Food or Fuel?

Trade-offs between food and biofuels globally and in small-scale organic agriculture

Sheshti Johansson
Faculty of Natural Resources and Agricultural Sciences
Department of Energy and Technology
Uppsala

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Abstract

There are great expectations on agriculture to provide both food and fuels in the future. Previous attempts to estimate the global bioenergy potential have produced varying results, indicating major uncertainty. This thesis investigated the global theoretical 'potential', or limit, for biofuels based on current agricultural systems. The results showed that use of edible crops for biofuels in the current global food system would lead to a global deficit of food. Producing biofuels from residues also proved to have uncertain 'potential' and could not exceed 8×10^3 TWh.

Despite the global limitations of biofuel production in the current food system, agriculture is essentially the only truly indispensable sector and may need to be independent of fossil fuels in the future due to depletion of these resources. Therefore a small-scale, low-input food system was studied to examine the effects of fuel self-sufficiency in farm work on food production and nutrient fluxes. It was found that using wheat or potatoes for ethanol production lowered food production by 23% and 18%, respectively, compared with the reference scenario of conventional diesel. The least impact on food production (94% of the reference scenario) was obtained by combining a draught horse and cold-pressed rapeseed oil produced on-farm. By producing the fuel on-farm, a larger degree of nutrient recycling could be obtained. The draught horse-rapeseed oil scenario had only a small phosphorus (P) deficit, but the potassium (K) deficit was significant in all scenarios except when potatoes were used for ethanol production. Potassium deficiency is not a problem on soils formed on sedimentary clay in Sweden, but for such alternative fuel system to be viable in other regions, some solution for recycling K will be increasingly required. Nitrogen (N) level was maintained in all scenarios due to the inclusion of N-fixing leys. The P level can be maintained in arable fields if bones are recycled. However, nutrients, especially K, are also moved from meadow to cropland.

Keywords: Biofuels, food production, food and biofuel production, global biofuel potential, small-scale agriculture, draught horse power, self-sufficiency, small-scale biofuel production

Author's address: Sheshti Johansson, SLU, Department of Energy and Technology, Box 7032, 750 07 Uppsala, Sweden
E-mail: Sheshti.Johansson@slu.se

Specialization may be a great temptation for the scientist. For the philosopher it is the mortal sin.

Sir Karl Popper

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Johansson, K., Liljequist, K., Ohlander, L. & Aleklett, K. (2010). Agriculture as provider of both food and fuel. *Ambio* 39 (2), 91-99.

II Johansson, S., Belfrage, K. & Olsson M. (2013). Impact on food productivity by fossil fuel independence – A case study of a Swedish small-scale integrated organic farm, *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science*, DOI:10.1080/09064710.2012.733020

III Johansson, S., Ohlander, L., Belfrage, K., Sundberg, C. & Hansson P-A. How the choice of biofuel system in a small-scale Swedish organic farm affects food production and NPK balance (manuscript).

Papers I-II are reproduced with the permission of the publishers.

Note: In Paper I the first author's name is cited as 'Johansson, K.', as in Kersti, while in Papers II and III it is cited as 'Johansson, S.', as in Sheshti. These two ways of spelling the name may unfortunately lead to misunderstanding, but refer to the same person.

The contribution of the authors to the papers included in this thesis was as follows:

I Sheshti (Kersti) Johansson and Karin Liljequist gathered the data and carried out the calculations together. Sheshti did the main part of the writing and layout of the paper, with supervision from Lars Ohlander and Kjell Aleklett.

II Sheshti Johansson carried out all calculations and the writing and layout of the paper. Data and background facts were provided by Kristina Belfrage. Initiative and supervision by Mats Olsson.

III Sheshti Johansson carried out all calculations. The text was written mainly by Sheshti Johansson, with contributions by Lars Ohlander. Data and background facts were provided by Kristina Belfrage, as were structural suggestions on the paper. Cecilia Sundberg and Per-Anders Hansson contributed to the structure and layout of the paper.

1 Introduction

1.1 Background

Growing awareness about how the climate is affected by increased greenhouse gas emissions and about depletion of natural resources, mainly fossil oil, are the main drivers behind the search for alternative fuels. From a technological point of view, biofuels are excellent for replacing fossil fuels, especially in the transport sector. Most of the biofuel types that exist today can be produced in liquid form and have an energy density close to that of their fossil fuel equivalents. Thus biofuels can be used in existing infrastructure, making them especially attractive for policy makers.

However, by widening the view from technology to system, the picture becomes more complex. Biofuels may perhaps replace fossil fuels locally, but fossil fuel dependence, environmental degradation and changes in the greenhouse gas balance of the atmosphere are global problems. Therefore the global context must also be studied. According to BP statistical review (2012), the global consumption of biofuels in the transport sector increased from 83 TWh to 685 TWh 1990-2011. This corresponds to averagely 2.3 TWh per year in 1990-2000 and 56.8 TWh per year in 2001-2011, or an exponential increase of approximately 20% per year over 20 years. Despite this very rapid expansion, no decrease in fossil oil consumption in the transport sector has been observed. On the contrary, oil consumption in the form of light and middle distillates (fuels mainly consumed in the transport sector) has increased by approximately 11.2 x 10^3 TWh over the past 20 years, while the corresponding increase in biofuels was 0.6 x 10^3 TWh. On an annual basis, oil consumption in the transport sector increased on average by 530 TWh per year in 1990-2000 and 550 TWh per year in 2001-2011. Thus the massive biofuel expansion did not even noticeably alter the rate of increase in fossil oil consumption in the transport sector during the past two decades. In 2010-2011 the increase in biofuels suddenly levelled out, to a mere approximately 5 TWh per year, from an increase of nearly 80 TWh in 2009-2010. Oil consumption continued increasing, however, by 410 TWh in 2010-2011. This is lower than the average rate during the decade, but still about 60 times more than the increase in biofuels in the same year. Thus, despite the large expansion in biofuels and several tough financial crises in the past decade, the consumption of fossil fuels in the transport sector has continued to increase. The data clearly show that even though local substitution may have occurred, biofuels did not replace any real quantities of fossil fuels in the global energy system (BP, 2012). Hence they only contributed to an overall increase in the amount of transport fuels available globally.

A feature in common for all renewable fuels is that technology cannot be decoupled from fossil fuels – the spinal cord of modern society (Höök, 2010). Most existing biofuels are of agricultural origin and modern agriculture is dependent on extensive fossil energy inputs (Giampietro *et al*., 1997). There is great controversy regarding the viability of biofuels. A wide range of studies have shown that biofuel production gives less energy than is needed for refinement of the biomass and that overall biofuel is far from being renewable (*e.g*. Ulgiati, 2001; Pimentel & Patzek, 2005; Felix & Tilley, 2009). On the other hand, a wide range of studies have reported results that indicate the opposite (*e.g*. Shapouri *et al*., 2004; Farrell *et al*., 2006; Ahlgren *et al*., 2010). An important reason for this discrepancy is differences in methodological approaches. Giampietro & Mayumi (2009) strongly denounce the idea of replacing fossil fuels with agro-biofuels as impractical and call for a better understanding:

> We do not need more sophisticated mathematical models, more data or additional fancy calculations, providing more accurate estimates. We believe that what is needed is a proper understanding of the issue, which allows us to see through the maze of numbers and make judgments using our common sense. (Giampietro & Mayumi, 2009, p. 12).

One way to create a better understanding of the issue is to turn back to basic terminology. Humans utilise energy carriers. There are two kinds of energy carriers, those which have been upgraded to a certain quality by human intervention and those which have not. The latter are usually referred to as ‘primary energy carriers’, *e.g*. oil, gas, coal, biomass, potential energy of water and wind blowing. Photons can be regarded as primary energy and the raw material used for producing nuclear power, usually uranium, also carries energy that humans did not intentionally put in the carrier. Those energy carriers which have been intentionally upgraded, *e.g.* electricity, diesel, ethanol, hydrogen gas *etc*., are usually simply called ‘energy carriers’. This is already confusing, and sometimes both primary energy and energy carriers are also called ‘energy sources’. In fact, the only sources of constant inflow of new energy to Earth are photons from the sun, radioactive decay and perhaps gravitational forces, primarily from the moon.

It is also important to remember the laws of thermodynamics. The first law states that energy cannot be created or destroyed, only converted, while the second law states that all real processes are irreversible, meaning that losses, an increase in entropy, are associated with them. We cannot create energy, but we can create energy carriers. When electricity is created, 70% of the energy content in the primary energy used is lost as heat (increased entropy) – a typical example of the second law of thermodynamics.

The question is thus how we can ever expect to achieve more energy in an energy carrier, *e.g.* a biofuel, than the primary energy (*e.g.* biomass) present in the raw material. As energy carriers cannot be produced without losses, this is of course impossible. Nevertheless, it is easy to interpret a calculation of positive ‘net energy’ return as though energy had actually been produced. It is important to bear in mind that such results (*e.g.* Shapouri *et al*., 2004; Hill *et al*., 2006; Farrell *et al*., 2006; Börjesson, 2006; Ahlgren *et al*., 2010) thermodynamically must refer to the conversion of energy carriers into other energy carriers (Giampietro *et al*., 2013). The input of the primary energy content of biomass is often neglected, while other primary energy sources are accounted for (*e.g.* Fredriksson *et al*., 2006; Hansson *et al*., 2007; Ahlgren *et al*., 2010; Zhu & Zhuang, 2012), with the underlying assumption that biomass carries solar energy that is free to use.

Different methodological approaches involve different aspects being disregarded, as the definition of the energy ratio can be defined in many different ways (Johansson, 2013). Furthermore, the choice of system boundary and the allocation method used have a very large impact on the results (Börjesson, 2008; Rehl *et al*., 2012). It is even the case sometimes that primary energy is aggregated with energy carriers (*e.g.* Paulsson, 2007; Zhu & Zhuang, 2012). It is actually a serious scientific problem that most studies on the viability of biofuels are not comparable with each other (Odum, 1996; Fraser & Kay, 2002), and one cannot help but wonder whether there is any value in continuing to produce more non-comparable data. It is easy to understand why Giampietro & Mayumi (2009) ask for common sense – common sense based on common scholarly knowledge.

Perhaps it can be argued that solar energy is free to us. On the other hand, solar energy received on Earth is a highly diluted energy source. The entire biosphere is adjusted to this energy inflow and it does a lot of work even ‘unharvested’ by humans, such as driving weather systems and ecosystems. In the case of harvesting solar energy for human benefit, it could work as a proxy for land requirement. The theoretical efficiency of conversion of the total incident sunlight radiation by photosynthesis to glucose energy is approximately 13%. In reality, for C4 plants the efficiency of photosynthesis is around 4.5% and for C3 plants around 3% due to a range of physiological losses (Gilland, 1985). This means that quite large land areas are needed to meet a small part of the fuel requirement in *e.g.* the transport sector.

Compared with fossil oil and even though both are primary energy, biomass is much more diluted with respect to its energy content. One kg of oil contains approximately 42 MJ chemical energy. Wood contains less than half that amount if entirely dried, about 19 MJ per kg dry matter. Straw and cereal grain are usually dried down to 14-15% water content, at which they contain around 14-15 MJ/kg (Jernkontoret, 2007). Oil is contained in geological formations, while biomass harvest requires large areas of land – land that is currently used for feeding the global population or for fulfilling other anthropogenic or ecological functions.

Food prices have a strong positive correlation with oil prices, as seen in Figure 1. One interpretation is that food production is energy-intensive and as prices increase for various inputs (most of them fossil fuel-based, *e.g.* fuel for machinery, fertilisers and pesticides), the price of food increases as well. Another interpretation has been made by FAO (2009) among others in relation to the ‘food crisis’ in 2008. They concluded that increased biofuel production is leading to competition between food and fuel, and hence the price of food rises. A combination of both these may the true explanation, since as fossil fuel prices rise there is also more incentive to expand biofuel production. Both price trends also correlate with the global economic cycle, which is not surprising as oil is one of the main players in the global economy (Fantazzini *et al.*, 2011; Archanskaïa *et al.*, 2011; Tverberg, 2011).

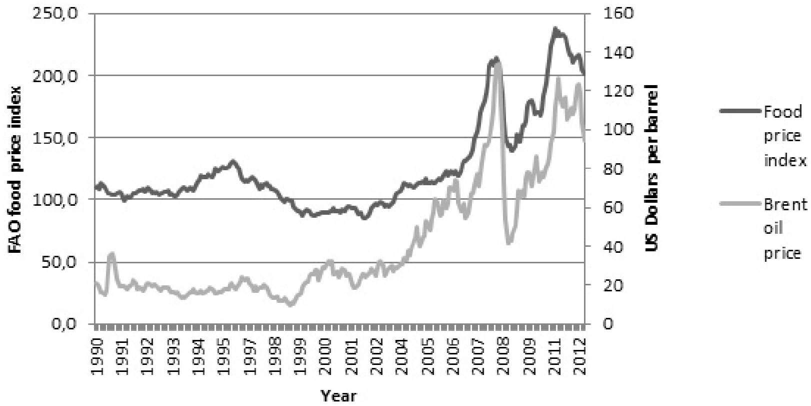

Figure 1. Fluctuations in the FAO Food Price Index (FAO, 2012) and the Brent Crude Oil Spot Price (US Department of Energy, 2012) in the period 1990-2012.

