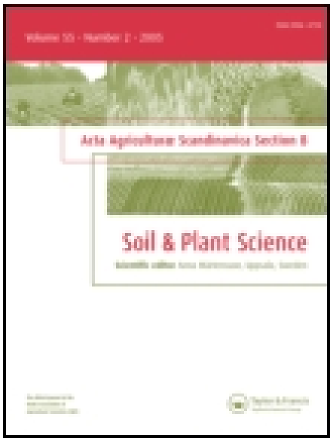

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Impact on food productivity by fossil fuel independence - A case study of a Swedish small-scale integrated organic farm

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ORIGINAL ARTICLE

Impact on food productivity by fossil fuel independence – A case study of a Swedish small-scale integrated organic farm

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Abstract
The large-scale industrial agriculture that provides the majority of food at present is dependent upon fossil fuels in the form of tractor fuel, mineral fertilizers, pesticides, and irrigation. Yet, the age of cheap and abundant fossil fuels will likely come to an end within the coming decades. In this case study, the productivity of a small-scale farm (8 ha arable land, 5.5 ha meadow, 3.5 ha pasture and 18 ha forest) independent on fossil fuels by using organic methods and draught horse power was investigated. The aim was to quantify its productivity when the animal composition and possible alternatives to tractive power were varied. After an analysis of possible solutions, three scenarios for tractive power were selected: draught horse power, diesel tractor, and combination of draught horse power and rapeseed oil fueled tractor. A model that calculates the amount of food available at the farm in terms of meat, milk egg, and crops, converts it into energy units and calculates how many people can be supplied from the farm was developed. The most reasonable of the scenarios studied was when draught horse power was combined with tractor (and combine harvester) driven on locally produced rapeseed oil. Then the farm will have access to all advantages with the tractor and harvester, e.g., timeliness in harvest and lifting heavy loads, and the renewability and efficiency of draught horse power on smaller fields, and lighter operations. This system was able to support between 66 and 82 persons depending on crop yields, milk yields, meat production, fuel demand for the tractor, and availability of forest grazing. Most likely the production capacity lands on ability to support approximately 68–70 persons, and the farm may require fossil fuels to support more than 80 persons. If all farmland globally was to be operated with the same productivity, this would be enough for supplying the global population with food at present.

Keywords: *Biofuel production, draught horse power, horse traction, organic agriculture, self-sufficiency, small-scale biofuel production, small-scale farming.*

Introduction

The UN Food and Agriculture Organization, FAO (2009) stated that agricultural production must be doubled in order to provide the food required by 2050. On the contrary, Johansson et al. (2010) showed that the global vegetal production amounts to almost double the global requirement of food. As the largest postharvest losses in the global food production is due to converting cereals into meat (Johansson et al., 2010), FAO may be correct in their statement, given that the meat consumption from industrially bred cattle, as well as biofuel production from edible products, will continue increasing at the same rate as today. But what if that is not possible?

The large-scale industrial agriculture that provides the majority of food at present is dependent upon fossil fuels in the form of tractor fuel, mineral fertilizers, pesticides, and irrigation. Yet, the age of cheap and abundant fossil fuels will likely come to an end within the coming decades (Höök et al., 2009; IEA, 2010), phosphorus is mined with increasing percentage of heavy metals (Cordell, 2010) and water scarcity is increasing due to overuse of rivers and depletion of groundwater aquifers (Postel, 1998; Pfeiffer, 2006; Falkenmark & Rockström, 2008). On top of this, the production of nitrogen fertilizer has significantly altered the global nitrogen cycle, as the total fixation of atmospheric N_2 into reactive

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nitrogen forms has more than doubled over the last century (Sutton et al., 2011). The European Nitrogen Assessment (Sutton et al., 2011) identified consequences such as eutrophication and acidification in fresh waters, loss of biodiversity, cancer, and respiratory diseases due to high nitrate concentrations in water and air, foliar damage and increased susceptibility of pathogens in plants and changes in soil organic matter as a result of losses of biodiversity in soils.

Concerning food security it may be wise to search for solutions of producing food that are not dependent upon fossil fuels. As food security is also affected by climatic variability and environment the food system must be resilient and not contribute to global environmental damage. Therefore, it is important that agriculture reduces its impact on the global carbon and nitrogen cycles.

Organic agriculture attempts to reduce its impact on the nitrogen cycle as mineral fertilizer is not used. Larsson and Granstedt (2010) found that the nitrogen leakage into the Baltic would be halved and the leakage of phosphorus eliminated if the countries surrounding the Baltic Sea would convert to organic farming. Larsson and Granstedt also argue that this would be possible without a significant decrease in yields. However, the yields are usually a main argument against organic farming.

The Swedish Board of Agriculture has for several years presented data on up to 50% lower yields of organic farming compared to conventional farming (www.sjv.se); de Ponti et al. (2012) found an average global organic/conventional yield ratio of 80% based on a literature and statistical data-survey; and Seufert et al. (2012) found, in a similar way, that the ratio was 75%, though strongly varying with crop. Because of the gap in yields between conventional and organic agriculture, there is a widespread comprehension that organic farming would fail to supply the global population with sufficient of food. But as the crop production globally yields far more than is needed, can not a decrease in crop yields be acceptable if animals do not eat what humans can eat? And if the system is dependent on renewable resources?

The most important must be that agriculture produces enough food to prevent famine, and it should also be of adequate quality to ensure health. Nevertheless, despite the fact that sufficient amount of food is produced, even after postharvest losses and meat production (Johansson et al., 2010), nearly one billion people suffer from famine and an equally large part lack adequate nutrition (Misselhorn et al., 2012). Additionally, obesity is an increasing problem. As the food system is failing so many people, it is surprising that it is still argued that the food system must continue producing the same products at an unchanged or increased rate.

