Crop Production without Fossil Fuel

Production Systems for Tractor Fuel and Mineral Nitrogen Based on Biomass

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Abstract

With diminishing fossil fuel reserves and concerns about global warming, the agricultural sector needs to reduce its use of fossil fuels. The objective of this thesis was to evaluate different systems for biomass-based production of tractor fuel and mineral nitrogen fertilisers, which at present are the two largest fossil energy carriers in Swedish agriculture. The land use, energy input and environmental load of the systems were calculated using life cycle assessment methodology.

Two categories of renewable tractor fuel were studied: first generation fuels and second generation fuels, the latter defined as fuels not yet produced on a commercial scale. An organic farm self-sufficient in tractor fuel was modelled. Raw material from the farm was assumed to be delivered to a large fuel production facility and fuel transported back to the farm, where it was utilised. In general, the second generation renewable fuels had higher energy balance and lower environmental impact than the first generation fuels. However all systems studied reduced the use of fossil fuels to a great extent and lowered the contribution to global warming. The land needed to be set aside for tractor fuel varied between 2% and 5% of the farm's available land.

Two major routes for biomass-based production of mineral nitrogen for conventional agriculture were studied, one based on anaerobic digestion and one on thermochemical gasification of biomass. The crops studied were able to produce between 1.6 and 3.9 tonnes N per hectare in the form of ammonium nitrate. The use of fossil fuel for ammonium nitrate production was 35 MJ per kg N in the fossil reference scenario, but only 1-4 MJ per kg N in the biomass systems. The contribution to global warming can be greatly reduced by the biomass systems, but there is an increased risk of eutrophication and acidification.

It is clear that the agricultural sector has great potential to reduce the use of fossil fuel and to lower the emissions of greenhouse gases by utilising biomass resources. However, there are many other issues to be addressed when utilising biomass energy, for example the trade-off between different environmental impacts and the use of limited resources such as fresh water, phosphorus and ecosystem services.

Keywords: agriculture, fossil fuels, biofuels, bioenergy, diesel, nitrogen fertiliser, life cycle assessment, global warming, acidification, eutrophication

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Dedication

I dedicate this thesis to Gubben Gran, Skruttfian and Prinsen.

It suddenly struck me that that tiny pea, pretty and blue, was the Earth. I put up my thumb and shut one eye, and my thumb blotted out the planet Earth. I didn't feel like a giant. I felt very, very small.

Neil Armstrong

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 Hansson, P.A., Baky, A., Ahlgren, S., Bernesson, S., Nordberg, A., Norén, O. & Pettersson, O. (2007). Self-sufficiency of motor fuels on organic farms – Evaluation of systems based on fuels produced in industrial-scale plants. *Agricultural Systems* 94(3), 704-714.

II Ahlgren, S., Baky, A., Bernesson, S., Nordberg, Å., Norén, O. & Hansson, P.A. (2008). Future fuel supply systems for organic production based on Fischer-Tropsch diesel and dimethyl ether from on-farm-grown biomass. *Biosystems Engineering* 99(1), 145-155.

III Ahlgren, S., Baky, A., Bernesson, S., Nordberg, Å., Norén, O. & Hansson, P.-A. (2009). Tractive power in organic farming based on fuel cell technology – Energy balance and environmental load. *Agricultural Systems* 102(1-3), 67-76.

IV Ahlgren, S., Baky, A., Bernesson, S., Nordberg, Å., Norén, O. & Hansson, P.-A. (2008). Ammonium nitrate fertiliser production based on biomass – Environmental effects from a life cycle perspective. *Bioresource Technology* 99(17), 8034-8041.

V Ahlgren, S., Bernesson, S., Nordberg, Å. & Hansson, P.-A. Nitrogen fertiliser production based on biogas – Energy input, environmental impact and land use (manuscript).

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

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

I Collected some input data for the calculations, wrote part of the paper together with the co-authors.

II Planned the paper together with the co-authors. Carried out the data collection and impact assessment. Wrote the paper with input from the co-authors.

III Planned the paper together with the co-authors. Carried out the data collection and impact assessment together with Baky. Wrote the paper with input from the co-authors.

IV Planned the paper together with the co-authors. Carried out the data collection and impact assessment. Wrote the paper with input from the co-authors.

V Planned the paper together with the co-authors. Carried out the data collection and impact assessment. Wrote the paper with input from the co-authors.

Abbreviations

AN	Ammonium nitrate
DME	Dimethyl ether
FC	Fuel cell
FTD	Fischer-Tropsch diesel
FU	Functional unit
GHG	Greenhouse gas
ICE	Internal combustion engine
LCA	Life cycle assessment
MeOH	Methanol
RME	Rape methyl ester

1 Introduction

Modern agriculture, as we know it, is dependent on the input of cheap fossil fuels. This was acknowledged already in the 1970s by Odum, who pointed out that potatoes were not made from sun but from fossil fuel (Rydberg, 2007). However, fossil fuels will run out sooner or later, or become too expensive to use. If we no longer have access to cheap fossil fuels, how will we then produce enough food, and energy, for a growing world population?

Even if the fossil resources were to last longer than anticipated by various peak oil theories, the combustion of fossil energy leads to emissions of carbon dioxide. These emissions and their impact on the climate system are regarded by many people as the greatest threat to humanity.

This thesis addresses the question of how agricultural production can be carried out in a modern and efficient way without fossil fuel inputs.

1.1 Energy use in Swedish agriculture

The total use of energy in Swedish agriculture is estimated to be 9.2 TWh (33 PJ) per year (Figure 1). The energy use can be divided into two parts, direct and indirect. The direct energy is the energy used on farms, while the indirect energy is the energy used for producing purchased inputs, although not including the production of machinery and buildings.

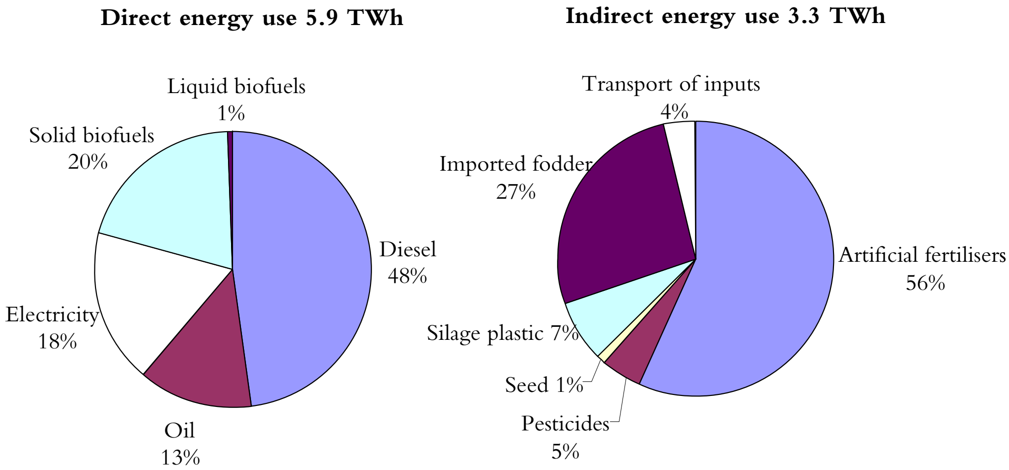

Figure 1. Direct and indirect use of energy in Swedish agriculture. Based on SJV (2009b), SCB (2008), Edström *et al.* (2005) and Jenssen & Kongshaug (2003).

The largest direct energy use is the use of fossil diesel (primarily for tractor fuel). Fossil oil and solid biofuels (mainly wood products and straw) are used for heating animal houses and drying grain (SCB, 2008). Electricity is primarily used in animal production. The Swedish electricity production mix consists mainly of hydro and nuclear power and only 3.5% is based on fossil energy (Energimyndigheten, 2008).

The largest indirect energy use is the production of fertilisers. The energy used for fertiliser production is largely due to production of nitrogen fertilisers, the main energy carrier being natural gas. The energy consumption for nitrogen production was assumed here to be 39 MJ (11 kWh) per kg N, which is an average European figure based on Jenssen & Kongshaug (2003). To a large extent the other indirect energy inputs are also based on fossil resources, for example silage plastic and the production of imported fodder.

Together, diesel and nitrogen fertilisers represent about 51% (4.7 TWh or 17 PJ per year) of the total energy use in agriculture.

1.2 Use of alternative tractor fuel

Before the 20th century, the use of fossil fuels was rare in agriculture. Animals such as horses and oxen were commonly used as a power source, and still are in many developing countries. To fuel these power sources, renewable energy was needed in the form of animal feed. Steam-powered tractors were developed in the early 20th century, but were soon replaced by petrol- and kerosene-powered tractors (Carroll, 2002). In a period during World War II, the use of liquid fossil fuels for tractors was restricted due to supply limitations. In Sweden, the problem was solved by converting tractors to operate on wood or coal gas.

In the Swedish agricultural sector at present, the use of alternative tractor fuel, mainly rape methyl ester (RME), is a moderate 1.4% of fossil fuel use on an energy basis (SCB, 2008). However, many research and demonstration projects for renewable tractor fuel or mixes of fossil and renewable fuel have been conducted. For example in the 1980s, the use of vegetable oils as tractor fuel was given a lot of attention (Jones & Peterson, 2002) and this is still a relevant research topic (Bernesson, 2004; Grau *et al.* in press). Research is also being conducted on ethanol (Bernesson *et al.,* 2006) and biogas (Lampinen, 2004) for use in tractors.

In a European Union funded project, a solar-powered agricultural vehicle has been developed (Mousazadeh *et al.*, 2009). Batteries are charged up with solar power and used in small agricultural vehicles up to 40 hp, a system that can work well in the Mediterranean climate.

The manufacturer New Holland has recently released a concept tractor, a fuel cell 75 kW tractor operated on compressed hydrogen stored in an integrated tank under the hood (Figure 2). The use of fuel cells in tractors is not a new concept however, as the world's first fuel cell vehicle was a tractor built in 1959 by Allis Chalmer (Figure 2). It was equipped with 1008 individual alkaline fuel cells and had an output of 15 kW of electricity (Andújar & Segura, 2009).

Figure 2. Left: the first fuel cell vehicle in the world, an Allis Chalmer tractor built in 1959 (photo courtesy of Science Service Historical Image Collection). Right: the new fuel cell concept tractor built by New Holland in 2008 (photo courtesy of New Holland).

1.3 Production of renewable tractor fuel

Most agricultural tractors, harvesters and other machines operate on diesel. The production of alternative fuel for tractors would therefore be the same as for any other diesel vehicle. Although there is no official classification of renewable fuels into groups, it is common to refer to first and second generation fuels.

First generation renewable fuels are usually defined as those that can be produced with current technology on a commercial scale. Ethanol is produced via a fermentation process from sugar-rich crops such as sugar beet and sugar cane and from starch-rich crops such as cereals (Balat & Balat, 2009). Fatty acid methyl esters (FAME), sometimes referred to as bio-diesel, also belong to the first generation fuels. An example of FAME is RME, produced from transesterification of rapeseed oil. FAME can also be produced from animal fat, palm oil, soy oil, *etc.* (Basha *et al.*, 2009). Biogas from anaerobic digestion of crops and waste is also referred to as a first generation fuel (Börjesson & Mattiasson, 2008).

Second generation renewable fuels are usually defined as those fuels that are not yet produced on a commercial scale. Examples are ethanol from lignocellulosic material and fuels produced via thermochemical gasification of non-food biomass and waste such as Fischer Tropsch diesel (FTD), dimethyl ether (DME), hydrogen and methanol (RENEW, 2008).

In a thermochemical gasification process, the flow of oxidation medium (usually air, oxygen or steam) is restricted. Instead of producing heat as in a combustion process, the main product is an energy-rich gas. Depending on the oxidation material and the configuration of the gasifier, the gas consists of a mixture of carbon monoxide, hydrogen, methane and carbon dioxide (McKendry, 2002). The gas also contains a number of unwanted substances such as particles, tar, nitrogen compounds, sulphur compounds and alkali compounds, which have to be removed. After cleaning, the gas can be upgraded in a steam reforming and shift conversion step in order to increase the yield of hydrogen and carbon monoxide (Balat *et al.*, 2009):

$CH_4 + H_2O \rightarrow CO + 3H_2$ (steam reforming)
$CO + H_2O \rightarrow CO_2 + H_2$ (water-gas shift)

If necessary, carbon dioxide can be separated from the exiting gas flow. The cleaned and upgraded gas consisting of carbon monoxide and hydrogen is usually referred to as synthesis gas or simply syngas. The syngas can be converted to many different fuels in reactors with different catalysts, pressures and temperatures.

The conversion of solids to liquid and gaseous fuels is not new, as gasification of coal has been performed since World War II. However, using biomass as the raw material sets new demands on gasification technology, not least for the gas cleaning phase (RENEW, 2008).

Sometimes even a third generation of renewable fuels is mentioned, defined as new and hybrid processing technologies that convert organic materials to fuels (Ruth, 2008). This includes for example cultivation of cyanobacteria or microalgae that produce hydrogen. Artificial photosynthesis is also a promising concept; research is being conducted to imitate the enzymatic process that green plants use to capture sunlight and split water molecules into oxygen and hydrogen (STEM, 2007).

1.4 Production of mineral nitrogen

Use of artificial fertilisers based on fossil fuels became common after World War II, significantly increasing yields, and is considered as one of the prerequisites for the global population growth we have seen in the last century (Smil, 2001).

