Energetic analysis of draught animal hay harvest

An alternative look at cellulosic biomass

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Abstract: *For most of human history, biomass has been the primary energy input for society. Concerns regarding climate change, resource depletion and energy security have prompted renewed interest in the use of biomass as an energy source. Draught animals, in addition to being a traditional means of utilizing biomass, can be used to harvest biomass. Data from oxen-powered haying at Green Mountain College in Vermont show an energy return on energy invested (EROI) of 5.93 for pelletized grass, with 80% of the energy input being renewable. Comparisons with other draught animal hay harvesting systems suggest that this performance is mediocre. Modest goals for system improvements could raise the EROI to over 10. Due to their competitive energy efficiency and low capital requirements, draught animals deserve more serious examination as a renewable energy source.*

Keywords: *animal traction; alternative energy; low-input agriculture*

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Recently, much attention has been given to renewable biomass as an energy source. The USA has invested heavily in ethanol and biodiesel production, although there has been significant concern and debate regarding their energy efficiency, non-energy resource efficiency and potential environmental impacts (Hammerschlag, 2006). Second-generation biofuels, based on cellulosic materials such as maize stover and perennial grasses, have drawn significant interest because of their potential for a much higher energy return on the energy invested (EROI) and lower environmental impacts (Naik *et al*, 2010; Sanderson and Adler, 2008).

One issue preventing biomass-based technologies from achieving their full potential as a sustainable source of energy is that they are embedded in an agricultural system that faces the same challenges to sustainability as society as a whole. While agricultural intensification increases harvested yields of food and energy, these yields come at the price of resource depletion, climate change impacts and other environmental issues (Matson *et al*, 1997). With the exception of fossil fuel depletion, these issues are rarely accounted for in net energy analyses (Mulder and Hagens, 2008). Given the potential for biomass to be a renewable energy source, it merits consideration with regard to whether sustainability can be increased by altering the production system to be less reliant on non-renewable energy sources and to have less impact overall.

One mechanism for achieving this is to consider the use of draught animals as a renewable alternative to petroleum-fuelled machine power for biomass production and harvesting. Given that the draught animals themselves can be fuelled by the biomass harvested, this offers the potential for a system with extremely low reliance on outside energy inputs. In this paper we discuss the potential for draught animals to be utilized for biomass production and look at the energy returns that result from their integration into other production systems. We also present data on the use of oxen for hay production and generate a first-order estimate of the EROI of using oxen for home heating production and on-farm power production.

Issues in energy efficiency of animal traction

The field of agricultural energy analysis is characterized by inconsistent methodologies often leading to very different results (Mulder and Hagens, 2008; Murphy and Hall, 2010). Furthermore, net energy analysis typically draws equivalence between different sources of energy, despite large differences in social and environmental costs associated with different sources (Edwards, 1976; Mulder and Hagens, 2008), as well as differences in energy quality (Cleveland, 1992). Energy accounting for labour presents various choices of methodologies (Fluck, 1981), with some authors (for example, Pimentel and Pimentel, 2007) using different methodologies for estimating labour or animal energy inputs for different systems within the same text. Jones (1989) outlined these concerns over 20 years ago, yet little progress has been made in standardizing solutions to these problems.

The comparative energy efficiency of animal traction is a complicated topic, and results are primarily dependent on the way systems boundaries are drawn. In most (if not all) situations, the gross energy efficiency of draught animals is lower than that of mechanical traction: that is, the energy content of feed needed to sustain draught animals is greater than the energy content of fuel required to accomplish the same work with a tractor (Ward *et al*, 1980). Some studies even show energy ratios less than unity for animal-powered systems based on high energy values assigned to animal maintenance and animal manure (Pimentel and Pimentel, 2007). These authors showed lower energy consumption for oxen to plough one acre than for a tractor, but the calculations were based on feed consumption only during the days when the oxen worked and at a rate of 10 h/day. If oxen are assumed to work an average of 5 h/day (counting days off) over the course of a year, the difference disappears. Capper *et al* (2009) estimated a slightly lower annual energy use from using a tractor rather than a team of horses, while Gupta *et al* (1983) calculated that oxen-powered farms in India used 2.4 times more energy per ha than farms dependent on tractors. Rydberg and Jansén (2002), in a model comparing Swedish farming in the early and late twentieth century, showed that horses required more 'emergy' per joule of traction generated than tractors. In line with these other studies, Bender (2001) estimated 5% gross efficiency for a horse, compared with 20% for a tractor. Estimates for conversion efficiency of cattle range from 3% to 10% (Hurst and Rogers, 1983).