However, if feeding animals is such a large loss, why keep animals at all? In organic agriculture it is very important to have a large part of ley in the crop sequence to fix nitrogen. As a matter of fact, ley is actually important in all agriculture, because ley crops contribute significantly to maintaining and improving soil structure which is one of the most important parameters for plant growth (Ohlander, 2001). A good soil structure supports the plant roots and enables them to reach micronutrients and it can store water in its aggregates. Ley also keeps the weeds and parasites away, as well as prevent nutrient leakage.

As ley is grown in organic farms by necessity it is a large waste not to feed it to animals, since animals upgrade this product, that humans cannot eat, into for us very valuable products such as milk, meat, and leather. But, e.g., the cow-breeding has gone towards as high-quantity lactating and fast-growing breeds as possible, which is achievable with feed concentrate (grains and oil-crop meals) and antibiotics that prevent the animal to put too much energy into its immune system. Feeding one of the “modern” cow breeds with nothing than forage would result in starvation, as it would not be able to eat forage in sufficient amount fast enough to keep up with the milk production.

Another advantage of keeping cattle is that they can graze large areas a large part of the year, hence making use of meadow and forest-land that is else wise difficult to use for crop production. However, since the modern cows have too large udders they cannot move in those environments. Therefore, if we are to make use of the ruminants’ excellent inherent skills to convert for humans’ inedible products to highly desirable such, we may need to search for older breeds that are smaller and can feed on poorer forage.

In any agricultural system there are many sources of losses in the production. Cereals that are meant to be milled for bread-flour must be of high quality, and usually a large part is sorted out. Poultry are good waste eaters as they feed on this production that is not at adequate quality for humans. They can also eat slaughter waste, be let out on the fields after harvest to eat the spills, spread cattle manure as they eat nonmetabolized seed, eat household waste, or clean the garden from snails. Hence, poultry can also feed on products that humans can not eat or encounter for various reasons. Keeping several species at the same farm makes more use of the farmland and helps control parasites. Different species, e.g., cows, horses, and sheep, graze different parts of the grass, and the productivity of the pasture is larger as different animals succeed each other.

Such system can seem very old-fashioned, but is it not trivial that life under a heavily restricted access to land and resources led to systems that make optimal use of what resources there are? The question is rather if such systems can supply the global population with enough food or not. The proposed solutions: smaller cows, a range of animal species at the farm, integrating animal, and crop production – this kind of system is difficult to operate at large industrial scale. Large-scale has been needed to produce the large amount of food that is produced at present, but at the same time, this large-scale is a part of the problem. Large-scale requires large machinery (with large fuel demand and soil compaction problems), and large monocultures need pesticide and mineral fertilizer to do well. Rosset (2000) argues that small-scale multi-functional farms are more productive and efficient than large-scale farms.

In this case study, we investigate the productivity of a small-scale farm that is independent on fossil fuels by using organic methods and draught horse power. The aim is to test its productivity by varying the animal composition and possible alternatives to tractive power. The productivity is measured by "number of people the farm is able to supply," which will be denoted N_P.

Methods

Description of site and farm system

The selected research object is a small farm already managing several research projects. There has been a careful quantifying of the resource usage, local and auxiliary, as well as measuring, e.g., harvest levels. The farm is located in Roslagen, in south eastern Sweden (approximately 59°52′N, 17°40′E). The area is characterized by a rather flat landscape with altitudes ranging from 0 to 100 m a.s.l. The landscape is patchy with small fields with water-laid sediments and decomposing peat, intersected by hills of bedrock, and glacial till. The glacial till is rich in calcium carbonate. The climate is characterized by an average annual precipitation of 637 mm and an average annual temperature of 5.7°C (SMHI, 2010). The climate is further characterized by droughts in the early growing season.

A reference group of eight farmers is tied to the farm, to contribute with their expertise as they have long-term experience as organic farmers. The reference group has been involved especially in the trials around the crop sequence.

The farm consists of 8 ha arable land, 5.5 ha meadow land, 3.5 ha pasture land, and 18 ha forest land, of which 10.5 ha are grazed. As the farm is integrating several animal species and crops, it is relevant that the farm size is adequately small that the farm can be handled by one family. The size of farm may also be a matter of importance regarding biodiversity and, e.g., Belfrage et al. (2005) found that there were twice as many bird species in a small as in a large farm, where birds are good indicators of biodiversity in general. Maintaining biodiversity is important, since biodiversity performs a variety of ecological services beyond the production of food in agroecosystems, including recycling of nutrients, regulation of microclimate and local hydrological processes, suppression of undesirable organisms, and detoxification of noxious chemicals (Altieri, 1999).

Animals and crop sequence

The majority of organic animal farms in the area use a crop sequence that includes 60% ley, e.g., usually as following sequence: ley, ley, ley, winter seed, and spring seed with re-seeded ley crop. Such a crop sequence seldom fails, and the large amount of ley effectively holds the weed away as experienced by the research farm and the reference group. However, this is more or less a farm entirely dedicated for fodder production for cattle. In order to increase food production the fraction of ley should ideally be reduced in favor for edible production. According to experience in the reference group 35–40% ley is a lower limit, and the research farm has through three years of trials with the new sequence (described below) concluded that 37.5% of ley was possible at this site, but need a lot of mechanical weed control.

To be able to make use of land that would be difficult to grow crops on with organic methods (i.e., meadow and forest), Swedish Mountain cows are used for grazing. They also feed well on the forage produced from ley. The reference group experienced that a combination of different animal species: cow, sheep, and poultry, increases the productivity of the farm. The seed fraction that is mostly sorted away is 35–40% of the oat production and 6–7% of the wheat production, which is why poultry is needed to make use of all products at the farm. Many parts of Sweden have also recently been troubled by snail-invasion in gardens, destroying the production of vegetables. Poultry has proven to keep them away at the research farm. Therefore, the ecosystem services they provide are difficult to manage with other means.