Thus, a key question is: *Can agriculture provide the world with both food and fuels?*

Several attempts have been made to estimate the global bioenergy potential. The International Energy Agency (IEA, 2007) proposed the bioenergy share to be 200-400 EJ (56 x 10^3 - 110x10^3 TWh) by the end of this century. Either as 36 x 10^3 - 72 x 10^3 TWh of transport fuels or 28 x 10^3 - 56 x 10^3 TWh by what the IEA call ‘average expected conversion factors’.

These projections are quite optimistic considering that the global primary energy supply was approximately 148 x 10^3 TWh in 2010 (IEA, 2012). This is double the amount of primary energy used in the early 1970s. Hence, it took almost 40 years to double the energy consumption to present levels (IEA, 2012). As can be seen in Figure 2, fossil fuels constitute in total 81% of global primary energy supply, biomass and waste constitute 10% and solar power and wind power constitute less than 1%.

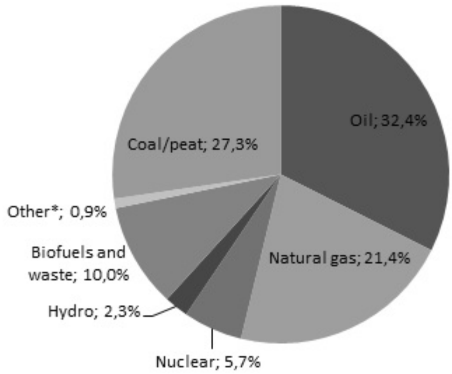

Figure 2. Global primary energy supply in 2010 (IEA, 2012).

Another study by Ladani & Vinterbäck (2009) concluded that 5% of the global primary production of biomass, or 225 EJ (62.5 x 10^3 TWh), is undoubtedly sustainable and that the entire energy requirement in 2050, an estimated 1000 EJ (278 x 10^3 TWh) "*…should be possible with sufficient political support*".

Beringer *et al*. (2011) suggest 36 x 10^3 - 75 x 10^3 TWh primary production of biomass by the year 2050, Hoogwijk *et al*. (2003) 9 x 10^3 - 315 x 10^3 TWh, Fischer & Schrattenholzer (2001) approximately 42 x 10^3 TWh (15% of global primary energy in 2050) and European Biomass Industry Association (2012) 69 x 10^3 - 125 x 10^3 TWh by 2050 (based on estimates from WEC, WEA and IPCC). Smeets *et al*. (2004) suggests 60 x 10^3 - 353 x 10^3 TWh in 2050 by converting pastures to energy crops, with residues contributing 16 x 10^3 - 20 x 10^3 TWh in 2050 depending on crop production and surplus forest growth contributing 0 - 10 x 10^3 TWh.

It is immediately apparent that the claims made in these studies of global bioenergy potential are most uncertain, with results ranging from 9 x 10^3 - 353 x 10^3 TWh. Considering system-related constraints on biofuel production, it is questionable whether it is justifiable at all to produce such large quantities of biofuels. Agricultural practices have already contributed to us approaching or exceeding "planetary boundaries" such as nitrogen usage and biodiversity loss (Rockström *et al*., 2009). Water scarcity due to overuse of rivers and depletion of groundwater aquifers can also be attributed to agriculture (Postel, 1998; Pfeiffer, 2003; Falkenmark & Rockström, 2008), as can problems with soil erosion, soil compaction and salinization (Young, 1998).

1.2 Aims

There are great expectations on agriculture to provide a growing population with both food and fuels. The aim of this thesis was to investigate food production related to biofuel production at global and local scale.

Aims in Paper I:
Previous estimates of global bioenergy potential range widely, indicating large uncertainty. The aim of Paper I was to answer following questions as accurately as possible: How much energy does the biomass in global agriculture contain at present? How large a proportion of that can be made available for biofuel given that food production is not jeopardised?

Aims in Paper II:
Paper II examined similar questions to those asked in Paper I, but at farm level. Paper II focused on biofuels in the context of being self-sufficient at farm level and how that affects food production. The overall aim was to investigate how the productivity of a small-scale farm using organic methods was affected by varying the animals kept and possible alternatives to tractive power.

Aims in Paper III:
Paper III was a continuation of Paper II and went deeper into the farmer's perspective by asking: How does the introduction of an energy crop affect the crop sequence? and How is that related to food production and what does it mean for the farm nutrient balance? The overall aim of the study was to develop scenarios for fuel self-sufficiency for farm work and assess and compare these regarding their impact on food production and nutrient fluxes on farm level.

1.3 Linking the papers

The main purpose of agriculture is to provide people with an adequate food supply. However, it is now being proposed that the agricultural sector should contribute to significant production of fuels in order to allow transition into a 'fossil fuel-free' society. Unfortunately, biofuels have so far not contributed to decreased quantities of fossil fuels being used in a global context. However, humanity is facing a range of global challenges, spanning from poverty, inequity, malnutrition, lifestyle diseases and an endocrine-disrupting environmental chemical cocktail effect to biodiversity loss, climate instability and resource shortages of primary energy sources such as fossil fuels, metals and other materials. Agriculture stands at the centre of global land use patterns affecting all these global challenges. People may manage without driving cars or flying regularly to other continents, but they cannot survive without food. Thus, if there is a global shortage of fossil fuels, it seems logical that agriculture itself, the only truly indispensable sector, needs to be independent of that source of energy.

How can a food system that aims at minimising its effects on humanity's global challenges be self-sufficient in terms of fuels? Can adequate amounts of food be produced even if biomass on the farm is used to provide energy for the farm work? Paper I shows that the possibilities to supply the transport sector with biofuels are strongly limited. However, that study was only a snapshot of the current, highly fossil fuel-dependent farming system managing to produce these high yields. What if that system is not possible in the future? Will most of the population starve, or can a lower level of food production be acceptable?

In 1824, the famous physician Nicolas Léonard Sadi Carnot wrote about not maximising the power outtake from engines, but rather seeking optimisation:

> We should not expect ever to utilize in practice all the motive power of combustibles. The attempts made to attain this result would be far more harmful than useful if they caused other important considerations to be neglected. The economy of the combustible [efficiency] is only one of the conditions to be fulfilled in heat-engines. In many cases it is only secondary. It should often give precedence to safety, to strength, to the durability of the engine, to the small space, which it must occupy, to small cost of installation, etc. To know how to appreciate in each case, at their true value, the considerations of convenience and economy which may present themselves; to know how to discern the more important of those which are only secondary; to balance them properly against each other; in order to attain the best results by the simplest means; such should be the leading characteristics of the man called to direct, to co-ordinate the labours of his fellow men, to make them co-operate towards a useful end, whatsoever it may be. (Carnot, 1824, translation in Giampietro & Mayumi, 2009, p. 145).

Maximisation of a single parameter, *e.g.* yield, is perhaps just as harmful for agriculture. Looking for a system that yields less food may be beneficial in many ways instead of only having one purpose, a situation which may be just as harmful as maximising one parameter in an engine. As Carnot highlights; safety, strength and durability are more important. Papers II and III attempted to study trade-offs for a better balance and multi-functionality in the food system. Even though Paper I shows that there are severe limitations to producing biofuels globally using the present food system, Papers II and III act as hypothetical cases of change in the system – what does it take in order for food production to be less dependent on fossil fuels and less harmful to the environment? What would the farm look like and what are the limitations for its food production capacity?

However, the work in Papers II and III is not entirely hypothetical, as it was based on a real farm with a suggested food system addressing several environmental issues. Time and resources limited the investigations reported in Papers II and III to only one farm, but still permitted quite in-depth discussions on what affects food production when farm-produced biomass is used for tractive power and farm operations.

2 Theory and context

This chapter provides some technological and theoretical background in order to give a better understanding of the context of the work.

2.1 Biofuels

There are several ways of obtaining biofuel from biomass. Different technologies are commonly referred to as first, second or third generation. The first generation includes ethanol from sugar and starch, biodiesel and biogas, which are produced at commercial scale at present. Fuels derived from cellulosic material such as ethanol and derivatives from synthesis gas, or ‘syngas’, belong to the second generation and are not produced commercially but at pilot scale. Even so, gasification of biomass is well-known and *e.g.* the Fischer-Tropsch process was used in Germany during the two world wars for converting coal into liquid fuel (Höök & Aleklett, 2010). Hydrogen gas, fuel cells or other energy carriers that are predicted to still be quite far from large-scale implementation can be counted as third generation. Below is a very brief guide to the different first and second generation technologies.

2.1.1 First generation biofuels

Ethanol

The simplest way of producing ethanol is by yeast fermentation of sucrose. Therefore crops with high sugar content are suitable, with sugarcane in particular contributing a substantial part of global ethanol production. Starch is a polymer of glucose that, with aid of enzymes in a hydrolysis process, is relatively easy to split into simple sugars. Hence starch-rich crops such as maize and wheat are also commonly used as raw materials for ethanol production. The main production steps using starch-rich grain include grinding, cooking, liquefaction, saccharification, fermentation and distillation. The main product is ethanol, and the co-product, dried distillers grains solubles (DDGS), can be used as animal feed (Butzen & Haefele, 2012). In the sugarcane process, a fibrous material called bagasse is a co-product.

The ethanol yield varies among different crops. On a fresh weight basis, sugarcane yields approximately 75-85 l/tonne, sugar beet 100-110 l/tonne and maize 370-420 l/tonne, while other grains (wheat, rye, barley *etc*.) dried to 14% moisture content yield 340-385 l/tonne (Johansson & Liljequist, 2009). Since crops rich in starch and sugar comprise a large part of the human diet worldwide, the production of first generation ethanol contributes to competition between food and fuel.

Biodiesel

Transesterification is a process whereby an alcohol, typically methanol, replaces glycerine in vegetable oil, in the presence of a catalyst (Bernesson *et al*., 2004). The result of the chemical reaction is a fatty acid methyl ester (FAME), namely biodiesel, plus glycerol.

Any oil crop can be used for oil extraction, giving pure plant oil and oil seed meal. The meal can be used as animal feed and the vegetable oil is important in the human diet. Hence there is also explicit competition between food and fuel when it comes to biodiesel. The most important crops for biodiesel production are oil palm, which has a biodiesel yield of approximately 160 l/tonne, soybean with 210 l/tonne and rapeseed with 460 l/tonne (Johansson & Liljequist, 2009).

Biogas

Biogas is produced when organic material is digested by anaerobic bacteria in an environment deficient in oxygen. The digestion can be divided into four steps: *Hydrolysis* (where complex molecules are broken down into water-soluble compounds), *acid formation* (CO_2 and H_2-formation, further degradation of larger molecules into intermediate shorter chains), *acetate formation* (intermediate products degraded into acetate) and *methane formation* (acetic acid is digested by methanogenic bacteria and methane is formed) (Anker ThyØ & Wenzel, 2007).

Biogas typically consists of 65% methane (CH_4) and 30% carbon dioxide (CO_2), and the rest is approximately 3% ammonia (NH_3) and hydrogen sulphides (H_2S) (Alvarez, 2006), although this varies depending on the substrate. The sulphides are corrosive and must be eliminated if the gas is to be used in an engine. In addition, water must be removed from the gas. In order to raise the methane content in the fuel, carbon dioxide should also be separated from the gas. It may be possible to use non-upgraded biogas as fuel, but that would result in a very large gas container and short operating distance. However, upgrading can be expensive and requires large facilities in order to be efficient and biogas may be more effectively used for heating, electricity production or as fuel for cooking.

2.1.2 Second generation biofuels

Ethanol

Ethanol from lignocellulosic biomass, such as wood, grass, straw, corn stover *etc*., requires some additional pretreatment of the biomass before the ordinary fermentation process is possible (Abbasi & Abbasi, 2010). Currently several technologies for pretreatment are being tested. Pretreatment includes both physical size reduction and thermochemical processes to break down lignocellulose and transform it into sugars with good enzymatic digestibility (Zhu & Zhuang, 2012). Zhu & Zhuang (2012) describe and compare several technologies for pretreatment. The performance of the methods depends largely on type of substrate (soft or hard wood) and most methods are still on laboratory scale.

Lignocellulosic feedstock can yield up to 400 litres of ethanol per tonne of dry matter (Johansson & Liljequist, 2009). A by-product from the lignocellulosic ethanol process is lignin, which for example can be used directly for heat generation through combustion, or for phenol production by flash pyrolysis (Cherubini & Ulgiati, 2010).

Syngas derivatives

Gasification is a process whereby material is oxidised in the presence of oxygen at a regulated level (stoichiometric). Before gasification, the material must be dried. The resulting syngas is a mixture of mainly CO and H_2, but CO_2, CH_4, C_2H_6 and C_2H_4 are also present. A few corrosive by-products, namely H_2S, NH_3 and HCl, are also produced and need removal before further processing of the gas (Sues *et al*., 2010).

