Farm-scale Production of RME and Ethanol for Heavy Diesel Engines

- with Emphasis on Environmental Assessment

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Abstract

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Renewable fuels such as rape methyl ester (RME) and ethanol for heavy diesel engines can be produced with different systems solutions regarding *e.g.* scale of production. The main purpose of this thesis was to assess the environmental load during small-scale production of RME and ethanol. This was achieved by carrying out limited LCAs, including air emissions and energy requirements. The influence of using alternative plant sizes and fuel production strategies, as well as systems for making organic farms self-sufficient in farm-produced RME, ethanol and biogas, was also evaluated.

For using natural resources as efficiently as possible, it is important that the machines for making the fuels are optimised. Therefore, the influence of some press parameters on capacity and oil extraction efficiency of a small rapeseed oil expeller was studied. It was found that to achieve a high capacity and a high oil extraction efficiency, the press was best operated with a small nozzle and a rather high screw speed.

On a systems level, the LCAs showed that the dominating step in the production of RME and ethanol was crop cultivation, in which production of fertilisers, followed by soil emissions and tractive power, made major contributions to the environmental load. The differences in environmental impact and energy requirements between small-, medium- and large-scale plants were small for both fuels. The longer transport distances to a certain degree outweighed the higher oil extraction efficiency, higher energy efficiency and more efficient use of machinery and buildings in the large-scale system. The results were largely dependent on the method used for allocation of the environmental burden between the fuels and the by-products, whereas the influence of uncertainty in input data and of some alternative production strategies was small.

For organic farming, the production and use of RME had a favourable energy balance and resulted in valuable by-products, but was less positive in other aspects, while the production of ethanol was very energy consuming. Biogas production had a low relative requirement for arable land and thus lower cultivation and soil emissions. For all fuels studied, the global warming emissions were approximately halved in comparison to conventional farming.

Keywords: oil extraction, rape methyl ester, RME, ethanol, bioenergy, fuel production, life cycle assessment, LCA, small-scale, large-scale, heavy engines.

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Contents

Appendix

Papers I-IV

The present thesis is based on the following papers, which will be referred to in the text by their Roman numerals:

I. Bernesson, S. 1998. Influence of some physical press parameters on capacity and oil extraction efficiency of a small oil expeller. *Swedish Journal of Agricultural Research,* 28, 147-155.

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

III. Bernesson, S., Nilsson, D., Hansson, P-A. 2004. A limited LCA comparing large- and small-scale production of ethanol for heavy engines under Swedish conditions. *Submitted to Biomass and Bioenergy*.

IV. Fredriksson, H., Baky, A., Bernesson, S., Nordberg, Å., Norén, O., Hansson, P-A. 2004. Use of farm-produced bio-based motor fuels on organic farms – evaluation of energy balances and environmental loads for three possible fuels. *Submitted to Agricultural Systems*.

Papers I and II are reproduced by permission of the journals concerned.

Background data to Papers II and III are published in:
Bernesson, S. 2004. Life cycle assessment of rapeseed oil, rape methyl ester and ethanol as fuels – a comparison between large- and small-scale production. *Swedish University of Agricultural Sciences, Department of Biometry and Engineering, Report 2004:01.* Uppsala, Sweden. 273 pp.

Notes on the authorship of Paper IV:
Bernesson contributed to the system description and the input data for the RME and ethanol production plants. He also contributed to the evaluation of the results.

Introduction

Background

Transport is becoming more and more important in society. In Sweden, the consumption of diesel oil and petrol has increased from 47 TWh in 1970 to 73 TWh in 2000 (STEM, 2003a). A changeover to bio-based fuels is therefore an important step towards a more sustainable society. Rapeseed oil, rape methyl ester (RME) and ethanol with ignition improver are possible bio-based fuels that can be used in diesel engines. The production of biodiesel (vegetable oil esters) has increased and was 1.064 million tonnes in the EU in 2002 (EBB, 2003), of which about 3 500 tonnes were produced in Sweden (Norup, pers. comm. 2002). The production of fuel ethanol has also increased and in 2001 was 2.2 million cubic metres produced in the EU, 8 million cubic metres in the USA and 12 million cubic metres in Brazil (Schmitz, 2003). In Sweden, 50 000 cubic metres of ethanol were produced from cereals (mostly wheat) (Agroetanol, 2003) and 13 000 cubic metres of ethanol from wood (Baff, 2003) in 2003.

In 2001, energy use in the transport sector in Sweden was 108.5 TWh, approx. 23% of the total energy use, of which 97% was of fossil origin and 3% electricity for rail transport (STEM, 2003b). In 2002, 0.7% of the fuel energy used for road transport had its origin in biomass (Feldhusen *et al.*, 2004). Globally and in the EU, the transport sector is responsible for 30% of the total energy use. Major work is going on in the EU to increase the use of bio-based fuels. The goal of the Commission is for 5.75% of the total volume of fuels to be of renewable origin by the end of the year 2010 (EC, 2003).

Of the total emissions to air in Sweden in 2000, 33% of the CO_2, 2% of the SO_2, 47% of the NO_x, 56% of the CO and 20% of VOC (volatile organic compounds) had their origins in road traffic (STEM, 2003b). Here, biofuels would provide a great potential for reduction of compounds that contribute to global warming, especially fossil CO_2-emissions.

Historically, both vegetable oils and alcohols were obvious as motor fuels when transport began to be motorized approx. 100 years ago. Rudolf Diesel used peanut oil as a fuel when he developed the diesel engine at the end of the Nineteenth Century (Tickell, 2000). The early diesel engines were easily powered by straight vegetable oil, as their fuel systems were built for heavy oil fuels. Rudolf Diesel believed that vegetable oil would be an important fuel in his engine in the future. Alcohols were common as fuels in the first otto engines used for transportation in the beginning of the Twentieth Century. Both Henry Ford (founder of the Ford Motor Company (Ford, 2004)) and Charles F. Kettering (the head of research at General Motors) said in the 1920s that alcohol was the ‘fuel of the future’ (Kovarik, 1998). In Sweden, a fuel consisting of 25% anhydrous ethanol and 75% petrol ‘Lättbentyl’ was marketed from 1925 until the end of the Second World War (Schulze, 1988).

Fuels from agricultural crops have become more common as vehicle fuels during recent years. Rapeseed oil- and ethanol-based fuels have been used as fuels in tractors, buses and other diesel engined vehicles.

Rape is an oil plant (*Brassica napus*) with small dark seeds that have an oil content of 40-50%. For rape, the oil in the seeds can be extracted mechanically in an oil press or chemically with a solvent. Normally 65–80% of the oil can be extracted in an oil press (Widmann, 1988; Norén, 1990; Bernesson, 1993, 1994; Head *et al.*, 1995; Kaltschmitt & Reinhardt, 1997). Using solvent extraction, approximately 98% of the oil can be extracted (Norén, 1990; Kaltschmitt & Reinhardt, 1997). Solvent extraction is only used in large plants.

Wheat (*Triticum aestivum*) is a cereal that normally contains 58-62% starch (Kaltschmitt & Reinhardt, 1997). The starch can be degraded to glucose monomers, which can be fermented to ethanol. For wheat, 84-93% of its starch can be converted to ethanol depending on the process used (Kaltschmitt & Reinhardt, 1997; Jacques, Lyons & Kelsall, 1999).

As a fuel, rapeseed oil is more viscous than normal diesel oil, and therefore the engine must be modified to use it straight. The oil can be heated before it is injected into the cylinder (Tickell, 2000) or the engine can be an Elsbett engine (a variant of the direct-injected diesel engine) (Bernesson, 1993, 1994). Rapeseed oil consists of triglycerides, which comprise a glycerine molecule connected to three fatty acids (Norén, 1990). The oil can be transesterified in an operation whereby three methanol (or ethanol) molecules replace the glycerine molecule; the result is three monoesters (a fatty acid connected to a methanol) with a viscosity similar to that of normal diesel oil. This fuel can be used in ordinary diesel engines with little or no adjustment. If methanol is used for the transesterification of rapeseed oil the resulting fuel is called rape methyl ester, often shortened to RME.

Ethanol is a fuel with a high octane number that is suitable for use in otto engines but it has poor ignition properties for diesel engines. One way to improve the ignition properties before use in diesel engines is to add an ignition improver to increase the fuel's cetane number (Haupt *et al.*, 1999). The compression ratio is usually also increased to limit the requirement for an ignition improver. Spark plugs, glow plugs and two-fuel systems with alcohol and diesel oil can also be used to help improve ignition (STU, 1986). The engine must also be modified for a higher fuel flow because of the lower heat value in ethanol compared to diesel oil. Before being sold as a fuel, the ethanol must be denatured to prevent it being used as a drink (Sekab, 2003).

The production of rapeseed oil, RME and ethanol can be carried out on many different system scales. In large-scale systems, process heat can be both produced and used more efficiently (Kaltschmitt & Reinhardt, 1997), while processing technologies for rapeseed also have higher extraction efficiencies (Bernesson, 1993; Head *et al.*, 1995; Kaltschmitt & Reinhardt, 1997). However, the transport of raw materials to the processing plant and the transport of residual products back to the farms are long-distance. Small-scale systems have been of great interest in Sweden, for example because of the simple and less expensive process technologies involved (Norén & Danfors, 1981; Norén, 1990; Norén *et al.*, 1994) and the possibility to increase rural employment (Danielsson & Hektor, 1992). Furthermore, the transport of raw materials and residual products is substantially decreased.

Organic farming can be used to produce fuel raw materials such as rapeseed or wheat in a more environmentally friendly way. In organic agriculture, synthetic pesticides and fertilisers are not used (EC, 2004; OFRF, 2004). Organic farmers use cover crops and sophisticated crop rotations to modify field ecology, effectively disrupting habitats for weeds, insects and disease organisms. Weeds are also controlled through mechanical tillage, hand-weeding and flame weeding. The soils are fertilised by manure, compost and by using suitable crop rotations, *e.g.* growing cereals after nitrogen-fixing leguminous plants. Yields may be 30-40% lower with organic farming than with conventional farming when wheat and rapeseed are cultivated (Mattsson, 1999).

In organic farming, there is an effort to use only bio-based energy and renewable raw materials, with the aim of achieving a sustainable production system (SJV, 2001). Estimations show, however, that the organic farms in Sweden annually consume approx. 36 000 m^3 diesel oil (Baky *et al.*, 2002), which can scarcely be considered sustainable in the long term. Furthermore, this consumption will increase as the scale of the organic farming increases. A change to bio-based fuels is supported by the Swedish authorities (SJV, 2001) and will be a logical step towards a food production system on Nature's terms.

When something is produced, some natural resources always have to be used. Natural resources include *e.g.* land and water during agricultural production; iron, aluminium, rubber and mineral oil during production of machines; and energy as fuel, heat or electricity (Lindfors *et al.*, 1995; Lindfors & Svensson, 1996; Wenzel, Hauschild & Alting, 1997; Lindahl, Rydh & Tingström, 2001; Rydh, Lindahl & Tingström, 2002). Some natural resources are renewable and others are not.

During many human activities, undesirable chemical compounds are spread into the Earth's atmosphere. They act in different ways and therefore contribute to different kinds of damage to the environment. Four of the most important types of environmental damage are global warming, acidification, eutrophication and photochemical ozone formation.

Components such as CO_2, N_2O, CH_4 and halocarbons contribute to the global warming of the Earth's atmosphere (Wenzel, Hauschild & Alting, 1997; IPCC, 2001). The mechanism is that the Earth's atmosphere absorbs part of the energy emitted as infrared radiation from Earth towards space, and is thereby heated. The above-described components are very effective at such heat absorption and if they accumulate in the atmosphere they contribute to a warming of the atmosphere. This has happened during the past few centuries because of combustion of fossil fuels such as coal, oil and natural gas. Since 1750, the atmospheric concentration of the two main global warming gases CO_2 and CH_4 has increased by 31% and 151% respectively (IPCC, 2001). Because of global warming, the global average temperature is predicted to rise by 1 °C, up to almost 6 °C, and the global mean sea level to rise by 0.1 m, up to almost 1 m, according to some climate change models (IPCC, 2001). In some areas of the World, there will be an increased risk of droughts and floods during the next hundred years if the above predictions are accurate.

When acids and compounds that can be converted to acids (such as SO_x, NO_x, NH_3 and HCl) are emitted to the atmosphere and deposited in water and soil, the addition of hydrogen ions may result in a decrease in pH, *i.e.* an increase in acidity (Wenzel, Hauschild & Alting, 1997). This has consequences in the form of a widespread decline in coniferous forests in many places in Europe and the USA, and increased fish mortality in mountain lakes in Scandinavia and central Europe. The acidification also causes corrosion damage to metals and disintegration of surface coatings and mineral building materials.

Substances containing nitrogen (N) or phosphorous (P) cause nutrient enrichment as an impact on ecosystems (Wenzel, Hauschild & Alting, 1997), in air emissions mainly as NO_x, NH_3. As a rule, the availability of one of the nutrients above is a limiting factor in the ecosystem, and if this nutrient is added, the growth of algae or plants is increased. In aquatic ecosystems, this can cause oxygen deficiency to occur in the bottom strata due to the increased algal growth and subsequent breakdown of algae at the bottom. On land, ecosystems poor in nutrients, such as raised bogs and heathlands, are gradually disappearing as a result of addition of nitrogen.

Volatile organic compounds with their origins in solvents and emissions of unburnt fuel from road transport, heating *etc.* are often degraded within a few days of being released to the atmosphere (Wenzel, Hauschild & Alting, 1997). The reaction involved is an oxidation, which occurs under the influence of sunlight. In the presence of oxides of nitrogen (NO_x), ozone can be formed. The oxides of nitrogen are not consumed during ozone formation, but have a catalyst function. This process is termed photochemical ozone formation. Ozone is an unstable gas with a half-life in the troposphere of a few weeks. Ozone attacks organic compounds in plants and animals or materials exposed to air. This leads to an increased frequency of respiratory tract problems in humans during periods of photochemical smog in cities. For agriculture, it causes a reduction in yield.

Compounds may also be persistently or directly toxic to humans (human-toxic) and/or ecosystems (ecotoxic) (Wenzel, Hauschild & Alting, 1997). Persistent substances may accumulate in organisms and/or cause cancer or reduced fertility. Substances contribute to ecotoxicity if they affect the function and structure of the ecosystems by exerting toxic effects on the organisms that live in them. The toxic effect can be either acute or chronic. Ecotoxic and human-toxic effects are caused by *e.g.* substances in pesticides, heavy metals, *etc.* A very great number of industrial emissions are toxic.