The crop sequence that has been tested was developed to give a range of different food products so that the farm ideally can supply the entire food requirement to its buyers. The eight-year crop sequence is as follows (each crop is grown on 1/8 of the total area of 8 ha arable land, i.e., 1 ha):

(1) Lucerne (*Medicago sativa* L.) harvested only once (in June). The plot is then manured and ploughed and thereafter sown with winter rapeseed [Canola, *Brassica napus* L. ssp. *Oleifera* (Metzg.)].
(2) Rapeseed harvested in July. The plot is ploughed and sown with winter wheat (*Triticum aestivum* L.).
(3) Winter wheat undersown with Crimsom clover (*Trifolium incarnatum* L.).
(4) Potato (*Solanum tuberosum* L.) and vegetables (for calculations we simplify "vegetables" into "lettuce" (*Lactuca* L.), not to overestimate its energy content that we use for calculating the productivity).
(5) Buckwheat (*Fagopyrum esculentum* Moench).
(6) Oat (*Avena sativa* L.) with undersown lucerne.
(7) Lucerne, harvested two times.
(8) Lucerne, harvested three times.

Requirement of tractive power

The scenarios were decided on the basis of the demand for tractive power together with the specific crop yields at the farm. The farm is at present operated with a small (47 hp) diesel tractor, and threshing is done by a locally owned combine harvester. The diesel requirement for all tractor operations and threshing has been measured to 809 l in year 2010.

As the choice of crop sequence aims at having as many different crops as possible, there will be few possibilities for converting crops into biofuels. A theoretical calculation on converting available crops with the given yields, according to conversion factors and methodology described by Johansson and Liljequist (2009), into different kinds of biofuels: rape methyl ester, ethanol from wheat, ethanol from straw, and biogas lead to the conclusion that within given crop sequence, the farm only has enough raw material to supply the tractor requirement by biogas (that was based on using manure and straw from a mixed deep litter bed) or ethanol if all wheat and part of the straw is used. However, then no wheat would be available for food and no straw for forage and straw bed, which is how we use it at present. As a matter of fact, none of the conventional biofuel systems are practically possible within the context of being self-sufficient at this scale, since large-scale facilities are required for most biofuel technologies (Fredriksson et al., 2006; Hansson et al., 2007) and biogas requires storages or a distribution system (Kimming et al., 2011).

For a combination with draught horse power the farm yields enough to theoretically have raw material for all biofuels. If the tractor and combine harvester is used for the heavy work (plowing, threshing, manure spreading, and bailing), one North Swedish horse can replace the "easier" operations (haying and pressing, turning of hay, harrowing, sowing and turning, inter-rowing, and gathering of potatoes and vegetables), reducing the diesel demand to 320 l. However, the only realistic scenario for fuel in combination with draught horse power in this scale was the alternative where a part of the on-farm pressed rapeseed oil is used for the tractor and harvester.

Efficiency of draught horse power

This farm is small enough to be managed with one horse, which it has been done previously. However, experience from other farms in the same size, three large horses, e.g., the North Swedish kind, have almost been able to compete with a small tractor in terms of power output.

The energy in the fodder that the horse does not need for its maintenance is directly convertible into tractive power. Approximately one-third of the gross energy the horse consumes in its forage passes the digestive system and comes out as manure (Schmidt, 2000; Rydberg & Jansén, 2002). This "loss" is, however, concentrated and can be reused as fertilizer, so in reality it is not entirely a loss. The rest of the energy is digestible, but there are losses in the form of urine energy (however, this loss is also used as a fertilizer since it is mixed with the manure), and heat loss energy for digestion and maintenance. The energy for maintenance, i.e., the fodder requirement for a resting animal, is 73% of the metabolizable energy for all types of animals (Björnhag et al., 1989, p. 246). The metabolizable energy is approximately 95% of the digestible energy, i.e., 5% is lost in urine and methane.

The total biomass-efficiency can be defined by following equations:

$$\eta_{\text{tot}} = \eta_{\text{dig}}\eta_{\text{met}}\eta_{\text{work}}$$

where

$$\eta_{\text{dig}} = \frac{\text{digestible energy}}{\text{total energy intake}} = 0.67 \text{ (since 33\% is lost in manure)}$$

$$\eta_{\text{met}} = \frac{\text{metabolizable energy}}{\text{digestible energy}} = 0.95 \text{ (since 5\% is lost in urine and manure)}$$

$$\eta_{work} = \frac{\text{energy available for work}}{\text{energy needed for maintenance}} = 1 - 0.73$$
$$= 0.27 \text{ (since 73\% is lost for maintenance)}$$

hence

$$\eta_{tot} = \eta_{dig}\eta_{met}\eta_{work} = 0.67 * 0.95 * 0.27 \approx 0.17$$

when all the losses are considered, the efficiency of a draught horse lands on approximately 17%. That is, 17% of the fodder intake is convertible into tractive power.

The calculated efficiency is significantly lower than a diesel driven tractor (approximately 35%), yet compared to other biofuels the "fuel-efficiency" (i.e., the efficiency of biomass conversion to mechanical work) of a horse is comparable. For example, in biogas production, about 25–60% of the energy in the biomass is converted into methane, depending on the substrate and technology. If used in an internal combustion engine (otto or diesel), approximately 55–75% of the energy is lost as heat. Thus substrates with the lower conversion efficiencies (around 25%), used in an engine (25% efficiency), gives a total biomass efficiency around 6%, which is far lower than draught horses. However, the efficiency of the horse may land on something similar to this if it is accounted that it need energy for maintenance even at rest.

Another assessment was made in the Scientific American 1973 (Hermans, 2011) on the efficiency of animals and vehicles. The horse is according to this study, moving more efficient than a car (Figure 1).