The basic component in current industrial nitrogen fertiliser production is ammonia. Ammonia is formed in the Haber-Bosch process, the overall reaction being $N_2 + 3H_2 \rightarrow 2NH_3$. At present, the production of ammonia is most commonly based on steam reforming of natural gas, but gasification of coal and heavy oil also occurs (Appl, 1999). The fossil resource is needed to produce the hydrogen used, while the nitrogen is derived from normal air.

However, if biomass can replace the fossil fuel, it would be possible to produce mineral nitrogen fertilisers based on renewable sources. In the wake of the 1970s energy crisis, some research was carried out to investigate the possibilities of producing nitrogen fertilisers without fossil fuel (Grundt & Christiansen, 1982; Dubey, 1978). These studies were based on electrolysis of water to produce the hydrogen needed for ammonia synthesis. A more recent project with water electrolysis is being carried out in Minnesota, US. A demonstration plant is about to be built with a windmill driving an electrolysis process that supplies hydrogen to a small-scale ammonia production plant (Hagen, 2009).

Ammonia can be used directly as a fertiliser, as is done for example in the US (IFA, 2009). In Europe, however, it is more common for the ammonia to be further processed into solid fertilisers, as a straight nitrogen fertiliser or as a combined fertiliser with phosphorus and potassium. The most commonly used straight nitrogen fertilisers in Europe are ammonium nitrate

(AN) and calcium ammonium nitrate (CAN), accounting for 43% of the nitrogen sold in fertilisers (EFMA, 2009). Ammonium nitrate is produced by reaction of ammonia and nitric acid. Carbonate can be added as a filler in a final step to produce calcium ammonium nitrate (EFMA, 2000).

1.5 Emissions from Swedish agriculture

According to the Swedish national inventory report (Naturvårdsverket, 2009a), greenhouse gas (GHG) emissions from Swedish agriculture amounted to 8.43 million tonnes CO_2-equivalents during 2007, corresponding to 13% of national greenhouse gas emissions. This is mainly from animal production (methane) and soil emissions (nitrous oxide). However, that figure does not include the production of inputs such as diesel, fertilisers and imported fodder, nor carbon dioxide release from organic soils.

In a study by Engström *et al.* (2007), the emissions of GHG from the entire food chain, including the food industry, exports and imports, was calculated to be about 14 million tonnes CO_2-equivalents. In another study, conducted by the Swedish Board of Agriculture (SJV, 2008), the GHG emissions from agriculture were estimated to be 15 million tonnes CO_2-equivalents per year, the largest contribution coming from nitrous oxide emissions from soil (Table 1). However, that report points out the large uncertainties in these quantifications, especially for the nitrous oxide emissions from soil and the carbon dioxide from managed organic soils.

Table 1. *Distribution of greenhouse gas emissions from Swedish agriculture (SJV, 2008)*

Nitrous oxide from nitrogen in soil	30 %
Carbon dioxide from managed organic soils	25 %
Methane from animal digestion	20 %
Production of mineral fertilisers	10 %
Methane and nitrous oxide from manure (storage and spreading)	7 %
Carbon dioxide from fossil fuels	7 %
Imported feed	3 %

As can be seen in Table 1, the production of fertilisers and use of fossil fuels account for only 17% of the GHG emissions from agriculture. However, some of the other larger items are emissions that are steered by biological activities and therefore difficult to control. The nitrogen and diesel are however production systems where there is a practical possibility to lower the GHG emissions.

The leaching of nitrogen and phosphorus from agricultural soils is a large contributor to eutrophication of water. Of total anthropogenic emissions, 40% of both the nitrogen and the phosphorus are estimated to originate from agriculture. Other emission sources are sewage plants, domestic sewage systems and industry (SJV, 2009a).

Emissions of ammonia from agriculture contribute to both eutrophication and acidification. About 90% of the ammonia emissions in Sweden originate from agriculture (Naturvårdsverket, 2009b). Ammonia emissions mainly occur in manure management (storage and spreading), from grazing and when applying mineral nitrogen fertilisers to soil. Another source of eutrophication and acidifying emissions is NOx from combustion of diesel and oil.

1.6 Organic farming

Organic production is defined by a number of fundamental characteristics drawn up by the International Federation of Organic Agriculture Movements (IFOAM) that are implemented in production standards regulated by control organs on national level. One of the principal aims of organic production is to use renewable resources to the greatest extent possible in production and processing systems (IFOAM, 2006). This ought to cover the use of fossil fuel for tractors, currently a topic of debate within the organic movement (see for example KRAV (2009) and TPorganics (2008)).

Certified organic production comprised 7% of Sweden's arable land during 2007 (SJV, 2009b). However, there is a great deal of land cultivated organically that receives European Union subsidies for organic production, but is not certified. Taking this into account, 17% of arable land is cultivated organically in Sweden (SJV, 2009b).

In organic farming the use of mineral fertilisers is prohibited. The nitrogen requirement can be met by adding organic fertilisers such as manure, but on stockless farms it is common to use green manure, *i.e.* at regular intervals cultivate a nitrogen-fixing crop, which is ploughed under. This means that the average yields per hectare and year in a crop rotation are lowered, since not every year brings a harvest. Furthermore, the use of chemical weed and pest control is prohibited in organic farming, which can lower the yields.

There are many studies on the differences in energy input between organic and conventional farming, for example Gomiero *et al.* (2008), Bailey *et al.* (2003), Dalgaard *et al.* (2001) and Cederberg & Mattsson (2000). There are differences in results between studies, but for crop production in general it seems that organic agriculture has lower yields per hectare. However, since no mineral nitrogen is used the energy input per hectare is lower. As a result, in most studies the overall energy input per unit mass of crop in the organic production is equal to or lower than that in conventional. Since mineral fertilisers are not used in organic farming, the dominant fossil energy use is in tractor fuel consumption.

2 Objectives and structure of the work

To ensure that agriculture can provide a reliable supply of food and energy to society in the future, a transition from fossil fuels must occur sooner or later within the agricultural sector. Even if fossil fuel availability does not diminish within the near future, it is important to reduce the emissions of greenhouse gases in order to slow down global warming. For organic farming it is also a matter of principle, as the general aim of organic production is to achieve a sustainable production system, based on renewable resources and local supply of production inputs (IFOAM, 2006). The Swedish organic regulatory organisation KRAV also has the goal of minimising the use of fossil energy (KRAV, 2009). Since the energy debate is raging and public interest in the energy issue is generally high, organic production without fossil fuels would be a way to increase the credibility and competitive power on the market. In addition, since the costs of fossil energy carriers are increasing, another major reason for increased use of renewable energy is strictly financial – to decrease overall production costs.

The two largest energy carriers in Swedish agriculture are diesel fuel and mineral nitrogen fertilisers.

2.1 Objectives

The overall aim of this thesis was to study how the use of fossil fuels in crop production can be reduced. The more specific objective was to evaluate production systems for biomass-based tractor fuel and mineral nitrogen using life cycle assessment (LCA) methodology. Land use, energy inputs and environmental load were calculated for a number of selected systems. Furthermore, the estimated costs and the technical appropriateness of the systems were discussed. The systems studied were selected on the basis of literature reviews and evaluation of the technical suitability of the systems for the agricultural sector. These systems included both organic and conventional agricultural methods, as well as both existing and emerging energy conversion technologies.

2.2 Structure

The thesis deals with tractor fuel and mineral nitrogen fertilisers for organic and conventional production, produced with existing and emerging technologies (Figure 3).

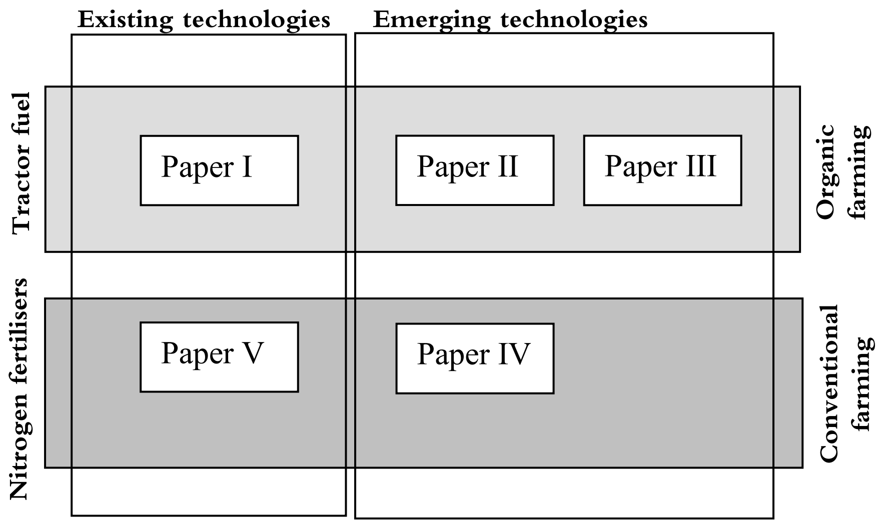

Figure 3. Output, technology and farming system studied in Papers I-V of this thesis.

Paper I investigated an organic farm assumed to be self-sufficient in tractor fuel. The fuels studied were ethanol, RME and biogas, assumed to be produced with existing technology from winter wheat, rapeseed and ley, respectively. The energy balance, land use and environmental load from cradle to grave were calculated for the different systems. In paper I the costs for the farmer was also evaluated.

Paper II studied the same organic farm self-sufficient in tractor fuel, but with the fuels FTD and DME produced via gasification of straw and Salix. Gasification of biomass is classified here as an emerging technology. The energy balance, land use and environmental load from cradle to grave were calculated for the different systems.

Paper III studied the same organic farm self-sufficient in tractor fuel, but with the fuels methanol and hydrogen. These fuels were assumed to be produced via gasification of straw and Salix. One scenario with hydrogen produced from reforming of biogas was also studied, with ley as the raw material for the biogas. The study was of a futuristic character, as the tractors were assumed to driven by fuel cells (FC). The energy balance, land use and environmental load from cradle to grave were calculated for the different systems.

Paper IV investigated the production of mineral nitrogen via gasification of straw and Salix. The fossil energy use, land use and environmental impact were studied from cradle to factory gate for 1 kg of nitrogen. The use of the nitrogen was hence not included in the study, which is a difference from the previous papers. Since the study assumed gasification of the raw material, it is classified here as an emerging technology. The raw material was assumed to be conventionally produced.

Paper V studied the production of mineral nitrogen from cradle to gate but with existing technology, a system possible to implement at the present time. Conventionally grown ley and maize were studied as raw materials for biogas production, with the biogas then distributed via pipelines to a large-scale nitrogen fertiliser production plant.

3 Life cycle assessment in the context of the present work

3.1 LCA basics

Life cycle assessment (LCA) is a methodology used for studying the potential impact on the environment caused by a chosen product, service or system. The product is followed through its entire life cycle. The amount of energy needed to produce the specific product and the environmental impact are calculated. The life cycle assessment is limited by its outer system boundaries (Figure 4). The energy and material flows across the boundaries are looked upon as inputs (resources) and outputs (emissions).

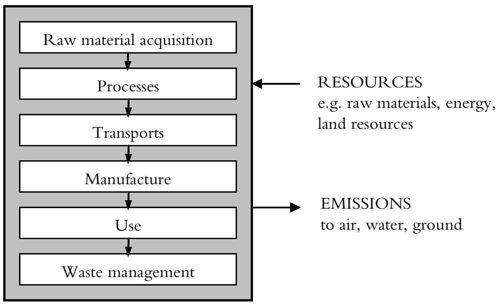

Figure 4. The life cycle model. Based on Baumann & Tillman (2004).

The methodology for the execution of a life cycle assessment is standardised in ISO 14040 and 14044 series. According to this standard, a life cycle assessment consists of four phases (Figure 5). The first phase includes defining a goal and scope. This should include a description of why the LCA is being carried out, the boundaries of the system, the functional unit and the allocation procedure chosen. The second phase of an LCA is the inventory analysis, *i.e.* gathering of data and calculations to quantify inputs and outputs. The third phase is the impact assessment, where the data from the inventory analysis are related to specific environmental hazard parameters (for example CO_2-equivalents). The fourth phase is interpretation, where the aim is to analyse the results of the study, evaluate and reach conclusions and recommendations (ISO, 2006). In an LCA study, the phases are not carried out one by one but in an iterative process across the different phases.

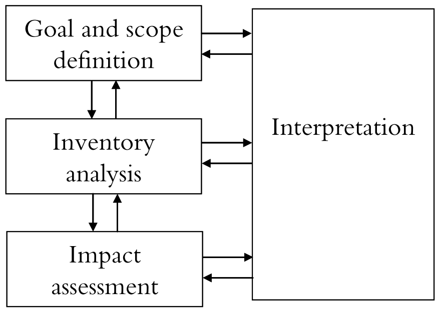

Figure 5. Stages of an LCA (ISO, 2006).

There are two main types of LCA studies; attributional and consequential. The attributional LCA study (sometimes also referred to as accounting type LCA) focuses on describing the flows to and from a studied life cycle. The consequential LCA (sometimes also referred to as change-orientated type LCA) focuses on describing how flows will change in response to possible decisions. Some authors state that attributional LCA are mainly used for existing systems, while consequential LCA are used for future changes (for example Baumann & Tillman, 2004). However as Finnveden *et al.* (2009) point out, both types of LCA can be used for evaluating past, current and future systems.

The type of LCA carried out has an impact on many of the methodological choices in an LCA. For example in handling of by-products, the attributional LCA uses an allocation based on mass, monetary value, *etc.* In a consequential LCA, a system expansion is instead often the choice, *e.g.* trying to determine the consequences of a new by-product appearing on the market. It also affects the choice of data; in a consequential LCA marginal data are used as it studies a change in a system, while an attributional LCA uses average data.