Life cycle assessment

Life cycle assessment (LCA) can briefly be defined as a process to describe summed resource and environmental consequences coupled to all activities from 'cradle to grave' needed for a product or service to fulfil its function (Lindfors *et al.*, 1995; Lindfors & Svensson, 1996; ISO, 1997; Wenzel, Hauschild & Alting, 1997; Lindahl, Rydh & Tingström, 2001; Rydh, Lindahl & Tingström, 2002).

In an LCA, environmental aspects (*e.g.* emissions, energy requirements, natural resources, *etc.*) from raw material acquisition to final disposal are systematically addressed as regards product and service systems. The depth of detail and time frame of an LCA study may vary to a large extent, depending on definition of goal and scope. An LCA normally does not simply describe the environmental effect from just one product or one service, but instead compares products or services that fulfil the same function. LCAs are above all useful for identifying the potential for environmental improvements during the production and use of a product.

There are four phases in an LCA-study according to ISO 14040 (ISO, 1997): 1. Goal and scope definition; 2. Inventory analysis; 3. Impact assessment and 4. Interpretation (Fig. 1). During the whole study there are demands for continuous interpretation and updating of data and results.

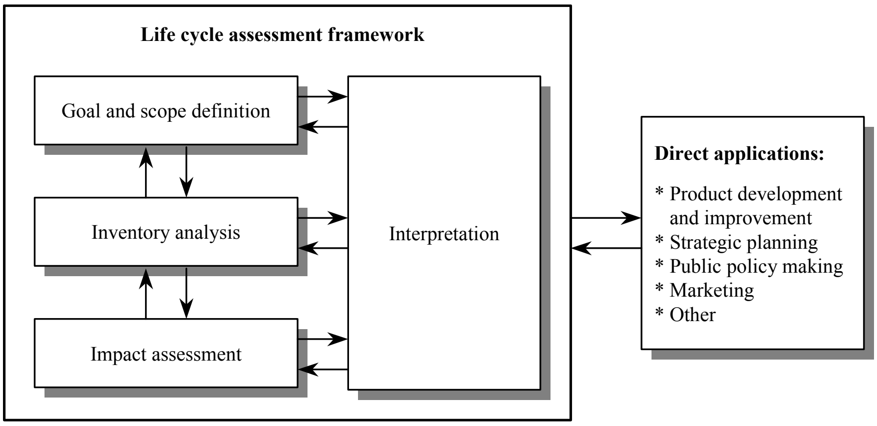


Fig. 1. Framework for life cycle assessment (ISO, 1997).

During an LCA the emissions can be categorised into different impact categories *e.g.* global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), and toxicity (to ecosystems and humans) (Lindfors *et al.*, 1995; Wenzel, Hauschild & Alting, 1997; Lindahl, Rydh & Tingström, 2001; Rydh, Lindahl & Tingström, 2002). Waste to be dumped or landfilled and use of natural resources is often also included in LCAs. The energy requirement is often included too, because transformation of energy to forms suitable for production processes contributes to large proportion of the emissions.

Because of the classification into different impact categories, the results are easier to grasp. Sometimes the results are also valued using some form of valuation method. There is no scientific basis for reducing LCA results to a single overall score or number, since trade-offs and complexities exist for the systems analysed at different stages of their life cycle.

When a production process contributes to several products, the total system environmental load has to be shared between these in a suitable way. This process is called allocation. Several methods may be used for allocation in LCA (Lindfors *et al.*, 1995; Wenzel, Hauschild & Alting, 1997; ISO, 1998; Lindahl, Rydh & Tingström, 2001; Rydh, Lindahl & Tingström, 2002), and there are no obvious rules regarding the most appropriate method. The choice of allocation method may impact on the final results considerably, and it is therefore important to bear in mind the effects of allocation on the results of a study.

If possible, allocation should be avoided and one way to achieve this is to expand the system, *e.g.* when the environmental load for product A in Fig. 2 is to be calculated (Lindfors *et al.*, 1995; ISO, 1998; Lindahl, Rydh & Tingström, 2001; Rydh, Lindahl & Tingström, 2002). The system studied produces two products, A and B_1, in the same process. In expansion, a system that produces a product B_2 is included in the system. The products B_1 and B_2 correspond to each other and have the same function. Afterwards the environmental load corresponding to product B_2 is subtracted from the studied system and the resulting system corresponds to the environmental load for product A. In studies dealing with production of RME and ethanol: product A corresponds to RME, product B_1 to rapemeal and product B_2 to soymeal; or product B_1 corresponds to process glycerine and product B_2 to fossil glycerine; or product A corresponds to ethanol fuel, product B_1 to distiller's waste and product B_2 to soymeal.

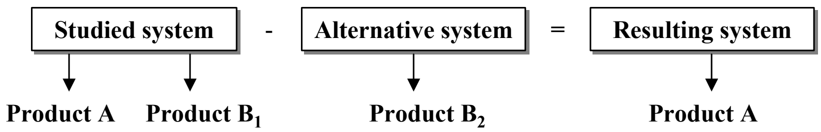


Fig. 2. The principle for expansion of systems boundaries to avoid allocation (after ISO, 1998; Lindahl, Rydh & Tingström, 2001; Rydh, Lindahl & Tingström, 2002).

When some type of allocation is necessary, the flows into and out of the system should be shared between its products in a way that reflect their underlying physical relationships, for example based on energy content, so-called physical allocation (Lindfors *et al.*, 1995; Wenzel, Hauschild & Alting, 1997; ISO, 1998; Lindahl, Rydh & Tingström, 2001; Rydh, Lindahl & Tingström, 2002). When physical relationships cannot be stipulated or used as a basis for allocation, the inflows between products should be allocated in a way that reflects other connections *e.g.* economic connections (Lindfors *et al.*, 1995; Wenzel, Hauschild & Alting, 1997; ISO, 1998; Lindahl, Rydh & Tingström, 2001; Rydh, Lindahl & Tingström, 2002). According to ISO 14041, physical allocation should be preferred before economic allocation (ISO, 1998). Economic allocation may sometimes be preferable, *e.g.* if the energy quality differs between the products studied.

To carry out a complete LCA including all conceivable emissions is in most cases too time- and resource-consuming. Therefore the emissions considered in the LCA normally have to be limited in some way, for example by only studying the most important air emissions.

Some life cycle assessments (LCAs) and/or energy analyses have been conducted to study the environmental load when RME and ethanol are produced and used as fuels (Johansson, Brandberg & Roth, 1992; Börjesson, 1994; Ragnarsson, 1994; Almemark, 1996; Blinge, 1998; Hovelius, 1999; Hovelius & Hansson, 1999; Patyk & Reinhardt, 2000; General Motors Corporation *et al.*, 2001; L-B-Systemtechnik, 2002). However, all these studies consider large-scale production. Gärtner & Reinhardt (2001) and Reinhardt & Gärtner (2002) carried out an LCA study for small-scale RME production, but their results are only valid for German conditions. Small-scale production of ethanol was studied by Almemark (1996) in a scenario analysis.

Objectives

The main purpose of this thesis was to assess the environmental load during production of rape methyl ester (RME) and ethanol fuel on farm scale. Another important purpose was to compare the results for farm-scale production with the results for larger scales. The overall objective was to find systems with less environmental impact and natural resource use for future production of these biofuels.

The objectives for the different parts included in the thesis were:

1) To investigate how a small screw oil press should be operated in order to ensure a high capacity and oil extraction efficiency (Paper I).
2) To analyse whether the use of small-scale RME production systems reduces the environmental load in comparison to medium- and large-scale systems (Paper II).
3) To analyse whether the use of small-scale ethanol fuel production systems reduces the environmental load in comparison to medium- and large-scale systems (Paper III).
4) To evaluate energy balance and environmental load for systems making organic farms self supplying with RME, ethanol or biogas fuels (Paper IV).

Extraction of rapeseed oil

Materials and methods

Oil extraction

To investigate the influence of some press parameters on the capacity and oil extraction efficiency of a small screw oil press (Paper I), a Komet® S87G press was used (Fig. 3). It had a stated capacity of 5 l oil/h (4.6 kg oil/h).

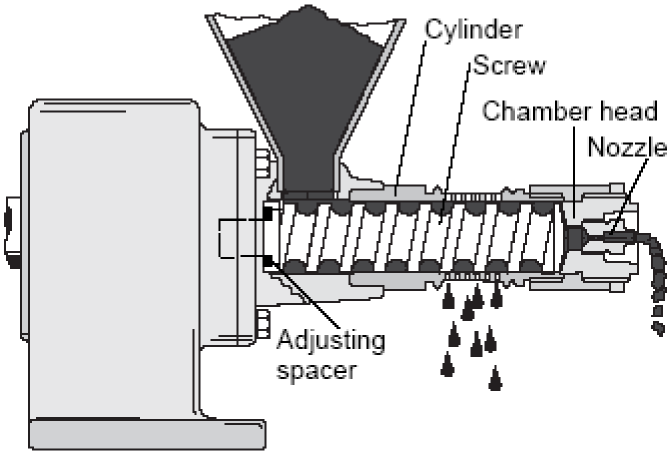


Fig. 3. Cut-away view of the oil press Komet® S87G. Illustr: Kim Gutekunst.

The oil press was operated at four screw speeds with nozzles of three different sizes and two different types. All the nozzles, at all screw speeds, were also tested with an adjusting spacer (Fig. 3) that moved the press screw closer to the press chamber head. The seed used was spring rape (*Brassica napus*).

Five samples were taken for each adjustment consecutively without a break. After each change of screw speed or nozzle, the press was allowed to run for at least 25 minutes, without any measurements, while waiting for stable pressing conditions. For each sample, the press was run for 300 s, after which the oil and meal were weighed.

Statistical analysis

For the statistical analyses, the MIXED procedure of the Statistical Analysis System for Windows version 6.10 (SAS Institute Inc., 1992) was used. The MIXED procedure was chosen because it is capable of handling non-randomly chosen data. To do this, a factor for time was included in the model. This time factor was a series starting with the number 1 for the first sample in the first adjustment and finishing with the number 184 in the last sample in the last adjustment. The REPEATED statement of procedure MIXED was used on the first time factor on the whole model (everything) to specify a covariance structure. A first-order autoregressive covariance structure was fitted. Akaike's information criterion was used to determine whether the correlation factor should be kept in the model. A second time factor for each adjustment was also introduced into the model, starting with the number 1 for the first sample in each adjustment and normally finishing with the number 5 for the last sample in each adjustment.

In the procedure MIXED, during the data processing of the model equations, non-significant parameters were excluded in a sequential testing procedure for fixed effects in Type I SS and Type III SS. The terms in this procedure were tested with a significance level of 0.05.

Results

Capacity and oil extraction efficiency were strongly dependent on nozzle inner diameter and on screw speed (Fig. 4 and Eqs. 1-2). Capacity always increased with screw speed and usually also in proportional to the nozzle size (Fig. 4 and Eq. 1). However, for nozzles with a normal press channel without an adjusting spacer, at higher screw speeds, the capacity was increased with smaller nozzles. For the other three nozzle type combinations, with or without an adjusting spacer, the capacities were about the same at the highest screw speeds. At lower screw speeds, the differences in capacity were greater between the nozzles studied. Nozzles with a normal press channel without an adjusting spacer normally resulted in the highest capacity, closely followed by nozzles with a long press channel without an adjusting spacer, nozzles with a long press channel with an adjusting spacer and nozzles with a normal press channel with an adjusting spacer (Fig. 5).

For nozzles with a normal press channel and an adjusting spacer, the capacity (kg oil/h) is described by:

$$CAPR = -3.78 + 0.336\ NOZ + 0.118\ REV - 0.00331\ NOZ\ REV - 0.000297\ REV^2 \quad (1)$$

and the oil extraction efficiency (%) is described by:

$$EFFR = 57.6 + 6.26\ NOZ - 0.148\ REV - 0.489\ NOZ^2 \quad (2)$$

where:
NOZ = nozzle inside diameter (mm),
REV = press screw rotation speed (rev/min).

Similar equations were derived for the other oil press adjustments (see Paper I).

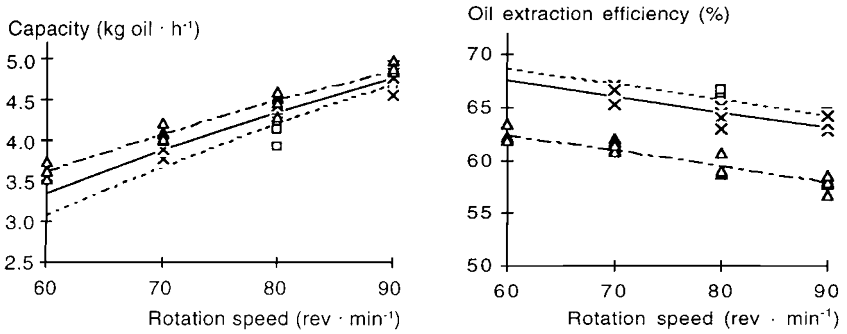


Fig. 4. Capacity and oil extraction efficiency, nozzles with normal press nozzle channel with an adjusting spacer, with different rotation speed of the press screw for different types of nozzles. - - - - 6 mm nozzle, calculated; ——— 8 mm nozzle, calculated; — - — - — 10 mm nozzle, calculated. □ 6 mm nozzle, experimental; ✕ 8 mm nozzle, experimental; Δ 10 mm nozzle, experimental.

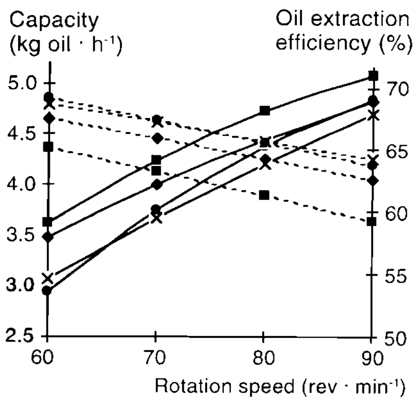


Fig. 5. Capacity and oil extraction efficiency with different sorts of nozzles, with 6 mm inner diameter and with or without an adjusting spacer, calculated values. ——— capacity, - - - - - oil extraction efficiency. ■ normal press nozzle channel without an adjusting spacer, ◆ long press nozzle channel without an adjusting spacer, ✕ normal press nozzle channel with an adjusting spacer, ● long press nozzle channel with an adjusting spacer.