Scenarios

Three scenarios are studied:

(1) Draught horse power;
Three North Swedish horses are doing all field operations.

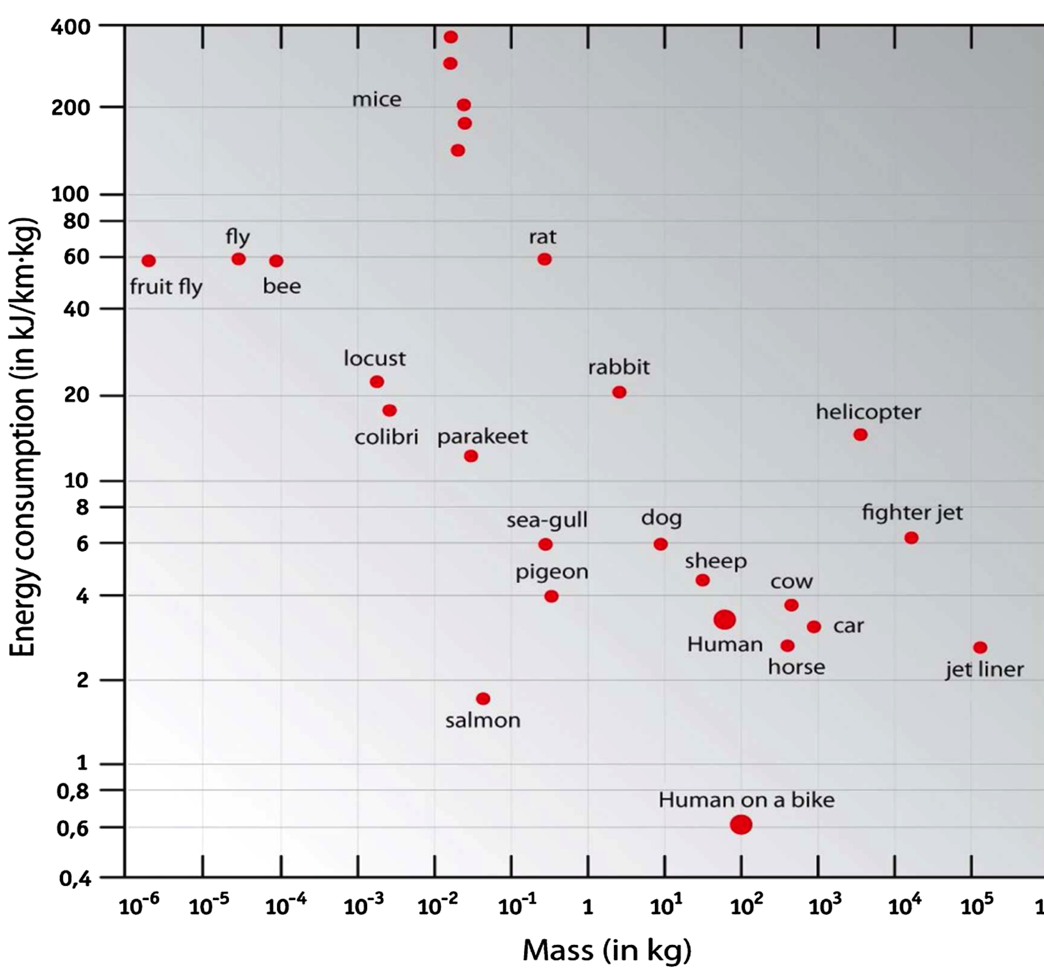

Figure 1. We calculated the biomass efficiency of the horse to 17%. Similarly, an assessment of Scientific American in 1973 indicates that the horse works efficient enough to be comparable with a Jet liner when computing the energy it takes to move 1 km/kg. According to this study the horse works even more efficient than a car (but a human on a bike beats them all). The horse is more efficient than the human as well, which may be a reason why we have chosen to work with horses many centuries. Adapted from Hermans (2011, p. 61).

(2) Diesel;
Fossil fuel diesel is used for all field operations.

(3) Draught horse power combined with rapeseed oil;
One North Swedish horse is used for the easier operations, tractor and combine harvester fueled on rapeseed oil for heavy operations.

Method for calculations

A model that calculates the amount of food available at a farm in terms of meat, milk egg, and crops, converts it into energy units and calculates how many people can be supplied from the farm was developed in MS Excel. The energy requirement for a human being spans between 760 kcal/day for a newborn baby and 3300 kcal/day for a regularly exercising 18- to 30-year-old male (Swedish Food Administration, 2007). We have assumed an average energy requirement of 2500 kcal/day and capita.

Our idea is that animals should not eat what is edible for humans. Hence the number of animals is decided by the amount of forage available, and for poultry the number is decided by the availability of cereals that are sorted away and inedible intestines after slaughter. For ruminants the amount of forage is fixed since we are testing a fixed crop sequence. The amount of poultry on the other hand is dependent on the variable amount of slaughter waste produced. The protein intake should not exceed 20%, and we included an IF-function that fixed the number of poultry on the maximum possible amount if the available slaughter-waste reached above 20% of the fodder intake.

The model can elaborate with different animal compositions, harvests, and forage availability to find out what amount of humans that can be supplied on a given area and also to find different scenarios where a part of the production is used for producing biofuel. The cow and horse population is chosen manually and the amount of sheep is decided as a function of what forage is left.

The input data to the model are the amount of forage available at the farm from harvest and grazing, as well as harvest from all crops at the farm. The calculations in the model include feed plans for cattle, horses, sheep, and poultry as well as food requirements for humans. We have used energy units (MJ) to measure the amount of forage, crops, food, and feed requirements. For the feed plans we have considered the protein requirements, but since the protein demand turned out to be fulfilled as the energy requirement was fulfilled (lucerne is rich in protein), we decided to leave it out of the model for simplicity. Hence, we only use the energy requirement as a mean for evaluating the amount of animals the farm can hold, as well as the amount of humans the farm can supply.