The main criticism of the attributional LCA is that it does not capture the real environmental costs of a system, while the main criticism of the consequential LCA is that it is very complex and requires many assumptions, which makes the results highly uncertain. However, there is not always a clear line between the two different types of LCA and it not unusual to use a combination of the two approaches, for example combining allocation and system expansions for different parts of the system.

3.2 LCA, energy and resources

LCA, energy and resources are closely linked, as almost any life cycle includes use of energy and resources of some sort (de Haes & Heijungs, 2007). In fact, life cycle assessment can be said to originate from the early energy and resource analyses in the 1960s (Hunt *et al.*, 1996). Energy analysis is often included as a step in the execution of a life cycle assessment, calculating the cumulative energy demand, often divided into renewable primary energy carriers (*e.g.* biomass) and non-renewable primary energy carriers (*e.g.* coal, oil, gas) (Jungmeier *et al.*, 2003). The energy demand is often expressed as primary energy, which is defined as the energy extracted from the natural system before transformation to other energy carriers (Baumann & Tillman, 2004). In LCA of energy systems, it is common to determine the energy balance, often calculated as the primary energy input divided by the energy output for the product studied.

Accounting for resource use in LCA is more complex. First of all, there is a distinction between abiotic and biotic resources. The abiotic resources can be accounted for by stating mass flow to the system studied. The flow can be related to the technical or economic reserves of the resource to get an idea of the impact on resource depletion (Finnveden *et al.,* 2009). Resources can also be connected to exergy consumption, which gives an indication of how much usefulness of a resource that is depleted in a studied system (Finnveden, 1997). The depletion of biotic resources is more difficult to quantify and has so far received little attention (Finnveden *et al.,* 2009).

3.3 LCA case studies of renewable fuels and mineral nitrogen

There are many LCA studies carried out for renewable fuels, often under the name WTW (well-to-wheel) studies. These case studies are to a large extent directed towards policymakers as a support in strategic decision-making, guiding the selection of the right fuel, raw material and production process

(Hillman, 2008). Some of these studies are more extensive (*e.g.* Jungbluth *et al.*, 2008; Edwards *et al.*, 2007; Wang, 2007).

For mineral nitrogen based on fossil hydrocarbons a few LCA studies have been carried out, mainly with the focus on GHG emissions (Wood & Cowie, 2004; Jenssen & Kongshaug, 2003; Davis & Haglund, 1999). No LCA-studies on nitrogen based on renewable resources have been found in literature, although as mentioned before there are some early studies on nitrogen production based on hydrogen from electrolysis, but only addressing energy inputs and costs. There are also several LCA studies on production of hydrogen based on biomass, mainly for use as vehicle fuel, for example in the above-mentioned WTW studies.

3.4 LCA and soil systems

Agricultural systems are very complex by nature, as they deal with biological systems where local conditions can play a large role for the end LCA results. The yield of crops is one such example. The yield of a certain crop is of course determined by external factors such as choice of variety and rate of fertilisation, but it is also governed by local factors such as soil properties, weed pressure and climate.

The addition of nitrogen (organic or mineral) to a cropping system can have a large impact on the results of an agricultural LCA study. Of course, the production of the fertiliser has to be accounted for, but also the effects of applying the nitrogen to the soil, which can have a major influence on the results. This is because part of the nitrogen metabolised by micro-organisms can be converted to nitrous oxide (N_2O), which is a potent greenhouse gas. The amount of mineral nitrogen converted to nitrous oxide depends on many factors, for example the initial form of the nitrogen, temperature, soil moisture content and oxygen supply (Kasimir-Klemedtsson, 2001). There are few published studies presenting measurements of nitrous oxide emissions from Swedish cultivated land. On an international level, many different measurement studies have been conducted, but the results show great variations (Snyder *et al.*, 2009).

There are also a number of mathematical models for calculating nitrous oxide emissions. A model described in Edwards *et al.* (2007) calculates the N_2O emissions based on the carbon content of the soil. Another example is Crutzen *et al.* (2008), who used a top-down model to estimate the N_2O emissions. By studying air bubbles in ice cores, a pre-industrial level of nitrous oxide in the atmosphere could be determined. By assuming that the increase in nitrous oxide levels in the atmosphere since then is anthropogenic and deducting the documented emissions from industrial activities, the contribution from agriculture could be calculated. Using this method, the emissions of nitrous oxide are estimated to be 3-5% of added nitrogen.

Another method commonly used in LCA studies for estimating the N_2O emissions from soil is described in IPCC (2006). The method is based on assumption of a linear relationship between nitrous oxide emissions and the amount of nitrogen added to the soil in the form of commercial fertilisers, farmyard manure, nitrogen-fixing crops and crop residues. With measurements as base data, IPCC (2006) assumes that 1% of applied nitrogen is emitted as nitrous oxide. The method was in fact originally intended for national reporting of greenhouse gases under the United Nations Framework and not for use in LCA, which is one of the major criticisms of using this methodology. However, in the absence of other appropriate models, this is often considered to be the most detailed method. In greenhouse gas reporting to the UN it is also possible for member countries to use national emission factors. The Swedish emissions factors are shown in Table 2.

Excess nitrogen can also be carried away with water. The leaching of nitrogen contributes to eutrophication, but also indirectly to global warming, as part of the leached nitrogen is converted to nitrous oxide emissions. IPCC (2006) has developed a method for the calculation of indirect emissions of nitrous oxide. The method takes into account nitrous oxide emissions produced when nitrogen leaches out with runoff water from the field, as well as the proportion of added nitrogen that volatilises as ammonia and is re-deposited on the ground, causing the formation of nitrous oxide. In the reporting of greenhouse gases under the United Nations Framework, national factors can be used for calculating indirect nitrous oxide emissions (Table 2).

Table 2. *Emissions factors for N_2O (N_2O-N as % of N-supply)*

	Swedish national emissions factor (Naturvårdsverket, 2009a)	IPCC emissions factor (IPCC, 2006)
Mineral fertiliser	0.8	1
Manure	2.5	1
Crop residues	1.25	1
Extra increment due to cultivation	0.5 (kg N_2O-N/ha/year)	--
Indirect from leached N	2.5	0.75
Indirect from deposition of N	1	1

Another issue that has attracted much attention amongst agricultural LCA practitioners in recent years is the carbon stock changes associated with cultivation. The global carbon pool in soils down to 1 metre depth is about twice the amount of carbon present in the atmosphere (Kätterer *et al.*, 2004). It is therefore feared that even small changes in the soil carbon pool could have an impact on climate change. In general, management options that influence soil organic carbon content include tillage intensity, removal of crop residues, use of fertilisers and manure and inclusion of perennial crops or fallow periods in the crop rotation (Cherubini *et al.*, 2009; Marland *et al.*, 2003; Paustian *et al.*, 1997). However, the change in carbon stocks due to cultivation of a certain crop on mineral soil is rather small, perhaps a few hundred kg C, compared with the total carbon stocks in the soil of 40-90 ton C per hectare (Berglund *et al.*, 2009). Because of the difficulties in determining these relatively small carbon fluxes, soil carbon changes are not always included in LCA studies. British Standards (2008) recommends that carbon changes should not be included in LCA calculation unless there is a change in land use, *e.g.* the conversion of non-agricultural land to agricultural land, whereby large fluxes can be expected. A Swedish review of agricultural GHG calculation methods reached the same conclusion (Berglund *et al.*, 2009).

3.5 LCA and land use

In many LCA of biofuels based on agricultural biomass, land use is one of the impact categories. Land use can be expressed as the number of hectares needed per functional unit (FU), which would be referred to as the direct land use. However, in recent years it has become more common in LCA practice to include the indirect land use. When growing crops for energy purposes, land is needed. If the land used for bioenergy crops has previously been used for other activities, for example cereal production or pasture, it is probable that the demand for these products will still continue to exist. The demand for the products previously produced from the land now occupied by bioenergy crops can be met by increasing the yields on the same land, or more likely, by moving the activities to another location. This moving of activities can cause land use changes, for example by utilisation of previously uncultivated land within the country in question or outside that country (Cherubini *et al.*, 2009).

Including land use *changes*, both direct and indirect, in the LCA calculations can affect the results. According to a study by Searchinger *et al.* (2008), an increase in corn-based ethanol in the US would result in land use changes in countries such as Brazil, China and India. Including the soil carbon losses due to this land use change nearly doubled the GHG emissions of ethanol compared with a fossil reference. Another illustrative example is the so-called 'carbon payback time' for biofuels described in a study by Gibbs *et al.* (2008). The carbon emitted during production and due to land use changes is weighed against the benefit of reducing the use of fossil fuels. The amount of years it takes for the production to pay back in terms of GHG emissions is referred to as the carbon payback time. For expansion of land into tropical ecosystems, it was found that the payback time is decades to centuries, while expanding into degraded land or already cultivated land provides immediate carbon savings. However, including land use changes in LCA can be controversial since it includes a number of assumptions and uncertain data and since there are no appropriate models for this type of calculation (Sylvester-Bradley, 2008).

Using land can also influence other soil quality parameters such as soil fertility, soil structure, soil erosion rate, water-holding capacity and nutrient balance (Röing *et al.*, 2005). Another important effect due to land use can be changes in biodiversity. How, and whether, to include possible degradation effects on soil and biodiversity in LCA studies due to land use is an ongoing discussion (Schmidt, 2008; Finnveden *et al.,* 2009).

Not all land use is negative, however. An increase in soil carbon can of course be counted as a negative contributor to global warming, but there are other land use parameters that are more difficult to reflect in an LCA study. For example, cultivating Salix on land contaminated with hazardous compounds (such as cadmium) can help clean up the soil, in a process known as phytoremediation (Mirck *et al.*, 2005). Another example is that there can be an increase in biodiversity associated with land use, especially for organic and extensive land use, which can be difficult to account for in LCA studies (Trydeman Knudsen & Halberg, 2007).

4 Organic farm self-suffient in tractor fuel (Papers I-III)

4.1 System description

A hypothetical 1000 ha stockless organic farm situated in south-western Sweden was modelled. The seven-year crop rotation included two years of green manure crops to supply nitrogen to the other crops in the rotation. It was assumed that the raw material for fuel production had to be produced within the 1000 ha available land. The raw material was assumed to be harvested and transported to a fuel production plant and the fuel returned to the farm, where it was utilised (Figure 6). The raw materials and fuels studied are listed in Table 3.

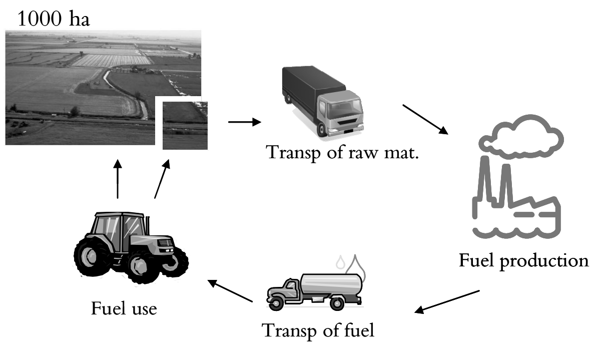

Figure 6. Schematic description of the system studied in Papers I, II and III. Raw material for fuel production is collected within the 1000 ha of available land. The raw material is transported to a fuel production plant and the fuel transported back to the farm, where it is utilised. The functional unit is defined as the motor fuel needed to cultivate the 1000 ha. Fuel for transport is not included in the functional unit but calculated as an external energy input to the system.

Table 3. *The combinations of raw material, fuel and tractor propulsion technology (internal combustion engine ICE and fuel cells FC) studied in Papers I, II and III*

Raw material	Fuel	Tractor technology	Included in paper
Winter rapeseed	RME	ICE	I
Winter wheat	Ethanol	ICE	I
Ley	Biogas	ICE	I
Salix	FTD	ICE	II
Salix	DME	ICE	II
Straw	FTD	ICE	II
Straw	DME	ICE	II
Salix	MeOH	FC	III
Salix	H_2	FC	III
Straw	MeOH	FC	III
Straw	H_2	FC	III
Ley	H_2	FC	III

The functional unit (FU) in all systems was defined as the amount of motor fuel needed to cultivate 1000 ha of the given organic crop rotation during one year, including the fuel needed for fuel raw material production.

It is important to note that the results from the different papers are not directly comparable, mainly due to the different assumptions in time-scale and system boundaries. Time-scale differences in first and second generation renewable fuels for example arise when making assumptions on process energy for fuel production. In Paper I, it was assumed that the process energy needed for the fuel production was supplied from external energy sources. This will have an impact on the energy balance and on the environmental load, but no land use was allocated for that purpose. Papers II and III were of a more futuristic character, assuming energy-optimised fuel production plants. By utilising part of the incoming raw material and waste energy, they covered their own need for energy in the process. However this meant that the land use also included a share of fuel production energy.

One important differing assumption concerning system boundaries is the soil emissions from ley. In Paper I, ley was harvested for biogas production. The digestate from biogas production was then allocated from the system based on the economic value of the nutrients in the digestate. In Paper III ley was also harvested for biogas and hydrogen production, but the digestate with all its nutrients was assumed to be returned to the cultivation. Since the original purpose of growing ley was to supply nitrogen to the organic crop rotation, it can then be argued that biogas production should not be burdened with the emissions associated with ley grown as a green manure. The ley is just ‘borrowed’ for fuel production. In other words, in Paper I the emissions from ley cropping were accounted for in the biogas scenario, while in Paper III the ley was considered a free resource and was therefore not burdened with the associated soil emissions.

