Environmental Systems Analysis of Arable, Meat and Milk Production

Helena Elmquist
Faculty of Natural Resources and Agricultural Sciences
Department of Biometry and Engineering
Uppsala

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Abstract

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Emissions to air and water are related to both soil and plant processes and production-related choices regarding fertilisation, feeding strategy, *etc*. made by farmers. The main purpose of this thesis was to study the environmental impacts of agricultural production by developing simulation models describing the physical flows of farm production for different scenarios. The SALSA models (*S*ystems *A*na*l*ysis for *S*ustainable *A*griculture) were constructed and case studies carried out on arable, pig meat and milk/meat production. These environmental systems analyses encompassed the entire process from production of input materials (fertilisers, fuel, electricity, *etc*.) via on-farm processes (machine operations, crop growth, soil/plant emissions, emissions from animals and manure storage, *etc*.) until products were ready at the farm gate. Simulation outputs in terms of land use and environmental impacts for eutrophication, acidification, global warming potential and primary energy use were evaluated using Life Cycle Assessment methodology. A combined model was also constructed to reflect the interplay between the decision-making farmer and arable production. This was accomplished by linking SALSA to a decision model.

The SALSA models proved to be valuable tools in studying the environmental impacts of the processes involved. Since the environmental impacts and energy use values obtained by simulations were divided by the amount of crops, milk, meat, *etc*. produced, yield had a major influence on the outcome. Nitrogen use was a key factor affecting both yield and all environmental categories. Another important factor was choice of manure management system, where large amounts of ammonia could be emitted, contributing to eutrophication and acidification. There were considerable differences in the environmental effects of crops and feed ingredients. The pig growth study showed that by choosing feedstuffs with a low environmental impact during production, some of the environmental burdens could be avoided. Feed produced on-farm in combination with synthetic amino acids was environmentally favourable for pig production. Simulations of the milk/meat production system indicated that high-level milk production complemented with meat production from a suckler herd gave slightly lower environmental impacts than low-level milk production due to the higher milk production efficiency from more concentrates in the feed. Mineral fertiliser production, fuel for machinery operations and drying were significant energy uses in crop production. In livestock production, electricity for operation of buildings and milking equipment, long-distance shipping of soybean meal, production of plastic silage wrapping and diesel fuel for feeding were significant energy uses. Emissions contributing to global warming potential originated mainly from enteric fermentation in animals and nitrous oxide emissions from soils and recipient waters. Development of the combined simulation model demonstrated the possibility of operationally integrating research from social sciences and natural sciences. The results showed the importance of society supporting more environmentally friendly production in improving sustainability in agriculture.

Keywords: SALSA models, Environmental Systems Analysis, Life Cycle Assessment (LCA), dairy production, growing finishing pigs, arable production, microsimulation

Author's address: Helena Elmquist, Department of Biometry and Engineering, SLU, P.O. Box 7032, SE-750 07 UPPSALA, Sweden, E-mail: Helena.Elmquist@bt.slu.se

Sammanfattning

Elmquist, H. 2005. *Environmental Systems Analysis of Arable, Meat and Milk Production.* Doctoral dissertation. ISSN 1652-6880, ISBN 91-576-7011-0.

Syftet med denna avhandling var att skapa datormodeller för att kunna studera miljöeffekter och resursanvändning för olika alternativa produktionssätt. SALSA modellerna (Systems AnaLysis for Sustainable Agriculture) konstruerades för att kunna simulera växtodling samt gris- nötkött och mjölkproduktion på gårdsnivå. De fysiska flödena beräknades utifrån produktion av insatsmedel (gödsel, bränsle, el, *etc*.), via processer och aktiviteter på gården (maskinarbeten, emissioner från gödsling, skörd, torkning, *etc*.) till dess att produkterna var färdiga för att kunna säljas från gården. Livscykelanalysmetodik användes för att kunna utvärdera miljöeffekter avseende eutrofiering, försurning, växthuseffekt och primär energi. En mikrosimuleringsmodell konstruerades också, kopplad till SALSA, för att kunna simulera en bondes beslutsval utifrån miljö, ekonomi och skicklighet att förutsäga det mest lönsamma alternativet.