Choice of input data

Data needed to evaluate the amount of fodder produced (e.g., its content of metabolizable energy and digestible protein) and feed plans for ruminants were taken from the study of Spörndly (1989) and for poultry Cisuk (1994) and the Swedish Board of Agriculture Counselling Group for Laying Hens (2003). Feed plans for the horses were calculated from the web-based fodder calculator of the Swedish University of Agricultural Sciences (SLU), (Hippocampus, SLU, 2010). In order not to underestimate the requirement for horses it was assumed that they were at hard forestal or agricultural work 6 h/day half the year, and easy work load (30 min/day) for half the year, and that they also were pregnant.

The energy content of livestock products and crops were taken from the food database of the Swedish Food Administration (2011) and from the study of Johansson and Liljequist (2009).

Since the period of trial with the crop sequence is only three years, yield levels might not be representative. Therefore, levels on harvests were estimated using data both from the research farm, neighboring farms, the reference group, and from literature. The diesel requirement was measured during 2010, a "normal" year that is representative.

We investigated the outputs of two breeds of the Swedish Mountain cow: Small (approx. 250 kg) and large (400 kg). The research farm has experienced that the larger breed give 25 l/day in the high lactating period and end at 10 l/day at 300 days after calving, which results in almost 5300 l/year given a linear approximation for the decrease between days 1 and 300. This is rather optimistic, but has been possible to produce with the 400 kg cow without feed concentrate. There are also rapeseed expelles available, which can give approximately 1–2 kg/day in the most high-lactating month, which may be enough to keep up the assumed production. Experience of the smaller breed is a milk production spanning from 10 to 8 l/day during 300 days, giving around 2700 l/year, however, this may also be an optimistic scenario. These yields were experienced from a few individuals, and according to farmers with experience from larger herds of Swedish Mountain cow, these milk yields are possible but optimistic. Therefore, in the main scenarios we have assumed that the large cow gives 20–10 l/day linearly decreasing over 300 days, resulting in approximately 4500 l/year, and for the small cow a yield of 10–2 l/day during the same period, giving totally 1800 l/year. The larger yields which we measured from a few individuals are instead tested in the sensitivity analysis.

The amount of poultry is decided by the amount of sorted away cereals, 35% for oats and 6% for wheat. We chose the lower level (see "Methods" above) not to overestimate the amount of poultry. Poultry can feed on intestines as well and this is also used as a function for deciding amount of poultry. However, no intestines descending from poultry was included in their feed share, and if the amount of intestines exceeded 20% of the total feed, the number of poultry was fixed at the maximum level that was 70 individuals.

The number of animals of each species is set in adult individuals, but it is not reasonable that all adults give milk or offspring. Regarding cows we have assumed that one-third of them are younger and only two-thirds of the individuals give milk and offspring. Regarding sheep 20% of the adults are assumed to be too young to give offspring and the rest give two lambs each every year. For the poultry we assume that all of them produce egg, but 50% are slaughtered every year, however, reproduction enables the population to be constant. After a few years in production the adult animals would be slaughtered, but we have excluded this and only included meat from offspring, not to overestimate the meat production.

In time of slaughter, the offspring of the large cow breed has a living weight of 160 kg, small cow breed 100 kg, lamb 20 kg, and poultry 3 kg. Bones are 30% of the living weight, and intestines are assumed to be 30% of the deboned slaughter weight. Of the intestines we assume that 50% is edible for humans. There are 200 eggs/hen every year, and an average weight of an egg was measured to 72.5 g, which gives 14.5 kg egg per hen.

Input data to scenarios

Animal products. The milk production was set to 4500 l/year for large cows and/or 1800 l/year for small cows. Each hen gives 200 eggs/year. The deboned weight of large calf was 112 kg, small calf 70 kg, lamb 14 kg, and hen 2.1 kg. Energy contents are given in Table I.

Table I. Energy contents for animal products as input to calculation model.

Animal	Meat (MJ/kg)	Edible Intestine (MJ/kg)	Inedible intestine (MJ/kg)	Milk (MJ/kg)	Egg (MJ/kg)
Calf	6.9	5.16	4.02	2.99	
Lamb	6.9	5.75	5.49		
Hen	6.0	5.21	4.65		5.9

Production of forage. Forest grazing was 980 kg dry matter (DM)/ha at 10.5 ha and pasture grazing gave 2940 kgDM/ha and was used on 3.5 ha. The lucerne production was totally 33,600 kgDM (40 tonnes harvest, DM content 84%) and hay from meadow was totally 16170 kgDM (5.5 ha). We also accounted for residues as forage, totally 6630 kgDM (calculated with harvest index from cereal production, according to Johansson & Liljequist, 2009).

Vegetal production. For all scenarios we chose to use the crop sequence that have been developed and tested at the research farm. The yields are given in Table II. In the net edible production we have included deduction of seed for reproduction, cereal harvest that is sorted away (used for poultry), 1% shrinkage, 20% postharvest losses of potato and vegetables, and milling percentage of 78% for wheat, and 70% for oats, according to Johansson and Liljequist (2009). The chaff and bran from milling is fed to poultry.

Studied cases. The fodder requirement for maintenance of the cattle is dependent on its weight, and a smaller animal require less fodder. Naturally a smaller cow also produces less milk. However, it is an intricate balance since the energy needed to

Table II. Input data of vegetal production.