4.2 Results

4.2.1 Energy balance

The energy input was calculated as primary energy and allocated to the fuel production based on the economic value of the fuel and the by-products from the systems. The energy input was calculated as the cultivation of raw material (with the produced fuel used in the tractors), transport of raw material, process energy for fuel production (Paper I) and transport of fuel back to the farm.

The fossil energy input, total energy input and energy in the fuel produced and the energy balance for the different systems in Paper I are presented in Table 4. RME has a high energy balance since the energy output from rapeseed cultivation is high compared with the input. The large allocation to by-products from fuel production (rapeseed meal) makes the balance even more favourable.

The fossil energy input is mainly due to transport of raw materials and fuels, and to a certain extent energy input for fuel production. The transport distance was set to 25 km in all scenarios in Paper I.

Table 4. *Fossil energy input in fuel production, total energy input in fuel production and the energy in the fuel produced for the scenarios studied in Paper I. The allocation was based on the economic value of the by-products. The energy balance is calculated as the output divided by the allocated total energy input*

Raw material	Fuel	Allocated fossil energy input (GJ)	Allocated total energy input (GJ)	Energy in fuel produced (GJ)	Energy balance
Raw oil	Diesel	2019	2019	1905	--
Winter rapeseed	RME	7	238	1983	8.3
Winter wheat	Ethanol	15	651	1697	2.6
Ley	Biogas	42	893	2914	3.3

The fossil energy input, total energy input and energy in the fuel produced and the energy balance for the different systems in Papers II and III are presented in Table 5. Because of high fuel conversion efficiency, the systems based on second generation renewable fuels generally had good energy balances. Systems based on fuel cell technology had the best energy balances, since the conversion efficiency was high in fuel production and in the tractors. The exception was the ley to hydrogen system, due to low efficiency in fuel production.

The high energy efficiency for the second generation renewable fuels can also be explained by the fuel production facilities studied having been assumed to be self-sufficient in energy and with part of the incoming biomass used to drive the process. In the energy balance evaluation this means that for scenarios with external input of process energy to fuel production (Paper I), the energy content of the process energy carrier was included in the calculation. However, in the self-sufficient cases (Papers II and III) only the cultivation and transport of the raw material needed for process energy were included.

Fossil energy input is mainly due to transport of raw materials and fuels. The transport distance was set to 100 km in all scenarios in Papers II and III except for the ley to hydrogen scenario, in which it was set to 25 km. The fossil energy use in the FTD and DME scenarios was relatively high as transport was assumed to be carried out with trucks driven with natural gas-based FTD and DME with high primary energy conversion factors.

Table 5. *Fossil energy input in fuel production, total energy input in fuel production and the energy in the fuel produced for the scenarios studied in Papers II and III. The allocation was based on the economic value of the by-products. The energy balance is calculated as the output divided by the allocated total energy input*

Raw material	Fuel	Allocated fossil energy input (GJ)	Allocated total energy input (GJ)	Energy in fuel produced (GJ)	Energy balance
Salix	FTD	124	189	1812	9.6
Salix	DME	114	188	1872	10.0
Straw	FTD	153	238	2124	8.9
Straw	DME	109	195	1975	10.1
Salix	MeOH	41	80	1252	15.6
Salix	H_2	47	75	1067	14.2
Straw	MeOH	42	65	1271	19.5
Straw	H_2	48	66	1080	16.3
Ley	H_2	57	199	1206	6.1

4.2.2 Land use

The calculated land use for the hypothetical 1000 ha organic farm self-sufficient in different tractor fuels is presented in Tables 6 and 7. The land use is expressed as both the allocated value and the non-allocated value. The non-allocated value is the total amount of land needed for fuel production, while the allocated land use is for the fuel after allocation to by-products. It could be argued that the non-allocated land use, which is the actual land use, should be counted. However, as the farm was assumed to deliver raw material to a larger production facility, taking back only the amount of fuel needed for the farm, it can perhaps not be asked to deliver enough raw material to cover the by-products as well. The difference in allocated and non-allocated land use was particularly clear in the FTD scenarios due to the high amount of by-products (naphtha, kerosene and electricity) in fuel production.

The allocated land use for the renewable fuels studied in Paper I was 4% of the available 1000 ha for RME and 5% for ethanol (Table 6). In the biogas scenario, land was not required to be set aside, but 35 ha of the 286 ha of available ley in the crop rotation had to be harvested.

Table 6. *Allocated and non-allocated land use for the systems studied in Paper I. The allocation was based on the economic value of the by-products. The reduced area of cash crops was based on allocated land use*

Raw material	Fuel	Non-allocated land use (ha)	Allocated land use (ha)	Reduced area of cash crops (ha)
Winter rapeseed	RME	85	44	44
Winter wheat	Ethanol	55	54	54
Ley	Biogas	42	35	0

For the second generation fuels studied in Papers II and III based on gasification of Salix, between 2 and 4% of the available land needed to be set aside. When utilising straw as raw material no land needed to be set side. In the crop rotation studied, straw can be collected from oats, rapeseed, rye and winter wheat, which are cultivated on approximately 570 ha of the available 1000 ha. In the scenarios studied in Papers II and III, 8-14% of the straw-producing area needed to be harvested for fuel production.

Table 7. *Allocated and non-allocated land use for the systems studied in Papers II and III. The allocation was based on the economic value of the by-products. The reduced area of cash crops was based on allocated land use.*

Raw material	Fuel	Non-allocated land use (ha)	Allocated land use (ha)	Reduced area of cash crops (ha)
Salix	FTD	108	34	34
Salix	DME	38	38	38
Straw	FTD	261	82	0
Straw	DME	70	70	0
Salix	MeOH	20	20	20
Salix	H_2	18	18	18
Straw	MeOH	53	53	0
Straw	H_2	48	48	0
Ley	H_2	44	44	0

Ley was utilised as raw material for biogas production in Paper I and for hydrogen production in Paper III. As ley is already grown in the crop rotation for nitrogen-fixing purposes, no land needed to be set aside for fuel production. In Paper I, an estimated 35 ha ley were needed, while in Paper III 44 ha were needed. The difference in land use can mainly be explained by the differing assumptions on process energy for fuel production. In Paper I the energy needed for fuel production (heat and electricity) was assumed to be externally produced. In Paper III, however, the fuel production plants were assumed to be self-sufficient in energy and a larger amount of biomass and land was then needed. In return, the energy balance improved. The difference in allocation strategy for the digestate as well as the tractor propulsion efficiency can further explain the difference in land use between the ley scenarios.

4.2.3 Global warming

The results of the global warming impact assessment for the different systems in the papers are shown in Figure 7. If diesel had been used as tractor fuel, the equivalent figure would be 157 700 kg CO_2-equivalents per functional unit. The emissions of nitrous oxide from soil had a large impact in all the scenarios except for the ley to hydrogen scenario, which was freed from soil emissions (see Section 4.1). The nitrous oxide emissions were calculated as direct and indirect emissions using national emissions factors (Naturvårdsverket, 2003).

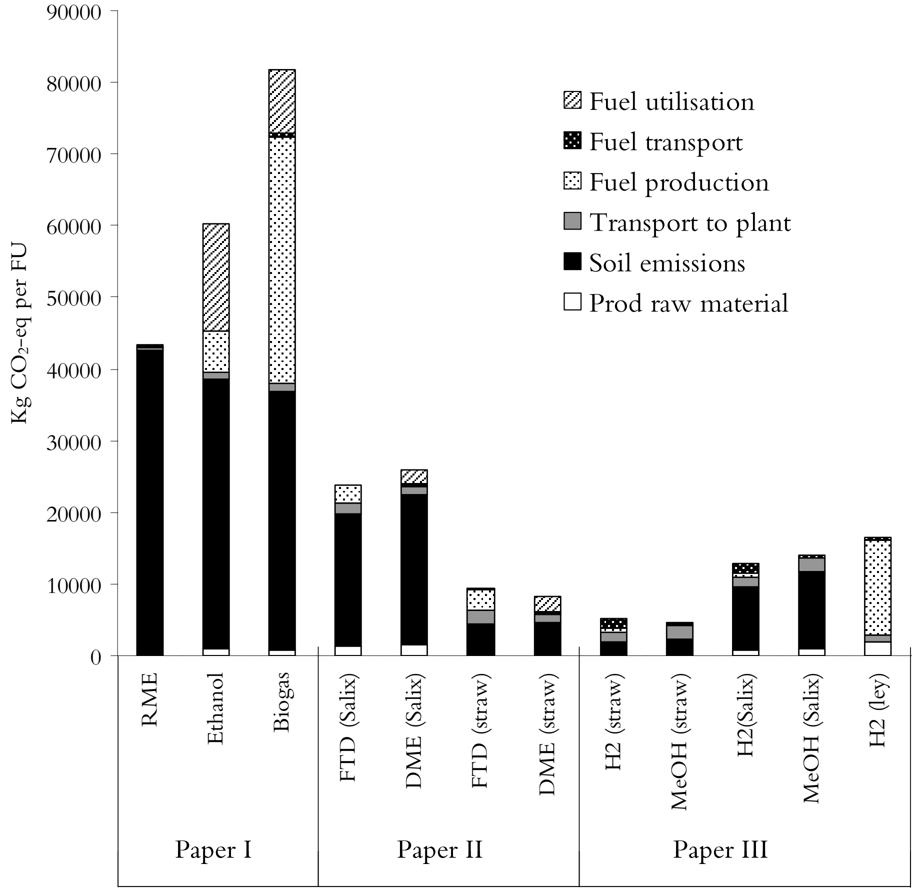

Figure 7. Contribution to global warming potential expressed as kg CO_2-equivalents per functional unit (FU) for the systems studied in Papers I, II and III.

4.2.4 Eutrophication

The results of the eutrophication assessment for the different systems in Papers I–III are shown in Figure 8. If diesel had been used as tractor fuel, the equivalent figure would be 10 542 kg O_2-equivalents per functional unit. The RME and ethanol systems are the only ones based on annual crops and have a greater eutrophication potential than the other scenarios studied, mainly due to leaching of nitrogen and phosphorus. Ley and Salix have lower leaching of nutrients since they are perennial crops. Based on the economic value of crop and straw, the straw scenarios were allocated only part of the soil emissions from crop production, which explains the low leaching emissions in those scenarios.

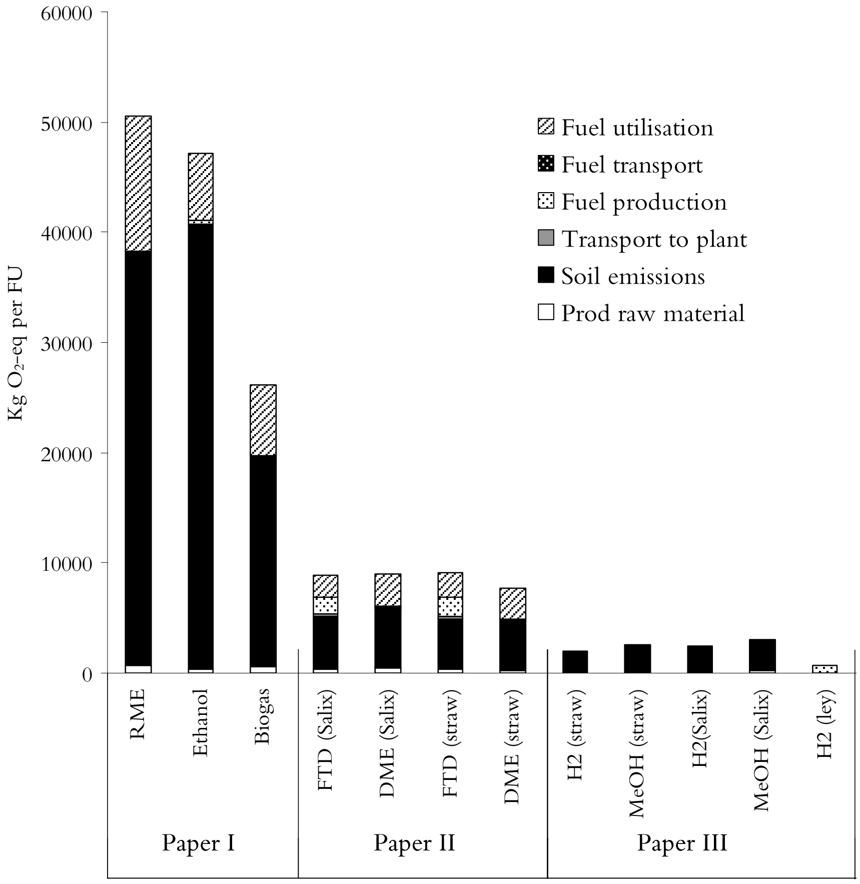

Figure 8. Contribution to eutrophication potential expressed as kg O_2-equivalents per functional unit (FU) for the systems studied in Papers I, II and III.

4.2.5 Acidification

The results of the acidification impact assessment for the different systems in Papers I–III are shown in Figure 9. If diesel had been used as tractor fuel, the equivalent figure would be 1 251 kg SO_2-equivalents per functional unit. The contribution to acidification originated mainly from fuel utilisation emissions in the scenarios with ICE, soil emissions and in the FTD scenarios from fuel production.