SALSA modellerna visade sig vara mycket användbara redskap för att analysera produktionssystemen. Val av data, beräkningsmetoder samt val av systemgränser och allokeringsmetoder visade sig ha stor inverkan på resultaten. Skördenivåer och utbyte i animalieproduktionen har även stor betydelse eftersom miljöpåverkan relateras till den skörd, mjölk och köttmängd som systemen ger. En nyckelfaktor som är viktig både för skörden och för alla miljöeffekter är mängden kvävegödsel som används per hektar. En annan central faktor är val av stallgödselsystem eftersom stora mängder ammoniak kan förloras från stall, lager och vid spridning av gödsel vilket har betydelse för både eutrofiering och försurning. Dessutom påverkas samtidigt hur mycket kväve som måste ersättas med t.ex. konstgödsel.

Miljöpåverkan skiljde sig markant åt för olika grödor och produktionen av olika foderråvaror. Resultat från grisstudien visade att en del av miljöeffekterna kunde minskas genom att ersätta sojamjöl med syntetiska aminosyror samtidigt som råproteininnehållet i fodret minskade. I mjölk/köttstudien gav högre mjölkproduktion något mindre miljöeffekter jämfört med låg mjölkproduktion beroende på bättre utnyttjande av fodret. Konstgödselproduktion, maskinkörningar och torkning var de mest energikrävande aktiviteterna i spannmålsproduktionen. I mjölk/kött produktionen användes mest energi till mjölkanläggningen i stallet, för transport av sojamjöl, för produktion av ensilageplast och till traktorkörning vid utfodring av köttdjur. Emissioner av växthusgaser kommer huvudsakligen från idisslarnas metanproduktion samt från lustgasemissioner från jord och vattendrag. Resultaten från simuleringarna med mikrosimulerings/beslutsmodellen kopplad till SALSA visade på lovande möjligheter med att kombinera humaniora och naturvetenskap i en beslutsmodell samt vikten av väl utformade samhällsstöd och styråtgärder för att jordbruket ska kunna bli uthålligt ur såväl ett ekologiskt som ekonomiskt perspektiv.

Keywords: SALSA modeller, Miljösystemanalys, Livscykelanalys (LCA), mjölkproduktion, grisproduktion, spannmålsproduktion, mikrosimulation

Adress: Helena Elmquist, Institutionen för biometri and teknik, SLU, Box 7032, 750 07 UPPSALA, Sweden, E-mail: Helena.Elmquist@bt.slu.se

Det ska du veta att allting skapat är outgrundligt. Alla hava vi enahanda ande, men märkvärdigast är ändå korna, inga andra levande varelser är så oppfyllda av ande och liv, juvret som dignar av saven och fruktbarheten och buken deras som rymmer fyra magar och ini alla fyra är det livet, och ögonen deras som förstår och förlåter meste allt, och skinnet som dallrar av glädjen…..

ur Merabs skönhet av Torgny Lindgren

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List of publications

This thesis is based on the following papers, referred to in the text by their Roman numerals. Published papers are reproduced with kind permission of the publishers.

Paper I-IV

I. Elmquist, H. Strid Eriksson, I. Öborn, I. Nybrant, T. (2004). Environmental systems analysis of winter wheat, spring barley and spring rapeseed – a study on effects of nitrogen fertiliser application rates using a simulation model. (Manuscript)

II. Lindgren, U. Elmquist, H. (2004). Environmental and economic impacts of decision-making at an arable farm – an integrative modeling approach. (Accepted to be published in Ambio, volume 34 no 4-5, 2005)

III. Strid Eriksson, I. Elmquist, H. Stern, S. Nybrant, T. (2005). Environmental Systems Analysis of pig production – The impact of feed choice. Int J LCA, volume 10 no 2, 143-154.