Crops	Energy content (MJ/kg)	Yield (kg/ha)	Area grown (ha)	Seed for reproduction (kg/ha)	Sorted out (feed for poultry) (kg)	Net production (edible) (tonnes)	Net production (edible) (GJ)
Rapeseed		1500	1	40		0.6	9.6
Winter wheat	14.9	3500	1	200	210	2.4	35.6
Potato	3.3	20000	0.5	1500		7.3	24.3
Oats	15.4	3000	1	200	1050	1.2	18.6
Buckwheat	14.7	1500	1	60	90	1.3	19.7
Vegetables	0.7	60000	0.5	300		23.6	17.4
Sum							125

produce milk is dependent on the milk yield, and a cow that produces less milk also need less energy for milk production. To investigate the significance of milk and meat production depending on cow size, we chose to investigate two sizes of the Swedish Mountain cow, one larger (400 kg) and one smaller (250 kg), and the research farm had specific experience of these. Either a larger number of the smaller cow breed can be used or fewer of the larger size.

In scenario I there are three horses present and five cases considered:

(1) 17 adult larger cows (the largest amount possible), 1 adult sheep, 65 hens
(2) 17 adult smaller cows, 37 sheep, 70 hens
(3) No cows, 158 sheep, 70 hens
(4) 22 small cows (the largest amount possible), 2 sheep, 64 hens
(5) 15 large cows, 19 sheep (better balance between species), 68 hens

In scenario II there is a diesel-driven tractor and no horses, five cases are considered:

(1) 19 adult larger cows (the largest amount possible), 7 sheep, 67 hens
(2) 19 smaller cows, 48 sheep, 70 hens
(3) No cows, 183 sheep, 70 hens
(4) 25 small cows (the largest amount possible), 5 sheep, 65 hens
(5) 18 large cows, 16 sheep (better balance between species), 69 hens

In scenario III there is one horse, and the amount of rapeseed oil available for humans is decreased with 320 l (e.g., it is assumed that the tractor and combine harvester operates on same efficiency as with conventional diesel). Six cases are considered:

(1) 18 adult larger cows (the largest amount possible), 8 sheep, 67 hens
(2) 18 smaller cows, 47 sheep, 70 hens
(3) No cows, 175 sheep, 70 hens
(4) 24 small cows (the largest amount possible), 4 sheep, 65 hens
(5) 17 large cows, 17 sheep (better balance between species), 68 hens
(6) 10 large cows, 10 small cows, 11 sheep, 67 hens

Results

Results of scenarios

The results of the scenarios with different cases are presented in Tables III–V below for scenario I–III, respectively. The results are presented by N_P, i.e., the number of people the farm can supply, and the milk production per person is calculated per week, as well as the meat/egg/intestine production per capita.

As seen in Table III the system with the larger cow can support most people, and there is a large difference, 20 persons less can be provided if the maximum amount of small cows are used (case 4) compared to if the maximum amount of large cows is used (case 1). It is evident that the milk production has a large impact on N_p, as case 3 where there is no milk production has the lowest productivity. A better balance between the species, case 5, decreases N_P with three persons compared to having the maximum amount of large cows (case 1).

The relation between the cases in scenario II (Table VI) are similar to scenario I (Table III), but in Table IV it is shown that the diesel driven system can support two more large cows and a number of more sheep thanks to removing the three large North Swedish horses from the system. This result in an increase of seven persons for the case where a good balance between species is used (case 5).

Even if the amount of large cows and the amount of sheep is larger in scenario III than in scenario I (as seen in Table V), N_P is landing on similar values as in scenario I. The reason is that the rapeseed oil

Table III. Results for scenario I – draught horse power with 3 North Swedish horses, no tractor.

Case	Case description	Large cows	Small cows	Sheep	Hens	N_P	Milk per person and week (l)	Meat/egg/intestines per person and week (kg)
1	The largest amount of large cows possible	17	0	1	65	79	12.4	0.230
2	Same amount but changed to small cows	0	17	37	69	56	7.0	0.410
3	No cows	0	0	158	70	42	0	1.140
4	Largest possible amount of small cows	0	22	2	64	59	8.5	0.260
5	Better balance between cows and sheep	15	0	19	68	75	11.6	0.290

Table IV. Results for scenario II – no horses, tractor and combine harvester fueled by conventional diesel.

Case	Case description	Large cows	Small cows	Sheep	Hens	N_P	Milk per person and week (l)	Meat/egg/intestines per person and week (kg)
1	The largest amount of large cows possible	19	0	7	67	84	13.0	0.260
2	Same amount but changed to small cows	0	19	48	70	58	7.5	0.470
3	No cows	0	0	183	70	43	0	1.290
4	Largest possible amount of small cows	0	25	5	65	62	9.2	0.290
5	Better balance between cows and sheep	18	0	16	69	82	12.6	0.290

Table V. Result for scenario III – draught horse power for easier loads are covered by one North Swedish horse, heavier loads are done by tractor and combine harvester fueled by rapeseed oil.

Case	Case description	Large cows	Small cows	Sheep	Hens	N_P	Milk per person and week (l)	Meat/egg/intestines per person and week (kg)
1	The largest amount of large cows possible	18	0	8	67	79	13.2	0.270
2	Same amount but changed to small cows	0	18	47	70	54	7.7	0.490
3	No cows	0	0	175	70	40	0	1.340
4	Largest possible amount of small cows	0	24	4	65	58	9.5	0.300
5	Better balance between cows and sheep	17	0	17	68	76	12.8	0.300
6	Equal amount of large and small cows	10	10	11	67	69	11.7	0.300

contributes to approximately same amount of food energy as the amount of meat that can be produced by removing two of the horses. In scenario III we also added another case (case 6), to investigate the impact of mixing small and large cows. N_P was seven persons less in case 6 than in case 5. Case 5 also had a very good balance between cows and sheep, which is important for optimizing the ecosystem services the combination produces. Yet, in reality, case 6 may be more probable since a herd of cows will not all be of the same size.

Sensitivity analysis

We chose to make the sensitivity analysis in scenario III case 6.

The yields of the crop production at the farm are compared with average organic and conventional yields in Sweden for years 2005–2010 in Table VI.