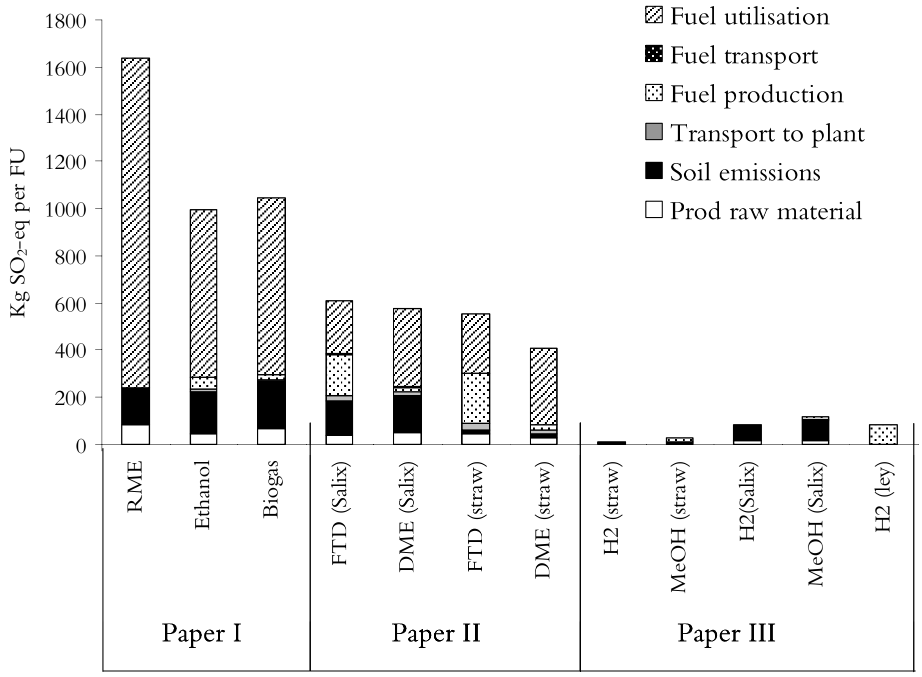

Figure 9. Contribution to acidification potential expressed as kg SO_2-equivalents per function unit (FU) for the systems studied in Papers I, II and III.

4.3 Discussion of the results

4.3.1 Results compared with diesel

In Figure 10, the results of the environmental impact assessment are illustrated relative to the 1000 ha farm using fossil diesel as tractor fuel. Compared with diesel, all the renewable fuel scenarios studied had a lower impact on global warming. However, the eutrophication potential in the systems studied in Paper I was larger than for fossil diesel. In terms of acidification, all the biomass-based fuel alternatives had a lower impact except for RME due to high fuel utilisation emissions.

It is important also to note that the use of fossil energy is strongly reduced in all the biomass alternatives studied compared with the use of diesel based on fossil oil.

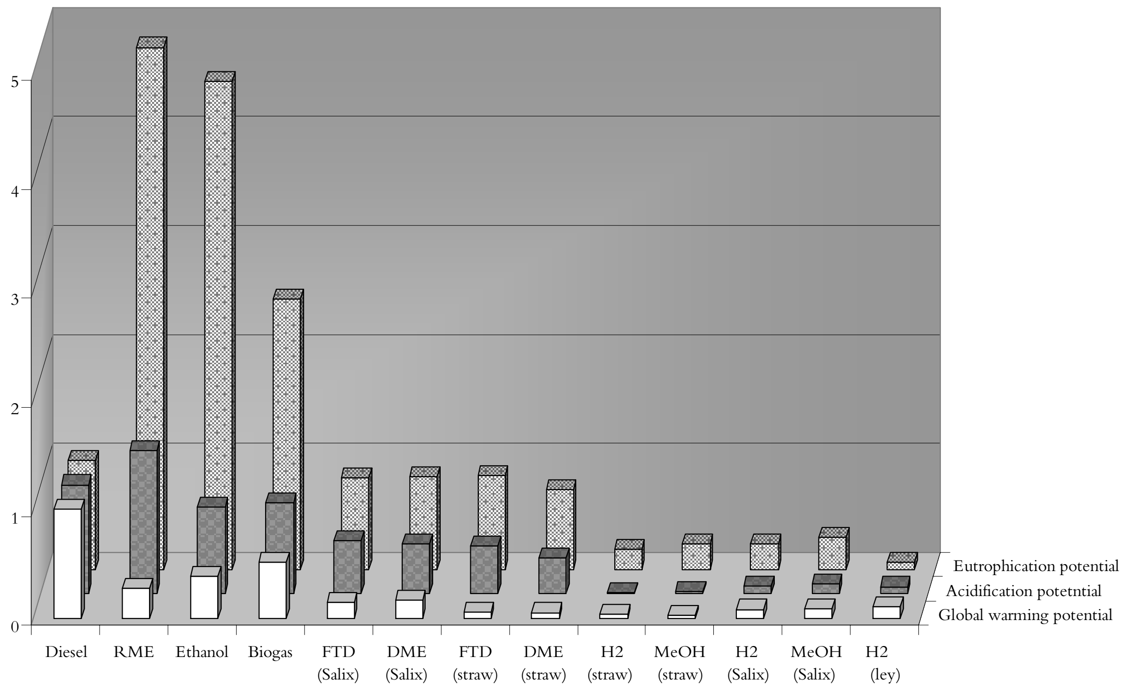

Figure 10. Environmental impact in the scenarios studied relative to the fossil diesel reference.

As mentioned earlier, the system boundaries were different in the different studies, complicating comparisons between the papers. One such assumption was the soil emissions in the ley scenarios and the energy supply for fuel production. A few more issues that can affect the results are discussed below.

4.3.2 Including machinery

The input energy needed for the production of buildings and machinery was not included in these studies. The energy for manufacturing of machinery has been studied in the literature but the results vary, mainly due to assumptions on the lifetime of machinery and the energy requirement for steel production (Mikkola & Ahokas, 2010). Börjesson (1996) studied the energy input for a number of different crops and reached the conclusion that machinery accounted for 5-15% of total energy input in crop production. In studies by Bernesson *et al.* (2006) and Bernesson *et al.* (2004), the machinery in production of RME and ethanol accounted for 1-2% of total energy input.

What is interesting for the present study is to identify any differences in energy input and emissions during manufacturing of ICE and FC tractors. In a study by Pehnt (2001), the production of fuel cell stacks made up 10-23% of total GHG emissions from an FC vehicle running on hydrogen or methanol produced from natural gas. The study was based on the existing composition of FC stacks, not optimised for weight or material usage. According to Ally & Pryor (2007), future generations will use different design concepts that will make many of the present components obsolete and dramatically improve energy efficiency. Furthermore, manufacturing is an emerging technology that can be improved in large-scale applications. In a more optimistic study by Hussain *et al.* (2007), no significant difference was found in energy use and GHG emissions from the manufacture of FC and ICE vehicles over their life cycle.

In conclusion, the energy and environmental costs for machinery are quite low in most studies. The difference between a tractor with FC and ICE propulsion is difficult to assess, but most likely there is no substantial divergence in a long-term perspective.

4.3.3 Economic allocation and price fluctuations

In Papers I-III, economic allocation was used as a base case for handling of by-products. In Paper I, by-products from fuel production were allocated; distillers' waste from ethanol production, rapeseed expeller and glycerine from RME production and digestate from biogas production. No sensitivity analysis was carried out in Paper I, but in a study by Fredriksson *et al.* (2006) the same systems were considered (RME, ethanol and biogas) but for on-farm fuel production. The results are comparable for the two studies. In Fredriksson *et al.* (2006), a 20% change in oil price and rapeseed expeller gave a 9% change in energy use and environmental impact. In the biogas case, a 20% change in the price of digestate gave a 3% change in energy use and environmental impact.

The sensitivity to assumptions on the economic value of the by-products was also tested in Papers II and III for the global warming potential results. The FTD process was assumed to give rise to a large amount of by-products, mainly naphtha and electricity. A 20% change in naphtha price only gave a 3% change in GHG emissions, while a 20% change in electricity price gave a 8% change in GHG emissions. In several scenarios straw was used as raw material for fuel production. Straw was allocated a share of the environmental impact of crop production. A 20% increase in straw price gave a 7-10% increase in GHG emissions.

In conclusion, utilising economic allocation involves making assumptions on price levels of the products. It is therefore important to test the sensitivity of the system to fluxes in price. However, in the scenarios studied here, a 20% change in price for selected parameters did not change the general conclusions of the studies.

4.3.4 Soil carbon and nitrous oxide

Including changes in soil carbon can have large effects on the results. In the scenarios studied in Paper I, no changes were made compared with normal cash crop production that could change the soil carbon content in the ethanol and RME scenarios. In the biogas scenario, ley was harvested and the digestate allocated from the system. However only 35 ha of 286 ha ley were assumed to be harvested per year and a large share of the carbon was probably retained in the roots (Torssell *et al.*, 2007) so the extent to which this will influence the soil carbon content is uncertain. In Papers II and III, straw was removed from parts of the winter wheat and rye fields, which could have a negative impact on the soil carbon content. However, in an organic crop rotation with a large proportion of green manure, the soil organic matter content will be relatively high (Röing *et al.*, 2005; Freibauer *et al.*, 2004) and removing a small proportion of the available straw will be of minor importance. In Papers II and III scenarios were studied where part of the cultivated area was assumed to be taken out of the crop rotation to grow Salix, a crop with a lifetime of at least 20 years. This could have an impact on the soil carbon content. In the sensitivity analysis in Paper III, the effect of an increase in soil carbon of 133 kg C ha^{-1} $year^{-1}$ was to lower the global warming impact of the Salix scenarios by 61-69%.

The direct and indirect emissions of nitrous oxide gave a large contribution to the global warming impact, especially when utilising cash crops (rapeseed and winter wheat) for fuel production. Salix production also gave emissions of nitrous oxide, mainly due to unharvested leaf litter. However, there are great uncertainties in the quantification of N_2O emissions. As an example, the emissions factor for direct N_2O emissions was set to 0.8% of applied N as recommended in the Swedish national inventory report, but the uncertainty in this emissions factor is estimated to be 80% (Naturvårdsverket, 2009a). In Papers II and III, a 20% reduction in N_2O emissions tested in the sensitivity analysis gave a 7-16% reduction in global warming impact potential.

In conclusion, nitrous oxide emissions from soil played a crucial role for the global warming impact results. Including soil carbon changes could also affect the results, especially in the Salix scenarios. However, nitrous oxide and carbon emissions from soil are very difficult to determine with high accuracy.

4.3.5 Choice of functional unit

The functional unit was chosen based on a farmer's perspective. A farm has a given amount of land, in this case set to 1000 ha. If the farm wants to be self-sufficient in tractor fuel, raw material production has to take place within this available land.

However, this complicates the comparison between the alternative fuels studied here, as there are different amounts of cash crop outputs from the systems. In the straw and ley scenarios, the output is the same as in a situation without fuel production. In the scenarios with wheat and rapeseed part of the output is used for fuel production, while in the Salix scenarios part of the cultivated area is taken out of the crop rotation. It could be argued that the reduced output of crops simply reduces the grain surplus on the world market. During the first years of the 21st century cereal consumption exceeded production, forcing a depletion of world stocks. During the last couple of years, however, production of cereals has been higher than consumption (FAO, 2009).

However, it could also be argued that the crops will be produced somewhere else, leading to indirect land use. In the sensitivity analysis in Paper III, the changes in global warming potential were studied when the reduced amount of output crops due to Salix cultivation was accounted for. It was assumed that the missing output was replaced by winter wheat conventionally grown in Sweden on existing farm land. The sensitivity analysis indicated that the results for the Salix scenarios doubled when the cultivation of wheat to compensate for the reduced output was included. However, since the GHG emissions were already very low compared with the diesel reference scenario, this did not affect the conclusions of the study.

Furthermore, transport energy was not included in the functional unit, but considered as an external energy input. The required transport work is different in the systems depending on the assumed transport distance, bulk and moisture content of the raw material and the energy density of the fuel. If the fuel needed for transport had been included in the functional unit, the differences in transport requirements would have been reflected in the land use, and consequently in the environmental impact categories.

In LCA of agricultural products the functional unit is often expressed as a hectare or a kg crop. When it comes to biofuels the functional unit is often a MJ. None of these functional units would have been suitable for the present study. In addition, there are few LCA of agricultural systems with which to make comparisons. However, in a paper by Halberg *et al.* (2008), in which a Danish organic farm producing its own energy was studied, the energy use and GHG emissions were evaluated. The functional unit was defined as a 39 ha organic farm unit and two alternative crop rotations for bioenergy production were modelled, where the production of crops was reduced. It was assumed that the reduced production of crops was silage barley in the base case used as feed on the farm. The reduced amount of barley was replaced by import of the missing amount from a system outside the farm.

In conclusion, the functional unit in the present study was well chosen, but it would perhaps have been appropriate to include the indirect land use, unless it can be proven that the reduced output reduces a grain surplus on the world market. Alternatively, another functional unit could have been chosen in which the same amounts of output crops were produced in all the systems and where the renewable fuel for both tractors and transport was included.

4.4 Discussion of the techno/economic systems

It is not only the energy balance and environmental impact that needs to be evaluated for the biofuel systems, since it is equally important that the systems can be implemented in practice, that they are robust and user-friendly and that the costs are reasonable. In general, liquid fuels are easier to handle than gaseous fuels. For gaseous fuels, delivery to the farm, storage and re-fuelling are more complicated than for liquid alternatives. The working range of gas-powered tractors is also shorter, requiring frequent refuelling. If costs allow, a solution for distribution of fuel could be a pipeline to the farm. For new tractors that do not need to be retro-fitted with gas tanks, the amount of on-board gas could be increased. For hydrogen, the high conversion efficiency in fuel production and use in fuel cells could motivate such technical solutions.