The oil extraction efficiency was dependent on the inner diameter of the nozzle and the rotation speed of the oil press screw (Fig. 4 and Eq. 2). Smaller nozzles had higher oil extraction efficiency than larger ones. There were only small differences between the two smallest nozzles. The differences between the two largest nozzles were greater. The trend was the same for all press screw speeds and all types of nozzles. Higher press screw speed resulted in lower oil extraction efficiency. Adjustments in which the press screw was moved forward with an adjusting spacer had higher oil extraction efficiency than without a spacer (Fig. 5). The main conclusion in the study was that to achieve a high capacity and a high oil extraction efficiency, the press was best operated with a small nozzle and a rather high screw speed.

Environmental assessment of RME and ethanol fuel production

Method

System description

The system for production of RME is described in Fig. 6 (see also Paper II) and the system for production of ethanol fuel in Fig. 7 (see also Paper III). The processing of rapeseed and wheat for production of the RME and ethanol, respectively, was assumed to take place at plants that service 40 ha (small-scale), 1 000 ha (medium-scale) and 50 000 ha (large-scale). Assuming that 10% of the total area around small-scale plants was cultivated with rapeseed or wheat, and 5% and 1% of the area around medium- and large-scale plants, respectively, the transport distances were calculated with equations developed by Overend (1982). The collection areas were assumed to be circular. The reduction in share of total area with rapeseed or wheat for larger plants was a result of the increased share of non-farm area as the territory included was enlarged. On farm level, however, one seventh of the cultivated area was rapeseed or wheat for fuel production (Papers II and III).

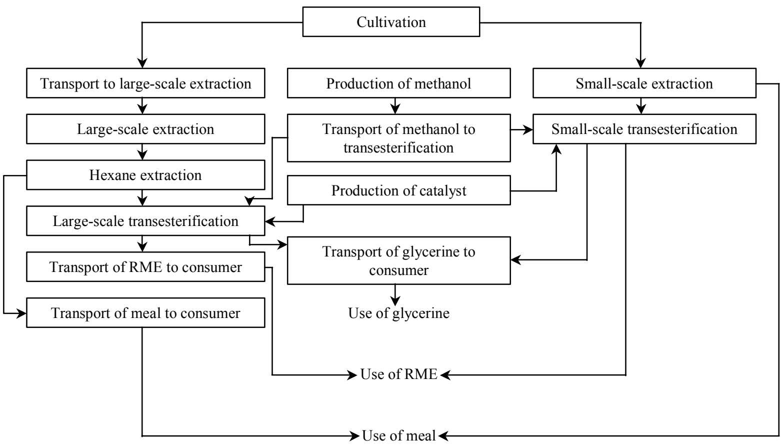


Fig. 6. Flow-chart showing the operations (in boxes) that were included for small- and large-scale production of RME. For the medium-scale system, the same operations as for the large-scale were used, with the exception of hexane extraction. The operations 'cultivation', 'production of methanol' and 'production of catalyst were identical for all scales.

The rapeseed or wheat was assumed to be processed to RME or ethanol fuel on the farm for the small-scale plants. The rapeseed or wheat was transported 7 kilometres for medium-scale plants and 110 km for large-scale plants. The RME and meal or ethanol fuel and wet or dried distiller's waste produced were assumed to be transported back to the farm, to make the comparison with small-scale plants fair.

During the production of RME, the oil was extracted mechanically, in all plants, and then transesterified (Fig. 6). The extraction in the small-scale plant was carried out with a hole cylinder oil expeller, and in the medium- and large-scale plants with strainer oil expellers. The extraction capacity of an oil expeller decreases with higher oil extraction efficiency and *vice versa* (Widmann, 1988; Maurer, 1991; Bernesson, 1993, 1994; Paper I; Schön, Strehler & Widmann, 1994). In this study, the oil extraction efficiency was assumed to be 68% in the small-scale plant (Bernesson, 1993, 1994), 75% in the medium-scale plant (Head *et al.*, 1995) and 98% in the large-scale plant (Maurer, 1991; Schön, Strehler & Widmann, 1994; Kaltschmitt & Reinhardt, 1997). The extraction efficiencies chosen correspond to oil extraction capacities that are realistic for each type of expeller in practice. In the large-scale plant, the extraction took place in two steps, pressing and hexane extraction. The more advanced solvent extraction technique with hexane was used in order to extract more oil from the seeds.

During the oil extraction and the transesterification, all process energy was assumed to be electricity. For the oil extraction, the consumption of electricity was 0.36 MJ/kg seed in the small-scale plant (Bernesson, 1993, 1994). In medium- and large-scale plants, the consumption of electricity was about 40% lower than in small-scale plants (after Bernesson, 1993, 1994; Kaltschmitt & Reinhardt, 1997). The requirement for electricity for the transesterification was assumed to be 0.60 MJ/kg RME (incl. heating of the oil) (Kaltschmitt & Reinhardt, 1997), for all plant sizes studied. The need for methanol and catalyst for the transesterification was assumed to be the same for all plant sizes based on the amount of rapeseed oil available for the process (Paper II).

The production of ethanol from wheat could be divided into three main processes (Fig. 7): the fermentation during which the raw ethanol is produced; the distillation during which the water is removed from the raw ethanol until the ethanol content is 95% (by volume); and the drying of the distiller's waste (not performed in medium- and small-scale plants). For production of ethanol fuel, the same production process was assumed to be used in all production sizes compared. In larger-scale plants electricity and heat (as steam) were assumed to be used more efficiently. In the large-scale plant the distiller's waste was assumed to be dried before transport back to the farm.

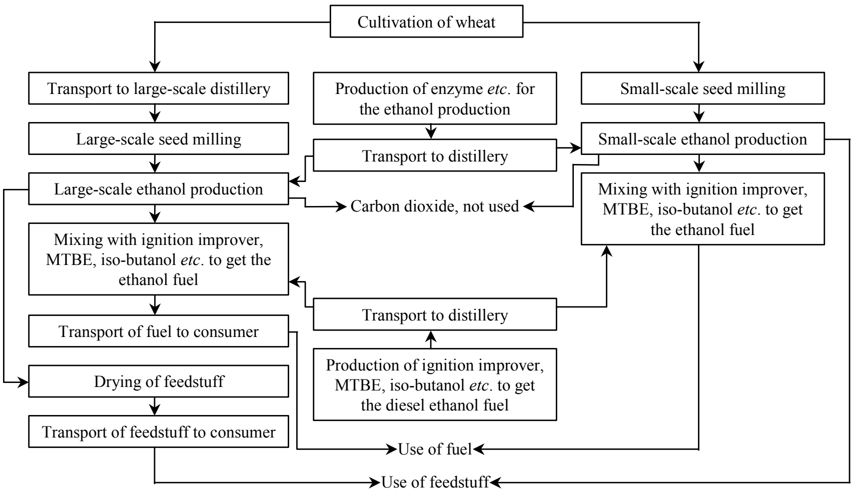


Fig. 7. Flow-chart showing the operations (in boxes) included in small- and large-scale production of ethanol. For the medium-scale system, the same operations as for the large-scale were used, with the exception of drying of distiller's waste (feedstuff). The operations 'cultivation', 'production of enzyme *etc.* for the ethanol production' and 'production of ignition improver, MTBE, isobutanol *etc.*' were identical for all scales.

For large-scale production of ethanol, the requirement for electricity for fermentation was 130 MJ/tonne wheat, for ethanol distillation 80 MJ/tonne wheat and for drying of distiller's waste 220 MJ/tonne wheat (after Jacques, Lyons & Kelsall, 1999; Agroetanol, 2003; Werling, pers. comm. 2003). The corresponding value for heat requirement was 230 MJ/tonne wheat for fermentation, 1 300 MJ/tonne wheat for distillation and 1 600 MJ/tonne wheat for drying of distiller's waste (after Jacques, Lyons & Kelsall, 1999; Agroetanol, 2003; Werling, pers. comm. 2003). For medium-scale plants, the electricity requirement was assumed to be 10% higher in the fermentation and distillation processes, while for small-scale plants it was assumed to be 20% higher. These figures were also applied for the heat requirement. For handling of distiller's waste in these plants, electricity was used for pumping the wet material out of the plant. The electricity requirements for this operation were assumed to be almost negligible in comparison to the drying of distiller's waste (Paper III). The efficiency of the large plant for production of heat (steam) was assumed to be 87.5%, according to data from the Agroetanol plant in Norrköping, Sweden (Agroetanol, 2003). The efficiency of the boilers in the small- and medium-scale plants was assumed to be 75% and 84%, respectively (Kaltschmitt & Reinhardt, 1997).

The need for chemicals in the ethanol production process and in making the ethanol into a fuel for heavy diesel engines was assumed to be the same independent of the plant size (Paper III).

Energy and materials used for the manufacture of agricultural machines, transport lorries and process machines for ethanol production, including spare parts, were calculated after data from Pimentel (1980) and Bowers (1992), revised by Börjesson (1994). Energy used for construction of buildings was calculated after data from Spugnoli, Parenti & Baldi (1992). Further calculation assumptions are described by Bernesson (2004).

LCA

The functional unit to which the total environmental load was related was 1.0 MJ of energy in the RME fuel or in the ethanol fuel delivered to the final consumer, *i.e.* 1.0 MJ_{fuel}. The energy content was expressed in the lower heating value (38.5 MJ/kg for RME and 25.1 MJ/kg for ethanol fuel).

The emission categories GWP, AP, EP and POCP were chosen because they are important both during the cultivation and in the fuel production. For these emission categories, there are also existing data for almost all production steps during production of the two fuels studied. Toxicity emissions were judged not to be of major importance and the fact that no data exist for many of the production steps were reasons to exclude the toxicity from the study. The impact of toxicity compounds was also too complex to be handled within the scope of this study. No problematic waste products were produced. Most natural resources, *e.g.* land and water, required to produce the two fuels are not limited in Sweden and therefore natural resources were excluded. Use of fossil mineral oil was accounted for within the GWP. Input primary energy was included as a fifth impact category because it provides a measure of how efficiently the two fuels studied can be produced. Five impact categories were also appropriate for obtaining easily understandable data from the LCA.

The LCA was limited to the air emissions: CO_2 (fossil origin), CO, HC (hydrocarbons except for methane), CH_4, NO_x (nitrous oxides), SO_x (sulphur oxides), NH_3, N_2O and HCl. These emissions were classified into the following environmental impact categories: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and photochemical ozone creation potential (POCP). The category indicators used are presented in Table 1. The energy needed in the operations was also included in the LCA. For all fuels used in the system, the energy contents were expressed in lower heating values.

Table 1. *Impact category indicators used in this study (Hauschild & Wenzel, 1998)*

Emissions to air	$GWP_{100\ years}$ (g CO_2-eq/g)	AP (g SO_2-eq/g)	EP (g PO_4^{3-}-eq/g)	POCP (g C_2H_4-eq/g)
CO_2	1			
SO_2, SO_x		1		
NO_x		0.7	0.13	
NH_3		1.88	0.35	
CO				0.04
HCl		0.88		
CH_4	23[a]			0.007
HC				0.4
N_2O	296[a]			

[a] IPCC (2001).

Allocation

For the physical and economic allocations, the environmental load was shared between RME, meal and glycerine or ethanol fuel and distiller's waste. The total energy and economic values of the products were calculated from the yield of each product and its lower heating value and price, respectively (Table 2). For RME production, the lower heating value and the price for the meal were calculated from its content of oil and water to take into account the differences between small- and large-scale production (Bernesson, 2004). In the physical allocation for production of ethanol, the same lower heating value was used for both wet and dry distiller's waste, because it was assumed that its value as a forage was independent of its moisture content. The price for wet and dried distiller's waste was the market price for these products (SBI-Trading, 2003; Werling, pers. comm. 2003). Data for the physical and economic allocations during small-scale production of RME and ethanol fuel are presented in Table 2. Data for medium- and large-scale production are presented in Papers II and III. Physical allocation was used in all base scenarios.

Table 2. *Data for the physical and economic allocations during small-scale production of RME and ethanol fuel*

Type of product	Product	Physical allocation			Economic allocation		
		Heating value[a]	Production	Share	Price[b]	Production	Share
	(kg/ha)	(MJ/kg)	(GJ/ha)	(%)	(SEK/kg)	(SEK/ha)	(%)
RME production:							
RME	730	38.5	28.0	45	6.30	4 600	58
Glycerine	80	17.1	1.4	2	4.40	350	4
Meal	1 630	20.1	32.6	53	1.80	3 010	38
Total			62.0	100		7 970	100
Ethanol fuel production:							
Ethanol fuel	2 070	25.1	52.0	61	6.30	13 050	94
Distiller's waste (9.1% DM)	18 920	19.5[c]	33.6	39	0.04	780	6
Total			85.7	100		13 840	100

[a] Lower heating value: RME (SMP, 1993); glycerine (Kaltschmitt & Reinhardt, 1997); meal calculated after Bernesson (1993, 2004); ethanol fuel calculated after Aylward & Findlay (1994), Solomons (1996), Schmitz (2003), Lif (pers. comm. 2003) and Sekab (2003); and distiller's waste calculated after Aylward & Findlay (1994) and Belab (2002).

[b] Prices: RME (Lindkvist, pers. comm. 2002); glycerine (Eriksson, pers. comm. 2002); meal calculated after Herland (pers. comm. 2002) and Bernesson (2004); ethanol fuel assumed to be as for Etamax D fuel sold by Sekab AB (Elfving, pers. comm. 2003); distiller's waste (9.0% water) calculated after Werling (pers. comm. 2003); and distiller's waste (90.9% water) (SBI-Trading, 2003).

[c] MJ/kg DM, measured on distiller's waste with a water content (wet basis) of 9.0%.

When replacement of fossil glycerine with glycerine from the transesterification was not included in the models for physical, economic and no allocation, it had to be discussed separately (for details see Bernesson, 2004). When fossil carbon atoms from fossil methanol replace the three biomass carbon atoms in the glycerine part of the rapeseed oil molecule, 100% biomass glycerine is produced.

In LCAs with physical or economic allocation, it is not obvious how these carbon atoms should be handled. However, they must be discussed or included in the calculations in some way. In this study they were handled on a discussion basis. However, the replacement of fossil glycerine was included in the model for allocation with an expanded system.

With expanded system allocation, the system was expanded so that: for RME production, rapemeal produced in the large-scale plant could replace imported (overseas) soymeal, and so that the rapemeal with higher oil content produced in the medium- and small-scale plants could replace soymeal mixed with soyoil; and for ethanol fuel production, the distiller's waste could replace imported (overseas) soymeal mixed with soyoil. The soymeal and the soyoil were mixed until the original protein and energy contents (as lower heat value) in the rapemeal or distiller's waste (dried) were reached. It was assumed that the soymeal products were transported from the harbour with an open-sided lorry to the farm for consumption (110 km). The emissions and energy needed for the production of soymeal and soyoil (Patyk & Reinhardt, 2000) were subtracted from the emissions and energy needed to produce the RME or the ethanol fuel. The glycerine from the transesterification process was assumed to replace glycerine produced from fossil propane gas.