A simple reaction with the synthesis gas involving CO and H_2 over a catalyst gives methanol (CH_3OH). The reaction is carried out at temperatures of around 200 ˚C and pressures of 77 bar. After a few circulations of steam to increase the efficiency of the conversion, the steam is sent into a distillation column. The unconverted gas is normally used for combustion and to generate electricity (Sues *et al*., 2010). Di-methyl ether (DME, CH_3OCH_3) is synthesised by the same process as methanol, but taken one step further over an acid catalyst:

$2CH_3OH => CH_3OCH_3 + H_2O$

The Fischer-Tropsch diesel process converts syngas into a range of hydrocarbons and waxes, and the products can be steered by temperature (Rahimpour *et al.*, 2012) and choice of catalyst, usually based on iron, cobalt and ruthenium (Ghasemi *et al.*, 2009). The diesel fuel produced is of high quality and free of sulphur. The by-products (*e.g.* naphtha, kerosene and waxes) are useful for other applications as well, but the fuel fraction is smaller in Fischer-Tropsch diesel than *e.g.* in methanol synthesis because of the range of products. Methane is also a possible syngas derivative.

2.2 Integrated farming systems

The UN Food and Agriculture Organization (FAO) stated that agricultural production must be doubled in order to provide the food required by 2050 (FAO, 2012). However, Paper I show that global vegetal production amounts to almost double the global requirement of food. Nevertheless, as the largest postharvest losses in global food production arise due to converting cereals into meat (see Paper I), the FAO may be correct in its statement if meat consumption from industrially bred cattle, as well as biofuel production from edible products, continue increasing at the same rate as today. But what if that is not possible? Can a decrease in crop yields be acceptable if animals do not eat what humans can eat, and the system is dependent on renewable resources?

The most important consideration must be that agriculture produces enough food to prevent famine, and this food should also be of adequate quality to ensure health. However, despite the fact that sufficient food is being produced at present, even after post-harvest losses and meat production, nearly one billion people world-wide are suffering from famine and an equally large number lack adequate nutrition (Misselhorn *et al.*, 2012). In addition, obesity is an increasing problem in the Western world. Thus as the food system is failing so many people, it is surprising that it is still argued that it must continue producing the same products at an unchanged or increased rate.

If feeding animals is such a large loss, why keep animals at all? Ley is an important feature of the crop sequence, and it is a waste not to feed it to animals, since animals upgrade this product, which humans cannot eat, into very valuable products to humans such as milk, meat, fur and leather. Another advantage of keeping cattle is that they can graze for a large part of the year, hence making use of meadow and forest land that is otherwise difficult to use for crop production.

In any agricultural system there are many sources of losses in the production. Cereals destined to be milled for bread flour must be of high quality and often a large proportion is rejected. Poultry are good waste-eaters as they feed on this agricultural produce that is not of adequate quality for further processing. They can also eat slaughter waste, can be let out on the fields after harvest to eat the spill seed, spread cattle manure as they eat non-metabolised seed, eat household waste and clear gardens of snails. Hence poultry can also feed on products that humans cannot eat or encounter for various reasons. Keeping several species on the same farm makes more use of farmland and helps control parasites. Different species, *e.g.* cows, horses and sheep, graze different parts of the pasture and the productivity of the pasture is higher as different animals succeed each other. Carbon recycling through manure is also facilitated by keeping cattle.

By integrating animal and crop production, the land is multifunctional and what is a waste from one process can be used in another. It opens up the possibility of keeping cattle for their original purpose – to upgrade indigestible biomass into food. However, this also places limits on the amount of meat that can be produced.

2.3 Crop sequence

The crop sequence is a basic component in the cropping system. A well composed sequence helps in maintaining good soil structure, which in turn is important for water permeability, root penetration and thereby availability of both water and nutrients, and for limiting erosion. A good soil structure supports the plant roots and enables them to reach micronutrients and it can store water in its aggregates. It is also favourable for soil organisms, *e.g.* earthworms and mycorrhiza. Deep rooted or leafy crops are often not only weed-tolerant, but can also outcompete weeds. Hence, it is beneficial to rotate such plants with more weed-susceptible plants. Control of pests and diseases is helped by alternating between crops with different characteristics. It may also be helped by taking advantage of allelopathy and pest-repellent crops (Rydberg & Milberg, 2000; Zeng *et al*., 2008; Bertholdsson, 2012). If certain crops are cultivated too often, for example to meet the energy demands, *e.g.* rape seed, this may accumulate soil-borne diseases which can compromise all cultivation of rape or its crop relatives (Lampkin, 1990). Certain crop sequence effects, such as those of growing wheat after *Brassica* crops, have been shown to be generally significant, irrespective of country (Angus *et al*., 2011).

A sustainable crop sequence includes dinitrogen (N_2) fixing ley crops, particularly in organic farming (Ohlander, 1990). Ley crops contribute significantly to maintaining and improving soil structure, which is one of the most important parameters for plant growth and preventing nutrient leakage (Ohlander, 2001). Leys can also keep weeds and parasites away, or at least reduce their effect.

2.4 Small-scale agriculture

An important reason for studying small-scale agriculture is that it is easier to maintain high biodiversity on a small farm (Belfrage *et al*., 2005). The concept of small-scale refers to a farming system that is locally adapted and utilises local resources and local ecosystem services (Björklund & Helmfrid, 2010). This means that the actual farm size of 'small-scale' farms varies widely depending on the local context. For example, in the study on biodiversity on small farms vs. large farms by Belfrage *et al*. (2005), the small-scale farms included had field sizes below 5 ha and more than two crops per ha. These farms were in the same region of Sweden as the farm studied in Papers II and III.

The trend in farm size at present is towards larger farms (Swedish Board of Agriculture, 2013), and there is some controversy regarding the productivity of smaller farms. However, studies of smaller farms with multi-functional land use, much like a larger scale of gardening, have in several cases shown larger total productivity than on larger, less diversified farms (Cornia, 1985; Rosset, 2000; Halweil 2006; Barett *et al*., 2009; Horlings & Marsden, 2011; de Schutter, 2011). This is known as the 'paradox of scale' or 'inverse farm size-productivity relationship'.

Regarding the 'efficiency' of different farm systems, the first step is to define what to measure. Large-scale farms tend to have higher labour productivity, while smaller farms may have more efficient use of land (Rosset, 1999). The Green Revolution may have contributed to increased yields, but at the cost of dramatically reduced resource use efficiency in agricultural production (Giampietro *et al*., 1997).

2.5 Bioenergy in small-scale – solutions in practice

A tractor can exert a considerable amount of power, just at the right time. By using a fuel that is not included in the present photosynthetic cycle, an illusion of efficient work is achieved. This makes the comparison of fossil fuels with biofuels rather inadequate. If the energy and power used in the conversion process of fossil biomass into liquid fuels for modern engines were to be taken into account, *i.e*. the amount of pressure exerted by the geological formations and other forces through time that formed the oil and later the energy and materials required to pump it up and refine it into fuels, the process would be rightly judged as highly inefficient. As the geological time perspective is not comparable with the time perspective of the human economy, we are accustomed to not considering all the work put into the formation of oil. This work is considered 'free' to humans, or to living species and operating machines.

Thus, when investigating the efficiency of a tractor engine, we can almost rightly propose that it is approximately 35% if the engine is operating on diesel. As the fossil fuel is freed from present photosynthesis by the work of geological time, we only have to consider the losses in the thermodynamic conversion of chemical energy content into work. However, when studying biomass from the present photosynthetic cycle, the losses in the conversion of biomass into liquid fuel properties cannot be disregarded. Take rapeseed for example. It consists to almost 50% of oil. If all that oil is extracted for fuel use, 50% of the mass would be lost. Oil contains more energy than carbohydrates and proteins, almost twice as much in fact. Hence approximately one-third of the energy content is 'lost', or at least not available for combustion in an engine. It certainly has a value as feed, but that value is of a different quality and not comparable with the value of a fuel (Giampietro & Mayumi, 2009). Assuming that the engine operates on rapeseed oil with the same efficiency as on conventional diesel and that differences in energy content are not taken into account, the efficiency of conversion of the chemical energy of the biomass into work is reduced to 0.66 x 0.35, which equals 23%.

Experience at Risø DTU National Laboratory for Sustainable Energy has shown that the methane content in biogas production can vary between 25-60% depending on the substrate used[1]. Assuming that there is an engine that can convert the methane into work at the same efficiency as the conventional diesel engine, the biomass efficiency will be 8-21%. Even considering second generation fuels, such as Fischer-Tropsch diesel, the efficiency of biomass into work will be as low as 17%, as the conversion efficiency of wood into diesel is 48% according to Lowisin (2007). When instead considering a living metabolic process, *e.g.* a horse exerting power, the efficiency of biomass into work is also approximately 17% (calculation described in detail in Paper II). Hence, biofuel in a tractor is comparable with draught horse power, but fossil oil in a tractor is not. This is perhaps an even more appropriate comparison than biofuels and fossil fuels, since the horse and biofuels operate in the same space of time, or photosynthetic cycle. The fact that most biofuels also give biologically useful

[1] Personal communication, lab assistant Stefan Heiske, 2010

by-products is further evidence of the validity of the comparison with draught horse power.

This may give another perspective on biofuels – is it simply a long detour to achieve something that is already achieved by nature? There are of course a range of parameters that distinguish the living system from the technological system. One of these is that the biofuel is storable, which makes it possible to gather a large amount of energy for power outtake when wanted. The horse must operate slowly and regularly. However, this reasoning shows the position of draught horse power in the discussion of biofuel as an important alternative, which is why it was included in our studies.

Draught horse power also has the advantage that the horses do not need to eat what humans can eat, *i.e*. they make use of the indispensable leguminous leys, their ‘waste’ is recyclable and useful on the farm, they can reproduce by themselves and they can gather their fuel by themselves a large part of the year. Furthermore, draught horse power gives less soil compaction, and their size and power potential may be quite well suited for small-scale agriculture, to once again speak of ‘optimisation’. What they cannot do is exert a large amount of power in a very short time or lift heavy loads, which are the greatest benefits of the tractor and combine harvester. Therefore Papers II-III also included the possibility of combining draught horse power with these technological inventions.

One advantage of working closely with the farm and the farmer’s points of view in Papers II and III was that impractical solutions could be ruled out. Biogas from ‘waste’, for example, is a widely promoted fuel nowadays. We found that firstly, the study farm does not produce any waste products. The manure is collected together with straw in deep litter beds, which enable the cattle to be outdoors all year since the bed keeps the heat. This, as well as having a rather small herd, keeps the cattle healthy and the farm has never had any problems with diseases. The water content of manure must be rather high to enable biogas production, and the liquid manure method is therefore most beneficial. For the reasons mentioned, this manure handling method is unsuitable for a farm with the properties described. In rural areas in developing countries, *e.g*. in China, biogas digesters are installed with very simple means in order to produce fuel for gas stoves (Johansson, 2007). The farm studied in Papers II and III may be able to produce biogas for that purpose, but upgrading and storage for use as tractor fuel on the farm was judged to be highly impractical.

As mentioned in section 2.1, second generation biofuels are out of the question for some time to come, since they are only produced at pilot scale. There are older methods including fuel from wood, *e.g*. generator gas, but from the reasoning above it can be quickly recognised that a draught horse is probably a simpler and safer alternative. Arguments are emerging for the use of straw as raw material for biofuel (*e.g*. Ahlgren *et al*., 2010; Cherubini & Ulgiati, 2010; Kimming *et al*., 2011); the main reason being that it should not compete with food production. Yet in the system studied in Papers II and III, all products are used at the farm in different processes. Straw is important for the litter beds and as forage. It is also important to recycle the straw to the fields in order to maintain the soil organic carbon stocks. Therefore in such an integrated farming system, the use of residues for biofuel production would actually negatively affect food production and the whole farming system.

This practical-theoretical reasoning led to the conclusion that the biofuels possible in the studied context were restricted to pure rapeseed oil cold-pressed on the farm or converted to RME in a commercial plant, ethanol from wheat processed in a commercial plant or potatoes processed on the farm, or draught horse power. Using rapeseed oil required combination with draught horse power to reduce the tractor requirement, since the amount of rape which can be grown in the crop sequence is limited due to the risk of soil-borne diseases.

3 Methodology

3.1 Global survey – Paper I

Paper I calculated the energy content of global agricultural production in order to compare it with food and fuel demand. Data on primary production, *i.e.* the primary intent of crops, such as wheat grain and not the straw, were taken from the UN Food and Agricultural Organization database 'FAOSTAT'. Data from 2006 were used in Paper I, as this was the latest available set of data at that time. In this thesis, the results are recalculated using more recent data from 2010. The energy content per unit weight of crop was calculated from the chemical composition of each crop. Agricultural residues are also interesting for biofuel production. The amount of residues was derived from the data on primary production through the harvest index, HI, which is equal to the ratio of the yield of the primary product in tonnes of dry matter to the total above ground biomass in tonnes of dry matter.

In order to evaluate the amount of food produced and compare it with food demand, deductions from the total primary production were made for requirements of seed for reproduction, postharvest losses in storage and losses in upgrading, such as conversion of cereals into meat and oil crops into oil. Furthermore, inedible crops and parts of crops were withdrawn. All quantities were expressed in terms of calorimetric energy values to facilitate comparison of agricultural production in relation to demands for food and fuel.

Conversion factors for biomass into ethanol, biodiesel and biogas were calculated and used to create different scenarios of possible biofuel production from agriculture. For details of the data and calculations, see Paper I and Johansson & Liljequist (2009).