Difficulties in analysis

The lower energy ratios and higher energy use shown above are reflective of particular types of accounting methodologies; most studies also draw broad equivalence between energy forms with very different qualities and externalities. Animals run largely on sources of energy that are renewable, rather than fossil fuels. While corn and grass can be used as a fuel for both animals and tractors, bio-ethanol refineries convert energy resources into fuel at an efficiency of only 30–39% (Pimentel and Patzek, 2005), which would eliminate much or all of the energetic advantage of tractors. These differences are reflected by Bender (2001), who estimated lower land needs for feeding horses to cultivate farmland than for producing biofuels to run tractors, and by Rydberg and Jansén (2002), who showed that 60% of emergy for horse traction came from renewable sources, compared with only 9% for tractors.

Furthermore, using the gross energy content of feeds consumed by work animals is inconsistent with methodologies used for other systems. In many systems, much of the grass consumed by draught animals is self-harvested forage, often from 'native' pasture. In energy analysis, naturally occurring pools of carbon in vegetation or soils are not normally charged as energy inputs to agricultural systems that consume them indirectly. For example, Pimentel and Pimentel (2007) and Ward *et al* (1980) do not assign an energy value to standing vegetation burnt in swidden agriculture. It therefore stands to reason that no energy charge should be assigned to grazed natural forage. In contrast to the studies mentioned above, when draught animals and their feed crops grown on-farm are regarded as being within the systems boundaries of the farm system, their energy efficiency is often higher than machine-powered farming and comparable with human-powered farming (Craumer, 1979; Finison, 1979; Mulder and Dube, 2014).

Animal utilization

One of the most important factors affecting the efficiency of draught animals is the degree to which they are utilized. Hours worked per animal per year range widely. Interestingly, the highest and lowest numbers found in the literature were from the same study (Chantalakhana and Bunyavejchewin, 1994) concerning buffaloes used for work in Indonesia. In that study, animals were reported to work anywhere from 30 to 2,400 h/yr. Most data reported in the academic and historical literature cite between 200 and 1,000 h/yr (Morrison, 1936; Nordell and Nordell, 2012; Wilson, 2003). In the early twentieth century, agronomists reported 690–1,470 hours/animal/year on farms in the USA, while modern animal-powered production (Nordell and Nordell, 2012) and subsistence farmers (Wilson, 2003) tended to utilize their animals less fully, with possible negative consequences for energy efficiency. In a long-term study of a mixed-traction model farm in Kansas, a team of horses that was utilized only 120 h/yr reduced the farm's overall energy efficiency by 20–30% (Baum *et al*, 2009).

Lawrence (1985) estimated that 5.5 hours of heavy work/day increased the dietary energy requirements of oxen by around 42–67%. Extrapolating from this suggests that increasing the animal hours worked per year from 200 to 1,000 would increase the feed energy required by 25% or less, thus increasing feed to work conversion efficiency by 300%. Increasing animals' intake of energy is often achieved by feeding higher-quality feedstuffs, such as grains, which may be much harder to produce, so increases in system efficiency due to increased utilization may be lower. The relatively low marginal (compared with fixed) costs of additional work done by working animals have caused some authors to comment on the relative efficiency of horses in traditional European mixed farming systems. In these systems, sowing and harvesting grains, roots and hay, hauling manure and feed and transporting people keeps animals busy year-round, while subsistence farming in the tropics tends to use animals largely for ploughing during a short period of time (Ward *et al*, 1980; Wilson, 2003).

Integrating draught power with cellulosic biomass production for energy

Grass and other cellulosic biomass have been used for millennia as the primary non-food energy inputs into human culture. In recent years, novel means of using these energy sources have been proposed, including cellulosic ethanol. Some uses, such as pelletizing grass biomass (Jannasch *et al*, 2004) or burning biomass for electricity, have been implemented to a limited degree. Using technologies invented in the late nineteenth and early twentieth century, animal traction can be employed in all steps of the hay harvesting process. Integrating animal power into biomass energy harvesting could produce renewable biomass energy using solely renewable energy. As a case study examining the energy efficiency of such an integration, we report data on the energetics of utilizing oxen as a means of converting grass into useful energy for biomass harvesting.

