, with an energy ratio of 0.48.

6.2. Accounting for Human Energy Inputs

One of the more difficult elements to account for in net energy analysis in agriculture is the amount of energy that should be assigned to human labor. Fluck and Baird (1980) assessed several different approaches which range from (at the low end) using muscular energy as we have used here to a high-end estimate derived from the overall energy consumption per individual in a given economy, as argued for by Costanza (1980). Fluck (1981) proposed estimating the energy consumption per person that was just associated with their ability to work, what he termed "sequestered energy." These estimates lead to dramatically different energy estimates per hour of labor depending on social context (Pimentel and Pimentel 2008). While some analysts simply ignore human energy investments (Giampietro et al. 1994), it has been suggested this is not valid when the substitution of energy for labor is a point of consideration (Stanhill 1984).

For studies such as ours, this is not a trivial consideration. As can be seen in Figure 3, the energy return for our three systems changes dramatically with methodological choice for how to account for human energy. Accounting for the sequestered energy makes all three LEAFS systems net energy negative by a wide margin Indeed, the change is so dramatic as to make all other areas of uncertainty inconsequential. This is clearly a fundamental question regarding the role of human labor in an ecological economic system and perhaps suggests that labor should not be considered as part of the energy input but rather conceived of as a separate input. Removing

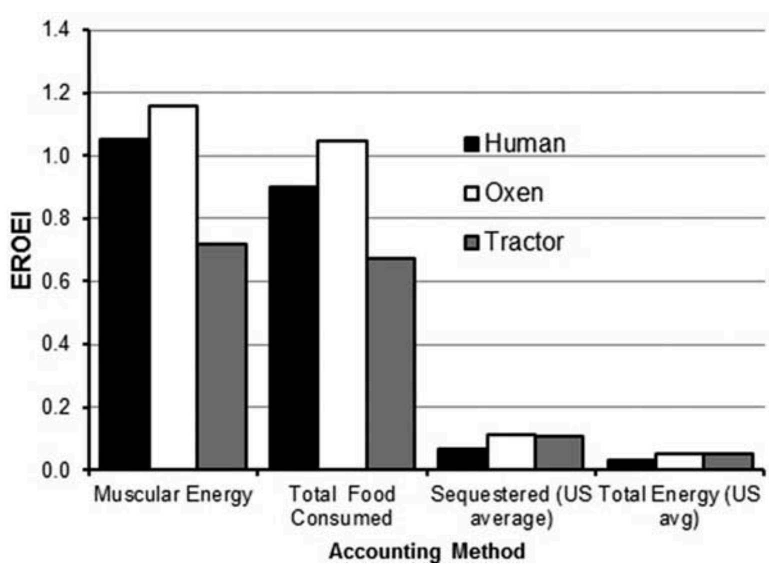

FIGURE 3 Energy input per unit of output for LEAFS systems, by labor accounting system.

human energy from our calculations does not alter efficiency calculations substantially.

6.3. Sensitivity Analysis

Although there has been a significant increase in the number of net energy studies in agriculture, there are still many opportunities for improvement, particularly with regard to data availability. Our study uncovered several important energy inputs to small-scale vegetable production for which multiple, consistent embodied energy estimates were unavailable. This is probably most apparent in the area of fertility maintenance. Estimates for municipal solid waste compost production range from 60 MJ/m^3 (Van Haaren et al. 2010) to 1200 MJ/m^3 (Martínez-Blanco et al. 2009) with Moore (2010) reporting 9.5 MJ/m^3 for hand-turned compost. Similarly, our estimates for the embodied energy in compost-based potting soil are first order estimates as we were unable to uncover any studies in the literature. As can be seen in Figure 2, potting soil and compost are estimated to be significant energy inputs. Similarly, mixed organic fertilizer was charged based on average numbers for conventional fertilizer, because no estimates were available. Some ingredients have much lower embodied energy than their conventional counterparts (e.g., rock vs treated phosphate), other ingredients are waste products (e.g., animal protein meals), and the embodied energy for other ingredients (e.g., oyster meal) is entirely unclear. Furthermore, the fertilizer is not made to a specific recipe (exact proportions of ingredients may change with price), and other companies make similar products with different ingredients. A broadly applicable, accurate estimate of the embodied energy of mixed organic fertilizer may not be possible.

Another fertility-related input is the planting of cover crops. The energy in cover crop seed is estimated to be more than a quarter of the total energy input for the human and oxen systems, and almost 16% of the tractor system input. While there are numerous studies of the energy needed for small-grain seed production, we were only able to uncover one estimate for vetch, from a dated study (Pimentel 1980) and only two estimates for pea seed, which were divergent by a factor of more than 15 (Pimentel 1980; Burgess 2012). The use of legumes for nitrogen fixation is critical to maintaining yields without energy-intensive nitrogen fertilizer, (Stanger et al. 2008; Pimentel and Pimentel 2008) and indications are that legume seeds are much more energy intensive to produce than small grains. Table 3 shows our estimate for vetch seed to be 22 times higher than rye seed. Although organically grown cover-crop seeds were used in the trial, no specific numbers are available for their embodied energy. Large divergences in estimates of the energy costs of organic fertility sources create uncertainty about the magnitude of environmental benefits from organic techniques, especially if these techniques also result in reduced land use efficiency.

Another open question is how to assess the energy cost for antique farm equipment, when on the one hand, the pieces would most likely be sold for scrap metal if not used for farming, but on the other, widespread adoption of animal-powered farming would require the manufacture of new animal-drawn farm equipment on a large scale. There remains a significant need for standardization in net energy analysis (Mulder and Hagens 2008).

While these uncertainties point to a need for more academic research and assessment, the positive aspects of these results do suggest several broader actions. More research and development effort should be dedicated to optimizing these systems and technologies, as the development of more efficient tools and systems for low-input farming has not been a research priority. Furthermore, as the literature becomes more solidified as to the energetic costs of various inputs, effort should be taken to increase the energetic efficiency of the most costly inputs, as well as educating farmers to understand where energy use can be reduced in their operations.

7. CONCLUSION

Although new hydrocarbon resources in North America have somewhat placated concerns about future energy availability, fossil fuel use remains a crucial weak link in societal sustainability. Here we have presented evidence from the LEAFS research plots at Green Mountain College suggesting that human and draft animal powered systems can reduce the usage of fossil resources in vegetable production while remaining economically competitive when implemented at a scale that facilitates direct marketing.

Human and animal power dramatically reduce the amount of energy throughput that can be achieved in an agricultural system while increasing labor requirements. They significantly increase energy efficiency through a tradeoff of labor for energy suggesting they have a role to play in a climate and energy limited future that may well have a surplus of human labor.

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