IV. Elmquist, H. Mattsson, B. (2004). An environmental systems analysis of three milk production strategies and their complementary production of meat, focusing on nutrient flows (Manuscript)

Notes on the authorship of the papers

In Paper I, the studied was planned, carried out and described mainly by the respondent. The respondent was responsible for data and simulations of the study and the development of sub-parts in the SALSA arable model, namely nitrogen and phosphorus leaching from land, yield model, fertilization, production of fertilizers, ammonia emissions from plants, seed production and energy production.

In Paper II, the respondent was responsible for simulations, further development of the SALSA arable model, text describing the environmental simulations of the SALSA arable model and validation of the decision patterns of the microsimulations due to decision criteria. The integrated model is a result of co-operation between the scientists.

In Paper III, the respondent was responsible for some of the SALSA arable model parts, (see Paper I) used in the study and consequently parts of the grain production.

In Paper IV, the study and the SALSA cow model were developed and carried out mainly by the respondent.

1. Introduction

Since the 1950s, Swedish agriculture has undergone large structural changes. Production has changed to more specialised entities, operations have become more mechanised and the use of production materials and long distance feed imports has increased. This development within agricultural production, which has led to higher production efficiency, has also had drawbacks, such as increased environmental impacts and increased dependence on non-renewable natural resources.

The work described in this thesis was carried out in the interdisciplinary research programme Food 21 (www-mat21.slu.se). Food 21 started in 1997 as a multidisciplinary research programme dealing with the entire food chain, with the long-term goal of defining optimal conditions and developing systems and technologies for a sustainable food chain that offers consumers high quality products. Although the programme dealt with the entire food chain, there was a rather strong emphasis on agricultural production and its environmental impacts.

In order to study the environmental effects caused by the physical flow for several substances used in agriculture and various activities on different scales simultaneously, a systems analysis perspective is called for. With methods from environmental systems analysis, it is possible to obtain an overview of the farm production system, where environmental key factors can be identified and new technologies and management strategies can be tested before they are implemented in reality.

There are a number of methods available for analysis of different environmental consequences from agricultural production: LCA (Life Cycle Assessment), energy analysis, nutrient balances, *etc*. This thesis describes the work on development and application of computer models for studies of the physical flows of energy and substances in farm production – from cradle to farm gate – focusing on interactions within the systems. These so-called SALSA models (***S**ystems **A**na**l**ysis for **S**ustainable **A**griculture*) were developed to be a flexible tool for different kinds of studies with the focus on evaluation of alternative production scenarios.

This thesis addresses questions regarding the environmental impacts relative to production as a consequence of, for example, the farmer's production allocation choices of input materials; whether low level milk production is more environmentally friendly than high and the environmental impact of feed choices for pig production. The models were used for simulations of the physical flows, from resource production until the products were ready to be delivered at the farm gate. All this information had to be aggregated to produce a general view of the environmental impacts, and for that purpose, methodologies from LCA were used.

1.1 Background

1.1.1 Agricultural production in Sweden

In 2002, the arable land in Sweden amounted to 2.7 million hectares, and less than 2% of the economically active population was engaged in farming in Sweden (SCB, 2003).

In certain areas, the effects of arable land use are very influential since there is a large proportion of agricultural land, especially along the coast in the south of the country. Most of the arable land is used for grass/clover production and other green fodder crops (36%), followed by barley (15%), wheat (12%) oats (11%) and fallow (10%). Other relatively common crops in Sweden include potatoes, sugar beet, grain legumes and oilseed crops (SCB, 2003). Climate conditions lead to a large yield variation from south to north in Sweden. Most of the arable land is used for feed production and mixed farming, where the manure is used within the crop rotation.