Oxen-powered hay harvest at Green Mountain College

Methods

This analysis used four years' data from haying activities at Cerridwen Farm, Green Mountain College in Poultney, VT. The work was accomplished using a team of Guernsey steers aged 7–11 through the course of the dataset, each weighing approximately 900 kg. The grasses harvested were from perennial pasture that had not been ploughed in at least 20 years. The soil type was Teel silt loam (Soil Survey Staff, nd). The primary species was orchard grass (*Dactylis glomerata* L.), with several other forage grasses, red clover (*Trifolium pratense)* and minor remnants of an alfalfa (*Medicago sativa)* stand planted over a decade ago.

The hay was harvested with restored antique equipment including a riding sickle bar mower, a side-delivery hay rake with forecart, a pull-behind loose hay loader and a hay wagon. The hay was loaded into the barn using the oxen to pull an antique hay fork system on a track. The only direct energy inputs were the physical efforts of the farm workers and the oxen. Data in this study represent only first cutting hay, harvested between 30 May and 30 June.

The hay was mowed using two workers, one driving the oxen while the other monitored the cutter bar. Hay raking was accomplished using only a drover, whereas loading required a second person riding the wagon using a pitchfork to assemble a load. Loading in the barn usually used three workers, as two people worked with the hay fork and one drove the oxen to pull the fork up and over to the stack.

Hay was weighed with a hanging scale attached to the hay fork. Forage tests were obtained for two years' hay crops, which were used to calculate dry matter percentage. Draught for various tasks was sampled multiple times for each task, with more measures being taken under conditions when draught was assumed to vary more due to conditions such as variable biomass density during harvest or when loading a wagon. Draught measurements in the first two seasons (2009–2010) were taken using a hydraulic dynamometer. During the second two seasons (2011–2012), measurements were taken using a digital dynamometer with wireless transmitter. No significant discrepancy was noted between the two systems. In order to calculate the work energy generated by the oxen, distance travelled was estimated using a pedometer attached to the drover.

Time required for other oxen maintenance tasks, including moving and watering animals on pasture in the summer, and feeding hay and handling manure, was measured to create an estimate of additional time required for maintaining oxen.

Estimation of energy inputs

Based on the numbers above, animals were assumed to work a conservative 700 h/yr. Each ox was assumed to eat approximately 22 kg of hay/day, or about 2.2% of its body weight in dry matter, at a dry matter content of 91%, as shown in our forage tests. Work energy produced by the oxen was estimated using a sampling of measured values for draught and estimated values for distances travelled. Based on Lawrence (1985) and Fall *et al* (1997), oxen were assumed to convert muscular energy into draught at 0.33 efficiency, and to require 2 joules/kg of body weight/metre travelled for movement. Based on these factors and the data collected, excess metabolic energy consumption due to work was estimated.

Energy charged for depreciation of equipment was based on an estimated 80 MJ/kg (Barber, 2004), which is intermediate to estimates given by Kitani (1999) and Baum *et al* (2009) on embodied energy and a working life of 5,000 hours. Given that most of the equipment is antique, this is likely to be an overestimate, but it also allows for lubricants, replacement parts and miscellaneous energy expenditure related to equipment. Energy use by humans was modelled based on excess human metabolic energy. Calculations were based on 0.75 MJ/h, or a working rate of 200 watts (Loomis and Connor, 1992). A more precise estimate could be generated based on individual tasks, but human energy is a very small proportion of the energy used in our hay production system.

Forage tests were carried out to determine moisture content. Hay was estimated to contain gross energy of 18.88 MJ/kg of dry matter (Pagan, 1998).

Energy inputs and outputs were estimated based on two systems boundaries summarized in Figure 1. Framework 1 is a hypothetical animal-powered biomass harvesting operation. The energy flow coming out of the system is the chemical energy in the hay. The hay required to sustain the oxen and thus continue the process is regarded as the primary energy input associated with the oxen. Framework 2 examines hay production by and for oxen as a tractive power source for a working farm. The ability of the oxen to do work on a farm is considered to be the energy output of the process, and the work that the oxen do to harvest the hay to maintain themselves is considered the energy input. In both systems, human energy used for non-haying animal maintenance, as well as in the haying process and embodied energy in equipment, is also charged as energy input.