3.2 Small-scale case studies – Papers II and III

3.2.1 Site-description

The selected research object was a small farm already hosting several research projects in which there has been careful quantification of the resource usage, local and auxiliary, as well of *e.g.* harvest levels. The farm is located in Roslagen, south-eastern Sweden (approx. 59°52´N, 17°40´E). The area is characterised by rather flat landscape, with altitude ranging from 0 to 100 m above sea level. The landscape is patchy, with small fields with fluvial sediments and decomposing peat, intersected by hills of bedrock and glacial till. The glacial till contains calcium carbonate. The climate is characterised by mean annual precipitation of 637 mm and mean annual temperature of 5.7°C (SMHI, 2010). The region is prone to drought in the early growing season.

A reference group of eight farmers is associated with the study farm, in order to contribute their expertise as they have long-term experience as organic farmers. The reference group has been involved especially in trials concerning the crop sequence. The farm consists of 8 ha arable land, 5.5 ha meadow land, 3.5 ha pasture and 18 ha forest land, of which 10.5 ha are grazed. In Paper III, the forest grazing was neglected to facilitate the calculations.

The crop sequence tested has been developed to give a range of different food products. 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): oats with undersown lucerne, lucerne leys I, II, III, winter rapeseed, winter wheat, potatoes and vegetables and finally buckwheat. The vegetables grown are different kinds of tubers, lettuce, cabbages, leeks, onions and string beans. Cows and sheep feed on forage and poultry on slaughter waste and cereals of inferior quality.

The scenarios were decided on the basis of the demand for tractive power, together with the specific crop yields on the farm. The farm at present runs a 47 hp diesel tractor. Threshing is done by a locally owned combine harvester. The diesel requirement for all tractor operations and threshing was measured at 809 litres in 2010. If the tractor and combine harvester are used for the heavy work (ploughing, threshing, manure spreading and bailing), one North Swedish breed 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 litres.

3.2.2 Number of people the farm can supply (Np)

A model that calculates the amount of food available on a farm in terms of meat, milk, egg and crops, converts it into energy units and calculates how many people can be supplied (Np) by the farm was developed in MS Excel.

The energy requirement for a human being ranges between 760 kcal/day for a new-born baby to 3300 kcal/day for a regularly exercising 18- to 30-year-old male (Swedish Food Administration, 2007). Here we assumed an average energy requirement of 2500 kcal/capita and day.

A basic idea was that animals should not eat what is edible for humans. Hence the number of ruminants was decided by the amount of forage available. Regarding poultry, the number was decided by the availability of reject cereals and inedible intestines after slaughter. The model can elaborate with different animal species combinations, harvest levels and forage availability to determine the number of humans that can be supplied on a given area and also to produce 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 include the amount of forage available on the farm from harvest and grazing, as well as harvest from all crops on the farm. The calculations in the model include feed plans for cattle, horses, sheep and poultry, as well as food requirements for humans. We used energy units (MJ) to measure the amount of forage, crops, food and feed requirements. For the feed plans, we considered the protein requirements, but since the protein demand turned out to be fulfilled when the energy requirement was fulfilled (lucerne is rich in protein), we decided to leave it out of the model for simplicity. Hence, we only used the energy requirement when evaluating the amount of animals the farm can support, as well as the amount of humans the farm can supply. For details on the input data and calculations, see Paper II.

3.2.3 NPK balance

In Paper III the crop sequence was altered when investigating different biofuel scenarios. As a measure of the differences between scenarios, a farm NPK balance was carried out. The Focus on Nutrients programme (*Greppa Näringen* in Swedish) has developed a calculation programme focusing on NPK that can be used for individual farmers to predict a change in nutrient balance from a change in production pattern (Focus on Nutrients, 2013). The calculator includes a database on the content of NPK for most crops, livestock products, feed and fertilisers available in Sweden. It also includes functions for nitrogen fixation from different types of ley and annual atmospheric deposition of 4 kg N/ha. The calculation only takes into account inputs and outputs to the farm or chosen area. Therefore *e.g.* nutrient recycling with animal manure is not considered in the calculations since it never leaves the farm, *i.e.* it is neither an input nor an output.

The Focus on Nutrients calculator does not include nutrient leakage. Calculations of N and P leakage from arable land have been carried out by Johnsson *et al*. (2008). We used their average values for 2005 for the crops included in our crop sequence. Since K has very little or no impact on eutrophication, there is little or no data available on leakage of K. Much of it is recycled through manure. On sedimentary clay soils, weathering usually matches leakage, since the bedrock that formed these soils is rich in K. Therefore the nutrient balances of this study did not include leakage of K. See Paper III for the data on leakage, as well as the input data for the nutrient balances.

3.2.4 Scenarios in Paper II

In Paper II, the model of Np (number of people the farm can supply) was used to explore the impact of draught horse power on food production. This was done without altering the crop sequence developed for the farm. The main impact of food production would be due to altering the cow herd in this case. Therefore the effects of cow size and milk yields were also studied. Two cow breeds were studied; small and large Swedish Mountain cows, approximately 250 kg and 400 kg body weight respectively. Arguments for the choice of cow breeds are given in Paper II.

Three different scenarios were examined:

- I. Conventional diesel for farm work (reference scenario)
- II. One draught horse combined with rapeseed oil for farm work
- III. Three draught horses for all farm work

For each scenario, five cases were investigated:

1. The largest possible amount of large cows
2. Same amount as in 1, but changed to small cows
3. No cows
4. The largest possible amount of small cows
5. Better balance between sheep and cows

3.2.5 Scenarios in Paper III

In Paper III, the crop sequence was altered within the possible limits in order to model the impacts of self-sufficiency in biofuels on Np and NPK balance. The model of Np was used to compute input data for the NPK balances.

Four scenarios of fuel for tractive power were studied:

I. Conventional diesel for tractor (reference scenario)
II. Rapeseed oil for tractor combined with one draught horse
III. Ethanol from wheat as tractor fuel. The ethanol produced off-farm in large scale facility
IV. Ethanol from potato in tractor, ethanol produced on farm

In each scenario, four cases were investigated:

1. Nutrient balance for only the arable land, 8 ha, where hay from meadow is considered an input, but pasture is neglected as nutrients are recycled when animals graze.
2. Nutrient balance for the whole farm, 17 ha, where arable land, pastures and meadows are included. This case gives a landscape perspective and we neglected the uneven distribution of nutrients at a local scale.
3. Nutrient balance for the whole farm (17 ha) adding an input of recycled bones after slaughter.
4. Same as case 3, but with added human urine and faeces from the population which the cropping system is able to supply with food.

4 Results

4.1 Global biofuel 'potential' vs. food production

The energy content of global agricultural primary production was calculated and compared with the global food requirement of on average 2500 kcal/capita (*i.e*. assuming that no-one is starving). The data on global agricultural production in Paper I are from 2006, but crop production has increased from 2006 until present. The latest data update from FAO is from 2010. Figure 3 shows the calculation for 2010, using exactly the same method as in Paper I. The gross energy is the energy content of the total primary production of agriculture, *i.e.* excluding the biomass of residues, and amounts to 21 x 10^3 TWh. Seed for reproduction, 0.7 x 10^3 TWh has been subtracted, and the 'losses' column includes the inedible products, such as nutshells, husks and forage, as well as postharvest losses in storage according to Paper I, amounting in total to 1.4 x 10^3 TWh. The meat and dairy products are added, 1.3 x 10^3 TWh. The small line on the top of that column represents fish, seafood and game meat. 'Feed' refers to feed concentrate of cereals for meat and dairy production, which is the single largest loss in the current global food system, 4.7 x 10^3 TWh. Feed concentrate from oilseed crop meals is divided into two scenarios, which is the basis of the 'high case' and 'low case' given in the next column. The 'net energy' refers to the energy content of the net production that is currently available as food. This 'net energy' does not include edible production already being used for purposes other than eating, *e.g.* as biofuels, cosmetics or in the chemicals industry. In the 'high' case, the net energy amounts to 10 x 10^3 TWh and in the 'low' case 7.2 x 10^3 TWh.

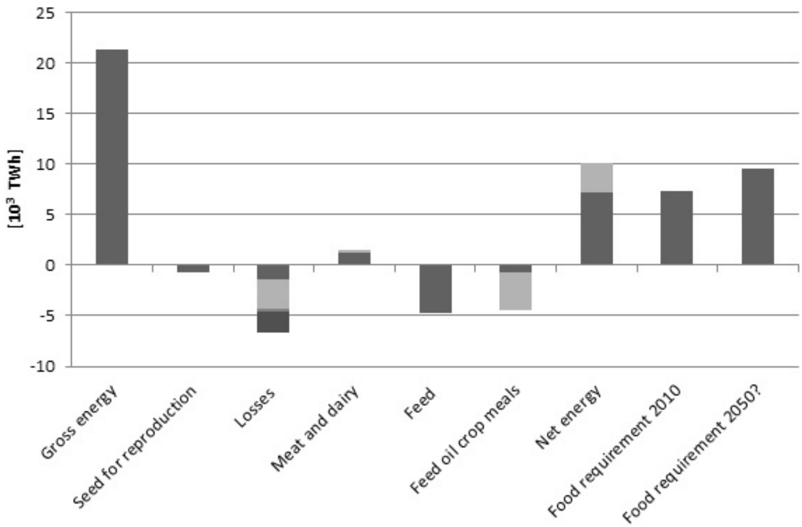

Figure 3. Gross energy content in crop production, losses and net energy content available as food. For calculations of losses and scenarios (high case and low case), 'losses' include inedible products such as nutshells, husks and forage, as well as postharvest losses in storage. The small line on the top of the 'Meat and dairy' column represents fish, seafood and game meat. 'Feed' refers to feed concentrate of cereals for meat and dairy production. The food requirement is calculated assuming that humans need 2500 kcal/day.

From 2006 to 2010, global gross food production increased from 19.9 x 10^3 TWh (see Paper I) to 21.4 x 10^3 TWh (Figure 3). The largest increase was in nut production, 25% in four years. Sugar crop production increased by 14%, oil crops and fruit by 12%, pulses by 11% and cereals by 9%. The largest decrease was in forage crops, which dropped by 22%. Fibre production also dropped, by 3%, and roots and tubers by 1%. This redistribution led to a significant change in the results relative to Paper I. In the 'low case' scenario, there was a deficit of approximately 120 TWh for 2010, provided that the global population of 6.89 billion needed 7.3 x 10^3 TWh for food in that year. In the 'high case' scenario, there was a surplus of around 2.8 x 10^3 TWh in 2010, whereas in 2006 even in the low case there was a small surplus (Paper I).

Although there may be a global deficit of food at present, the results indicate that if losses are reduced, the population in 2050 (assumed to be 9 billion) can be fed. There is thus no need to increase food production simply to cover the food demand, but rather to improve distribution and decrease waste, as can be seen in Figure 3. This is especially true in livestock production systems, where animals currently eat what humans can eat instead of only converting grasses to edible products. Agricultural production is also heavily dependent on auxiliary energy input, and it is questionable whether agriculture can produce the same yields in the future with declining availability of fossil fuels.

Figure 3 shows that the use of edible crops for biofuel production would lead to a global deficit of food. Besides, this use of edible products cannot contribute much to biofuels anyway. For example, Figure 4 shows how much ethanol could be produced if all maize or all sugarcane were to be used, or if all oil from soya beans or oil palm were to be used for biodiesel production. If all sugarcane grown in 2006 had been used for ethanol production, there would definitely have been a global deficit of food, and the contribution would have been less than 3% of the total demand in the transport sector. If all palm oil produced globally in 2006 had been used for biodiesel, it would have been able to contribute 1%, while also leading to a global deficit of food. Maize, the most widely grown crop globally, could have supplied approximately 6% of the global transport demand, while also leading to a severe deficit of food.

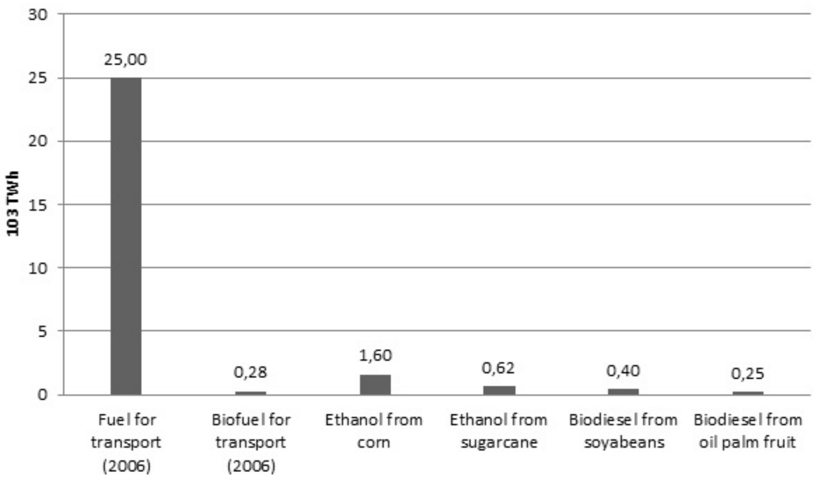

Figure 4. Biofuel production if all globally produced maize (corn), sugarcane, soybeans or oil palm fruit had been used for biofuel production, compared against biofuel consumption and overall fuel consumption in the transport sector in 2006. From Paper I.