Pig meat production corresponds to 3.2 million pigs per year and most pig meat consumed in Sweden is produced within the country (SBA, 2001; SBA, 2002). The total amount of milk delivered to Swedish dairies amounted to 3206 thousand tons in 2003 (SCB 2004) with an average milk production per cow of 8939 kg ECM (energy corrected milk)/year[1] (Svensk Mjölk, 2004). The largest proportion of Swedish beef (70%) originates from replacement animals and calves from dairy production (Cederberg, 2002). The main income for dairy farmers (92%) comes from milk production due to low prices for calves and beef (Cederberg, 2002). Swedish feed rations for cattle are based on a mix of roughage and concentrates. Swedish statistics show that the average proportion of roughage is 8.6 kg dm/cow and day (Bertilsson, 2002).

Pig fattening can today be characterised to a large extent as specialised, with large units and with breeding including both sows and piglets or breeding with pig fattening specialisation. During the past 20 years, the average herd size for breeding animals has increased fivefold to 77.4 animals per farm, while for fattening pigs it has quadrupled to on average 336 animals per farm (SCB, 2003). The objective of achieving a biodiverse landscape has led to new subsidies for areas for grazing animals, which has led to a doubling of the numbers of cattle for meat production during the past 20 years and the herd size for the average Swedish beef herd in 2002 was 56.4 animals per farm (SCB, 2003). The average dairy herd size has more than doubled during the past 20 years and in 2002 the average herd size on a Swedish dairy farm was 37 dairy cows (SCB, 2003).

Farmers have been facing a more constrained economic situation regarding their business during recent decades and Swedish agriculture has undergone large structural changes. de Toro (2004) describes the economic trend from 1991 until 2003 for cereal farmers, where cereal prices have halved and the costs for machine operations have increased by 14% for depreciation, 24% for labour, 28% for repairs and 54% for energy. A similar trend has affected livestock production,

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[1] Average for cows associated with the Swedish dairy product control programme

with reduced prices for marketable produce and increased costs for input resources.

The management component of a farming system is a dynamic function of goals, information feedback and controls. Obviously, decisions and actions of the individual farmer are extremely important, both for the finances of the farm business and for the total emissions and resource use from the production chain (Figure 1). However, actions are limited by structural and local constraints and by personal limitations. There are structural constraints imposed by legislation in order to reduce nutrient losses from the agricultural sector, regulations on manure management, demands for winter-green areas in sensitive areas, restrictions on stock density due to lack of available land for manure spreading, *etc.* (Swedish Board of Agriculture, www.jordbruksverket.se).

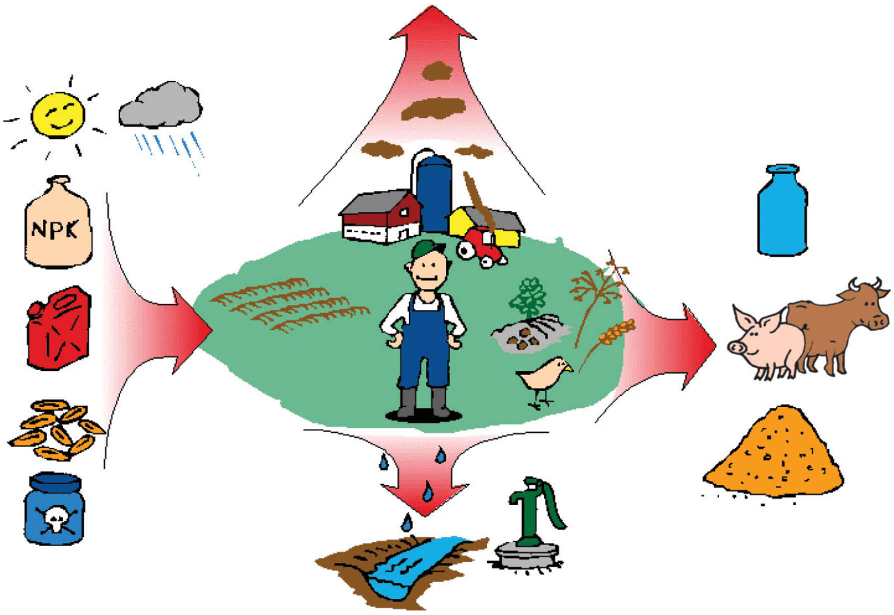

Fig. 1. The farmer's decisions on amounts of resources and types of activities affect yield and cause environmental impacts on air, soil and water bodies. Illustration Kim Gutekunst.