The annual costs for raw material and fuel production, transport of raw material and fuel, farm storage costs and eventual costs for modification of tractors for the new fuels were evaluated in Paper I. The calculated costs of RME, ethanol and biogas systems were €94 200, €72 950 and €111 240, respectively. Using diesel, the annual costs would have been €33 545 based on a diesel price of € 0.6 per litre.

For the more futuristic systems described in Paper II the corresponding costs were estimated to be €30 780 and €26 050 for FTD from gasification of straw and Salix, respectively. For DME the costs were evaluated at € 32 040 and €30 120 from straw and Salix, respectively (Ahlgren *et al.*, 2007). This is based on assumptions of future development of fuel production technology and commercialisation.

The systems described in Paper III are of high technological complexity, for example concerning the hydrogen infrastructure and fuel cell technology. These systems will need some years before they reach commercial-scale production. It is therefore difficult to evaluate the costs and the extent of development of surrounding technological systems that could facilitate a transition to an energy self-sufficient farm.

The fuel production plants studied in the gasification scenarios are very large-scale in order to cover the high investment costs required for the gasification and cleaning equipment. However, this imposes special requirements on biomass logistics, especially for straw, which is a bulky material. One way to solve the large-scale biomass supply at a reasonable cost could be to use transport means other than trucks, such as train and boat. The storage of biomass at large-scale facilities is also an issue which needs be addressed further.

4.5 Conclusions of Papers I, II and III

It can be concluded that it is difficult to compare first and second generation fuels, as they have different intrinsic values. For example, second generation renewable fuels are not produced on a commercial scale yet, and the modelling reported in the literature on the plausible yield of the fuels often assumes production plants that are self-sufficient and energy-optimised.

Furthermore, methodological choices made in the studies, for example choice of functional unit and not including soil carbon in the calculations, rendered comparisons between the fuels complicated. However, even when these assumptions are taken into account it can be concluded that compared with the diesel reference, use of fossil fuel was greatly reduced in the scenarios studied. The global warming potential was also lower in all scenarios, but in some cases the eutrophication and acidification potential could be higher. The second generation renewable fuels studied in Papers II and III based on thermochemical gasification generally performed better in all environmental categories than the first generation renewable fuels. The use of straw or ley as raw material is especially attractive, as it does not require land to be set aside for fuel production. When crop residues or ley were not utilised as raw material for fuel production, the land use varied between 1.8% and 5.4% for the 1000 ha organic farm self-sufficient in tractor fuel.

5 Mineral nitrogen from biomass (Papers IV and V)

5.1 System description

Two different routes for production of biomass-based nitrogen and four different raw materials were studied (Figure 11). In Paper IV, thermochemical gasification of straw and Salix was considered. The biomass was assumed to be transported to a large-scale facility where gasification and nitrogen production were also assumed to take place. This made it possible to match the energy flows of the different processes.

In Paper V, regional-scale production of biogas via anaerobic digestion of ley and maize was studied. The biogas was assumed to be injected into a gas grid and the nitrogen to be produced elsewhere, this because the optimal scale of nitrogen production is much larger than the optimal scale of biogas production.

To cover the crop fertiliser requirements, ash produced in the gasification process and digestate from the biogas process were assumed to be returned to the crop production. Furthermore, a fraction of the ammonium nitrate produced was assumed to be used in the cultivation. A reference scenario with natural gas as raw material for ammonium nitrate production was also studied.

The functional unit in both studies was 1 kg of fertiliser nitrogen, as ammonium nitrate (3 kg AN, 33.5% N) at the gate of the production facility.

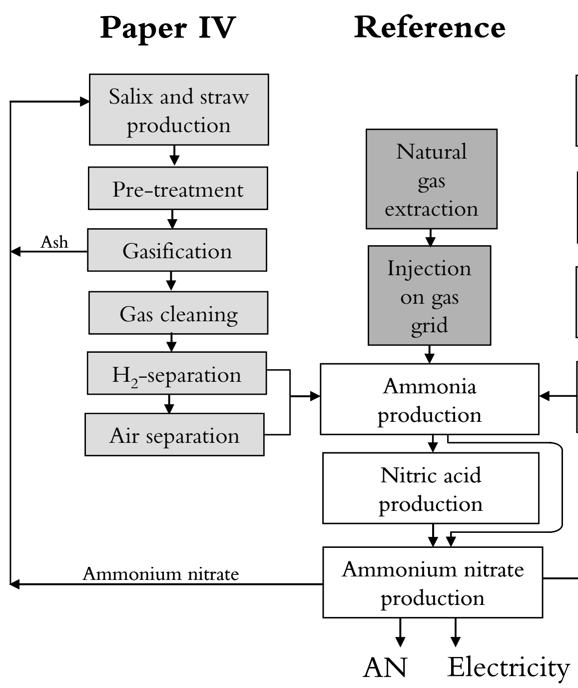

Figure 11. Flow chart of the systems studied in Papers IV and V. The end products of the systems are ammonium nitrate (AN) with 33.5% nitrogen content and electricity.

5.2 Results

5.2.1 Fossil energy input

The allocated primary fossil energy input for the reference case natural gas-based ammonium nitrate was calculated to be 34.6 MJ per kg nitrogen. The allocation was based on the economic value of the nitrogen and electricity produced. For straw and Salix the corresponding values were 1.3 and 1.2 MJ per kg nitrogen, respectively. For ley and maize, the primary fossil energy input was calculated to be 3.7 and 2.3 MJ per kg nitrogen as ammonium nitrate, respectively.

5.2.2 Land use

The amounts of nitrogen calculated to be produced per hectare before and after reduction for ammonium nitrate returned to the cultivation are presented in Table 8. The nitrogen requirement in the straw case was based on the allocation between winter wheat and straw. Salix is a plant with low nitrogen requirements. Ley and maize have higher nitrogen requirements but a large proportion of these requirements were covered here by return of the digestate. Salix has the highest nitrogen production per hectare due to high yields (10 ton dry matter per ha and year was assumed) and high conversion efficiency. For straw, 4.3 ton dry matter was assumed to be collected per ha. Ley has a lower production potential compared with maize due to lower crop yield and lower methane production potential. The ley yield was assumed to be 6 ton dry matter per hectare and year and the maize yield 10 ton.

Table 8. *Gross amount of nitrogen in the form of ammonium nitrate (AN) assumed to be produced per hectare, the amount returned to crop production and net production in the different scenarios. In the anaerobic digestion scenarios, nitrogen is also returned via the digestate*

Raw material	Biomass conversion technology	Gross production (kg N/ha)	Returned AN to crop production (kg N/ha)	Net production (kg N/ha)
Straw	Gasification	1624	9	1615
Salix	Gasification	3978	64	3914
Ley	Anaerobic digestion	1680	40	1640
Maize	Anaerobic digestion	3612	43	3569

5.2.3 Global warming

The calculated impact on global warming potential is presented in Figure 12. In the natural gas scenario, the impact originates from carbon dioxide emissions in ammonia production and from nitrous oxide emissions in nitric acid production. In the biomass scenarios, the cultivation of raw material made a large contribution to the global warming potential, mainly due to nitrous oxide emissions from soil.

Nitrous oxide emissions from nitric acid production occur in both the natural gas and the biomass scenarios. In the ley and maize scenarios, methane leakage from biogas production and emissions from stored digestate also contributed to global warming and are included here in the nitrogen production bars in Figure 12.

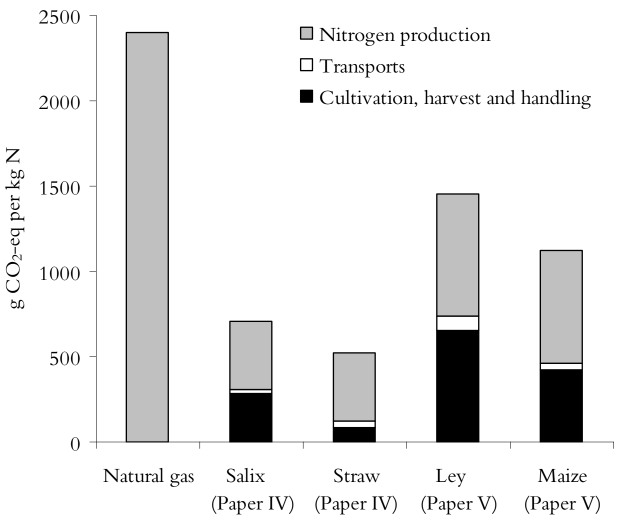

Figure 12. Contribution to global warming potential (kg CO_2-equivalents per kg N) from the scenarios studied in Paper IV and V.

5.2.4 Eutrophication

The eutrophication potential impact of the scenarios studied is shown in Figure 13. The main contribution in the biomass systems comes from soil emissions due to leaching of nitrogen and to some extent phosphorus. Salix has low leaching of nutrients since it is a perennial crop with low nutrient requirements and deep roots, allowing for efficient uptake of nutrients. Based on the economic value of crop and straw, the straw scenario was allocated only part of the soil emissions from wheat production. Together with high efficiency in the conversion to nitrogen, this explains the low leaching emissions in the Salix and straw systems. Maize, which is a spring-sown crop, has higher nitrogen requirements and nitrogen leaching per hectare than ley. However, because of the higher crop yield and higher biogas yield for maize, the difference evened out in the end results for the two scenarios.

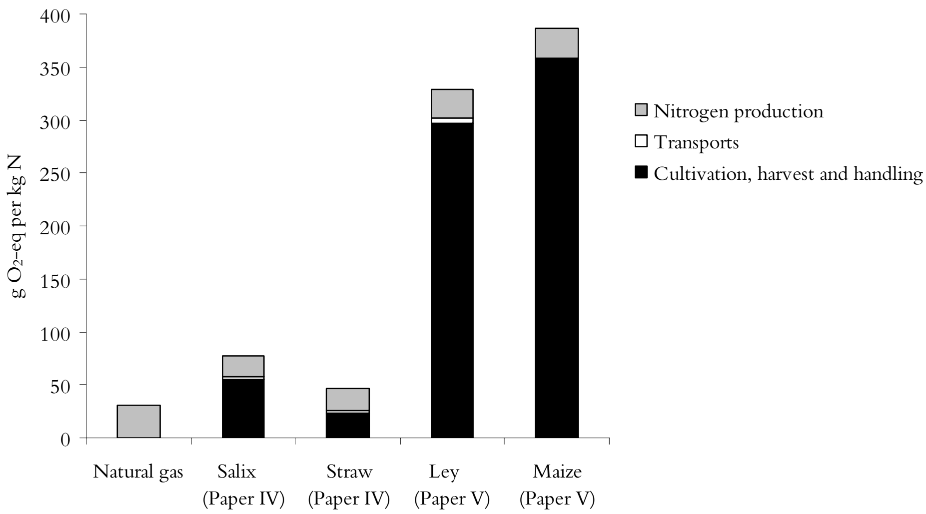

Figure 13. Contribution to eutrophication potential (kg O_2-equivalents per kg N) from the scenarios studied in Papers IV and V.

5.2.5 Acidification

The contribution to acidification potential of the scenarios studied is shown in Figure 14. In the ley and maize scenarios, the contribution was higher than for the other systems studied. This was mainly due to the spreading of digestate during cultivation, which gave rise to ammonia emissions. Emissions from nitrogen production also contributed to acidification, mainly due to ammonia emissions from the production facility.

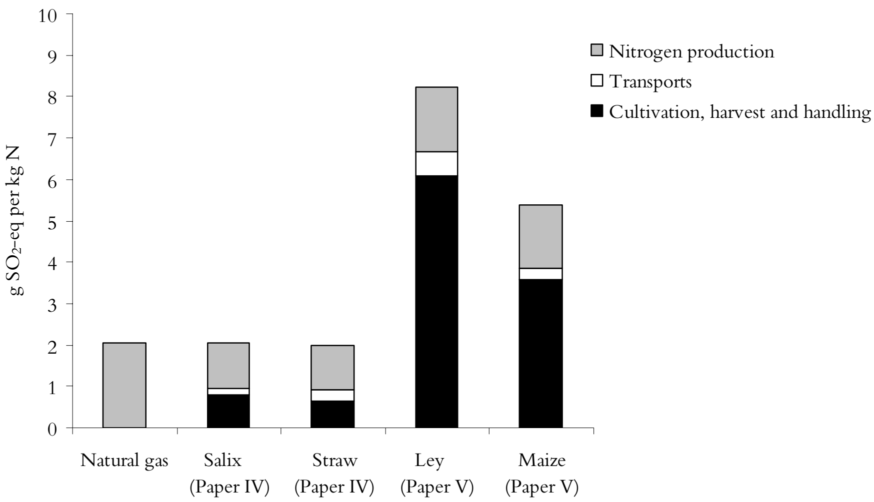

Figure 14. Contribution to acidification potential (kg SO_2-equivalents per kg N) from the scenarios studied in Papers IV and V.

5.3 Discussion of the results

The biomass to nitrogen systems studied here were all calculated to lower the impact on global warming compared with natural gas-based nitrogen. The eutrophication and acidification potential were found to be higher in the scenarios based on ley and maize than for the natural gas reference scenario. However, the use of fossil resources was much lower in the biomass-based systems. The trade-off between different impact categories is further discussed in Section 6.6.