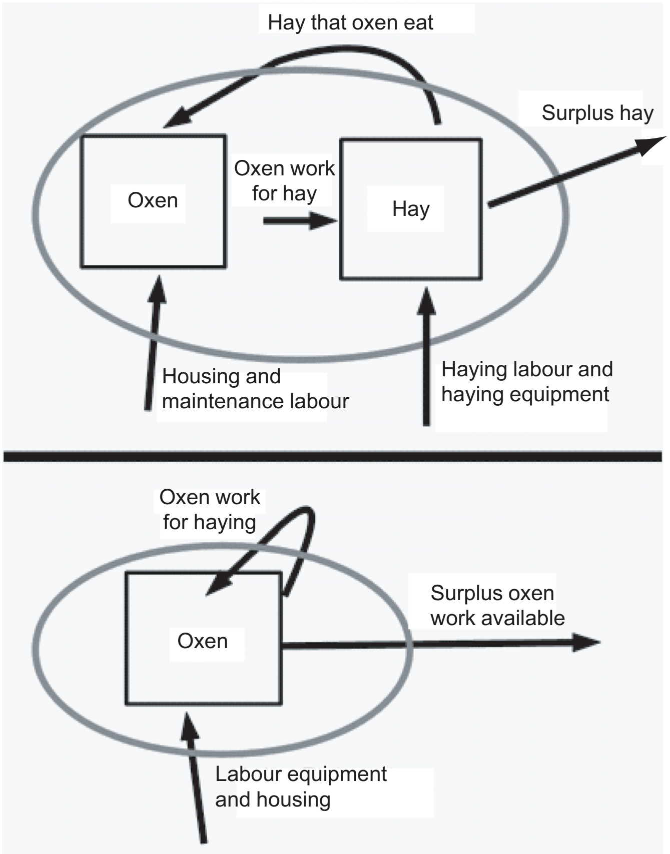

Figure 1. Two alternative frameworks for the analysis of oxen-powered haying. System boundaries are shown in grey.

Results

Tables 1 and 2 show the labour and energy inputs into hay production, as well as outputs. Table 3 shows the energy ratios for the two systems boundaries. Yields were relatively low, possibly due to past mining of native fertility by intensive cropping. When using hay as the primary unit of energy, an energy ratio of 6.32 was calculated, and 12.9 hours of labour were required for each ton of hay produced. This yields 24.0 GJ/ha net energy return to land, and 1.18 GJ/h net energy return to labour. The team of oxen required approximately eight tons of hay over the course of a six-month winter, meaning that 80 team-hours and 165 person-hours are required to generate feed for the team. Based on assumed work levels, this represents about 11% of the available work capacity of the team.

These energy ratios are slightly lower than those we calculated from several datasets presented by Pimentel and Pimentel (2007). These data are shown in Table 4. Note that the energy ratios reported in Table 4 are higher than those reported in the original text because we recalculated the energy outputs in Table 4 to be heat of combustion.

Discussion

Sensitivity analysis

The energy ratios delivered in this analysis are lower, probably much lower than potentially achievable, given that the oxen used were of suboptimal breed, hay yields were low, drovers were often students, and equipment performance could have been improved through more

Table 1. Human and oxen labour in hay production.

	Mowing	Raking	Loading	Transit	Unloading	Total
Team, h/ton	4.80	1.87	1.21	0.71	1.20	9.79
Human, h/ton	10.18	2.09	2.95	1.49	3.39	20.10
Labour for oxen maintenance, h/t	1.54	0.60	0.39	0.23	0.38	3.13
Average draught (kg)	148	105	194	114		

Table 2. Energy inputs for different parts of the haymaking process (MJ/ton).

Energy input	Mowing	Raking	Loading	Transit	Unloading	Total
Equipment energy	30.13	9.38	6.08	2.66	0.75	49.00
Human energy	3.60	1.40	0.91	0.53	0.90	7.34
Human energy for oxen maintenance	1.15	0.45	0.29	0.17	0.29	2.35
Hay needed for oxen	942.72	366.66	237.61	138.72	235.87	1,921.59
Energy expended by oxen	55.66	39.54	27.57	20.83	1.14	144.74
Energy output						17,180.80

Table 3. EROI for oxen haying system using two different systems boundaries.

System boundary	Oxen input	Output	EROI
Energy for society	Energy in hay feedback	Energy in hay	6.32
Energy for farm	Oxen metabolic energy	Available oxen metabolic energy	9.14

Table 4. Energy efficiency of haying systems described by Pimentel and Pimentel (2007).