Sensitivity and scenario analyses

In the sensitivity analysis, the influence of increasing and decreasing some production factors by 20%, one at a time, was studied for both production of RME and production of ethanol fuel (Papers II and III).

In the scenario analysis, for both RME and ethanol fuel production, the extent to which some alternative realistic scenarios affected the results was investigated. The following scenarios were studied:

- For RME: ploughless tillage; use of Salix, which is a biofuel, as a raw material for the methanol production instead of natural gas (this makes the RME a 100% biofuel); use of electricity mainly produced from fossil fuels (fossil fuel electricity), instead of Swedish electricity; use of catalysts for reduction of the CO, HC and NO_x emissions (by 81%, 77.5% and 6%, respectively) from diesel engines in cultivation and transport; use of the RME fuel produced for cultivation and transport; use of plants at locations where all transport distances are doubled; and improved oil extraction efficiencies for the small- and medium-scale plants, from 68 to 73%, and from 75 to 80%, respectively.
- For ethanol fuel: straw harvest (physical and economic allocation); ploughless tillage; steam produced by Salix wood chips (cultivated on farm land) instead of spruce wood chips; ignition improver and denaturants of bio-origin instead of fossil fuel origin; use of electricity mainly produced from fossil fuels (fossil fuel electricity), instead of Swedish electricity; use of catalysts for reduction of the CO, HC and NO_x emissions (by 81%, 77.5% and 6%, respectively) from diesel engines in cultivation and transport; use of the ethanol fuel produced for cultivation and transport; use of plants at locations where all transport distances are doubled; and improved energy efficiencies and

decreased energy requirements in the production operations, for the small- and medium-scale plants, to the same level as for large-scale plants.

Monte Carlo simulation

For ethanol fuel production, the sensitivity analysis was followed by Monte Carlo simulations (Vose, 1996; Wenzel, Hauschild & Alting, 1997; Lindahl, Rydh & Tingström, 2001; Rydh, Lindahl & Tingström, 2002) to evaluate whether there were any statistically significant differences between production scales, provided that certain variations round the mean values of some input data were specified. The factors to be studied in the simulations were chosen on the criterion that they had an influence of at least about 2% in each environmental impact category studied (physical allocation) in any of the scales analysed. The cultivation operation, which was the same in all production scales, was excluded to isolate the production plants. Thus the factors studied (assumed to be independent between production scales) were: electricity requirement; steam requirement; boiler losses (1 – boiler efficiency); and emissions during production of: Beraid, MTBE and isobutanol.

For each environmental impact category, the input data of all factors studied were assumed to be normally distributed, with the following coefficients of variation: 5%, 10% and 15%, one at a time (see Table 6). By running a number of simulations for each coefficient of variation of the factors studied, small- and large-scale production were evaluated as shown in Fig. 8. The area below each curve in Fig. 8 is 1, and the task was to find the probability that the small-scale ethanol production showed a lower value than the large-scale production (Table 6). This was achieved with separate Monte Carlo simulations for each difference between the production scales (Fig. 9) for each emission category or energy requirement. The probability that the differences (Fig. 9 and Table 6) are lower than zero can then be calculated from the normal distribution (Montgomery, 1991).

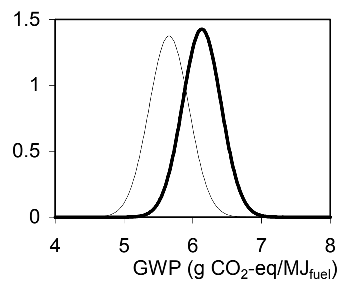


Fig. 8. Normal distributions obtained from Monte Carlo simulations for GWP (input coefficient of variation = 10%), comparing small-scale (———) and large scale (**———**) ethanol production (excl. cultivation). The difference between the mean values was 5.64-6.12=-0.48.

To understand what is happening during the Monte Carlo simulation, the course of events can be described mathematically (Eqs. 3-4). The core principle of the Monte Carlo method is the central limit theorem (CLT), which establishes how the empirical average of random samples converges to the true expectation (Montgomery, 1991; Vose, 1996; Dupire, 1998). It states that the mean $\bar{x}$ of a set of *n* variables (where *n* is large) (Eq. 3), drawn independently from the same distribution *f(x)* will be approximately normally distributed:

$$\bar{\mathrm{x}} = \mathrm{Normal}(\mu, \sigma/\sqrt{n}) \tag{3}$$

where μ and σ are the mean and standard deviation of the *f(x)* distribution from which the *n* samples were drawn.

The results from the Monte Carlo simulations were assumed to be normally distributed or sufficiently normally distributed for the following calculations. The value of the standard deviation (*s*), obtained from the Monte Carlo simulation was considered to be the uncertainty value '*u*'.

The average values (emissions and energy requirement) from the Monte Carlo simulations ($\overline{x_1}$ and $\overline{x_2}$) were checked against their original values from the LCA calculations (μ_1 and μ_2). Differences greater than a few per cent for absolute values and approx. 10% for comparisons could indicate that the Monte Carlo simulation does not work as expected if the difference is not very small. The standard deviation obtained from the Monte Carlo simulation was assumed to be the true σ.

A pair of future values of the small-scale production and large-scale production of ethanol fuel is denoted by x_1 and x_2, respectively. The difference $x_1 - x_2$ is assumed to follow a normal distribution with mean $\mu_1 - \mu_2$ and standard deviation σ. Under this assumption:

$$P(x_1 - x_2 < 0) = P\left(z = \frac{x_1 - x_2 - (\mu_1 - \mu_2)}{\sigma} < \frac{-(\mu_1 - \mu_2)}{\sigma}\right) = \Phi\left(-\frac{\mu_1 - \mu_2}{\sigma}\right) = 1 - \Phi\left(\frac{\mu_1 - \mu_2}{\sigma}\right) \tag{4}$$

where:

$$\Phi(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$$

is the cumulative standard normal distribution (*cf.* Montgomery, 1991; Miller & Miller, 1993) (see Fig. 9).

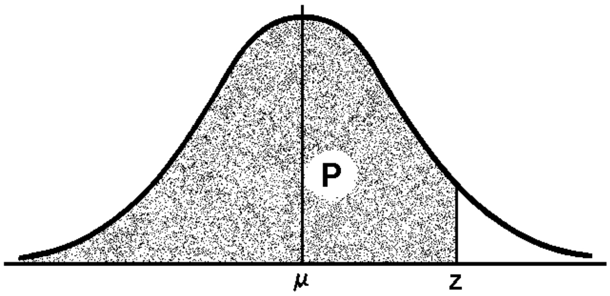


Fig. 9. Illustration of how the probability P is calculated from the normal distribution.

Results

Cultivation of rapeseed and wheat

The environmental impacts and the energy required for cultivation of the rapeseed and wheat are presented in Fig. 10. The total environmental impact for the production of winter rapeseed (Fig. 10a) was 2 400 kg CO_2-eq/ha, 14 kg SO_2-eq/ha, 2.4 kg PO_4^{3-}-eq/ha and 0.19 kg C_2H_4-eq/ha; and for production of winter wheat (Fig. 10b) 2 200 kg CO_2-eq/ha, 13 kg SO_2-eq/ha, 2.2 kg PO_4^{3-}-eq/ha and 0.22 kg C_2H_4-eq/ha. The impact from production of fertilisers, as well as the impact from soil emissions of N_2O and NH_3, was significant, especially on the GWP, AP and EP. The tractive power was also important, whereas seed drying and machinery inputs (energy requirement and emissions for the production of machines and buildings) made minor contributions. The influence of the other factors was negligible. Inputs from seed, heat for drying and electricity for drying and cleaning of the grain were higher for wheat due to the higher sowing rate and higher grain yields to be dried.

The total energy requirement was 12 GJ/ha for rapeseed production and 13 GJ/ha for wheat production. The total energy content in the rapeseed and wheat produced was 64 and 85 GJ/ha, which resulted in energy ratios of 5.4 and 6.5, respectively.

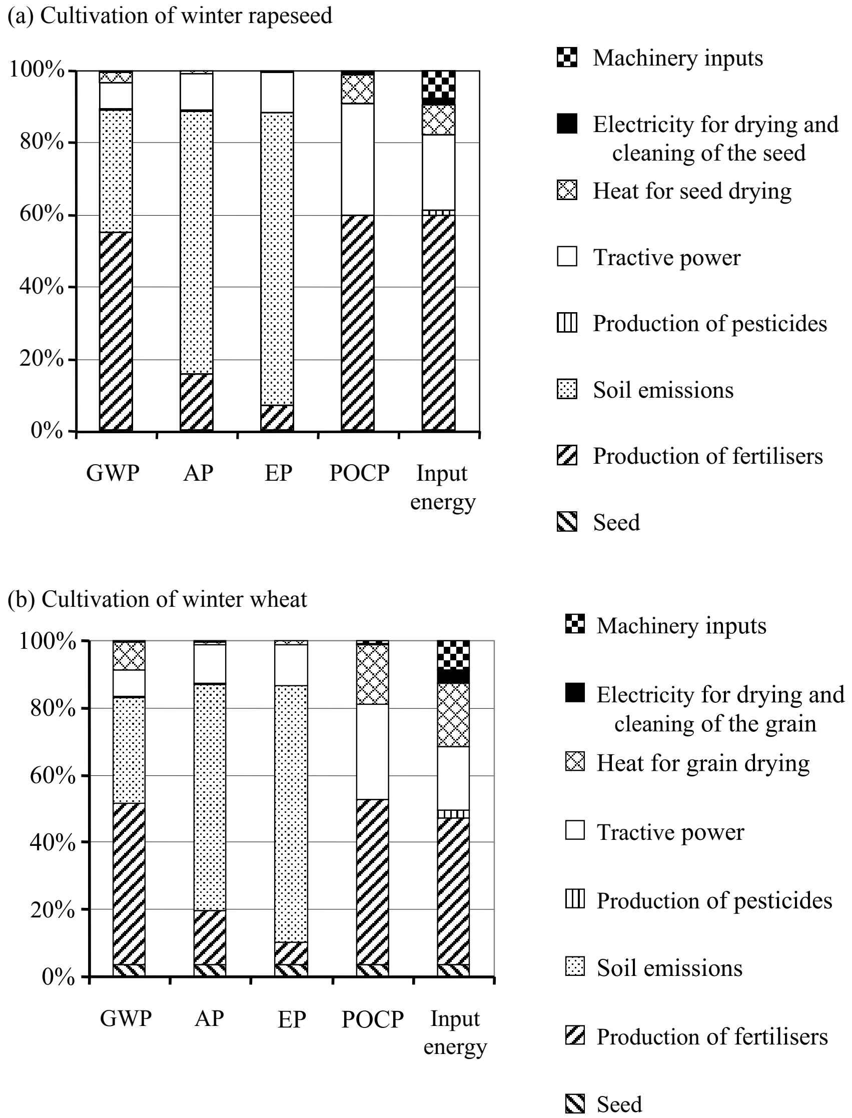
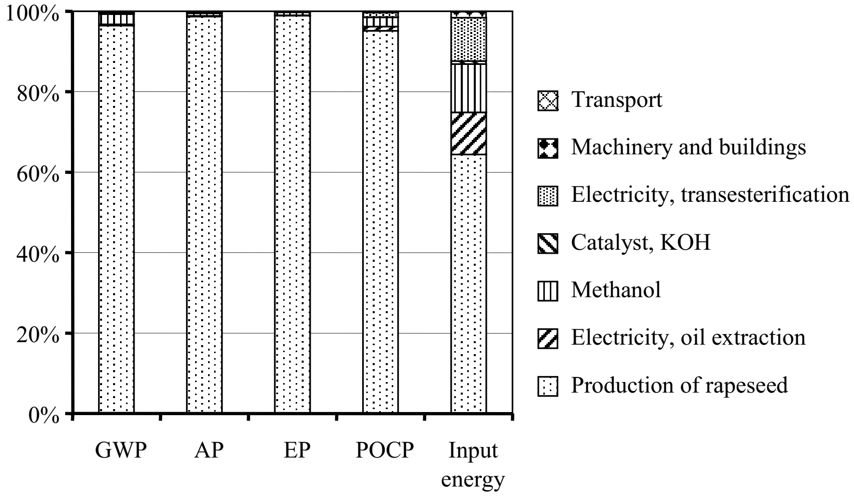


Fig. 10. Environmental impacts and energy requirements for the production of: a) winter rapeseed and b) winter wheat.

RME and ethanol fuel produced

The results for small-scale production of RME and ethanol fuel are described in Fig. 11. The total environmental impact for the production of RME (Fig. 11a) was 40 g CO_2-eq/MJ_{fuel}, 240 mg SO_2-eq/MJ_{fuel}, 39 mg PO_4^{3-}-eq/MJ_{fuel} and 3.3 mg C_2H_4-eq/MJ_{fuel} and for production of ethanol fuel (Fig. 11b) 31 g CO_2-eq/MJ_{fuel}, 200 mg SO_2-eq/MJ_{fuel}, 31 mg PO_4^{3-}-eq/MJ_{fuel} and 14 mg C_2H_4-eq/MJ_{fuel}. The total requirement for input energy for production of RME and ethanol fuel was 300 and 360 kJ/MJ_{fuel} respectively.

(a) Small-scale production of RME



(b) Small-scale production of ethanol fuel

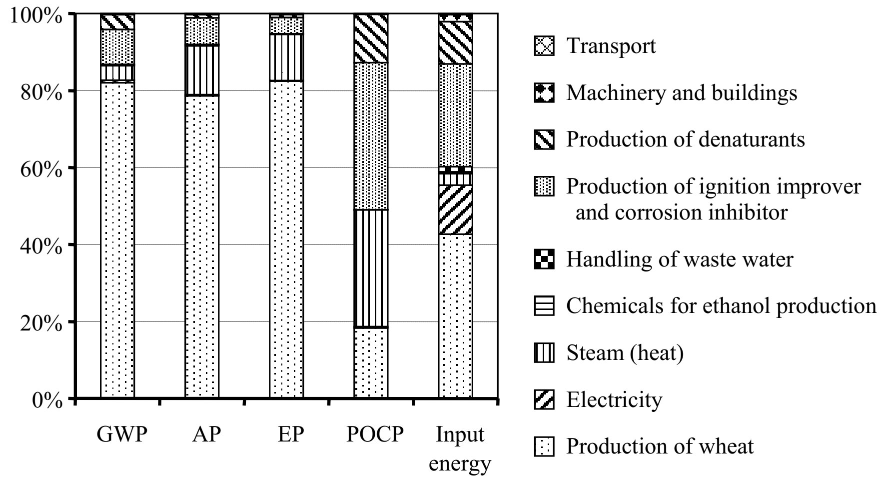


Fig. 11. Environmental impacts and energy use in small-scale production of: a) RME and b) ethanol fuel.