Since it seems unwise to use edible crops for biofuel production, we turned to the residues. Using the methodology, assumptions and conversion factors from Paper I, the theoretical limit of residues for biofuel production for 2010 was calculated (Figure 5).

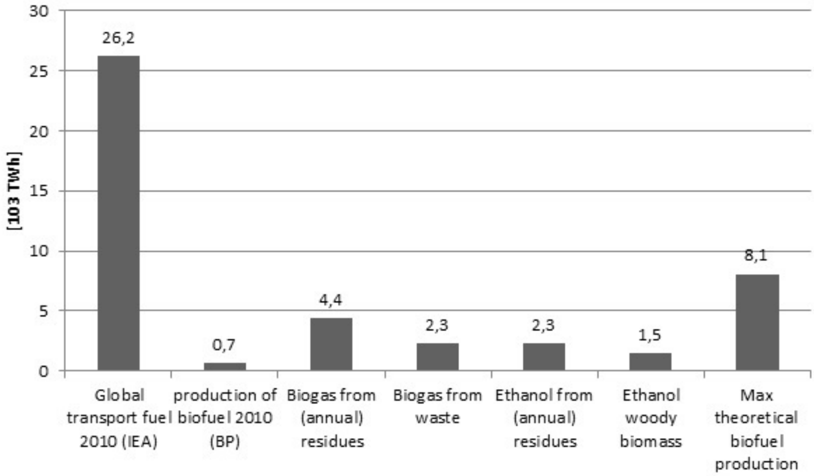

Figure 5. Theoretical limit of biofuel production from residues, based on the methodology in Paper I. For comparison of calculated results, data on global consumption in the transport sector (IEA, 2012a) and the global production of biofuels (BP, 2012) are given. There are two scenarios for annual residues: either a larger part is converted to biogas provided that the biogas residues are returned to the field (2/3 of total amount of residues), or a smaller part (1/3 of total amount of residues) is converted to ethanol. Woody biomass refers to perennial residues. The maximum potential (right) was obtained by adding biogas from annual residues and waste with ethanol from woody biomass.

There are two scenarios for annual residues: either a larger part is converted to biogas provided that the biogas residues are returned to the field, which is theoretically able to produce 4.4 x 10^3 TWh of biogas, or a smaller part is converted to ethanol, theoretically giving 2.3 x 10^3 TWh of ethanol. The maximum potential is obtained by adding biogas from annual residues and waste with ethanol from woody biomass, amounting to almost 8.1 x 10^3 TWh.

This calculation shows that the theoretical 'potential' of biofuels can replace approximately 30% of the transport fuel. However, statistics from various sources differ somewhat. For example, comparing the consumption of light and middle distillates of oil, this was 35.8 x 10^3 TWh in 2010 according to BP (2012). Thus if the calculated maximum 'potential' of biofuels is compared with this figure, it would only be able to replace about 20% of the global consumption of oil in the transport sector and that is still a quite optimistic result.

However, there are some other considerations involved. Biogas conversion just refers to theoretical conversion, not upgraded to fuel quality. Furthermore, all biofuel systems require energy for biomass conversion. The results in Figure 5 only show a theoretical limit to how much agriculture can produce without directly competing with food production and considering some restrictions on the use of residues due to maintenance of soil fertility. It is a theoretical calculation of how much raw material is present and how much it could yield in theory in the form of biofuel. In light of the assessments of global biofuel potential mentioned in the introduction to this thesis, the results are rather conservative. However, they are also more reasonable since they actually rely on real data of the current agricultural production system.

4.2 Biofuels and food production in a local small-scale perspective

Paper II focused on how food production is affected by taking biomass for farm work and how large this is compared with other factors such as yield variations. In Paper III the focus was on comparing different biofuel systems regarding food production and NPK balance.

4.2.1 Animals, yields and diets (Paper II)

In the model used, the interdependencies between animals on the farm are that the amount of horses limits the amount of cows and sheep, and the amount of slaughtered meat affects the amount of poultry, as they eat slaughter waste. For details of how the number of animals is affected by the different cases, see Paper II. Table 1 shows the effects on Np by draught horse power and different combinations of cows is given.

Table 1. Number of people the farm can supply, Np, of scenario I-III of cases 1-5 in paper II

Case	**Case description**	**Scenario I** Conventional diesel	**Scenario II** 1 horse and rapeseed oil	**Scenario III** 3 horses
1	The largest amount of large cows possible	84	79	79
2	Same amount but changed to small cows	58	54	56
3	No cows	43	40	42
4	Largest possible amount of small cows	62	58	59
5	Better balance between cows and sheep	82	76	75

Scenario III, with three draught horses, gives more food production than scenario II, combining one draught horse with rapeseed oil, in all cases except for case 5. However, by using pure draught horse power, the many benefits of the tractor as an all-round tool are not accessible. Therefore it is more reasonable to use scenario II than scenario III. Furthermore, in reality, there may be varying sizes of cows in the animal herd. If we assume that the number of large cows is equal to the number of small cows, Np is 69 in scenario II. The possible diet from this scenario is given in Table 2.

Table 2. 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

At a first glance, one can see that the milk consumption is rather large and meat consumption relatively small in this diet. However, the milk can be converted into *e.g.* butter, cheese and cream and it would not be too difficult to use it in most types of cooking.

A sensitivity analysis was carried out based on scenario II with equal numbers of small and large cows. A detailed description of the cases can be found in Paper II. The cases are briefly summarized in Table 3 together with the results on Np.

Table 3. Sensitivity of scenario II to reasonable changes

Case	Description	Number of people the farm can supply, Np	Np % of base case
a	Base case	69	100
b	Vegetal production at average organic yields in the country	66	96
c	Vegetal production at average conventional yields in the country	82	119
d	Optimistic milk yields	77	116
e	No forest grazing	68	99
f	70 % more forest grazing	70	101
g	20 % larger rapeseed oil demand for fuel	68	99
h	Keeping calves to two year slaughter weight instead of one year	67	97
i	20 % smaller production of forage	69	100

Vegetal production per hectare on the farm is somewhat larger than the average organic yields of the same crops in Sweden, and therefore Np is reduced in case b. Case c, with yields corresponding to average conventional yields, increased Np by almost 20%. Case d, larger milk yield, also had a significant impact on Np. The suggested milk yields in case d are optimistic, but not impossible with cows fed only on forage (see Paper II), and therefore there may be larger potential Np than shown in Table 1. However, since a larger number of people are fed by a larger amount of milk, the meat production per capita is decreased. In case h, on the other hand, where the calves are held to two years instead of slaughtered much smaller at one year, the meat production is increased from 300 g per person and week to just above 500 g. This only reduces Np by a few per cent, which may be a good compromise. Case g and increased fuel demand of 20% have no significant impact on food production, probably because the oil requirement is so small when most work is carried out by the horse.

4.2.2 Possible biofuels and NPK balance of altered production patterns (Paper III)

Using a crop to produce biofuel reduces food production relative to the system with a conventional diesel tractor. Therefore the number of people supplied will be affected even if the crop production nutrient-wise is leaving the farm. As can be seen in Table 4, scenario II is the most favourable of the biofuel scenarios in terms of Np. It can supply 65 persons, which is 94% of the initial number of persons in the base case (scenario I, with diesel as fuel). In second place comes scenario IV, which is able to supply 57 persons, 82% of the number of people supplied in scenario I. Scenario III, with ethanol from wheat, can supply the least amount of people in this study; 53 persons or 77% of that in scenario I. By changing the crop sequence to contain less ley and still having enough potatoes to cover the tractor demand for ethanol, food production could be held to 90% of the reference scenario. However, such a crop sequence would be difficult to handle and was therefore not studied further here.

Table 4: Amount of people the farm can supply

Scenario	**I**	**II**	**III**	**IV**
Description	Diesel	Rapeseed oil and horse	Wheat ethanol	Potato ethanol
Np	**69**	**65**	**53**	**57**
% of Np_I	**100**	**94**	**77**	**82**

As seen in Table 5, all scenarios have a surplus of N amounting to 740-780 kg for the whole farm of 17 ha (case 2), which is around 50 kg/ha in all scenarios. The K balance shows losses in most cases. However, the balance is positive for arable land (case 1). This is due to the K input from hay from meadows through manure application on arable land.

All scenarios show a deficit of P except for scenario IV, case 4, where P is sustained and even increased. By recycling bones, the deficit is cut by almost half (compare cases 2 and 3 in Table 5), and by recycling 80% of human urine and faeces the P deficiency is almost eliminated (case 4). However there is still a large deficit of K in case 4 in all scenarios. The results include leakage factors of both N and P, but not for K. Hence, in reality the deficit of K is larger. Recycling bones has a large impact on the total farm balance of P. Hence it is likely that it would be enough to recycle bones to arable land (8 ha) in order to maintain P availability.

Scenario III has a larger deficit of P and K than scenarios I and II. The number of people supplied, 53 persons (Table 4), is the lowest of all scenarios studied, leading to less urine and faeces as input in case 4.

The best scenario in terms of nutrient recycling is the potato-ethanol system in scenario IV. Case 4 of scenario IV has the uncontested lowest deficit of K, -33 kg compared with -142 kg in scenario II, which is in second place concerning K. There is also a surplus of P in scenario IV. Scenario III in case 4 comes in second place in regard to the P balance, with a deficit of -2.4 kg, corresponding to no more than -0.1 kg/ha. However, scenario III is in third place of the biofuel scenarios considering K, with a deficit of -142 kg. There are some complex interrelations in these results. For example, the K deficit is 1 kg larger in case 4 of scenario II than in scenario I. The output of K is smaller than in scenario I (see Paper III), and the result must depend on fewer people supplied and hence less nutrients being recycled. This in turn can depend on small overestimation of the K content in the recycled faeces.

The nutrients in the potatoes used for fuel stay on the farm in the form of stillage, fed to the cows or used directly as fertiliser. The wheat-ethanol plant may be able to send back the stillage with the transport, in which case it is usually dried (Agroetanol, 2013). Therefore the nutrients may be returned even in this scenario, which gives a surplus of P in scenario III of the same magnitude as in scenario IV, provided bones and human excreta are recycled (case 4). The N surplus would then be 85 kg larger and the K deficit 22 kg smaller, compared with the results for scenario III given in Table 5.

Table 5. Farm nutrient balance of scenarios I-IV [kg]

Scenario		**I**	**II**	**III**	**IV**
Description		**Diesel**	**Rapeseed oil and horse**	**Wheat ethanol**	**Potato ethanol**
Case 1: Only arable land, 8 ha					
	N	1017	1027	1007	1050
	P	-16	-14	-20	-0,9
	K	210	203	195	320
Case 2: Whole farm, 17 ha					
	N	750	760	740	780
	P	-68	-66	-97	-53
	K	-203	-201	-210	-84
Case 3: Whole farm 17 ha, recycling bones					
	N	750	760	740	780
	P	-31	-32	-35	-19
	K	-203	-201	-210	-84
Case 4: Case 3 plus recycling human excreta					
	N	989	985	940	980
	P	-0,5	-2.4	-11	5.5
	K	-141	-142	-162	-33

5 Discussion

5.1 Methodological limitations

5.1.1 Global survey

Energy content may be an understandable parameter for engineers, who have knowledge of the technologies behind biofuels and may suggest that these should replace fossil fuels. However, it can be misleading to exclusively use the energy content to measure agricultural production. The qualities which food and different kinds of biomass provide for humans and other species may appear to be disregarded. Therefore the results and methods used in Paper I should be read with consciousness of the many purposes of agriculture. This paper reflects only the properties of biomass that regards covering the energy in the human metabolic system and in fuel production.

Furthermore, the calculations are entirely theoretical. The results only state the amount of biofuel that can be obtained in theory by conversion of a given amount of raw material, thus neglecting energy used in the production processes of the chosen biofuel technologies. The results should thus be considered a theoretical maximum potential from the present global agricultural production system. The thesis includes no future projections, just a ‘snapshot’ of the current situation.

Another limitation is that the thesis does not include manure for biogas production. One reason is that a large proportion of the meat is produced from grazing cattle, and it was decided that the uncertainty of its quantity was too large to include.

For the residues, there were also a few limitations. One was that all residues are not harvestable, *i.e.* one-third is usually left in the field. It was also assumed that a fraction must be left, or returned to the field, to prevent depletion of soil organic carbon. We assumed that in the case when the residues are used for second generation biofuel and not biogas, the digestate would not be returned to the fields and therefore the availability of the residues is only one-third of the calculated harvest index. This may be considered generous in certain areas and too conservative in other areas, depending on the current status of soil organic carbon and land fertility. For example, Bernesson & Nilsson (2005) suggest that no residues should be harvested if the soil organic carbon content is below 4%. In that case, not even the 'black soils' of Ukraine could be harvested of residues, as the average soil organic carbon content there was estimated to be 3.2% in 2009 by the permanent representation of Ukraine to the European Council (European Council, 2009).