Farmers are also dependent on the common agricultural policy (CAP) with its goals of providing farmers with a reasonable standard of living and consumers with quality food at fair prices. Another key concept now mentioned in the CAP is preservation of rural environments (EUROPA - Activities of the European Union – Agriculture, www.europoa.eu.int/pol/agr/index_en.htm). Sweden's EU membership has led to increased trade within the EU-market and a new system of subsidies. One of the goals of the new subsidy system is to decouple subsidies from production in order to reduce the expensive excess production of agricultural products in the EU.

1.1.2 Environmental impact from agricultural production

The Swedish Government has established fifteen national environmental quality goals (Swedish Government, 1997) some of which are of major importance for the agricultural sector. These include: a varied agricultural landscape, a balanced marine environment, flourishing coastal areas and archipelagos, good quality groundwater, zero eutrophication, natural acidification only, and reduced impacts on climate. The overall aim is to hand over to the next generation a society in which the major environmental problems have been solved. Many of these goals are threatened by bio-physical flows related to agricultural production of arable crops, meat and milk products.

The environmental impact and resource use of the agricultural sector in Sweden related to the estimated total Swedish impacts are shown in Table 1. The categories included are use of energy and emissions of nitrogen, phosphorus, carbon dioxide, methane and sulphur dioxide, and their impacts in terms of eutrophication, global warming and acidification. Note that the figures in Table 1 show direct emissions or energy use from agriculture, and therefore manufacturing of resources, *e.g*. fertiliser production, are not included.

The main proportion of the ammonia emissions (90%) originates from the agricultural sector (Table 1). Dairy production is the largest Swedish source of ammonia emissions, contributing about 70% of the Swedish total (SCB, 2000a). Furthermore, 43% of the nitrate leaching from Sweden to the Baltic Sea, Kattegatt and Skagerack, when retention in lakes and waterways has been subtracted (Naturvårdsverket, 1997a), and 36% of the phosphorus leaching and run-off (Naturvårdsverket, 1997b) originates from the agricultural sector. Concerning global warming emissions from agricultural production, methane (62% of Swedish total CH_4 emissions) and nitrous oxide (N_2O) emissions (58% of Swedish total N_2O emissions) are the most dominant substances. Most of the methane emissions from the agricultural sector can be ascribed to the dairy sector because of enteric fermentation by ruminants and a smaller proportion also from anaerobic conditions during manure management. Nitrous oxides are released from the agricultural sector during soil processes such as denitrification and nitrification and also as a smaller proportion from manure storage. Carbon dioxide (CO_2) (2% of Swedish total CO_2 emissions) originates from the combustion of fossil fuel during machinery work and transportation. Of total national consumption, 2% of fuel is used directly on farms and 1% of total electricity is used on farms (SCB, 2001) excluding emissions from production of input materials. Other emissions from the agricultural sector are NOx emissions, which correspond to 7% of Swedish total emissions, and SOx emissions, which correspond to 1% of Swedish total emissions.

Table 1. *The relative contribution of environmental (Env.) impacts and resource use from the agricultural sector compared to the total Swedish contribution. The figures include the direct emissions or energy use from agriculture, i.e. manufacturing of resources is not included*

Impact category	Env. effects and resource use	Total annual Swedish emissions	Contribution of substances from the agricultural sector related to Swedish total, %
Eutrophication	NO_3 leaching[a]	65 000 ton N	43%
	Phosphorus run-off and leaching[b]	2 500 ton P	36%
	NH_3 emission[c]	45 700 ton N	90%
	NO_X emission[d]	93 739 ton NO_x	7%
Global warming	CO_2 emission [e, d]	66000 000 ton CO_2	2%[e]
	N_2O emission[f]	26 000 ton N_2O	58%
	CH_4 emission[f]	253 000 ton CH_4	62%
Acidification	NH_3 emission[c]	55 493 ton NH_3	90%
	SO_2 emission[d]	89 000 ton SO_3	1%
	NO_X emission[d]	308 000 ton NO_2	7%
Fuel and electricity consumption	Depletion of non-renewable energy[d]		2 % fuels 1% of electricity use