The results for the small-scale system for production of RME are described in Fig. 11a. As can be seen, the environmental impact from production of the rapeseed accounted for more than 95% of the total impact for all emission categories. Production of methanol was responsible for about one per cent to a couple per cent of the environmental impact, whereas the electricity was responsible for a few per cent. The other sources had influences less than one per cent. The energy required for the production of rapeseed was almost 65% of the total energy used (Fig. 11a). Production of methanol was responsible for 10-15% of the total energy requirement, and the electricity used for extraction and transesterification for about 10% each. The energy embodied in machinery and buildings accounted for just above one per cent, while the energy use in other production processes was negligible.

When it was considered that carbon atoms of biomass origin replaced fossil carbon atoms in the replaced fossil glycerine, the GWP decreased by 3.9 g CO_2-eq/MJ_{fuel} for all three RME plant sizes studied. If the replaced glycerine had been of biomass origin instead, the above described consideration would have been unnecessary.

The results for the small-scale system for production of ethanol fuel are described in Fig. 11b. As can be seen, the environmental impact from production of the wheat accounted for about 80% of the GWP, AP and EP, but only about 20% of the POCP. Production of ignition improver was responsible for a few to almost 10% of the GWP, AP and EP, but almost 40% of the POCP. Production of steam accounted for a few per cent of the GWP, more than 10% of the AP and EP and about 30% of the POCP. Production of denaturants was responsible for a few per cent of the GWP, less than one per cent of the AP and EP, and 10-15% of the POCP. The other sources had influences less than one per cent.

The energy required for the production of wheat was more than 40% of the total energy used. Production of ignition improver was responsible for almost 30% of the total energy requirement, and the electricity used for the process and production of denaturants for more than 10% each. Production of steam was only responsible for a few per cent of the total energy used, and the energy embodied in machinery and buildings and handling of waste water for one to a couple of per cent, while the energy use in other production processes was negligible.

Comparison between small- and large-scale production

In the comparisons between scales presented below, RME results are described first and then ethanol fuel results. Part-processes are described before the total system.

The change in environmental impact and energy use for medium- and large-scale production of RME in comparison to small-scale is shown in Tables 3-4. The results showed, for instance, that the impact categories for electricity used in oil extraction decreased by just over 40% per MJ_{fuel} for large- and medium-scale production in comparison to small-scale production. The difference in environmental impact and energy requirement for machinery and buildings was also large and decreased by almost 80% and almost 60% per MJ_{fuel} for large-scale and medium-scale production, respectively, in comparison to small-scale production. For large-scale plants, the energy requirement and the environmental load for transport increased by approx. a factor of 20 in comparison to small-scale plants (Table 3). The corresponding factors in medium-scale plants in comparison to small-scale plants were approx. 3.5 for the energy requirements and approx. 2.5 for the environmental load. However, when expressed in absolute terms, these changes (machinery and buildings and transport) were rather small in relation to the total energy requirement and environmental load (for small-scale production: hundredths and tenths of one per cent, except for one to a couple of per cent for energy requirements for machinery and buildings, see Fig. 11a) of the production system.

In general, the medium-scale system had lower total values of environmental impacts and energy requirement than the small-scale system (Table 4), but the differences were small, a tenth of one percent to a few percent. The differences for energy requirements were largest. The total differences between the small-scale plants and the large-scale plants were in general smaller.

The change in environmental impact and energy use for medium- and large-scale production of ethanol fuel in comparison to small-scale is shown in Tables 3-4. The results showed, for instance, that the environmental impact categories for electricity used in ethanol production decreased by approximately 20% per MJ_{fuel} and 10% per MJ_{fuel} for large-scale and medium-scale production respectively in comparison to small-scale production (Table 3). The environmental impact categories for steam (heat) had a more irregular behaviour. For medium-scale production in comparison to small-scale, energy requirements, GWP- and POCP-emissions decreased by approx. 20-70%, and AP- and EP-emissions increased by approx. 15-35%. For large-scale production in comparison to small-scale, EP-emissions decreased by a few per cent, energy requirement, GWP- and AP-emissions decreased by approx. 15-30%, and POCP-emissions decreased by almost 80%.

For steam production, the changes in emissions and energy requirements between plant sizes differed due to the fact that more efficient energy use in larger ethanol plants and extra use of heat for drying distiller's waste counteracted each other. The NO_x-emissions from the production of heat, which influenced both AP and EP, were also highest for medium-scale plants (Bernesson, 2004) and explain the results described above.

The differences in environmental impact and energy requirement for machinery and buildings were also large and decreased by approximately 80% per MJ_{fuel} and 60% per MJ_{fuel} for large- and medium-scale production, respectively, in comparison to small-scale production. For large-scale plants, the energy requirement and the environmental load for transport increased by almost a factor of 17 in comparison to small-scale plants (Table 3). The corresponding factors in medium-scale plants in comparison to small-scale plants were almost 4 for energy requirement and approx. 2.5 for environmental load. However, when expressed in absolute terms, these changes (machinery and buildings and transport) were rather small in relation to the total energy requirement and environmental load (for small-scale production: hundredths and tenths of one per cent, except for a couple of one per cent for energy requirements for machinery and buildings, see Fig. 11) of the production system.

In the total comparison, the POCP emissions were about 20% lower for both medium- and large-scale plants in comparison to small-scale plants (Table 4) due to higher HC-emissions (Bernesson, 2004). The production of steam had the greatest influence on the total differences between plant scales, because it made the largest contribution to environmental load (mainly from HC) (Fig. 11b) of those production factors that differed between production scales (Table 4 and

Paper III). Other emission categories and the energy requirement differed by only a tenth of one per cent or a few per cent between the production scales (Table 4).

Table 3. *Changes in environmental impacts and energy requirements for medium- and large-scale production of RME and ethanol fuel in comparison to small-scale production*

Production factors	Global warming potential	
	Change to medium-scale (%)	Change to large-scale (%)
Production of RME:		
Production of rapeseed	-2[a]	-1[a]
Electricity, oil extraction	-42[a]	-43[a]
Electricity, transesterification	-2[a]	-5[a]
Machinery and buildings	-57[a]	-78[a]
Transport	+140[b]	+1900[a]
Production of ethanol fuel:		
Production of wheat	0[a]	0[a]
Electricity	-10[a]	-20[a]
Steam (heat)	-20[c]	-22[d]
Handling of waste water	-2[a]	-5[a]
Machinery and buildings	-61[a]	-80[a]
Transport	+140[e]	+1600[a]

[a] All impact categories were approximately the same.
[b] AP: +150%; EP: +150%; POCP: +160%; and input energy +250%.
[c] AP: +16%; EP: +35%; POCP: -68%; and input energy -18%.
[d] AP: -16%; EP: -4%; POCP: -76%; and input energy -29%.
[e] AP: +140%; EP: +140%; POCP: +160%; and input energy +280%.

Table 4. *Total change in environmental impacts and energy requirements for medium- and large-scale production of RME and ethanol fuel in comparison to small-scale production*

Fuel and type of comparison	Change for emission category or energy (%)				
	GWP	AP	EP	POCP	Input energy
Production of RME:					
Change to medium-scale	-1.8	-1.7	-1.7	-1.9	-6.3
Change to large-scale	-0.1	+0.2	+0.3	+2.7	-3.8
Production of ethanol fuel:					
Change to medium-scale	-0.7	+2.3	+4.5	-20.6	-2.5
Change to large-scale	+1.5	+0.6	+2.7	-21.6	-1.7

Comparison of different allocation methods

The levels varied greatly when different allocation methods were used, for RME shown in Fig. 12 (see also Paper II). With ethanol fuel, physical, economic and no allocation (Table 5 and Paper III) behaved in the same way as for RME. For physical allocation, there was practically no difference between scales. With RME, the medium-scale alternative was the most favourable, but with ethanol fuel different scales were favourable depending on the emission category or energy requirement studied. For ethanol fuel production, small-scale plants were preferred for AP- and EP-emissions, and medium-scale plants for GWP- and POCP-emissions and energy requirements. As can be seen, the contributions for no allocation were in many cases more than twice as high as the contributions for physical allocation, especially for the RME. It can also be noted that with no allocation and economic allocation of the environmental load, for both RME and ethanol fuel, both environmental impacts and energy requirements were lowest for large-scale production.

Allocation with expanded system gave more variable results compared to the other allocation methods (Fig. 12) for the fuels studied. For RME some values were negative *e.g.* the energy requirement (Fig. 12 and Paper II). Negative values indicate that the system was a net supplier of energy. This was possible because the energy subtracted for replaced by-products exceeded the total energy needed for the production of RME. Negative values did not occur for the ethanol fuel production. Allocation with expanded systems resulted in small-scale plants being preferred in production of RME for AP- and POCP-emissions and energy requirement; and in production of ethanol fuel for GWP-, AP- and EP-emissions. Medium-scale plants were preferred in RME production for EP-emissions; and in ethanol fuel production for POCP-emissions and energy requirement. Finally, large-scale plants were preferred in production of RME for GWP-emissions.

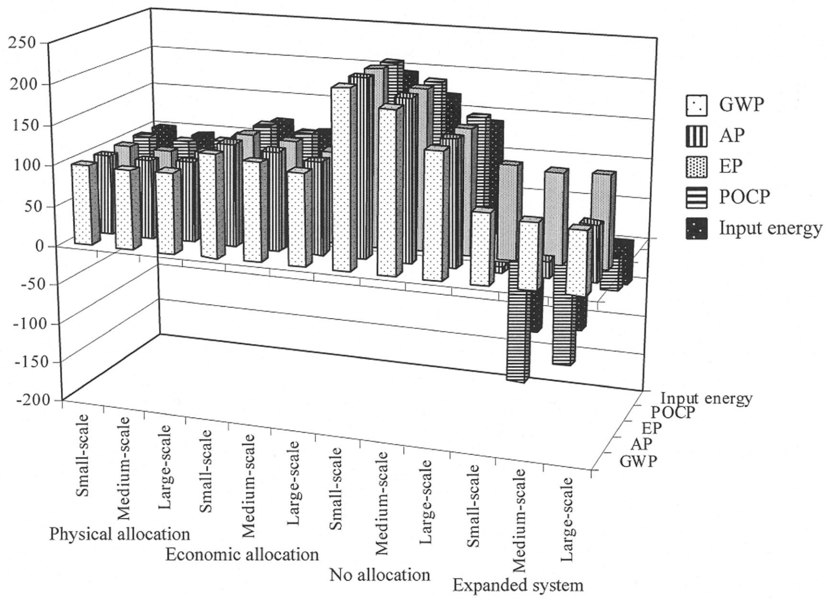


Fig. 12. Normalised (small-scale, physical allocation = 100) emission category and input energy values for production of RME at different scales and type of allocation.

Table 5. *Comparison of different allocation methods for production of ethanol fuel for the three production scales studied*

	GWP (g CO_2-eq/MJ_{fuel})	AP (mg SO_2-eq/MJ_{fuel})	EP (mg PO_4^{3-}-eq/MJ_{fuel})	POCP (mg C_2H_4-eq/MJ_{fuel})	Input energy (kJ/MJ_{fuel})
Physical allocation					
Small-scale	31.5	198	30.9	13.8	359
Medium-scale	31.3	202	32.3	10.9	350
Large-scale	31.9	199	31.7	10.8	353
Economic allocation					
Small-scale	45.9	286	45.2	15.4	464
Medium-scale	45.7	291	46.7	12.4	453
Large-scale	43.5	270	43.2	12.0	434
Expanded system					
Small-scale	28.3	33	25.6	10.1	137
Medium-scale	28.4	40	27.4	7.1	134
Large-scale	30.5	61	30.8	8.1	189

Sensitivity analysis

In the sensitivity analysis it was shown that all impact categories and energy requirements were quite sensitive to changes in grain yield and use of fertilisers. Changes in soil emissions, production of ignition improver, use of steam for ethanol production and use of tractive power also had an influence, but to a much smaller extent. The effects of the other changes were small or negligible.

The influence of increasing or decreasing the grain yield by 20% and increasing some other factors by 20% on the difference between small- and large-scale production was also studied (Papers II and III). It was demonstrated that the changes in the input parameters had a small or negligible influence on the difference between the two production scales.

Monte Carlo simulation

With the uncertainties assumed in this study, essential differences between scales were assumed to exist if the probability values in Table 6 were less than 0.05 or greater than 0.95. Thus, there were differences for all assumed input coefficients of variation for POCP. However, for a coefficient of variation of 5%, there were also differences for GWP and EP. The reason for the higher POCP-emissions in small-scale plants was the higher HC-emissions during production of heat (steam).

Table 6. *Small-scale plants in comparison to large-scale plants (small-scale minus large-scale) at different coefficients of variation of inputs (excl. cultivation)*

	GWP (g/MJ_{fuel})	AP (g/MJ_{fuel})	EP (g/MJ_{fuel})	POCP (g/MJ_{fuel})	Input energy (MJ/MJ_{fuel})
Original differences	-0.48	-0.0013	-0.00082	0.0030	0.0062
Uncertainty values from standard deviations:					
Input coefficients of variation: 5%	0.21	0.0019	0.00027	0.00042	0.0072
Input coefficients of variation: 10%	0.41	0.0038	0.00056	0.00082	0.0130
Input coefficients of variation: 15%	0.60	0.0055	0.00081	0.00120	0.0216
Probability that: small-scale < large-scale					
Input coefficients of variation: 5%	0.99	0.75	0.999	$1*10^{-12}$	0.19
Input coefficients of variation: 10%	0.88	0.63	0.93	0.0001	0.32
Input coefficients of variation: 15%	0.79	0.59	0.84	0.007	0.39

Scenario analysis

During production of RME, the most important changes in the results were observed when the methanol was produced from Salix instead of from natural gas, and when fossil fuel electricity was used instead of Swedish electricity (see Paper II). Methanol produced from Salix increased the energy requirement by more than 30%, but the GWP was almost unchanged. However, when the system boundary was expanded to include CO_2-emissions from the use of the RME in an engine, GWP decreased by 10%, because the carbon atom in the RME that originated from the fossil (natural gas) methanol was replaced by a carbon atom originating from the biofuel Salix. With electricity produced from more fossil fuel-rich raw material instead of Swedish electricity, the GWP and energy requirement increased by 14-20%.