Furthermore, it is difficult to know whether the possible global harvest of residues is available at all, or already in use for other purposes. One purpose may be of course to return soil organic carbon, but other usage of straw, *e.g.* as litter or forage for animals, material for buildings or as fibre for other products, exists around the world. Thus if there is not competition with food production, there may be competition with other functions.

Regarding uncertainties in the data, statistical reviews vary in quality among different countries, and in several cases the production data are based on estimates. There is also reason to believe that the FAO datasets are lacking good data on ley crops, rotational grasslands and pasture (Johansson & Liljequist, 2009).

5.1.2 Limitations of Papers II and III

The main limitation of the Np model concerns the input data. The yields of farm crops were measured in a 'normal' year, and deviations from that were thus not included in the number of people the farm could supply. The net edible production included deduction of seed for reproduction, reject food grain (used for poultry), 1% shrinkage, 20% postharvest losses of potatoes and vegetables, and a milling percentage of 78% for wheat and 70% for oats, according to Johansson & Liljequist (2009). The chaff and bran from milling were assumed to be fed to poultry. Despite these different types of losses being included in the model, there will always be unforeseen losses on a farm, *e.g.* crop failure due to bad weather, pests or diseases. Therefore the number of people that every scenario can supply with food should only be seen as the ideal situation, the theoretical capacity of the system. One uncertainty can be *e.g.* the yield of the leys, the basis for meat and milk production. The measured yield, 40 tonnes from the 3 ha at the farm, is relatively high compared with average yields in the country (Frankow-Lindberg, 2003; Frankow-Lindberg & Dahlin, 2013). Another major source of error may be milk production, which varies widely between individual cows.

The model concentrates on energy content for satisfying the diet of both animals and humans, which may be misleading for the same reasons as discussed above. There are many parameters that need to be considered in order to decide whether a diet is suitable for humans. We opted not to go into that issue, as food science is a large area to cover. What we present is therefore the diet that appears under the specific conditions stated. These conditions are nevertheless derived from an aim of addressing several global challenges at once by having a multi-functional farm system. Other crop sequences and animal herds would give other diets. We did not focus much on forest land as food-producing land, except that it can be grazed. There can also be nuts, fruit, honey and berries produced, giving the land even more multi-functionality than we investigated.

The chosen farm as a study object has quite specific properties. At present the average area of arable land on a farm in Sweden is 37 ha. The study farm, with its 8 ha of arable land, resembles more the conditions in the early 1900s, when the average farmer had 8.7 ha of arable land (Swedish Board of Agriculture, 2013). Taken together, the area of meadow and pasture for grazing is larger than the area of arable land, and the forested area is about the same size as the total area of meadow, pasture and arable land (Figure 6).

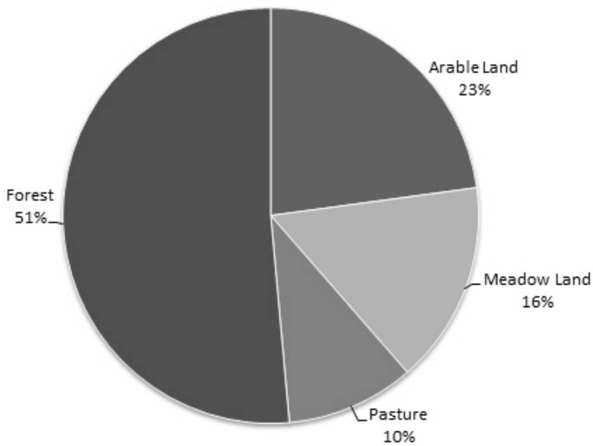

Figure 6. Land use distribution on the study farm, which resembles the pattern that was common in Sweden prior to the Green Revolution, when scaling up was done together with segregation of animal and crop production.

This composition of land use makes the study farm appropriate for rearing cattle, and it is also evident that the cattle require a larger support area than is needed for simply growing vegetal products. The forests owned on the farm are also known to have been grazed previously. Papers II and III can therefore be regarded as hypothetical scenarios for the future, *i.e*. if specialist large-scale farming had to be abandoned due to environmental problems associated with it, as well as difficulties in supplying enough tractive power in more renewable ways. Papers II and III can also be regarded more as case studies, since the data used are from one farm. However, the methods and approaches are general and transferable to all kinds of farming systems, either for studying what a change in land use would mean in terms of food production, or for studying the present food production on a farm.

The measure of Np shows how the introduction of an energy crop or setting aside production for biofuel would affect food production on the farm. However, the Np model is very simplistic. One advantage of this is that the measure is easy to grasp and communicate. A disadvantage is that most other parameters regarding sustainability of an agricultural system are disregarded. The study farm has tried its hardest to form a low-input system with a range of different products, making use of different land components and taking advantage of ecosystem services such as nutrient recycling. Despite this, nutrients in food are leaving the farm, and since inputs are very low the result is a net outflow of all other nutrients than nitrogen, which is maintained and even enhanced due to the efficient fixation in the leguminous leys.

The NPK balances in Paper III were mainly used as an additional parameter of comparison between the different scenarios. They were also used for investigating the impact of land use distribution, such as moving nutrients from meadows to fields, as well as the impact of recycling bones after slaughter and human excreta. It is difficult to draw any general conclusions from this, since the nutrient balance is very specific to the production enterprise. However, it was quite useful for investigating ‘hidden’ interrelations and degree of nutrient recycling and for comparing the scenarios.

There are some sources of error in the calculations regarding the nutrient leakage and recycling of bones and human excreta. Nutrient leakage varies widely depending on region and soil type. For example, the study farm lies in leakage region 6 specified by the models on nutrient leakage (Johnsson *et al.,* 2008). In this region the average leakage of N is 9 kg/ha, whereas in southern Sweden (region 1) the average leakage is 48 kg/ha. As the soils at local level may also differ from the average within the entire leakage region, that could have a significant impact on the results. However, those errors are equal in all scenarios, and in the comparison may be of less relevance.

Compared with Paper I, Papers II and III revealed a much higher degree of complexity of food production. It was therefore not possible to achieve unambiguous results, as the system contained a wide range of trade-offs that had to be made in order to find as optimal a multi-functional food system as possible. Papers II and III investigated some parameters, but for another farmer in another region other choices might seem more appropriate.

5.2 Implications from Paper I

Paper I only shows the theoretical limit of biofuels in a global perspective, neglecting energy used in the energy conversion process. Zhu & Zhuang (2012) summarised a literature survey on energy input to biorefineries and found that the energy requirement ranged from 2000-6000 MJ/tonne biomass for ‘soft’ or what were called ‘annual’ residues in Paper I, and 3000-6000 MJ/tonne biomass for hard wood, perennial residues. This large range may depend on different ways of accounting as well as differing technologies. When producing second generation biofuels, Paper I showed that almost 2300 TWh of fuel are theoretically available in the annual residues, and about 1500 TWh in the perennial residues. For the annual residues available globally, the energy requirement in the biorefinery step would amount to between 1500-8940 TWh according to the data presented in Zhu & Zhuang (2012). On accounting for the ‘perennial’ residues, the energy required in the conversion step would amount to 700-4300 TWh. Note that this calculation does not account for any energy required previous to the biorefinery step, such as gathering the residues and transporting them. Ulgiati (2001) states that:

> The ability of a biofuel system to support societal assets depends on how much energy it supplies to society after reinvesting part of the output in the production process as an alternative to fossil fuels (Ulgiati, 2001, p. 74).

A simple energy output/input ratio for the annual residues, assuming the lowest energy requirement from above (1500 TWh input energy in the process that gives 2300 TWh of fuel output) results in a ratio of 1.53. With the Ulgiati (2001) way of accounting, this in extension means that 3 litres of fuel must be produced to deliver 1 litre to society. However, the amount of ethanol in Paper I (2300 TWh) was based on the theoretical limit for residues for second generation technology, and the three-fold higher amount of residues required to make the system self-sufficient is not available globally. This in turn means that the global ‘potential’ must be cut even further. For the perennial residues, 2 litres must be produced in order to deliver 1 litre to society according to the studies giving low energy usage in the refinery. For those studies suggesting the larger ranges of energy requirements in the refinery step, the results indicate that there is no potential at all from global agriculture to produce biofuels. The processing step in the biorefinery, or all kinds of conversion technologies for biofuels, lower the theoretical limit significantly.

According to the assumptions made in Paper I, the potential for using residues for biogas is larger provided that the biogas residues are returned to the field. Such an assumption is not completely valid, since a lot of carbon is lost in the biogas process and hence the risk of lowering soil fertility is present in a biogas system. Assuming that *e.g.* Ahlgren *et al.* (2010) manage to cover most energy expenses in a biogas system, the net energy return for biogas of fuel quality should be 3.75 according to that study. The global theoretical limit for biogas was approximately 7000 TWh, and hence the energy required to obtain this is almost 1900 TWh. Since no more material is available for biogas, this lowers the theoretical limit for biogas accordingly. However, Pöschl *et al.* (2010) cite an energy balance for biogas conversion of 1.6 and if we use that value instead of 3.75 (Ahlgren *et al.*, 2010), then approximately 4400 TWh will be needed for the process, which lowers the theoretical limit to 2600 TWh instead of 7000 TWh.

As mentioned previously, the methodological approach has a large impact on the results. For example, Rehl *et al.* (2012) conclude that:

> The comparison of different LCA approaches to the same biogas system…revealed that the calculated environmental performance is affected considerably by the methodology chosen (Rehl *et al.*, 2012, p. 3775).

Rehl *et al.* (2012) achieved a negative energy balance while using attributional LCA compared with an energy return of 5-10 times using consequential LCA. These are two different approaches within LCA that differ through the way of *e.g.* handling allocation of co-products and system boundaries (see *e.g.* Rehl *et al.* (2012) for definitions).

From the results in Paper I (see also Johansson & Liljequist, 2009), it can be derived that the theoretical ‘potential’ of biogas from manure may be between 500-1600 TWh, given that the biogas conversion has an efficiency of 25-60% and that the manure contains one-third of the energy in the feed and forage (Björnhag *et al.*, 1989). It is still not very large in the whole picture, considering how large the global fuel demand is in reality. Furthermore, it is questionable whether it is desirable to keep animals in large feedlots and feed them with cereals that could be used for human food, in order to be able to gather their manure to achieve a globally very insignificant fraction of fuel.

5.3 Implications from Papers II and III

A novel idea in Papers II and III is the comparison of draught horse power with biofuels, which is argued to be an appropriate comparison above. Nevertheless the tractor is superior when it comes to power output, which affects the opportunity costs. If the soil is very wet, the horses may not be able to exert enough power. On the other hand, a tractor can lose up to 20% of its power by skidding on wet soils, and Arvidsson & Keller (2007) argue that horses are more favourable in that case. Experience from the study farm shows that the draught horse used could come out onto the fields earlier in the spring and later in the autumn, which prolongs the growing season. Furthermore, when the draught horse was not used for a couple of years a decrease in yields was observed, probably due to soil compaction.

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 if there is no access to liquid fuel at all. 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, *i.e.* the opportunity costs. Harvesting without a combine harvester is a very time-intensive operation. With larger farms and less labour, draught horse power may have been phased out partly due to the opportunity cost. In addition, the tractor is a well-adjusted all-round tool, as it not only manages the field operations, but also functions for *e.g.* lifting heavy loads as well. Should the tractor be entirely replaced by horses, there must be accompanying development of complementary tools, ideally not driven by fossil-fuelled engines. Therefore, if draught horse power is to be used, the scenario where it is combined with tractor is the most realistic.

The largest postharvest loss in the global food system is feeding cereals to livestock for meat production, and the reason the organic small-scale farm studied here can feed so many people is that animals do not eat what humans can eat. Instead, they fulfil their original purpose of converting inedible but indispensable leys into food. Furthermore, they manage to produce food from multiple types of land uses that are difficult or not desirable to cultivate with crops, contributing a vast amount of ecosystem services that are together very important, but equally difficult to quantify. It is evident from the diet presented in Paper II that milk production is of major importance for the amount of people the farm can supply (Np), despite the fact that each cow produced much less milk when fed on only forage than if it had been fed with a large proportion of feed concentrate. If no cows were present and meat production was by sheep only, the farm could supply 50% fewer people.

In a global context there is approximately 0.2 ha of arable land available per person, meaning each hectare must supply five people. The amount of pasture per capita globally is larger than the amount of arable land per capita (FAOSTAT, 2011), so if five people per ha of farmland are covered the amount of pasture need not be considered. The study farm has 11.5 ha of farmland (fields and meadows), meaning that 58 people could be supplied if all farmland globally were to be operated at similar productivity. This is achieved in the scenario using draught horse power combined with rapeseed oil, but not when using ethanol from wheat or potato for tractive power. Kimming *et al.* (2011) suggests using agricultural residues for biofuel production with the assumption that this would not affect food production. However in the study farm context there are no residues available, as all are used for the cattle-manure system and needed to be recycled. Or as Pollan (2006) describes a similar situation:

> In fact, when animals live on farms the very idea of waste ceases to exist; what you have instead is a closed ecological loop (Pollan, 2006, p. 68).