In the biomass to nitrogen systems, nitrous oxide emissions from soil gave a large impact on the global warming results, especially in the ley and maize scenarios. However, these emissions are very difficult to estimate. The nitrous oxide emissions from soil were calculated with the emissions factors stated in IPCC (2006), which also gives an uncertainty range for these factors. In the sensitivity analysis in Paper V, tests on the uncertainty range of the emission factors showed that the variation in global warming was so large that it could offset the entire reduction in global warming impact of using ley as raw material for nitrogen production.

However, there is also the matter of deciding the fossil reference scenario. In this case, best available technology was chosen for natural gas-based nitrogen production. When producing nitric acid, nitrous oxide is formed. In older production plants these emissions to air can be large, but in the present study it was assumed that modern emissions abatement techniques were used, greatly lowering the N_2O emissions. In terms of energy and feedstock consumption, new plants are better optimised in ammonia conversion and with energy recovery. In a modern natural gas to ammonia plant, approximately 82% of the gas is used as feed and 18% as fuel. In a study by Jenssen & Kongshaug (2003), the emissions when producing ammonium nitrate with old technology would result in 7.5 kg CO_2-equivalents per kg N, while a plant with new technology would generate 3.0 kg CO_2-equivalents per kg N.

In Paper IV, which dealt with emerging technologies for biomass conversion, it could be useful to have a high-tech fossil reference scenario. In Paper V, however, it is perhaps better to use present technology for the fossil reference scenario. As there are still many old plants running, the European average in 2003 was 6.8 kg CO_2-equivalents per kg N (Jenssen & Kongshaug, 2003) However, much has happened since then. The technology for emissions abatement has been further developed and another driver is that the fertiliser industry is nowadays included in the European greenhouse gas emission rights trading scheme, making it profitable for producers to reduce their emissions of nitrous oxides. It is therefore difficult to determine what the present fossil reference should be. The main supplier of fertilisers on the Swedish market states that the GHG production of nitrogen fertiliser in 2010 will be 2.9 kg CO_2-equivalents per kg N (Ahlgren *et al.*, 2009b), but the European average could be higher. An assumption that 10% of the ammonium nitrate delivered is produced with old technology (7.5 kg CO_2-eq per kg N) and 90% with new technology (2.9 kg CO_2-eq per kg N) results in an average figure of 3.4 kg CO_2-eq per kg N. This could be a better comparison for the results in paper V.

5.4 Conclusions of Papers IV and V

Papers IV and V show that great potential exists to produce mineral nitrogen based on gasification and anaerobic digestion of biomass. The crops studied were able to produce between 1.6 and 3.9 tonnes N per hectare in the form of ammonium nitrate. The use of fossil fuels can then be largely reduced, as well as the contribution to global warming. However, there is a risk that the contribution to eutrophication and acidification will increase in the biomass systems compared with the natural gas reference. Of the systems studied here, gasification of straw and Salix performed best. This was mainly due to high energy and nutrient use efficiency in the production of raw material, as well as high conversion efficiency to nitrogen.

6 General discussion

6.1 The concept of self-sufficiency

The concept of self-sufficiency in power on farms is not new. Before tractors came into common use, draught animals were used for field work. Part of the land then had to be set aside for producing feed for these animals. In a large part of the world, this is still the case.

Self-sufficiency can be considered on different scales, for example on farm, regional and national level. In Papers I-III, the self sufficiency was considered on farm scale. However, the farm was regarded as part of a larger fuel production system. The crops were transported to a large-scale facility and converted to fuels, allowing more energy-efficient conversion than if done on-farm. The organic farm was also self-sufficient in nitrogen by cultivating nitrogen-fixing ley in the crop rotation.

In Papers IV and V the self-sufficiency was not explicitly defined, but was regarded as more regional or national self-sufficiency. However, the concept of farm-scale self-sufficiency could also be applied to nitrogen fertiliser production. A conventional farm could then be self-sufficient in both fuel and nitrogen by delivering a certain amount of crops to the industry.

Why is it anyway important that agriculture is self-sufficient in energy, included embedded energy in nitrogen? There are a number of reasons for this. First, fossil fuels will run out sooner or later and agriculture, like the rest of society, will then have to look for other alternatives. Second, there is a general aim to reduce the environmental impact from agriculture. Third, if primary production (agriculture) is self-sufficient, it can deliver 'clean' products such as food and energy to the rest of society. This can be used as an added marketing value. For organic farming, the concept of self-sufficiency is particularly important since one of the basic principles in organic production is to use renewable and local resources. Fourth, it is a matter of food security. If the agricultural sector has a self-sufficient functional system, it will be less sensitive to instability on the oil and gas market. In a crisis situation, food production can then be secured with a reliable supply of fuel and nitrogen.

The extent of self-sufficiency achieved can be debated. A farm can never be completely independent of the surrounding society, as there will always be certain product (energy) flows to the farm. For example, manufacture of the tractors was not included in this study on self-sufficiency in renewable tractor fuel. The fuel for transporting the raw material to the fuel production plant and the fuel back to the farm was also not included in the self-sufficiency, but was counted as an external energy input to the system. Although some of these choices of system boundaries are debatable, as I see it there is no point in trying to be completely independent of the rest of the world.

Another alternative for farm self-sufficiency in fuels discussed in Paper I is the possibility of exchanging fuels. This is based on the fact that some fuels are less suitable for farms and more suitable for city vehicles. For example, ley is a good substrate for biogas production and can easily be grown within both conventional and organic crop rotations. However, the utilisation of biogas in tractors is quite expensive and complicated. If a biogas reactor is installed on the farm, there is a mismatch between biogas production and peak fuel requirements during spring and autumn. If biogas production is centralised, the biogas somehow has to be transported out to the farm, which could be a very expensive system. The fitting of gas tanks on tractors and the short range of gaseous fuels is another problem. The idea behind fuel exchange is that the farm delivers ley for biogas production, but instead of using biogas in the tractors, the farm can use the equivalent amount of another type of fuel better adjusted to the farm conditions. Paper I showed that in general, the scenarios based on fuel exchange were cheaper for the farm than the base case scenarios. The most economically favourable scenario was to sell biogas raw material to a plant and fuel the tractors with RME bought on the market.

6.2 Amount of biomass needed for tractor fuel and nitrogen

This thesis studied production systems for tractor fuel and nitrogen based on biomass. How much biomass is then needed to make Swedish agriculture self-sufficient in fuel and mineral nitrogen? As an example with future technology, our hypothetical organic farm self-sufficient in FTD from Salix required 3.8% of the cultivated area. However, this figure cannot be transferred to the entire Swedish agricultural sector since it relates to an organic farm with a specific crop rotation. Fuel consumption was calculated to about 57 litres diesel per hectare in the organic crop rotation studied here, while statistics show that the figure is closer to 100 litres per hectare as an average for all crops. In a study by Ahlgren *et al.* (2009a), the self-sufficiency in tractor fuel of Swedish agriculture was investigated. Using Salix as raw material for FTD, about 203 000 ha would be needed to supply Swedish agriculture with tractor fuel, equivalent to 7.7% of the arable land. In Paper IV, the amount of land required to make mineral nitrogen from Salix for Swedish agriculture was calculated to be around 42 000 ha, equivalent to 1.5% of the arable land. Thus, roughly 244 000 ha of Salix would be required, equivalent to 9% of the arable land. As diesel and nitrogen are the two major fossil energy-consuming items, setting aside this land would mean a large reduction in fossil energy use in Swedish agriculture.

For straw, which does not need land to be set aside, it is more appropriate to discuss the requirement in energy terms. Using straw as raw material for FTD, about 6.3 TWh straw would be needed to supply Swedish agriculture with tractor fuel (Ahlgren *et al.,* 2009a). Using data from Paper IV, 2.1 TWh of straw would be needed to supply Swedish agriculture with nitrogen. Together, roughly 8.4 TWh would be needed, which can be compared with the estimated straw potential of 4-7 TWh per year (see Section 6.4).

6.3 Best use of biomass resources

Is it a good idea to use biomass for transport fuel and nitrogen in order to lower anthropogenic GHG emissions? In a study by Gustavsson *et al.* (2007), a number of different scenarios for the use of biomass in Sweden were modelled. The highest GHG reduction was achieved by expanding the district heating system. Using biomass for heat is also a cost-effective option, which is reflected in the current use of biomass energy. In Sweden, 85% of biomass for energy is used for process heat in industry and in district heating systems, 10% is used for electricity production and 5% for vehicle fuel production (Börjesson *et al.*, 2009).

Even though replacing coal with biomass for heat production gives the largest GHG savings in the short term, the long-term conclusions can be different. It is expected that more transport fuels will be produced on other fossil resources than oil, for example gasification of coal. Biomass could then replace coal for vehicle fuel production with the same reduction potential as coal for heat production (Börjesson *et al.*, 2009).

Maximising the reduction in GHG emissions could be one criterion for best use of biomass. At a time when peak oil production is believed by many researchers to be past or getting close, the replacement rate of oil can be another criterion for best use of biomass. In sectors such as district heating and process heat in industry, oil has to a large extent already been replaced by other energy sources in Sweden. However, the transport sector is still heavily dependent on fossil oil. Replacing oil in Sweden would therefore primarily be aimed at the transport sector. A study by Gustavsson *et al.* (2007) examining the trade-off between oil use reduction and climate change mitigation showed that if a high GHG reduction is aimed for, the oil use reduction is less and *vice versa*. However, aiming for both reduced GHG emissions and oil use led to the following recommendations (Gustavsson, 2008): Replace oil and coal with biofuelled heat and power plants; expand the district heating grid; and replace fossil vehicle fuels with bio-based high efficiency alternatives, namely second generation fuels.

Nitrogen and tractor fuel are vital in maintaining high yields in crop production. It is therefore very important that agriculture continues to have a reliable supply of nitrogen and fuel, with the GHG savings being less important in this context. I therefore suggest that production of nitrogen and tractor fuel should not be regarded as competing with other uses of biomass, but as a fundamental prerequisite for continued production of food and energy for a growing world population. Better yet, the expected future expansion of bio-refineries, producing a combination of vehicle fuels, heat, electricity and/or chemicals, opens new doors. Because of the combination effect, biomass resources can be used to produce vehicle fuels and other products with high energy efficiency and low GHG emissions (Börjesson, 2008). The debate on whether to produce vehicle fuel, heat, electricity or nitrogen is then no longer an issue.

6.4 Availability of land and biomass

As seen in the present study, biomass residues are preferably used in order to avoid competition with food production and indirect land use. The largest agricultural residue source in Sweden is straw from cereal production. The use of straw for energy purposes at present in Sweden is about 0.4 TWh (Bernesson & Nilsson, 2005). The potential yield is difficult to estimate, as it is dependent on the amount of land used for straw-producing crops, the need for straw as a bedding material, the weather conditions during harvest and how often in a crop rotation removal of straw can be done without negative ecological consequences. Bernesson & Nilsson (2005) estimate the potential for straw as fuel to be 4 TWh per year, Börjesson *et al.* (2008) estimate it to be 6 TWh per year and the Federation of Swedish Farmers (Herland, 2005) estimate it to be 7 TWh per year.

During 2006, 1.2 TWh biogas was produced in Sweden, the majority from sewage sludge. Only 14 GWh biogas was produced from agriculture during 2006 (Englesson, 2009). The potential is however estimated to be much larger, 6.6 TWh per year from agricultural residues (87% from straw) and 4.1 TWh from manure (Avfall Sverige, 2008). This can be compared with the use of natural gas, which was 11 TWh in Sweden during 2007 (Energimyndigheten, 2008).

At present, Salix is cultivated on about 15 000 ha (SOU, 2007) in Sweden. However, there is an expectation that Salix cultivation will expand rapidly in coming years. According to the Federation of Swedish Farmers (Herland, 2005), by the year 2020, 100 000 ha of Salix may be grown, equivalent to about 4 TWh annual production. More optimistic projections by SOU (2007) estimate 200 000 ha Salix by 2020. Fallow land could be used for cultivation of Salix or other bioenergy crops. In the European Union, it was obligatory in the past to keep land in fallow (set-aside) in order to reduce overproduction of agricultural products. However, this rule was removed in 2007 and since then the area of set-aside has decreased. During 2008 set-aside land comprised 6% (150 000 ha) of arable land in Sweden (SJV, 2009b).

On a global scale, the consumption of biomass energy is at present 50 EJ or 14 000 TWh, which corresponds to 10% of global annual primary energy consumption. This is mostly traditional biomass used for cooking and heating (IEA, 2009). The future potential for bioenergy has been estimated in several studies (see for example Dornburg *et al.* (2008), Berndes *et al.* (2003) and Hoogwijk *et al.* (2003) for reviews). The results vary between very low potential (for example 27 EJ in Field *et al.,* 2008), and very high potential (for example up to 1548 EJ by 2050 in Smeets *et al.,* 2007)). The results are dependent on a number of assumptions, one of the most important being the expected yield increase. In large parts of the world there is doubtless great potential to increase yields with mechanisation, use of fertilisers and irrigation. If productivity in food production increases, there will be more land available for bioenergy production. For example, Smeets *et al.* (2007) estimate that in 2050, food demand can be met by reducing the food production area by 72% compared with today's land use for food. The potential is also dependent on future changes in world population and dietary choices. Stehfest *et al.* (2009) estimate that by 2050 an extra 40 EJ per year bioenergy could be produced globally with a restricted meat diet compared with a future with business as usual. When estimating the global biomass potential, the outcome is also dependent on natural restrictions imposed concerning for example protection of high biodiversity areas. van Vuuren *et al.* (2009) claim that many studies overestimate the bioenergy potential, since factors such as water scarcity, land degradation and protection of high bio-diversity areas are overlooked. van Vuuren *et al.* (2009) approximate the global bioenergy potential to 150 EJ by 2050, but 80 EJ of this would not be suitable for production due to land degradation, water stress and biodiversity issues.