When the RME produced was used for cultivation and transport in the system studied, GWP decreased by a few per cent and POCP by almost 25%. However, the categories AP, EP and energy requirement increased by a few per cent. For ploughless tillage AP, EP, POCP and energy requirement decreased by a couple of per cent. Other factors studied had only a minor influence on impact categories and energy requirement.

During production of ethanol fuel in the scenario with straw harvest, 46% of the environmental load for the cultivation was allocated physically to the straw according to its lower heating value. This resulted in reductions in GWP, AP and EP of almost 40%, in POCP of almost 10% and in the energy requirement of 20% (see Paper III). When the straw had an assumed value of 0.070 SEK/kg in the field (Nilsson, 1999) and the allocation was carried out according to monetary units, 2.5% of the environmental load for the cultivation was allocated to the straw, resulting in a reduction in the environmental load for the whole ethanol fuel production of a few percent. Thus, the choice of allocation method had a great influence on the results. In practice, however, the use of straw as a fuel in Sweden is limited, *e.g.* because of difficulties in harvesting a fuel with sufficiently low moisture content due to poor weather conditions during the harvest season.

Important changes in the results were also observed when the ignition improver produced was of bio-origin instead of fossil raw material origin. The AP, POCP and energy requirement increased by almost 60%, more than 230% and 70% respectively, whereas the GWP decreased by only about one per cent.

When the denaturants produced were of bio-origin instead of fossil raw material origin, their environmental impact categories behaved in a similar way to those from the ignition improver, increasing the AP, POCP and energy requirement by a few percent, almost 80% and almost 30%, respectively. With electricity produced from more fossil fuel-rich raw materials compared to Swedish electricity, the GWP increased by almost 25% and the energy requirement by more than 10%. Small-scale production with large-scale energy efficiency decreased the POCP and energy requirement by more than 20% and a few per cent, respectively. Other emission categories were almost unaffected. When the ethanol fuel produced was used for cultivation and transport in the system studied, GWP decreased by a few per cent. For ploughless tillage, AP and EP decreased by a couple of per cent. Other factors studied had only a minor influence on impact categories and energy requirement.

The influence of the alternative scenarios on the difference between small- and large-scales is shown in Table 9 in Paper II and Table 10 in Paper III. Most of the scenarios studied had small effects on the difference. For RME production, transport distances and choice of electricity were the most important factors. For ethanol fuel production, straw harvest, ignition improver, denaturants, choice of electricity, doubled transport distances and small-scale production with large-scale energy efficiency were the most important factors.

Farm-produced bio-based motor fuels on organic farms

Method

The environmental impact of producing and using RME, ethanol and biogas on organic farms was assessed with the LCA methodology. The requirements of energy and emissions caused in all processes from raw material acquisition through distribution and processing to end use were quantified. The impact categories calculated were use of primary energy, global warming potential, acidification potential and eutrophication potential using category indicators from IPCC (2001), Hauschild & Wenzel (1998) and Lindfors *et al*. (1995). In this part-study the eutrophication potential was expressed as O_2-equivalents instead of the previous PO_4^{3-}-equivalents (for EP: 1 g PO_4^{3-}-eqv. = 46 g O_2-eqv., see also Table 1).

System boundaries and delimitations

In order to enable comparisons between different scenarios, the common basis for the calculations was defined as the amount of farm-produced motor fuel that would cover the fuel demand at cultivation of 1 000 ha with a given crop rotation during one year. This rather large acreage was chosen as it corresponded approximately to the smallest plausible size of fuel production facility. One large or a number of small farms would work the production facilities together in much the same way as many farms do with agricultural equipment (de Toro & Hansson, 2004). The reason for including a whole crop rotation in the study was to define the amount of fuel needed in order to achieve self-sufficiency and to take crop rotation effects into consideration.

The system investigated included cultivation and handling of the amount of agricultural products needed to produce motor fuel for the entire crop rotation. The agricultural raw material produced was processed into motor fuel on the farm and the fuel utilised in field operations for the whole acreage. The system included the whole life cycle, including transport, for the products used within the system. Production of capital goods such as machinery and buildings for cultivation and fuel production was not included in the study, as Papers II and III showed that production of capital goods is of minor importance for the overall result.

Within the defined system boundaries, scenarios for RME, ethanol and biogas were identified. The fuel production and utilisation scenarios studied are shown schematically in Fig. 13.

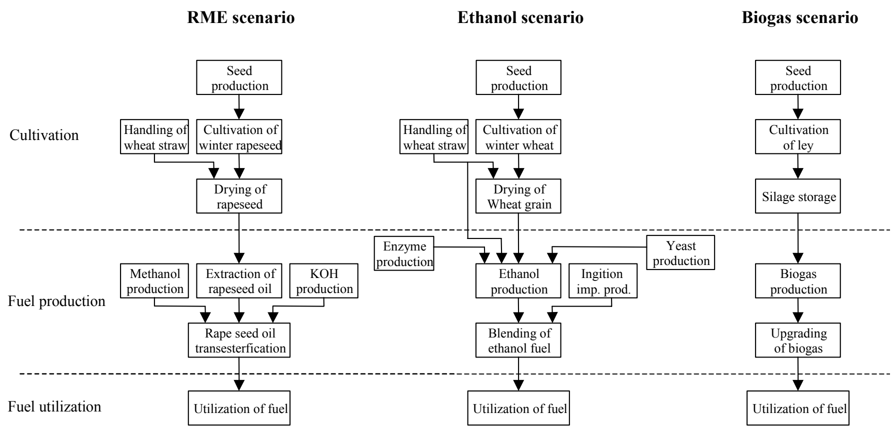


Fig. 13. Schematic description of scenarios studied.

The amount of bio-based motor fuel produced in the different scenarios was correlated to the fuel consumption for cultivation of 1000 ha. Surplus amounts of wheat, oilseed or ley were assumed not to be processed into fuel. The size of the processing plants was assumed to be adjusted to fit the amount of fuel required for the field operations at the 1000 ha farm.

Cultivation using organic production methods under Swedish conditions was assumed. The whole crop rotation for stockless organic farming was included in the model (Paper IV). It was designed to prevent problems with pests and weeds, require a minimum of cultivation and to be favourable in an economic perspective. Nitrogen was supplied by nitrogen-fixing crops grown twice in the rotation. The crop rotation for 7 years was: field beans, oats, green manure, winter rapeseed, winter wheat, green manure/ley and rye. For the study, it was assumed that each crop was grown on 143 ha each year and that the crops were evenly distributed over the total area.

Allocation

The environmental load was divided between the main products and the by-products in relation to their prices on the economic market (economic allocation). It was assumed that all by-products were sold at the farm gate. Another alternative may have been to use physical allocation. However some of the by-products, for example straw, have a high energy content but a low value, and it is obvious that the goal for the farmer is to produce grain, not straw. Physical allocation was therefore judged not to be the best alternative for this study.

Difficulties arise when studying cultivation of a single crop as each of the crops in the crop rotation in organic farming systems is affected by the cultivation of the other crops. One crop may influence the yield of other crops in the rotation through a positive preceding crop effect or influences on diseases. The methods for allocation of processes affecting other crops in the cropping plan developed by van Zeijts, Leneman & Wegener Sleeswijk (1999) were used. According to these methods the environmental impact of green manure should be allocated to all crops according to land use per crop in the cropping plan, as organic matter benefits all crops. For a leguminous cash crop, it could be assumed that only that specific crop profits from the nitrogen binding.

Production and use of RME, ethanol fuel and biogas

RME and ethanol fuel were produced with the same capacities and assumptions as for the small-scale plants described in Papers II and III. The annual production capacity was 65 m^3 RME or 110 m^3 ethanol (Paper IV). For the production of biogas from ley crop a continuous, single stage mixed tank reactor operating at a mesophilic temperature with a production capacity of 2 700 GJ methane per year was assumed (Paper IV). To utilise biogas as a motor fuel, carbon dioxide and corroding substances have to be removed. This was assumed to be done by use of a small-scale water scrubber with a flash-tank for re-circulation of methane. The use of electricity was set to 6% of the energy in the incoming gas and the loss of methane was assumed to be 3% based on Persson (2003). The cleaned gas was then assumed to be stored in high pressure storage at 200 bar. Use of biogas demands mounting of spark plug ignition systems or other quite extensive changes of the engines.

The fuel consumption and emissions when using diesel were calculated from figures presented by Lindgren *et al*. (2002), and then compensated for the characteristics of the different fuels (Paper IV). Factors for recalculation of fuel consumption and emissions from the diesel figures were calculated based on emission figures for heavy vehicles presented by Lingsten *et al*. (1997), Haupt *et al*. (1999) and Hansson *et al*. (1998). Emissions of CO_2 from utilisation of the fuels were not accounted for, as the CO_2 was of renewable origin. The methanol used for transesterification of rapeseed oil was of bio-origin. However, the ignition improver added in the ethanol scenario was made from fossil raw material.

Results

Land use

In production of motor fuel for self-sufficiency, the different scenarios require different amounts of land. In the RME scenario, 8.8% (88 ha) of the cultivated area was used on average for fuel production. For production of ethanol, 5.9% (59 ha) of the area was used on average and for production of biogas 3.8% (38 ha). In the assumed seven-year crop rotation, the maximum available amount of land was 14.3% (143 ha) for cultivation of rapeseed and winter wheat and 28.6% (286 ha) for cultivation of green manure that could be harvested as a ley crop.

Energy use

The input of primary energy for the scenarios studied is presented in Table 7 and divided between energy in fuels, electricity and heat. The cultivation figures included energy for cultivation and harvest of the area needed to produce raw material for the amount of fuel produced. The effects of transport to the farm and drying of the crop were also included. In fuel production, the energy used mainly consisted of electricity and heat for the processes and energy for production of input materials such as methanol and ignition improver. The energy inputs were allocated between the fuels produced and the by-products in each scenario. However, the non-allocated figures are also presented (Table 7). Furthermore, the energy content in all fuel produced (and used) is also presented for each scenario (Table 7). The amount of fuel produced was 49.8 tonnes RME, 67.6 tonnes ethanol or 70 000 nm^3 methane.

Table 7. *Primary energy used and energy content of the fuel produced for the scenarios studied (GJ)*

		Culti-vation	Fuel prod.	Total (allocated)	Total (not allocated)	Energy in fuel produced
RME	Fuel	111	0	111	237	1 873
	Electricity	3	45	47	99	
	Heat	35	1	36	77	
	Total	149	46	194	413	
Ethanol	Fuel	127	0	127	143	1 697
	Electricity	6	45	50	54	
	Heat	73	300	373	402	
	Total	206	345	550	599	
Biogas	Fuel	35	0	35	61	2 694
	Electricity	0	133	133	233	
	Heat	0	95	195	167	
	Total	35	228	263	461	

The amount of energy in the fuel produced (and used) differed between the scenarios studied. This was partly due to the difference in assumed engine efficiency for the fuels studied but also to a difference in the need for field operations. This need was lowest for the biogas scenario, since the biogas crop was insown in the previous crop, and therefore no extra energy-consuming soil preparation was needed. Due to the comparatively large area needed to produce the necessary amount of rapeseed, the amount of machine operations was rather high in the RME scenario. In ethanol production, large amounts of heat were used for the distillation. In the biogas scenario, production and cleaning of the gas required a lot of energy, mainly as electricity and heat.

The total energy efficiency, calculated as the energy in the fuel produced divided by the total allocated energy use, was 9.6 for RME, 3.1 for ethanol and 10.2 for biogas. The RME and biogas scenarios showed the lowest total energy inputs when the non-allocated values were compared. When the allocated values were compared, the more valuable by-products of the RME scenario resulted in the RME value being clearly lowest.

Environmental impacts

The potential environmental impacts of the fuel supply parts of the scenarios studied are presented in Table 8. As for energy use, the calculated potential environmental impacts were allocated between the fuels produced and the by-products. The soil emissions are presented separately, since they were found to have a major influence on some of the impact categories. The effects of the direct emissions from all tractor operations at the farm (utilisation of all fuel produced) are presented in Table 9. These figures were not allocated.

Table 8. *Potential environmental impacts of the fuel supply parts of the scenarios studied (allocated values)*

		RME	Ethanol	Biogas
Global warming potential	Cultivation	20	1 033	96
(kg CO_2-equivalents)	Fuel production	394	6 501	20 519
	Soil emissions	40 898	31 627	18 836
	Total	41 312	39 161	39 453
Acidification potential	Cultivation	78	57	8
(kg SO_2-equivalents)	Fuel production	2	53	3
	Soil emissions	150	142	103
	Total	230	252	114
Eutrophication potential	Cultivation	674	486	75
(kg O_2-equivalents)	Fuel production	9	199	13
	Soil emissions	36 060	38 345	9 493
	Total	36 743	39 030	9 581

Table 9. *Potential environmental impacts of direct emissions from all tractor operations at the farm (utilisation of all fuel produced) in the scenarios studied (non allocated values)*

	RME	Ethanol	Biogas
Global warming potential (kg CO_2-equivalents)	0	14 127	7 693
Acidification potential (kg SO_2-equivalents)	1 252	672	653
Eutrophication potential (kg O_2-equivalents)	10 889	5 839	5 674

The largest contributor of greenhouse gases was emissions from agricultural land (Table 8). The emission of N_2O from land is dependent on the amount of available nitrogen (see also Papers II and III). The RME scenario required the largest area for cultivation of raw material for fuel production and this scenario also showed the highest emissions from the land, even though a large proportion was allocated to the by-products of the scenario. Since the fuels used in cultivation were mainly based on biomass, the CO_2 emissions and thereby the GWP effects from the cultivation were relatively small when compared to the effects from the other parts of the system (Table 8). The RME scenario had relatively low emissions of climate gases from fuel production, whereas emissions from production of ignition improver in the ethanol scenario and emissions from biogas upgrading and storage gave a rather large contribution.

The GWP effects from ethanol utilisation (Table 9) are caused by the ignition improver, while the effects from utilisation of the biogas are caused by unburned methane in the tractor emissions. Since the methanol used in the RME production was assumed to be produced from biomass, the utilisation of RME causes negligible CO_2 emissions.

The emissions from cultivation made a considerable contribution on the acidification potential for the RME and ethanol scenarios (Table 8), whereas the effect of fuel production only was substantial for the ethanol scenario. In fuel production, the emissions for the ethanol scenario originated from burning of straw for heat and from production of ignition improver. Emissions from soil had the highest impacts on all scenarios.