By producing the fuel on the farm a larger amount of nutrient recycling can be obtained. The draught horse-rapeseed oil scenario had only a small deficit of P, but the K deficit was significant in all scenarios except when potatoes were used for ethanol production. Deficiency of K is normally not a problem in Sweden in soils formed from sedimentary clay, due to high input through weathering. However, for biofuel systems to be viable in other regions and/or in lighter soils, some solution for K recycling will be increasingly important. Nitrogen level was maintained in all scenarios due to the nitrogen-fixing leys. Phosphorus level can be maintained in the field if bones are recycled. However, the P-containing salts used to satisfy the mineral needs of the animals are likely to have been mined in Morocco or China, the two largest global P producers (Walan, 2013). Hence, even if there is a high degree of nutrient recycling, the system is dependent on resources outside the system. Other nutrients, especially K, are moved from meadow to field.

Regarding nutrient recycling from human excreta, there are large uncertainties in terms of the amount that can be recycled in reality. This is not only a logistics challenge, as the excreta must somehow be sanitised to prevent the spread parasites and deceases. Another problem is that excreta may contain pharmaceutical residues, trace elements and other substances that should not be accumulated in the soil, as they may end up in food products. Tidåker *et al.* (2007) studied local recycling systems at farm level, and also at community level (Tidåker *et al.*, 2006) and showed that there are possible ways of succeeding with nutrient recycling from human excreta. Furthermore, Winker *et al*. (2009) concluded that storage and appropriate treatment can minimise the risk of spreading pathogens and pharmaceuticals.

However, it will never be possible to gather and recycle all nutrients and all systems do suffer nutrient losses. Perhaps a larger circulation area is required, *e.g*. involving nutrient recycling from water-runoff bodies such as the Baltic Sea in the study region. This may be achievable by using fisheries waste or by mussel cultivation (Spångberg *et al*., 2013).

Low-input farming is desirable for reasons such as limiting the impact on the global carbon, nitrogen and phosphorus cycles, yet agriculture cannot prevail if soils are depleted of nutrients. On the other hand, it cannot be claimed that the use of mineral fertilisers is more sustainable in terms of soil nutrient level. The use of fertilisers containing only a few nutrients depletes the soil reserves of other nutrients (Young, 1998), which in turn may lead to less nutritious foods (Pollan, 2006). Thus optimisation between high yields and other values is worth an extra thought.

5.4 Future outlook

The search for alternatives for fossil fuels is currently based on an assumption that it is possible to replace fossil fuels. In order to look into the future, it might be useful to look into the past. Now we are trying to replace fossil fuels by biomass. Yet, not too long ago the global energy system went from being based on biomass into fossil fuels. What was the reason? It was definitely not a question of greater efficiency, as the early steam engines operated at an efficiency of 3% (Erlandsson, 2001), which a draught horse could outcompete. Rather, the transition was a result of the high energy density and the easily available vast amounts of reserves, primarily of coal in the beginning of the fossil era. The reserves were so large that efficiency in the beginning was of little interest as the power output could still exceed that of the biomass-based workforce.

Of course the reserves depleted locally quite quickly due to this overexploitation and a call was made for better efficiency in order to save coal. However, as the British economist William Stanley Jevons foresaw in his book *The Coal Question* (Jevons, 1865); the more efficient a resource is used, the more of that resource will be used. This relationship has probably always been valid for human resource usage of any kind. Most other natural resources have depleted at much less quantity, *e.g*. fire wood, whale oil *etc*. (Höök, 2010), but fossil fuels could continue expanding for more than a century. The global power outtake at present is more than has ever been utilised in the history of mankind, or of any other species. When society was based on biomass back in the beginning of the 19^{th} century, global energy consumption was less than 10×10^3 TWh per year (Smil, 2010), while now it is over 140×10^3 TWh per year (BP, 2012).

Paper I shows serious limitations of biofuel production from global agriculture. One might turn to forestry and propose that it could provide much more second generation biofuels. Yet even that is grasping at straws in the light of the enormous power outtake that has been enabled by geological forces. This power outtake is unlikely to be possible with much more diluted energy resources, irrespective of whether these come from agricultural origin or wood fuel grown with agricultural practices. Thus the real problem is not how to replace fossil fuels, since that is not possible, but rather how to cut the relationship between the wellness of society and energy consumption. A transition back to a bio-based society would demand a lower level of energy consumption, and therefore the focus on replacing the current amounts of fossil fuels is totally flawed. Of course it is difficult to foresee *e.g.* the development of nuclear energy. Yet time is against us even with that more dense energy source, since oil production is falling at a rate of 4-8 % per year, meaning that a new North Sea of oil, producing 5 million barrels per day, or approximately 3×10^3 TWh per year, must be taken into production every year just to compensate for present consumption (Fantazzini *et al.*, 2011). This is more energy falling away every year than the global supply of nuclear power, which took 40 years to increase from zero to present production of approximately 2.5×10^3 TWh. Natural gas underwent a nearly linear increase between 1971 and 2011 of approximately 230 TWh per year (IEA, 2012b), ten times less than oil production is falling. Thus it seems to be a larger challenge than any renewable source of energy can attempt to overcome. The global share of wind, solar and geothermal energy together is approximately 1.6×10^3 TWh, and it took 40 years to come from almost zero to this amount (IEA, 2012b). Thus society may be moving towards a lower level of power outtake, whether we like it or not.

In a situation of crisis and fuel shortage, it may be likely that fossil fuels will be focused to the food producers. Therefore a reduction in the fuel requirement, *i.e.* by combining technology with draught horses, may be a key for future fuel shortages rather than technologically complicated and logistically complex biofuel solutions. The enormous amount of power outtake we are currently using has also had severe impacts on the surface of earth and all living ecosystems. Perhaps the key towards cutting the relationship between new technologies and increasing energy consumption is to start adjusting technology to nature, instead of adjusting nature to technology, which has been the trend for at least the last century.

In pre-modern society where much less power was available, the global population was much smaller. It is indeed a challenge to find out how to produce food for 9 or 10 billion people without continued degradation of the Earth's ecological functions and with less energy. In essence, it is a question of equity, since we cannot even manage to keep humanity out of hunger and famine at present, despite the fact that there is so much power and food available. However, this might also be a question of 'optimisation', of serving many purposes with agriculture. Food systems like the one investigated in Papers II and III can produce a significant amount of food. All it takes is devotion and time, for naturally this kind of agricultural system craves much more labour. Jackson (2009) argues that cutting down on human resources – the only resource that is continuing to grow – is one of the great failures of the current economic system.

6 Conclusions

Based on the studies presented in this thesis, the following conclusions can be drawn:

- Using edible crops for biofuels in the current global food system would lead to a global deficit of food.
- Producing biofuels from residues would have uncertain ‘potential’, with a maximal theoretical limit of 8 x 10^3 TWh.
- The largest postharvest loss in the global food system is feeding cereals to livestock for meat production.
- Small-scale, low-input agriculture may have the potential to create systems with work based on biomass, without unduly reducing the amount of food produced.
- It is important to view the system as a multifunctional unit, because focusing on purely processed biofuels for tractors can significantly reduce food production, if not fitted into a well-functioning crop sequence.
- Draught horse power is comparable to other types of biofuels, and may be easy to integrate into a well-functioning crop sequence.
- In the scenarios tested, using rapeseed oil as fuel for a tractor combined with draught horses reduced the amount of liquid fuel required and had the smallest impact on food supply.
- The largest impact on food production was when using ethanol from wheat in a tractor.
- Potassium is moved from meadows to fields through hay and manure, but can in the long-term be a problem, as the total farm balance of K was very negative.
- A phosphorus deficit in the farm nutrient balance was almost eliminated by recycling bones after slaughter and human excreta.

References

Abbasi, T. & Abbasi, S.A. (2010). Biomass energy and the environmental impacts associated with its production and utilization. *Renewable and Sustainable Energy Reviews* 14 (3), 919-937.

Agroetanol (2013). *Agrodrank^{TM}*. Available online at:
http://www.agroetanol.se/en/Feed/Agrodrank/, accessed 2013-05-05

Ahlgren S., Baky A., Bernesson S., Nordberg Å., Norén O., Hansson P-A. (2010). *Future Vehicle Fuel Supply for Swedish Agriculture.* Department of Energy and Technology, Swedish University of Agricultural Sciences, Report 020, Uppsala, 2010.

Alvarez, H. (2006). *Energiteknik* (Vol. 3). Lund: Studentlitteratur.

Angus J., Kirkegaard J., Peoples M., Ryan M., Ohlander L., Hufton L. (2011). *A review of break-crop benefits of Brassicas.* 17th Australian Research Assembly on Brassicas (ARAB), Wagga Wagga

Anker ThyØ, K; Wenzel, H. (2007). *Life cycle Assessment of Biogas from Maize silage and from Manure- for transport and for heat and power production under displacement of natural gas based heat works and marginal electricity in northern Germany.*

Archanskaïa E., Creel J., Hubert P. (2011). The nature of oil shocks and the global economy. *Energy Policy* 42, 509-520

Arvidsson, J., & Keller, T. (2007). Soil stress as affected by wheel load and tyre inflation pressure. *Soil & Tillage Research,* Amsterdam, v. 96, p. 284-291

Barett, C.B., Bellemare, M.F., Hou, J.Y. (2009). Reconsidering conventional explanations of the inverse productivity-size relationship. *World development* 38, 88-97.

Belfrage, K., Björklund, J., Salomonsson, L. (2005). The Effects of Farm Size and Organic Farming on Diversity of Birds, Pollinators, and Plants in a Swedish Landscape. *AMBIO: A Journal of the Human Environment,* 34:582-588.

Berneson S., Nilsson D. (2005). *Straw as an energy resource – a review of existing knowledge.* Rapport Miljö och Teknik 2005:07, Uppsala

Bernesson, S., Nilsson, D., & Hansson, P.-A. (2004). A limited LCA comparing large- and small-scale rape methyl ester (RME) under Swedish conditions. *Biomass and Bioenergy*, 26 (2004) 545 – 559.

Beringer T., Lucht W., Schapoff S. (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy*, 3 (4) 299–312, August 2011

Bertholdsson N. O. 2012. Allelopathy- a tool to improve the weed competitive ability of wheat with herbicide-resistant black grass (Alelopecurus myosuroides Huds.). *Agronomy* 2, 284-294

Björklund J., Helmfrid H. (2010). *Klimatsmart lantbruk stor- eller småskaligt? Erfarenheter från ett deltagardrivet forskningsprojekt.* Centrum för uthålligt lantbruk, CUL, Swedish University of Agricultural Sciences. Fyris-Tryck, Uppsala

Björnhag, G., Jonsson, E., Lindgren, E., & Malmfors, B. (1989). *Husdjur- ursprung, biologi, avel.* Stockholm: LTs Förlag (in Swedish).

Börjesson P. (2006). *Livscykelanalys av Salixproduktion. Lunds tekniska högskola. Institutionen för teknik och samhälle*. Avd. för miljö och energisystem. Rapport nr 60, Lund, 2006

Börjesson P. (2008). Good or bad bioethanol from a greenhouse gas perspective – what determines this? *Applied Energy* 86 (2009) 589-594

BP. (2012). Statistical Review of World Energy 2012, Historical data 1965-2011. Available online at: http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481, Utilized 2012-07-13

Butzen S. & Haefele D., (2012). *Dry-grind Ethanol Production from Corn.* Available at https://www.pioneer.com/home/site/ca/template.CONTENT/products/end-use/htf/guid.B6C03E1D-1585-429E-ABA8-104FB904EB63, utilized 2012-06-17

Carnot S. (1824). *Reflexions sur la puissance motrice du feu sur les machines propres a developper cette puissance.* Paris: Bachelier, Libraire

Cherubini F., Ulgiati S. (2010). Crop residues as raw materials for biorefinery systems- A LCA case study. *Applied Energy* 87 (2010) 47-57

Cornia G.A. (1985). Farm size, land yields and the agricultural production function: an analysis for fifteen developing countries. *World Dev.* 13, 131-145

De Schutter, O. (2011). Report on the right to food. UN human rights council. http://rs.resalliance.org/?p=4612

Erlandsson O. (2001). *Tidiga förbränningsmotorers prestanda – en studie baserad på Statens Maskinprovningars meddelanden 1899-1995*. Institutionen för värme och kraftteknik, Lunds universitet, Lund

European Council (2009). *Permanent representation of Ukraine.* Available online at http://www.mfa.gov.ua/coe/en/4545.htm, accessed 2009-01-27

European Biomass Industry Association (2012). *Biomass resources and production potential.* Available online at: http://www.eubia.org/215.0.html

Falkenmark, M., Rockström, J. (2008). *Is there sufficient water to eradicate hunger worldwide? – A misleading question. Agriculture trade and development - Toward greater coherence,* Royal Swedish Academy of Agriculture and Forestry (KSLA)

Fan S., Chan-Kang C. (2005). Is small beautiful? Farm size, productivity and poverty in Asian agriculture. *Agricultural Economics* 32, 135-146

Fantazzini D., Höök M., Angelantoni A. (2011). Global oil risks in the early 21st century. *Energy Policy* 39, 7865-7873

FAO. (2009). *How to Feed the World in 2050.* Available online on:

http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf

FAO. (2012). *Food Price Index.* Available online at: http://www.fao.org/worldfoodsituation/wfs-home/foodpricesindex/en/, Utilized 2012-07-19

FAOSTAT. (2011). FAOSTAT, ResourceSTAT, Land. Statistics division 2011. Available at: http://faostat.fao.org/site/377/default.aspx#ancor (Assessed 20 december 2011).