Our yield of rapeseed is lower than average organic yields in Sweden, but for winter wheat and potato we managed to produce larger yields. If we assume average organic yields for mentioned crops, N_P dropped from 69 persons to 66. If we assumed the average conventional yields N_P increased to 82.

If we assume a more optimistic milk yield, 2700 l/year for the small and 5300 l/year for the large Swedish Mountain cow, N_P increased to 77 persons, but this also resulted in a decreased meat supply from 300 g/person and week to 200 g, since the cows need more forage for producing more milk, and hence the number of sheep was reduced.

The availability of forest grazing may be limited and we also investigated how much N_P is affected by removing forest grazing. However, this only reduced N_P by one person, from 69 to 68. The farm owns 18 ha forest, and if we instead assume that all that is grazed, N_P was equal to 70.

We have assumed that the fuel requirement of using rapeseed oil in a tractor is equal to that of using conventional diesel. However, using rapeseed oil instead may affect the performance of the engine, e.g., by lowering its efficiency. However, a 20% larger demand of rapeseed oil for the tractor only reduced N_P by one person.

In our base cases we assume that all calves are slaughtered at age one year. If we assume that they are kept another year it means that not only they will grow larger, but also the forage consumption would be larger and the amount of sheep will decrease. When analysing the sensitivity of that parameter we assumed that the slaughter weight was doubled

Table VI. Comparison of our crop yields with average organic and conventional yields.

Crop	Our yields (tonnes/ha)	Average organic yields (2005–2010) (tonnes/ha)	Average conventional yields (2005–2010) (tonnes/ha)
Rapeseed	1.5	1.9	3.3
Winter wheat	3.5	3.3	6.3
Potato	20.0	13.2	28.2
Oats	3.0	3.0	4.0

Source: Swedish Board of Agriculture, 2011.

during the second year. This reduced N_P to 67, but increased the meat production to 510 g/week.

The productivity of the farm is most sensitive to yields of crops and milk. The largest increase of N_P was in the case when the yields were assumed to be at the same level as average conventional yields. Higher yields in milk also had a significant impact on N_P. Other factors such as increased fuel demand or less forest grazing had no significant impact.

Diet

One of the aims for the crop sequence was to provide a more wholesome diet to the consumers than farms with specialized production. The diet from scenario III, case 6 is, on a weekly basis, presented in Table VII.

The milk production can be converted to 600 g butter a week, 600 g cream, or 1200 g cheese provided that it takes 10 l milk per kg cheese, and 20 l for butter and cream. An example can be that 3 l of milk is used without upgrading it, 25% of the remaining milk is used for cheese production, 50% for butter and 25% for cream. This would give approximately 200 g cheese and butter per person per week, and 1 dl of cream, and 3 l of milk. At first sight the dairy consumption seems very large, but milk and butter are important ingredients in bread that must be baked from the flour we produce.

Discussion

We have not included any calculations on labor. Yet, as the system includes several animal species, various crops and draught horse power, it is very likely to require significantly more labor than having more specialized farms. The horses must be trained, and ideally also wool, leather and feathers should be taken care of. Considering all different tasks that must be managed, even a small farm easily becomes a large operation in terms of labor. Many social challenges are hence encountered, such as where to get labor cheap enough to afford producing the food and for consumers to afford buying it, how to distribute it, and how to manage nutrient recycling. Presently there are regulations against feeding slaughter waste to poultry or recycling bones, and there are also regulations regarding distribution of milk that must be addressed.

Table VII. Possible weekly diet from scenario III case 6.

Product	Quantity	Unit (per week)
Rapeseed oil	70	g
Wheat flour	660	g
Oat meal	340	g
Buckwheat (whole)	370	g
Potato	2.030	kg
Vegetables	6.540	kg
Meat from lamb	49	g
Meat from calf	235	g
Meat from poultry	14	g
Egg	268/3.7	g/number of eggs
Milk	11.7	kg

Regarding draught horse power there are very few studies done where it is compared to other bioenergy systems. Talking about draught horse power usually awakes a lot of feelings, mostly very subjective as such. Either it is covered by romantic images of "the good old days," or the very thought of it smells reactionary. Yet, in comparison with other biofuels, it is not so bad regarding the efficiency of which the biomass is converted into tractive power. Most other biofuels need processing in some way, not to forget transports to and from the farm that would increase the fuel demand in the system. The processing facilities usually have some proportion of non-renewability, in electricity use, transports or chemicals for the process, (which are not accounted in this study as we only theoretically studied how far the available raw material at the farm would suffice), while the horse manages this processing on its own.

Maybe the most obvious drawback is that horses work slower than the tractor, and has a lower power output. Draught horses may have some advantage at wet soils where a tractor, when plowing, can lose about 20% of its traction power because of skidding (Arvidsson & Keller, 2007). Nevertheless the tractor is superior when it comes to power output which affects the opportunity cost. If the soils are wet, the horses may not be able to exert enough power.

When fossil fuels first entered agriculture it was to fuel the harvester, and not being able to use a combine harvester may be the largest drawback in the completely horse-driven system. The combine harvester can harvest large amounts in a short time, which is one important reason why yields have increased and pre-harvest losses have decreased. Timeliness is important for both sowing and harvesting and part of the income is lost for every day the operation deviates from the ideal time. This might be one reason why draught horses have phased out in favor for tractors, and thereby opened the possibility to increase yields with less labor demand. Harvesting without a combine harvester is also a very time-intensive operation.

The tractor is a well-adjusted all-round tool, while it not only manages the field operations, but also functions, e.g., for lifting heavy loads as well. Should the tractor be entirely exchanged by the horse there must be a development of complementary tools, ideally not driven by fossil fueled engines. Therefore, if draught horse power is to be used, the scenario where it is combined with tractor is the most realistic.