	Alfalfa	'Tame hay'	Switchgrass	UK intensive	UK 'efficient'
Input (GJ)	10.47	7.18	11.53	27.70	9.48
Yield (kg)	6,832	5,000	10,000	10,300	5,600
Output (GJ)	112.16	82.09	167.36	169.10	91.94
EROI	10.71	11.43	14.52	6.10	9.70
Pelletizing energy (MJ)	2.31	1.69	3.38	3.48	1.89
Pellet EROI	8.43	8.88	10.78	5.21	7.76

Table 5. Summary of working rate for various haying tasks (ha/team hour).

Study	Animals used	Mowing	Raking	Tedding
James (2007), Amish farmers	Horses	0.61	1.01	1.01
Yearbook of Agriculture (USDA, 1948)	Horses	0.36	0.81	–
Green Mountain College (2008–2012)	Oxen	0.23 (2)	0.36	–

Note: Number of workers, if greater than 1, is shown in parentheses.

regular maintenance. The potential improvements from some of these factors are hard to quantify, while others are easier.

First, extending the grazing season would exert a very strong influence on the energetics of animal-powered haying, as this reduces the amount of feedback required to sustain the process. Numerous studies have demonstrated that year-round grazing systems can maintain body condition on beef cattle with little supplemental hay, even in northern climates (Hedtcke *et al*, 2002). In Iowa, reductions of over 75% in hay feeding have been achieved by researchers (Janovick *et al*, 2004). A conservative reduction of 50% in hay feeding would increase the energy ratio to 9.14.

Higher hay yields would increase energy efficiency substantially. The resistance of the hay crop on the cutter bar of the mower was probably slightly less than 50% of the draught created by the implement (Harrigan, 2013), and the pulling force was less than 50% of the energy expended by the oxen while working (based on Lawrence, 1985). This implies that a 100% increase in hay yield would only increase the energy required by the animals by 20%; a doubling of hay yield could result in the oxen and workers harvesting up to 67% more hay per hour during the mowing, raking and loading phases. These efficiency gains are only possible up to a point: if the load becomes excessive, animal working efficiency will decrease. These hay yields of 3.1 t/ha per cutting would be closer to the yield potential of the land. The US Natural Resources Conservation Service (NRCS) estimates Teel series soils as having a yield potential of 9 t/ha of grass or grass–legume hay and over 10 t/ha for alfalfa (Soil Survey Staff, nd). Furthermore, grass for biomass can be harvested later than grass for hay, as the diminished forage quality is not a factor. Achievable increases in yield may increase energy efficiency by up to 50%.

Based on the wide range of animal labour utilization in farming systems, animal utilization could easily vary by +/–50%. This factor exerts a great deal of influence over the energy efficiency of the haying system. As maintenance required for the oxen, in the form of hay (and a small energy input in labour) represents over 90% of the energy input, a decrease or increase of 50% would give nearly the same percentage change in energy efficiency.

Other possible improvements

Table 5 compares the amount of time required for animal-powered farmers to accomplish various haying tasks. The Amish farmers studied by James (2007) mowed and raked hay approximately 170% faster than the oxen used in this study, while the 1944 horse farmers (United States Department of Agriculture, 1948) were 57–125% faster. Comparable numbers were not available for loading loose hay, hauling from the field or unloading hay in the barn. It is clear that horses are somewhat more labour-efficient, but it is unclear whether their energy efficiency is higher. In addition to a higher working rate, horses consume less feed than cattle, but the feed they consume must be of higher quality, including grain fed to working horses.

While horses are generally acknowledged to be more powerful working animals than oxen, the difference is certainly not of the magnitude shown here. Morrison (1936) stated that an ox could pull the same weight as a horse, but at only two-thirds the speed, and other sources cite the power output of an ox and a horse (for example, Chantalakhana and Bunyavejchewin, 1994), suggesting room for improvement in working efficiency.

Based on the considerations above, energy ratios of 10–25 are probably achievable using oxen power to harvest native grasses under ideal circumstances. In improved stands which are planted and fertilized, energy efficiency in the harvesting phase may be substantially higher, but with additional energy inputs in the form of oxen labour required for tillage and planting, and energy embodied in fertilizer.

Integrating grass biomass harvested by draught animals into energy utilization systems

Biomass for heating. If pelletizing hay is assigned an energy cost of 338 MJ/t, with a dry matter loss of 0.04 (Jannasch *et al*, 2004), then our oxen haying system achieves an EROI of 5.93 when integrated into a pelletizing system for home heating. This is similar to the most efficient producers of sunflower biodiesel in Vermont (Garza, 2011), an energy form that is blended with #6 diesel for home heating. As stated before, various improvements could easily push this number much higher, and the vast majority of energy required for the process is renewable, compared with the high requirement for non-renewable energy in biodiesel production.