Farrell A.E., Plevin R.J., Turner B.T., Jones A.D., O'Hare M.O., Kammen D.M. (2006). Ethanol can contribute to energy and economic goals. *Science* 311, 506-508

Felix E., Tilley D.R. (2009). Integrated energy, environmental and financial analysis of ethanol production from cellulosic switchgrass. *Energy* 34 (2009) 410-436

Fischer G., Schrattenholzer L. (2001). Global bioenergy potentials through 2050. *Biomass and Bioenergy* 20 (3), 151-159

Focus on Nutrients (2013): http://www.greppa.nu/vaxtnaringsbalans.4.1c0ae76117773233f78000645.html accessed 2013-01-08

Frankow-Lindberg B.E., Dahlin A.S. (2013). N_2 fixation, N transfer, and yield in grasslandcommunities including a deep-rooted legume or non-legume species. *Plant Soil* DOI 10.1007/s11104-013-1650-z

Frankow-Lindberg B.E. (2003). Kvantifiering av kvävefixering via baljväxter i fält – förslag till ny modell i rådgivningsprogrammet STANK (*Quantification of nitrogen fixation by legumes in the field - proposal for a new model in the counseling program STANK).* Department of crop production ecology, Report 5, Uppsala 2013

Fraser R., Kay J.J. (2002). Exergy analysis of eco-systems: Establishing a role for the thermal sensing, in D. Quattrochi and J. Luvall (eds*) Thermal Remote Sensing in Land surface Processes*, Taylor & Francis Publishers, London

Fredriksson H., Baky A., Bernesson S., Nordberg Å., Norén O., Hansson P-A. (2006). Use of on-farm produced biofuels on organic farms – Evaluation of energy balances and environmental loads for three possible fuels. *Agricultural Systems* 89:184–203

Ghasemi S., Sorhabi M., Rahmani M. (2009). A comparison between two kinds of hydrodynamic models in bubble column slurry reactor during Fischer-Tropsch synthesis: Single-bubble class and two-bubble class. *Chemical Engineering Research and Design* 87 (2009), 1582–1588

Giampietro M., Mayumi K., Sorman A.H. (2013). *Energy analysis for a sustainable future – multi-scale integrated analysis of societal and ecosystem metabolism*. Routhledge, Abingdon

Giampietro M., Mayumi K. (2009*). The Biofuel Delusion – The fallacy of large-scale agro-biofuel production.* Earthscan, London, UK.

Giampietro M., Ulgiati S., Pimentel D. (1997). Feasibility of Large-Scale Biofuel Production – Does an enlargement of scale change the picture? *BioScience* 47 (9), 587-600

Gilland B. (1985). Cereal yields in theory and practice. *Outlook on Agriculture* 14 (2), 56-60

Halweil B. (2006). Can organic farming feed the world? *World watch* 19, 18-24

Hansson P-A., Baky A., Ahlgren S., Bernesson S., Nordberg Å., Norén O., Petterson O. (2007). Self-sufficiency of motor fuels on organic farms – Evaluation of systems based on fuels produced in industrial-scale plants. *Agricultural Systems* 94, 704–714

Hill J., Nelson E. Tilman D., Polasky S., Tiffany D. (2006). Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *PNAS* 103 (30), 11206-11210

Hoogwijk M., Faaij A., van den Broek R., Berndes G., Gielen D., Turkenburg W. (2003). Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy* 25 (2003) 119-133

Höök M. (2010). *Coal and Oil: The Dark Monarchs of Global Energy: Understanding Supply and Extraction Patterns and their Importance for Future Production.* Acta Acta Universitatis Upsaliensis, Uppsala

Höök M. & Aleklett K. (2010). A review on coal to liquid fuels and its coal consumption. . *International Journal of Energy Research* 34, (10), 848-864.

Horlings L.G. and Marsden T.K. 2011. Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernization of agriculture that could feed the world. *Global Environmental Change* 21 (2), pp. 441-452

IEA, International Energy Agency (2007). *Potential contribution of Bioenergy to the World's Future Demand.* IEA Bioenergy: ExCo 2007:02. Available online at:
http://www.idahoforests.org/img/pdf/PotentialContribution.pdf

IEA (2012a). *Oil in world 2009.* Available online at:
http://www.iea.org/stats/oildata.asp?COUNTRY_CODE=29

IEA (2012b). Key world energy statistics. Available online at:
http://www.iea.org/publications/freepublications/publication/kwes.pdf

Jackson T. (2009). *Prosperity without growth – economics for a finite planet.* London and New York: Earthscan/Routledge

Jernkontoret (2007). *Jernkontorets energihandbok, Tabell över värmevärde och densitet för några vanliga bränslen.* Only published online, available at:
http://energihandbok.se/x/a/i/10127/Tabellovervarmevardeochdensitetfornagravanligabranslen.html . Utilized 2013-01-03.

Jevons W.S. (1865). 1906. *The Coal Question: an inquiry concerning the progress of the nation, and the problematic exhaustion of our coal mines,* 3rd edn. New York, Augustus M. Kelley.

Johansson S. (2013). Limits to biofuels, in Cifalleri L., Wagner F., and Wiersma D.S (eds) *New strategies for energy generation, conversion and storage,* EPJ Web conferences 54, Varenna

Johansson, K., & Liljequist, K. (2009). Can agriculture provide us with both food and fuel? - A survey of present agricultural production. Uppsala: UPTEC ES 09 011.

Johansson K., Liljequist K., Ohlander L., Aleklett K. (2010). Agriculture as provider of both food and fuel. *Ambio* 39 (2), 91-99

Johansson K., 2007. *Energy system of the Loess Plateau – A case study of changes during the rehabilitation period.* Uppsala University,Uppsala.
http://www.tsl.uu.se/uhdsg/Publications/Loess.pdf

Johnsson H., Larsson M., Lindsjö A., Mårtensson K., Persson K., Torstensson G. (2008). *Läckage av näringsämnen från svensk åkermark – beräkning av normalläckage av kväve och fosfor för 1995 och 2005 (Estimating nitrogen and phosphorus leaching losses from arable land in Sweden).* Rapport 5823, november 2008, Naturvårdsverket, Bromma, Sweden.

Kimming M., Sundberg C., Nordberg Å., Baky A., Bernesson S., Norén O., Hansson P-A. (2011). Life cycle assessment of energy self-sufficiency systems based on agricultural residues for organic arable farms. *Bioresource Technology* 102:1425–1432

Ladani S., Vinterbäck J. (2009*). Global Potential for Sustainable Biomass for Energy*. Report 013, Department of Energy and Technology, Swedish University of Agricultural Sciences (SLU). Available online at: http://pub.epsilon.slu.se/4523/1/ladanai_et_al_100211.pdf

Lampkin N. 1990. *Organic farming.* Framing Press Books, Ipswich, UK

Lowisin, C. (2007). *Engines and Fuel combinations.* Uppsala: Uppsala university.

Misselhorn A., Aggarwal P., Ericksen P., Gregory P., Horn-Pathanothai L., Ingram J., Wiebe K. (2012). A vision for attaining food security. *Current Opinion in Environmental Sustainability* 4:7–17.

Odum H.T. (1996). *Environmental accounting: Emergy and environmental decision making*, John Wiley, New York

Ohlander, L. (1990). Växtföljder (Crop sequences). i O. Hammar, *Växtodling 2. Växterna*. 291-321. Stockholm: LT:s Förlag.

Ohlander L. (2001). Vallen i växtföljden. *Vallbrev* 1;31 Januari 2001 (in Swedish)

Paulsson P. (2007). *Energy analysis of ethanol production; a case study of Lantmännen Agroetanol's production system in Norrköping.* Master thesis 2007:03, department of Biometry and Engineering, Uppsala 2007

Pfeiffer, D.A. (2003). *Eating fossil fuels.* From the wilderness publications

Pimentel D., Patzek T.W. (2005). Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower. *Natural Resources Research* 14 (1)

Pollan M. (2006). *The Omnivore's Dilemma – The search for a perfect meal in a fast-food world.* Bloomsbury Publishing Plc, London. ISBN 978-1-4088-1218-1

Pöschl M., Ward S., Owende P. (2010). Evaluation of energy efficiency of various biogas production and utilization pathways. *Applied Energy* 87 (2010) 3305-3321

Postel, S.L. (1998). *Water for food production: Will there be enough in 2025?* American institute of biological sciences

Rahimpour M.R., Jokar S.M., Jamshidnejad Z. (2012). A novel slurry bubble column membrane reactor concept for Fischer-Tropsch synthesis in GTL technology. *Chemical Engineering Research and Design* 90 (2012) 383–396

Rehl T., Lansche J., Müller J. (2012). Life cycle assessment of energy generation from biogas – Attributional vs. Concequential approach. *Renewable and Sustainable Energy Reviews* 16 (2012) 3766-3775

Rockström, J., Steffen, W., Noone, K., Chapin III, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., De Wit, C. A., Hughes, T., Van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K. Crutzen, P. & Foley, J. (2009). A Safe Operating Space for Humanity. *Nature* 461:472-475

Rosset P.M. (1999). *The multiple functions and benefits of small scale agriculture in the context of global trade negotiation.* Policy Brief No 4, Institute for Food and Development Policy, Oakland, CA, USA

Rosset P. (2000). The multiple functions and benefits of small farm agriculture in the context of global trade negotiations. *Development* 43:77–82

Rydberg N.T., and P. Milberg. 2000. A survey of weeds in organic farming in Sweden. *Biological agriculture and horticulture* 18:175-185

Shapouri H., Duffield J., McAloon A, Wang M. (2004). *The 2001 Net Energy Balance of Corn-Ethanol (preliminary)*. US Department of Agriculture, Washington, DC.

Smeets E., Faaij A., Lewandowski I. (2004). *A Quickscan of Global Bioenergy Potentials to 2050 – An analysis of the regional availability of biomass resources for export in relation to the underlying factors*. Report NWS-E-2004-109, FAIR Biotrade Project. Available online at: http://www.riaed.net/IMG/pdf/A_quickscan_of_global_bioenergy_potentials_to_2050.pdf

SMHI. (2010). Klimatdata (in Swedish). Available at: http://www.smhi.se/klimatdata/meteorologi/temperatur/dataserier-med-normalv%C3%A4rden-1.7354 (Assessed 21 december 2010)

Smil V.(2010). *Energy transitions – history, requirements, prospects*. Praeger, Santa Barbara, USA

Spångberg J., Jönsson H., Tidåker P. (2013). Bringing nutrients from sea to land – mussels as fertilizer from a life cycle perspective. *Journal of cleaner production* xxx (article in press) (2013) 1-11

Sues A., Juraščík M., Ptasinski K. (2010). Exergetic evaluation of 5 biowastes-to-biofuels routes via gasification. *Energy* 35 (2), 996–1007

Swedish Board of Agriculture (Jordbruksverket). (2013). *Yearbook of agricultural statistics 2013, including food statistics. Statistics Sweden, Agriculture statistics unit.* SCB Tryck, Örebro

Tidåker P., Sjöberg C., Jönsson H. (2007). Local recycling of plant nutrients from small-scale wastewater systems to farmlands – A Swedish scenario study. *Resources, conservation and recycling* 49 (2007) 388-405

Tidåker P., Kärrman E., Baky A., Jönsson H. (2006). Wastewater management integrated with farming- an environmental systems analysis of a Swedish country town. *Resources, conservation and recycling,* 47 (2006) 295-315

Tscharntke T., Clough Y., Wanger T.C., Jackson L., Motzke I., Perfecto I., Vandermeer J., Whitbread A. (2012). Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation* 151 (2012) 53–59

Tverberg G.E. (2011). Oil supply limits and the continuing financial crisis. *Energy* 37, 27-34

Ulgiati S. (2001). A comprehensive energy and economic assessment of biofuels: When “Green” is not enough. *Critical reviews in Plant Sciences*, 20(1):71-106(2001)

US Department of Energy. (2012). Brent Crude Oil Spot Price.

Source: US Department of Energy via wikiposit.org, available online at: http://wikiposit.org/uid?DOE.RBRTE, Update: http://wikiposit.org/w?action=dl&dltypes=comma%20separated&sp=monthly&uid=DOE.RBRTE

Walan P. (2013). *Modeling of Peak Phosphorus – A study of bottlenecks and implications for future production.* UPTEC W 13 011, Uppsala University, Uppsala

Winker M., Vinnerås B., Muskolus A., Arnold U., Clemens J. (2009). Fertiliser products from new sanitation systems: Their potential values and risks. *Bioresource and Technology* 100 (2009) 4090-4096

Young A. (1998). *Land resources – now and in the future.* Cambridge University Press, Cambridge.

Zeng, R.S., A.U. Malik, L. Shiming. (2008). *Allelopathy in sustainable agriculture and forestry.* 412p. Springer, New York, USA

Zhu J.Y., Zhuang X.S. (2012). Conceptual net energy output for biofuel production from lignocellulosic biomass through biorefining. *Progress in Energy and Combustion Science* 38 (2012) 583-598.

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