The acidification emissions caused by the fuel utilisation (Table 9) are for all fuels studied much higher than the total corresponding emissions caused by the fuel supply system (Table 8). The relatively high emissions of NO_x during utilisation of the RME produced had a clear effect on the total potential acidification of this scenario.

The potential eutrophication (Tables 8 and 9) caused by the scenarios studied was mostly due to losses of nutrients from agricultural land and emissions of NO_x from utilisation of the fuels produced. Nutrient leakage in each scenario was largely dependent on the area used for raw material production. The biogas scenario showed a lower value in comparison with the other scenarios.

Sensitivity and scenario analyses

Both the sensitivity and scenario analyses (Paper IV) were performed in the same way as in the studies comparing small- and large-scale production of RME and ethanol fuel (Papers II and III). The results also agreed very well with those results.

Discussion

Oil extraction

The results from the oil extraction study show that when rapeseed is processed, a small screw oil press should be operated with a small nozzle at low screw speed if high oil extraction efficiency is anticipated (Paper I). However, if a high capacity is expected, the oil press should be operated at a high screw speed. The chosen nozzle size is then of minor importance because the differences in capacity are small between the nozzle sizes at high screw speeds (Fig. 4). However, larger nozzles should be avoided in order to avoid a low oil extraction efficiency. Together this means that a small screw press is best operated with a small nozzle size and a rather high screw speed to get the best compromise of both high capacity and high oil extraction efficiency. A high oil extraction efficiency is necessary to use the land area resource as efficiently as possible and to reduce cultivation-associated emissions (see Papers II and IV).

The fact that the distance between the screw and press chamber head is important for the oil extraction efficiency indicates that the press operator must carefully monitor the wear on the press screw. When the screw becomes worn, the distance between the screw and the press chamber head increases.

LCA methodology in general

LCA as a method has both strengths and weaknesses. It is often used to compare products with the same function, *e.g.* RME and ethanol fuel, or to determine ‘hot spots’, *i.e.* parts of the life cycle that are critical to the total environmental impact (Robèrt, 2000). Since it does not focus on just one single effect from one single part of a product, the process of performing an LCA is a way of creating an overview of the total complexity of interactions between different processes in industrial society and ecosystems. In addition, it can be helpful in selection of products that have as low a negative influence as possible in Nature. Finally, it allows us to plan ahead, because we can simulate new conditions for the future, when various things like transport and electricity production systems, *etc.* have changed.

Some weaknesses of LCA are that there is a risk that important unknown environmental aspects may be omitted in the study, and that uncertainty in input data and choice of system boundaries and allocations may have a great influence on the results (Björklund & Rydberg, 2003). Furthermore, analysis that includes weighting of all impact categories to a single figure is a mixture of political valuations and research results that may make the outcome confused and difficult to interpret, and because of this such weighted analysis was excluded from this study. There is also a risk that qualitative aspects may disappear in the final interpretation because they tend to be obscured by the figures.

Functional units and system boundaries

The unit of allocation should be logical and easy to understand and use in the system studied. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related (ISO, 1997). This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis.

During comparison of plant sizes, the unit of allocation used in Papers II and III was 1.0 MJ of energy in the fuel delivered to the final consumer, which gave the functional unit 1.0 MJ_{fuel}. When the fuels were compared (see Bernesson, 2004) the use of the fuel also had to be included and a suitable functional unit was then 1.0 MJ of energy delivered on the engine shaft, *i.e.* 1.0 MJ_{engine}.

In Paper IV the calculations aimed to quantify the environmental load from production and use of all fuel needed on a 1000 ha organic farm, or group of farms. The fuel use was also included in order to make comparisons between fuel scenarios possible. Since the choice of fuel influenced the crop rotation, the amount of machinery operations needed and thereby also the amount of fuel needed, the whole crop rotation was included in the calculations.

The system boundaries are very important when different plant sizes and fuels are compared. When plant sizes are compared as in Papers II and III, the use of the fuel can be excluded because it gives the same emissions independent of the plant size. When different fuels are compared (Bernesson, 2004) the use of the fuels must be included in the system because *e.g.* RME and ethanol fuel have to be used in different engines with different emissions characteristics and different engine efficiency.

When plant sizes are compared, the production of the raw material (rapeseed for RME production and wheat for ethanol fuel production) may be excluded from the system if it is used with the same efficiency in all plant sizes compared. That is the case when ethanol fuel is produced but not when RME is produced because the oil extraction efficiency differs, as does the efficiency of the land use. Therefore the wheat cultivation was excluded in the Monte Carlo simulation in Paper III. In other parts of Paper III, the production of wheat was included in the system because the cultivation provided important data for the study (*e.g.* the importance of synthetic fertilisers).

Allocation strategies

The results show that the choice of allocation method has a great effect on the absolute levels of the environmental load figures calculated (see Fig. 12, Table 5 and Papers II-III). These differences indicate that when different biofuels or production strategies are to be compared against each other, it is very important that the results are calculated using the same allocation strategies and system limitations.

The great effect on the results caused by allocation strategy used may be seen as a weakness of the LCA method, but is more a result of the environmental load problem having many different aspects and seldom simple answers. This study focused mostly on physical allocation because of well-defined inputs, the value of which does not change over time. The results from physical allocation are also often easy to understand and easy to measure. Furthermore, it is often easy to follow the process from start to final use and therefore easy to get control over the system. Economic allocation works in the same way as physical allocation, with the difference that the prices of the products decide over the allocation. Prices are often easy to obtain on an existing market. Drawbacks are that prices may change over time and be different at different places. The results change in the same way and often a date must be given for when the prices are valid. Economic allocation may be preferred before physical allocation in systems that include products with different energy qualities or that would be too complicated for physical allocation (see Paper IV). A drawback with physical and economic allocation is, however, that they often do not consider the environmental impact when different by-products replace other products in later processes. In such cases, it is often better to use the expanded system allocation procedure.

With an expanded system, the environmental load from a system that is replaced by the by-products from the studied system is subtracted. If the values become negative, environmental load is saved for the expanded system. For example, from the expanded system calculations in this study it was shown that in a situation where there is a requirement for glycerine and a meal with a high fat and protein content, RME could be produced at the same time as energy is saved and POCP-emissions reduced (Fig. 12 and Paper II). Thus, allocation with an expanded system may be the fairest method if the system is studied on a higher systems level and the impact from a specific change in the total fuel production to end-use system is of interest. However, the drawback with this method is that a change in the assumptions regarding production of the replaced products may have very significant effects on the results. Potential problems are that these data may be difficult to obtain or badly documented. Because of these facts, expanded system allocation must be used with care.

In systems with physical, economic or no allocation, straight rapeseed oil fuel gives lower emissions and has a lower energy requirement than RME (Bernesson, 2004). The reason is that when the rapeseed oil is used straight, there is no requirement for resources for the transesterification and production of methanol, *etc.* However, with expanded systems, RME gives lower emissions and has a lower energy requirement than straight rapeseed fuel. The reason is that the by-product glycerine from the production of RME replaces glycerine of petroleum origin and a high environmental load. That environmental load is credited to the RME production process. The drawback with this procedure is that the results depend on how the by-product glycerine is used: does it replace glycerine of fossil or of biological origin?; or is it used at all?

It may be that physical allocation is the most suitable allocation method when a technical system is analysed, as in this study (Papers II and III), because of more stable results and well-defined input and output values. Allocation with an expanded system may be the most suitable allocation method when the systems are studied from a more society-orientated overall view.

Effects on environmental load of plant sizes and fuel choice

The results demonstrate that the differences in environmental impacts and energy requirements, with physical allocation, between small-, medium- and large-scale systems for the production and use of RME and ethanol fuel were small or even negligible in most cases. One reason was that the differences were swallowed up in comparison to the dominant emissions for production of rapeseed and wheat, *etc.* (Fig. 11), which did not directly contribute to differences between production scales. The cultivation production step was identical for all scales and therefore its contribution to the total difference might be small. Furthermore, in the large-scale system, the more efficient use of machinery and buildings, for RME production the higher oil extraction efficiency and for ethanol fuel production the more efficient use of energy were, to a certain degree, outweighed by the longer transport distances. However, all these factors were very small in comparison to cultivation.

With economic allocation, the differences between plant sizes were somewhat larger, compared to physical allocation. Then large-scale plants had the lowest environmental impact and energy requirement. Small-scale plants usually had the largest impact, especially for RME.

With allocation with an expanded system, however, the differences between the plant sizes were in most cases much larger. For production of RME, the meal with a much higher oil content from small plants meant that more resource-requiring soyoil in the soymeal could be replaced, and be an advantage for small-scale plants. However, this effect was counteracted by the fact that the higher oil yields from larger plants gave more glycerine to replace fossil glycerine. Fossil glycerine gives especially high global warming emissions when produced. Together these facts explain why the GWP was lowest for large plants and AP, POCP and energy requirement were lowest for small plants for allocation with expanded system. For production of ethanol fuel, the amount of soyoil and soymeal replaced by the distiller's waste was independent of the plant size. Because this environmental load was just subtracted from the unallocated system, the level of the absolute differences between the scales was the same for the expanded system as for the unallocated system. GWP, AP, EP and energy requirement were highest for large-scale production, principally depending on the extra operation for drying of distiller's waste in large-scale plants. POCP-emissions were higher in small-scale plants, principally depending on higher HC-emissions from the boilers used for the heat production in those plants.

During production of RME the area yield differed greatly between scales (28, 31, 40 GJ/ha for small-, medium- and large-scale plants, respectively). Large-scale plants therefore more efficiently use the land resource with associated emissions. However, by physical allocation this effect is hidden and not visible because the heat value in the oil not possible to use for RME production is allocated away to the meal by-product. With an unallocated system or a system with allocation with an expanded system, this effect is visible. This is the reason behind the emissions and energy requirement being lowest for large-scale plants in systems with no allocation (Fig. 12). For the expanded system, these effects were levelled out more or less by the high environmental load from the replaced products (see above for explanation). For ethanol production, there was no difference in yield between plant sizes and therefore no effects for different land utilisation between scales.

The differences between RME and ethanol fuel were much larger than between the production scales (Paper II and Paper III). For production of ethanol fuel, the GWP-, AP- (only for physical allocation) and EP-emissions were lower than for production of RME. However, the energy requirement was higher and the POCP-emissions were much higher (Paper II and III; Bernesson, 2004). The higher yield of ethanol fuel (52 GJ/ha) compared to RME (28 GJ/ha) was the main reason for the GWP-, AP- and EP-emissions being lower for ethanol fuel. The land resource with corresponding emissions was better utilised by the ethanol production. High POCP-emissions and energy requirement during production of ignition improver, heat and denaturants were the principal reasons for the higher POCP-emissions and energy requirements during production of ethanol fuel. The higher energy requirement also depended on the high requirements for electricity during production of ethanol fuel. Ignition improver could be excluded if the fuel were to be used in an engine designed to run on pure ethanol. Denaturants could be excluded if an alternative way could be found to prevent the ethanol being drunk.

Data quality

Results from sensitivity analyses, Monte Carlo simulations and scenario analyses indicate that the influence from unreliable data was not too high in the studies (Papers II, III and IV). Most data were therefore sufficiently reliable, although for influence on the results, the data for the soil emissions were probably the most unreliable. The emissions values for N_2O and NH_3 differ greatly (0-47.1 g N_2O/kg fertiliser-N and 0-70 g NH_3/kg fertiliser-N respectively) between different authors according to Patyk & Reinhardt (2000), with mean values of 19.6 g N_2O/kg fertiliser-N and 40 g NH_3/kg fertiliser-N as used in this study (Papers II and III). The influence on the EP-, AP- and GWP-emissions was high (Fig. 10 and Table 1). Comparing plant sizes and RME production, large-scale plants are favoured if these emissions are too high because higher oil extraction efficiencies give a more efficient use of the land. For ethanol fuel production such emissions have no importance for the comparison between plant sizes because they do not differ in how efficiently the land is used. It may be advisable to check how these data are treated when comparing the results with other studies and with fuels not treated in this study, because they may be important.

The data for machinery and buildings production were also less reliable, but because the influences of these data are small, they are swallowed up in comparison with the total emissions (tenth of one per cent for agricultural machinery and hundredths of one per cent for processing machinery) and energy requirements (see Figs. 10-11 and Bernesson, 2004). In a scenario with production of machines and buildings based on electricity produced mainly from fossil fuels instead of Swedish average electricity, the ratios between small- and large-scale systems for production of RME or ethanol fuel in emissions and energy requirement were only influenced to a minor extent (Bernesson, 2004). The data for machinery and buildings production are therefore of minor importance for the results and comparisons performed, even if they are underestimated by as much as a factor of 2-3.

Comparing the engine emissions with Swedish environmental class 1 diesel fuel for two sources used in this study (Aakko *et al.*, 2000 and Haupt *et al.*, 1999), the HC-, CO- and NO_x-emissions were 64, 39 and 16% higher, respectively, in Haupt *et al.* (1999). The values from Aakko *et al.* (2000) were used in this study because the engine used was newer and therefore assumed to be more representative. The figures give an indication of how large the uncertainty may be for the emissions values used for agricultural work, transport and use of the fuels produced in this study.

Comparison with results from related studies

Two main LCAs on RME have been performed in Sweden. The first of these was by Ragnarsson (1994) and the second by Blinge *et al.* (1997) and Blinge (1998). The CO_2-emissions presented by Blinge *et al.* (1997) and Blinge (1998) were approx. 50% of those in the present study. However, the CO_2-emissions presented by Ragnarsson were 160% of those in the present study. When we assumed that carbon atoms of biomass origin replaced fossil glycerine, the emissions presented by Blinge *et al.* (1997) and Blinge (1998) were then approx. 60% of those in the present study. For the other substances studied, the differences to the studies by Ragnarsson (1994), Blinge *et al.* (1997) and Blinge (1998) were about the same size as for CO_2. The soil emissions (NH_3 and N_2O) and SO_x-emissions were higher in the present study in comparison to the other studies. The energy consumed was the same in the present study and the studies conducted by Blinge *et al.* (1997) and Blinge (1998). The differences between the studies could principally be explained by somewhat different assumptions and systems boundaries. For example, the seed harvest was assumed to be 25% lower in Ragnarsson (1994) and 10% higher in Blinge *et al.* (1997) and Blinge (1998) than in the present study. This gives a corresponding lower or higher amount of RME over which to spread the emissions.