Draught animals for power on the farm. Even though this draught animal hay harvesting system was less energy-efficient than other hay harvesting systems shown in Table 4, the energy return for power production (Framework 2) is already higher than any existing on-farm fuel production technology, even without the above-mentioned improvements. At 20–25%, (Hurst and Rogers, 1983), the conversion efficiency of oxen metabolic effort while working to draught is similar to the conversion efficiency of fuel energy to draught for tractors (Bender, 2001). Thus, in terms of the ability to accomplish work on the farm, the output from Framework 2 is similar, or slightly higher than that of fuel. The 9.31 EROI is higher than even the most optimistic estimates for cellulosic ethanol (Hammerschlag, 2006) or biodiesel (Bona *et al*, 1999) while requiring very little non-renewable energy and low amounts of capital. On the other hand, oxen have lower power output than large tractors, which means that this energy must be harnessed over a longer period of time, requiring more labour.

Gross energy efficiency

While oxen seem to have the potential to deliver excess energy at a very low external input level, other ways of understanding energy efficiency make cattle seem highly inefficient. For instance, at the assumed levels of work, according to our data we estimate that slightly less than 5% of the gross energy in the feed consumed by oxen in the course of the year is converted into useful work on the farm. This is within the range of 3–10% found by Hurst and Rogers (1983). Interestingly, these estimates from India show that the energy content of manure is much higher than the energy value of work accomplished by working cattle. The authors also estimated that cattle converted forage energy to manure at 20% efficiency, and proposed that the service of concentrating the energy in vegetation found on roadsides and in ditches into manure for fuel could be the most important value provided by cattle in India. Similarly in our trials, if all manure from the oxen were recovered and anaerobically digested, about 18 GJ worth of biogas could be recovered, approximately eight times greater than the year-long draught energy output of 2.2 GJ. These results are consistent with those cited above; while oxen may be seen as energy-efficient in a farm systems context, on an input–output basis, the conversion of feed to metabolic energy to draught is highly inefficient.

Direct comparisons between the low-input system used in this study and the highly intensive systems reported in Table 4 are difficult because of differences in the energy inputs. While the tractor-powered, intensive haying systems showed somewhat higher energy efficiency, such systems generally convert high-quality energy inputs such as diesel fuel and natural gas into grass, which has a much lower relative quality. In the animal-powered haying system, the quality of non-labour energy inputs and outputs is generally equivalent. Cleveland (1992) suggests adjusting for the quality of the energy types as determined by market price, something worth considering in this regard, although issues are raised pertaining to systems with a high degree of human energy inputs. Rough estimates based on current market prices suggest that a GJ of human labour at the US minimum wage costs almost US$10,000, while grass hay, gasoline and electricity cost less than $13/GJ, $30/GJ and $50/GJ respectively.

A similar discrepancy emerges when considering the fact that most of the inputs in the oxen system are derived from renewable energy sources. Some analysts have used a metric of energy return on non-renewable energy invested to address the fact that some forms of energy input are considered more sustainable. The animal-powered haying system represents a return to earlier conceptions of energy return in ecology and anthropology in which it was generally assumed that a portion of the energy output was *in fact* reinvested as the primary energy input in the production system.

Conclusion

A review of the literature on the energy return on energy invested in animal traction has simultaneously demonstrated a lack of a clear understanding of the potential energy efficiency of draught animal power, especially in a developed country context, as well as the potential for draught animal power, by being integrated with other systems, to produce an energy return on investment that is comparable with many other renewable energy systems. We have shown positive energy return from harvesting perennial grasses using oxen, even with many existing limitations on our system. The energy return is competitive with other biomass-based renewable energy systems, though lower than some calculated values for mechanized hay production. Modest goals for improvements in energy efficiency could push net energy return much higher, to levels that are comparable to or exceed mechanized hay production and are higher than any renewable fuel other than firewood (Murphy and Hall, 2010).

Investment in further study of technologies and adaptation for animal traction appears warranted. Further research and development of draught animal technologies could keep this option open as an energy adaptation strategy for developed nations and could also provide this low-capital energy harvesting system to areas in the developing world with limited access to capital.

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