Another question related to future competition of land is weather we should be practicing organic agriculture, should we not try to maximise the production per unit of land? In a study by Wolf *et al.* (2003), the future global bioenergy potential in the year 2050 was studied based on two different types of agricultural systems; one high external input and one low external input system (similar to organic production). In the high external input scenario it was found that plenty of land could be released for bioenergy production, while in the low input scenario, no land at all was found to be available for bioenergy. However, there are other studies that claim that organic agriculture has great potential to feed the world and produce bioenergy (Badgley *et al.*, 2007; Halberg *et al.*, 2006). This is mainly based on the assumption that organic agriculture can increase yields compared with conventional low input practices in developing countries. This assumption on yield increases has been criticised (see for example Connor (2008) and Kirchmann *et al.* (2008)). However, it is not certain how an increase or decrease in production in a certain part of the world will affect the problems of global food and bioenergy supply. As Halberg *et al.* (2009) point out, at present we have enough food in terms of calories and protein to feed the world population, and yet there are almost 850 million starving people on this earth.

6.5 Constraints on transition to fossil fuel-free crop production

There are a number of technical constraints on transition to fossil fuel-free crop production. Biomass gasification was studied here for production of both tractor fuel and mineral nitrogen, but the technology for thermochemical gasification of biomass is still being developed. The main technical problems relate to the ash content of biomass, giving for example problems with sintering, deposition and corrosion. Tar formation is also a problem, leading to a need for complex tar removal systems as well as lower yield of syngas (Wang *et al.*, 2008). Difficulties in handling multiple varieties of biomass also limit the commercialisation of gasification technology (Digman *et al.*, 2009). Furthermore, biomass gasification plants need to be large-scale because of the high investment costs, which places extra requirements on the logistics system.

For implementation of biomass-based nitrogen fertilisers on farms, no changes would have to be made concerning the use phase, as the nitrogen is exactly the same as in the fossil alternative. For some of the tractor fuels studied, however, technical changes would be required in storage, refuelling and use in tractors. From the farmer's point of view, gaseous fuels such as hydrogen and biogas are difficult and more expensive to handle than liquid alternatives.

There are also a number of non-technical constraints on transition to fossil fuel-free crop production, the most obvious being the costs. Fossil fuels have long been so cheap that it has been difficult for alternatives to compete without subsidies and tax breaks. Funding for demonstration projects has also been limited, slowing the rate of technological learning needed for development of emerging technologies like biomass gasification and fuel cell technology.

The potential of expanding Salix cultivation is large, as mentioned previously. However, even though Salix plantations often show better profitability than conventional food crops, the increase in acreage grown has been much slower than anticipated (SOU, 2007). One explanation for the lack of enthusiasm from farmers could be that Salix has a life span of over 20 years, which lowers the flexibility of the land use. Since the political and economical arena is constantly changing, the subsidies and the profitability can be difficult to assess for such a long term commitment. One way to get around the problem of risky investment is to cultivate energy cops on contract. This is already the case with most Salix plantations in Sweden. The farmer plants and grows the Salix and the contractor harvests and transports the crop. The advantage for the farmer is that there is a guaranteed market and that no investment has to be made in specialist harvesting machinery.

There is also a land ownership issue. In Sweden, 45% of farm land is leased (tenancy agreements). Contracts usually run for one to five years, making it difficult to make long-term investments. It can also be difficult to lease land for cultivating energy crops. In a survey commissioned by Paulrud & Laitila (2007) in which landowners were asked about their willingness to lease their land for energy crops. Only 4% of the asked land owners where willing to lease land for Salix cultivation. For one-year crops such as wheat for ethanol production, the corresponding figure was much higher (25%). In the study by Paulrud & Laitila (2007), farmers were also asked whether they would consider planting bioenergy crops and 43% answered no. The reasons stated were mostly a combination of things, but the most important were low profitability (39%) and a belief that agricultural land should be used for food production (32%). This reveals that traditional opinions on how farm land should be used are just as important as hard facts about profits.

6.6 Weighting of environmental impact categories

As seen in the results of both biomass-based tractor fuel and mineral nitrogen, the contribution to global warming potential was lower than for fossil fuel alternatives. However, the contribution to eutrophication and acidification was often higher, or even much higher, than in the fossil fuel scenario. In a decision on whether to use the biomass alternatives, the question then comes down to the weighting of the environmental impact categories. Several methods exist in LCA for weighting different impact categories against each other. All weighting models are in principle built on ethical, moral and ideological values. The choice of weighting method is in itself an act of valuation. The different weighting methods can in general be divided into panel and monetisation methods. In the panel method a group of people are asked about their values and these are translated to weighting factors. Monetisation methods can for example be based on willingness to pay or how ecotaxes in a society are distributed (Finnveden *et al.,* 2009). Weighting different environmental impacts, regardless choice of method, is a controversial and difficult issue.

Without any scientific evidence, global warming seems to weigh heavily at the moment. To mention one example, the European Union has launched sustainability criteria for biofuels (European Parliament, 2009). These state that areas with high biodiversity or high carbon stocks must not be used for biofuel crop production and that the GHG emissions must be lowered by 35% compared with a fossil fuel reference scenario. However, nothing is said about other environmental effects such as eutrophication and acidification. One explanation could be that acidification and eutrophication are more regional problems, while GHG emissions pose global problems. As we live in a globalised era, it is perhaps natural that global problems receive more attention.

It is also possible to consider the use of fossil resources as an impact category. This thesis shows that utilising biomass for the production of tractor fuel and nitrogen lowers the use of fossil resources, even when the fossil energy used in biomass production is accounted for. In a future with diminishing and increasingly expensive fossil fuels this could be one of the determining factors for utilising biomass alternatives.

6.7 The concept of sustainability

The word sustainable is derived from the Latin word *sustinere*, meaning to hold up, support or withstand. Sustainability in agriculture in a broad context has been defined as the use of resources to produce food and fibre in such a way that the natural resource base is not damaged, and that the basic needs of producers and consumers can be met over the long term (Yunlong & Smit, 1994). In practice this could of course mean a number of things and will vary both temporally and spatially (Rigby & Caceres, 2001). To assess what is sustainable, very divergent parameters have to be evaluated, for example quantitative science-based data as well as more qualitative data concerning ecosystems, social and normative settings (von Wirén-Lehr, 2001). As Rigby & Caceres (2001) point out, it is only in retrospect that we can identify what sustainable practice is.

For many people, organic agriculture is synonymous with sustainability. This can be questioned, however, since organic farming like conventional farming and any other land use has an impact on the environment, such as emissions of greenhouse gases, nutrient run-off and soil erosion. Organic farming also uses a large amount of fossil fuels. However, the organic movement has identified a number of points of what is considered to be non-sustainable, and by applying a number of principles is trying to move away from these. In other words, organic farming aims at being sustainable, but it can be questioned whether it is in practice. Low-input is also sometimes identified as sustainable. Historically, however, low-input agriculture has in many places been non-sustainable, leading to degradation of soils and thereby civilisations.

Although it seems to be very difficult to determine what sustainable agriculture is, it can be concluded that careless use of limited renewable and non-renewable resources is not sustainable in the long run. A limited resource is fossil fuels. Other limited resources include phosphorus, water and ecosystem services.

Phosphorus, like nitrogen and potassium, is a macronutrient needed for high yielding crop production. Phosphorus is retrieved from phosphate rock, with reserves concentrated in just a few countries. Current global reserves are projected to be depleted in 50-100 years. However, unlike fossil fuels, phosphorus can be recovered from for example human excreta, manure and food residues (Cordell *et al.*, 2009).

Most crop water requirements are met by rainfall. However, 20% of crops worldwide need irrigation, especially in regions like North Africa, South Asia and North China Plains. The irrigation of agricultural land consumes 70% of all the water used by humans (de Fraiture & Berndes, 2009). In a future with expanding bioenergy plantations, the water demand will be even higher. In certain parts of the world, there is a large potential for increased water use (Latin America and sub-Saharan Africa), while in other parts of the world the limit of water exploitation has already been reached (for example in India and China) (de Fraiture & Berndes, 2009).

Ecosystem services are the benefits people obtain from ecosystems and can be seen as a limited resource. Such services include natural medicines, air quality regulation, climate regulation, pollination and soil formation to mention a few (World Resources Institute, 2005). It is clear that without these services, food and bioenergy cannot be produced. Loss of biodiversity is identified in a study by Rockström *et al.* (2009) as one of the most critical factors for a continued safe operating space for humanity.

6.8 Future research

Developments in LCA methodology, especially concerning land use in agricultural LCA, have had a major impact on research. For example, including the change in soil carbon stocks or including indirect land use has been shown in some recent studies to completely change the outcome. In this light, many of the previous biofuel LCA results may have to be revaluated.

In LCA of agricultural systems, nitrous oxide emissions from soil often have a large impact on the results. Unfortunately, these emissions are very difficult to determine. The models that are available are not intended, and often not suitable, for direct application in LCA. Field measurements are costly and the results vary significantly. Detailed models with lower uncertainty in nitrous oxide emissions, adjusted to LCA practices, would increase the usefulness of LCA of agricultural systems.

Oil for drying grain is a large energy-consuming item that was not addressed in this study. For fossil fuel-free crop production, drying or other conservation methods need to be investigated. It would also be interesting to study biomass-based alternatives to silage plastics.

Much research is being conducted on novel technologies for producing renewable vehicle fuels, for example production of methanol from recycled carbon dioxide, biodiesel from algae and hydrogen from artificial photosynthesis. This could be of interest for the agricultural sector, both as producers of raw material and as end-users of the fuel. For mineral nitrogen there are also many alternative production routes which need to be studied, for example utilising electrolysis for hydrogen feedstock production. However, all new solutions need to be studied from a systems perspective in order to highlight any hidden environmental costs.

Before any large-scale implementation of biomass-based tractor fuel or nitrogen production takes place, it would be appropriate to evaluate the practical performance on a demonstration scale, especially concerning the implementation on farm level. The research must be conducted in cooperation with farmers in order to make the systems possible to implement.

Last, I would like to mention the importance of continued comprehensive approach discussions and research of how we in a sustainable way can produce both food and energy for a growing world population.

7 Conclusions and final remarks

From Papers I, II and III it can be concluded that:

- Compared with the diesel reference scenario, the use of fossil fuel can be largely reduced by using farm raw materials to produce tractor fuel.
- Use of straw or ley as raw material is particularly attractive, as it does not require land to be set aside for fuel production.
- When crops were used as raw material for fuel production, the land use varied between 1.8% and 5.4% for the 1000 ha organic farm self-sufficient in tractor fuel.
- The global warming potential was lower in all biomass-based systems studied, but the eutrophication and acidification potential were higher in some cases.
- The second generation renewable fuels studied in Papers II and III based on thermochemical gasification generally performed better in all environmental categories than the first generation fuels.
- It is difficult to compare first and second generation fuels as they have different intrinsic values. For example, second generation renewable fuels are not yet available on a commercial scale and fuel yield predictions often assume plants that are optimised and self-sufficient in energy.
- Methodological choices made in the study, for example choice of functional unit, complicated the comparisons between the fuels.
- On the farm, liquid alternatives are easier and less costly to use than gaseous fuels.

From Papers IV and V it can be concluded that:

- The use of fossil fuels can be largely reduced by utilising biomass for production of mineral nitrogen.

- If ley and maize are used as raw material to produce biogas through anaerobic digestion, and the biogas to produce ammonium nitrate, approximately 1.6 and 3.6 ton of N can be produced per hectare from ley and maize, respectively.
- If straw and Salix are gasified to produce hydrogen, and the hydrogen used to produce ammonium nitrate, approximately 1.6 and 3.9 ton of N can be produced per hectare from ley and maize, respectively.
- The global warming potential was lower in all biomass-based systems studied. However, there is a risk that the contribution to eutrophication and acidification will be greater in the biomass systems compared with the natural gas reference scenario.
- Of the systems studied, gasification of straw and Salix performed best in the environmental impact categories. This was mainly due to high energy and nutrient efficiency in the production of raw material, as well as high conversion efficiency to nitrogen.

It is clear that the agricultural sector has great potential to reduce its use of fossil fuels and to lower emissions of greenhouse gases by utilising biomass resources. Scaling up the results for self-sufficiency on a national level was not feasible, but by using results from other studies it was estimated that Salix cultivated on 9% of the arable land would be sufficient to supply Swedish agriculture with both tractor fuel and nitrogen. It was argued that producing nitrogen and tractor fuel from biomass should not be regarded as competing with other uses of the biomass, but as a prerequisite for continued production of food and energy for a growing world population.

However, there are many other issues to deal with in sustainable production of crops, for example use of limited resources such as fresh water, phosphorus and ecosystem services. Furthermore, in many of the biomass systems studied here, the eutrophication and acidification emissions were larger than in the fossil reference scenarios. These emissions will have to be reduced or to be weighted lower than global warming. The use of fossil oil for grain drying is another issue that needs to be addressed. In addition, there are a number of technical constraints to overcome, as well as economic and social non-technical constraints. Seen on a global scale, agriculture also has to deal with difficult issues such as resource distribution and the protection of soil and biodiversity. Last but not least, we all need to take responsibility for our common future by wasting less food and making active consumer choices, such as eating less meat.

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