Production of RME has also been studied in a German LCA (Gärtner & Reinhardt, 2001 and Reinhardt & Gärtner, 2002). That study was similar to the present study but it was conducted under German or Central European conditions. The values obtained by Gärtner & Reinhardt (2001) and Reinhardt & Gärtner (2002) for the rapeseed production were very similar to the values in the present study (for most emissions categories and energy requirement, differences less than 20%). Total energy requirement and emissions in the German study are calculated using an expanded system where the by-product rapemeal is used as an animal feed in substitution of soymeal imported from the USA. Glycerine from the transesterification replaces conventional petroleum-based glycerine. The rapeseed fuel life cycles are credited for this use. In the present study, allocation with expanded system was studied as an alternative allocation method. However, the differences between the present study and the study by Gärtner & Reinhardt (2001) and Reinhardt & Gärtner (2002) increased after the transesterification, especially for AP-, EP- and POCP-emissions. These differences between the studies are probably due to the fact that Gärtner & Reinhardt (2001) and Reinhardt & Gärtner (2002) carried out their study under somewhat different assumptions (*e.g.* German conditions).

From the discussion above, the conclusion must be that the present study agreed rather well with previous LCAs on the production of RME for use as a fuel in engines.

Two main LCAs on ethanol fuel have been performed in Sweden. The first of these was by Almemark (1996) and the second by Blinge *et al.* (1997) and Blinge (1998). The CO_2-emissions presented by Ragnarsson (1994), Blinge *et al.* (1997) and Blinge (1998) were approx. 50-70% of those in the present study when ignition improver and denaturants were excluded. Most other emissions were higher in the present study compared to the other two studies, mainly depending on rather high emissions being considered for the heat (steam) production in the present study (Kaltschmitt & Reinhardt, 1997). However, the energy requirement was lower in the present study due to the fact that the energy requirement for ethanol production was calculated from the energy-efficient ethanol plant in Norrköping (Agroetanol, 2003) and that the ethanol in the present study was not dehydrated, which further decreases the energy requirement (Jacques, Lyons & Kelsall, 1999).

Comparison with use of fossil fuels

It is clear that the production and use of RME and ethanol fuel for heavy diesel engines reduce the GWP-emissions in comparison to the production and use of diesel oil (MK1). Based on data from the studies by SMP (1993), Aakko *et al.* (2000) and Uppenberg *et al.* (2001), the GWP-emissions for the production and use were reduced by more than 40% for RME and were reduced by more than 50% for ethanol fuel (based on g CO_2-eq/MJ_{engine} and small-scale system with physical allocation). However, the categories of AP and EP were both increased by approx. 80% for RME and by less than 5% for ethanol fuel, in comparison to MK1. The category of POCP was decreased by almost 70% for RME and increased by almost 50% for ethanol fuel. The energy requirement for the production and use of RME and ethanol fuel was approx. 5 times higher than for MK1 (Uppenberg *et al.*, 2001). The results from the scenario analysis in which the RME and ethanol fuel produced replaced MK1 confirmed these relationships.

The reduction in the global warming potential when the fuels produced were assumed to be used for the agricultural operations and transport during production of the fuels was rather small: approx. 4% decrease of GWP for RME production and 3-4% decrease of GWP for ethanol fuel production (emissions based on 1.0 MJ on the engine shaft (Bernesson, 2004)). The total Swedish global warming emissions are not influenced by this operation because global warming emissions are just moved from production of the fuels used to road transport, *etc*.

The total global warming emissions from petrol and diesel engine powered road transport were 19 million tonnes in Sweden in 2002 (Feldhusen *et al.*, 2004). The reduction of global warming emissions is 44-64 thousand tonnes for the production and use of RME and 117-119 thousand tonnes for the production and use of ethanol fuel from 50 000 ha, the area needed for a large-scale plant. This corresponds to 0.2-0.3% of the total Swedish global warming emissions for RME and approx. 0.6% of the same emissions for ethanol fuel. Ragnarsson (1994) and SOU (1996) state that it is possible to cultivate approx. 220 000 ha rapeseed in Sweden. It should be possible to use approximately half this area for RME production. SOU (1996) also states that 500 000 m^3 ethanol could be produced in Sweden from grain. With the conditions assumed in this study, this would correspond to about 220 000-230 000 ha winter wheat.

Economic considerations

Since the environmental impact was about the same size for different fuel production plant sizes, the choice of plant size could be made according to the economic profitability. Economic calculations demonstrate that the production costs were about halved for large plants in comparison with small plants for both fuels compared (Bernesson, 2004). The ethanol fuel was more expensive to produce than RME, independent of plant size. The costs for production of the fuels in small-scale plants were 0.65 SEK/MJ_{engine} and 1.1 SEK/MJ_{engine} for RME and ethanol fuel, respectively, when the rapeseed was purchased for 2.00 SEK/kg and the wheat for 0.97 SEK/kg (Agriwise, 2003) (1 € = 9.2 SEK). The cost for diesel oil MK1 was 0.52 SEK/MJ_{engine} in Sweden in 2003, excl. value added tax (after OKQ8, 2003; Bernesson, 2004). These figures demonstrate that the RME could be produced profitably and that the ethanol fuel is close to profitable production in large plants. It may also be possible to produce RME profitably in medium-scale plants, since such plants reduce the production costs by over 30% in comparison to small-scale plants.

Today, farmers have difficulties in achieving reasonable profitability when rapeseed or wheat is grown in Central Sweden (Bernesson, 2004). A more profitable solution could be for the farmers to join together and start a medium-scale plant and sell the RME or the rapeseed oil instead of the seed. However, the ethanol would probably be too expensive to produce in medium-scale plants. Production of RME and ethanol in small farm-scale plants cannot be recommended because of the high costs. Machinery, buildings and labour *etc.* are not used efficiently enough in such plants. The more simple process for production of RME also makes this fuel more suitable as a rural fuel. This allows production of RME to be recommended in medium- and in large-scale plants. Production of ethanol fuel could only be recommended in large-scale plants.

Biofuels in organic farming

Organic farming, treated in Paper IV, may provide a solution to the problem of the large environmental contribution from fertilisers in conventional farming in Papers II and III. In organic farming, only organic matter is used as fertiliser, and synthetic fertilisers are not allowed. It is possible to cultivate nitrogen-fixing crops, which provide both plant nutrients and, if digested, biogas fuel (Paper IV). The drawback with organic farming is lower crop yields, which result in a proportionally higher requirement for land, with correspondingly higher environmental load for each MJ of fuel produced.

The production of RME had the largest requirement for land, with a corresponding higher requirement for cultivation resources and higher emissions to land and water. The production of biogas had the least requirement for land. With the exception of CO_2, emissions during utilisation of the RME were high compared to those from the other fuels in the study. Like conventional farming in Paper III, the ethanol scenario used large amounts of energy in the process (Fig. 11b and Table 7). The straw, with a low economic value, was used for drying the grain and for process heat in the ethanol production, in contrast to the study presented in Papers II-III. In the biogas scenario, the potential emissions of methane from storage of digestate, upgrading of biogas and methane losses during utilisation of fuel caused negative impacts, mainly on global warming (see Table 1 and Table 8). During upgrading of biogas to be used in vehicles, the use of electricity was high, which affected the energy balance.

The energy balances for production of RME and ethanol fuel, 9.6 and 3.1, respectively, (Paper IV) differed greatly from energy balances calculated from values in Papers II and III for small-scale RME and ethanol fuel production with economic allocation, 2.8 and 2.2 respectively. The main reasons were the use of energy-demanding artificial fertilisers (Fig. 10) in conventional farming and the straw also being harvested and used as fuel in the organic farming system.

The organic farming system (Paper IV) gave approximately halved GWP-emissions in comparison to the conventional farming system studied (Papers II and III) for production and use of RME or ethanol fuel. The reasons were the avoided requirement for artificial fertilisers with their associated high emissions (Fig. 10), and some emissions in the organic system (Paper IV) being allocated away with the straw. GWP also decreased because the organic farm's own fuel was used for cultivation. The AP-emissions were about the same in the two cultivation systems studied. However, the EP-emissions were increased by a factor of 4-6, mainly depending on different systems boundaries, *e.g.* in Paper IV N- and P-emissions to water were also included. These values also increased because of the lower crop yields and different type of cultivation. For this comparison, the values in Papers II and III were recalculated to approximately match the values in Paper IV.

From a farmer's point of view, any system for supply of motor fuel must be reliable. The production of RME includes well-proven technology suitable for use in farm-scale application. If the higher cost of production in such small plants could be accepted in organic cultivation systems, farm-scale RME production plants could be recommended. However, the system is sensitive to low yields, with which the farms cannot be self-sufficient. Furthermore, these systems could only operate in the southern part of Sweden.

Reducing the environmental impact

To decrease the environmental impact of RME and ethanol fuel production in general, several strategies may be useful, but the results presented clearly show that increased seed harvest and decreased use of artificial fertilisers decrease the impact considerably. While the potential for increased seed harvest is constrained by biological factors and weather conditions, the potential for a decrease in the use of energy-demanding artificial fertilisers is much higher. Organic waste and sewage water can be used to fulfil the nutrient demands with a very limited energy cost, at the same time as high costs for water sanitation plants are avoided. Since the rapeseed and wheat will not be used as food, the hygiene demands on the fertilisers could be decreased and waste products normally not allowed in agriculture could be used. These principles have been extensively studied in Salix production (Hansson *et al.*, 1999) and could also be applied in rapeseed or wheat cultivation. However, there is a risk that organic waste and sewage water may contain heavy metals, pesticide residues or other undesirable organic substances.

To reduce the environmental load during production of ethanol fuel for diesel engines, something must be done about the ignition improver and denaturants. As shown in this study, the denaturants could be produced from biomass or eliminated from the fuel with *e.g.* another type of ignition system in the diesel engines (STU, 1986) or the amount required could be decreased by a higher compression ratio in the engines (STU, 1986). It is also probably possible to produce the ignition improver and denaturants with lower emissions. For RME production, it is possible to produce the methanol with bio-origin and with lower emissions. However, it is not possible to reduce the amount of methanol required for production of RME in the same way, because it is the product of a chemical reaction between rapeseed oil and methanol.

During use of the fuels produced, catalysts are the most effective way to reduce AP-, EP-, and POCP-emissions (Bernesson, 2004). Using the fuels produced for cultivation and transport is a good way to reduce GWP-emissions during the fuel production. Furthermore, it is important that tractive power and process electricity and heat to be produced with low emissions from renewable resources. As shown in Paper IV, organic farming is a good way to reduce emissions, especially those responsible for global warming. Crop cultivation must be performed in ways that minimize soil emissions.

In the future, new processes for the entire production process of biomass from seed to useful energy delivered by vehicles, agricultural machines, *etc*. must be studied using the methodologies discussed in this thesis. Other forms of biomass with higher production efficiencies or a lower price, such as cellulose-rich products like wood and straw, may be worthy of investigation. The production phase from biomass to wheel rotation energy also has to be as efficient as possible and the emissions have to be low or eliminated. Fuel cells fulfil both those demands. They require fuel in the form of hydrogen gas or methanol with the techniques currently in use but research is proceeding on the use of biogas (Ahrens & Weiland, 2003; Weiland, 2004) and ethanol (Baff, 2003) as alternative fuel sources for such cells. Fuel cells produce almost no harmful emissions at all, just H_2O and CO_2, and they deliver the energy as electricity.

It is possible to produce the hydrogen gas for the fuel cells from biomass, using different methods. One interesting method is to produce biogas that is cleaned and reformed to H_2 (Ahrens & Weiland, 2003). Another way is to produce a hydrogen-rich gas by gasification of biomass from forestry and agriculture (Bernesson, 1992; Hamelinck & Faaij, 2001). The gas produced is called synthesis gas (syngas) and is mainly a mixture of H_2 and CO. It is also possible to use synthesis gas for production of methanol, dimethylether (DME) or Fischer-Tropsch fuel for use in internal combustion engines (General Motors Corporation *et al.*, 2001; L-B-Systemtechnik, 2002).

Another possibility is to produce ethanol from ligno-cellulose rich materials. Much research is going on at the moment to improve this process (Wooley *et al.*, 1999), and a pilot-plant is being built in Örnsköldsvik (Baff, 2003). With these raw materials, the energy balance can be improved in comparison to that for grain.

Conclusions

A small screw press is best operated with a small nozzle and a rather high screw speed to get the best compromise of both high capacity and high oil extraction efficiency. Somewhat higher oil extraction efficiency could be obtained if the nozzle were changed to one with a long press channel, or if the press screw were moved closer to the press chamber head with an adjusting spacer.

The differences in environmental impacts and energy requirements (with physical allocation) between farm-scale systems and more large-scale systems for the production of RME and ethanol for heavy diesel engines were found to be small or even negligible. In the larger scale systems, the more efficient use of machinery and buildings, the higher oil extraction efficiency in the production of RME, and the more efficient use of energy in the production of ethanol were, to a certain degree, outweighed by the longer transport distances involved.

The results were largely dependent on the method used for allocation of the environmental burden between the RME or ethanol fuel and the by-products meal and glycerine or distiller's waste. This indicates that when different biofuel production strategies are to be compared, it is important that the calculations are based on the same allocation strategies. For example, when physical and economic allocation were used, rapeseed oil was preferred, whereas RME was preferred according to the calculations with the expanded system allocation method.

For the two fuels, the dominant production step was the cultivation, in which the production of fertilisers, soil emissions and tractive power made major contributions. For the production process of the RME fuel, the production of methanol and electricity for oil extraction and transesterification were the dominant steps, whereas for the production process of ethanol, the production of ignition improver, denaturants, heat and electricity were the dominant steps.

When RME, ethanol fuel or biogas were produced as agricultural fuels in organic farming systems, RME showed a favourable energy balance, higher emissions except for CO_2 during utilisation of the fuel and a high use of land, with associated cultivation emissions. For the ethanol scenario, the requirement for process energy was high and the utilisation of ignition improver and denaturants was associated with considerable emissions. The biogas scenario showed a relatively low need for land, but the methane emissions from the process were negative for global warming and the rather high requirement for electricity for upgrading the biogas to vehicle fuel was negative for the energy balance. Eutrophication emissions were favourable for the biogas scenario. Global warming emissions were reduced considerably in comparison to conventional farming systems, mainly due to the fact that artificial fertilisers are not used in organic farming.

Irrespective of production scale, the use of RME and ethanol fuel reduced the global warming potential (GWP) in comparison to diesel fuel. The photochemical ozone creation potential (POCP) was reduced by RME but increased by ethanol production and use in comparison to diesel oil. The acidification potential (AP), eutrophication potential (EP) and energy requirement (physical allocation) were increased in this comparison for the two fuels studied. RME and ethanol fuel would reduce the total Swedish global warming emissions from road transport by 0.2-0.3% and approx. 0.6% respectively, if produced from 50 000 ha, the area required for a large-scale production plant.

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