An advantage with the draught horse system is that horses reproduce themselves, not only securing their replacement but contributing to meat production or economic benefit if the offspring is sold. On the other hand, much human time, skill and energy are needed in order to breed and train horses to good draught animals. These values are difficult to quantify and evaluate in comparison to a tractor. It is difficult to find a reliable figure on how much energy is needed to manufacture a tractor. Some estimates are done with different methods and different results, e.g., with energy analysis (Sonesson, 1993; Mead & Pimentel, 2005) or emergy analysis (Rydberg & Jansén, 2002). However, it can be concluded that “manufacturing” a horse depends on renewable energy in fodder crops and human labor, whereas a tractor depends mainly on non-renewable energy and resources such as steel and iron.

Using raw rapeseed oil in an ordinary direct injecting diesel engine usually leads to coke formation on nozzles and seals because of the high viscosity of the fuel (Gruber et al., 2005). Therefore, it is not possible for practical reasons to use the pure vegetable oil directly in a diesel engine that has direct injection, which is the most common type of engine in tractors (Norén, 1991). It has been discussed whether a diesel engine on rapeseed oil functions better if blended with conventional diesel. However, the former Swedish State Machinery Testing Authority (Statens maskinprovningar) has investigated the effect of blending diesel with rapeseed oil, and concluded that there were still problems with coke formation (Norén, 1991). This would lead to higher maintenance costs, and there would also be a dependency on imported diesel.

To operate an existing engine on pure plant oil some adjustments must be made. The injectors need to be modified and the oil viscosity must be reduced with a pre-heating system. This kind of conversion is not necessarily very expensive or technologically difficult. In Germany there have been long term trials where conversion of tractors to operate on pure plant oil has turned out successful (Gruber et al., 2005). Norén (1991) states that the Elsbett engine, a kind of diesel engine with a duothermal combustion chamber (i.e., there are two zones instead of one in the combustion chamber, which lowers the cooling requirements) has been used with pure rapeseed oil without choking problems.

Rapeseed oil has similar advantage as the horses – it does not require any technologically advanced processing and can be produced locally at the farm, and therefore, may be a more appropriate solution than other types of biofuels when it comes to self-sufficiency.

The world population was approximately 7 billion in 2011 (US Census Bureau, 2011), the global arable land was in 2007 1.4 billion ha (FAOSTAT, 2011). Thus there is approximately 0.2 ha arable land per capita, or reversely each farm must provide at least 5 capita/ha. If we are to support the population within each country this figure would vary widely. We are studying a small-scale system that may require a local distribution, and then a regional measure of the amount of people farms must supply would be more adequate. However, the global number puts the productivity in a global perspective, which is important when discussing the global potential of food production from the studied farm system. Our farm with 11.5 ha of farmland should, according to the global measure, be able to support approximately 58 capita. Our calculations show that it is possible to support more than that, even if horses are used and the system is organic and small scale.

If we were to be nine billion people on earth and must supply 6.4 persons/ha, this farm need to be able to support at least 74 persons. This was possible to achieve if using the larger cow breed, both in the pure draught horse power scenario and when having one horse and tractor that operates on rapeseed oil. However, when we simulated a more realistic case with a mixture of large and smaller cows and milk yields accordingly, it was only possible to support 69 persons. Hence having cow breeds that manage to give high yields on forage and a limited amount of rapeseed expelles is important for the future if integrated organic farms are to become important in the food system.

Crop yields also turned out to be of major importance. If the yields could increase to conventional level, the farm could supply almost 15% more people. However, that productivity was comparable with the case when the farm operated with conventional diesel. As the conventional yields are dependent on fertilizer, diesel, and pesticides, we may conclude that the farm requires fossil fuel to provide above 80 persons.

Swedes eat on average 86 kg meat per person and year at present (Naturskyddsföreningen, 2011). Our scenario with the horse- and rapeseed oil- driven system produces 15.5 kg, and this figure includes meat, edible intestines and egg. Hence this type of system requires a significant decrease in meat consumption. The meat production can be risen up to 25 kg/person and year (500 g/week instead of 300 g/week) if the calves are kept until two years age, but it lowers the amount of people the farm can supply, however, only by two persons.

To be self-sufficient in energy on farm scale must be seen as an important parameter for securing food production. There is also a point in having a range of products, since if one crop fails there would at least be other products that success. Maintaining biodiversity has also been acknowledged as an important factor for environmental resilience (Rockström et al., 2009). Natural ecosystems tend to be quite resilient, and having a range of animals and crops interacting with each other is an attempt to mimic these. If the farm system is resilient chances are that crop failure would be less frequent, and therefore, it is affordable to have lower yields. Although, it is evident that the search for better adjusted crop sequences, higher yielding crops and efficient forage-converting livestock are important factors for developing integrated farming.

Conclusion

The most reasonable scenario for self-sufficiency for this farm is when draught horse power is combined with tractor (and combine harvester) driven on locally produced rapeseed oil. Then the farm will have access to all advantages with the tractor and harvester, e.g., timeliness in harvest and lifting heavy loads, and the renewability and efficiency of draught horse power on smaller fields and lighter operations. This system was able to support between 66 and 82 persons depending on crop yields, milk yields, meat production, fuel demand for the tractor, and availability of forest grazing. Most likely the production capacity lands on ability to support approximately 68–70 persons, and the farm may require fossil fuels to support more than 80 persons.

The milk production was of major importance in terms of farm productivity. Having a smaller number of large cows gave higher productivity than having a larger amount of small cows. If there were no cows at all, and only sheep were held on the forage available, the farm could supply almost 50% less people than when there were cows in the animal composition. The diet from this kind of system consist of a large part of dairy products and vegetables, but significantly less meat than is consumed on average at present.

If all farmland globally was to be operated with similar productivity as was achieved in this study, this would be enough for supplying the global population with food at present.

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