[a]Naturvårdsverket, 1997a. The figure refers to NO_3 leaching from Sweden to the Baltic Sea, Kattegatt and Skagerack when retention in lakes and waterways has been subtracted. [b]Naturvårdsverket, 1997b. [c]SCB, 2000a. [d]SCB 2001. [e]CO_2 emission from combustion of fossil fuel. [f]SCB, 2000b.

1.2 The FOOD 21 programme and problem identification

FOOD 21 was a large interdisciplinary research programme dealing with the entire food chain that started in 1997 and finished in 2005. In this programme, about a hundred researchers worked together to find ways of achieving ecologically and economically sustainable food production (www-mat21.slu.se). The programme plan stated that 'The overall long-term goal of the FOOD 21 Programme is to define optimal conditions and to develop systems and technologies for a sustainable food chain that offers consumers high quality products.'

The programme was divided into groups of projects: Crop production, animal production, product quality, systems analysis, consumer behaviour and farmer participation. Since the overall objective of FOOD 21 was to 'develop systems and technologies for a sustainable food chain' there was a need for tools for evaluation of different suggested alternatives and scenarios developed in the programme.

In one of the projects 'Modelling of Physical Flows at the Farm', the aim was to develop a tool for quantitative evaluation of environmental impacts of agricultural production and to perform some basic case studies. The tool was intended to be used for decision support by other researchers and decision makers, so its transparency and pedagogical merits were important. The work focused on arable, pig and milk/meat production.

The present thesis is based on the work carried out in this project as well as in another FOOD 21 project 'Modelling of the Farmers' Decision Processes at the Farm' (Elmquist, Lindgren & Mäkilä, 2004), in which the consequences of the environmental impact caused by different strategies of decision making were analysed.

The choice to build computer models was judged necessary to facilitate description of the complex farm production system and to permit analysis of different scenarios. Important key processes, interactions within the system and central activities were to be identified in order to find where improvements could be made. Furthermore, the potential of testing different scenarios to identify conflicting goals was deemed important.

In Food 21, a number of sustainability goals are defined regarding natural resources, the external environment, animal welfare, ethics, the economy, and farmer and consumer aspects (www-mat21.slu.se). The environmental impacts most relevant to modelling of physical flows are energy use, phosphorous use, eutrophication, global warming, acidification and land use.

1.3 Other studies

Environmental systems analysis comprises methods, tools and approaches for the systematic study of interactions between technical, economic, social and ecological systems, particularly for assessment of human activities, processes and products from environmental and sustainability points of view (von Malmborg, 2003). Experiences from environmental systems analysis modelling of waste handling and municipal wastewater using the model ORWARE (Eriksson *et al.*, 2002) show the advantage of using computer models for systems analysis when comparing the environmental load from different waste systems. Other examples are nutrient balances or nutrient budgets of farm production that have been increasingly used for nutrient management and as a basis for environmental policymaking (JTI, 2001; Oenema, Kros & de Vries, 2003). The element fluxes and balances on farms provide valuable knowledge about element accumulation, or depletion of soils, and they give an indication of the potential risks for emissions to water and air.

Several LCA (Life Cycle Assessment) studies of farm production have been made. By applying Life Cycle Assessment to farm production, large and important hot spots during production have been identified and the life cycle thinking (Wrisberg & Udo de Haes, 2002) has contributed new insights to the study of whole production chains (Lindfors *et al.*, 1995; Björklund, 2000; Guinée *et al.*, 2001 ; Baumann & Tillman, 2004). An LCA study for primary production of barley on farm level has been carried out in Finland (Katajajuuri & Loikkanen, 2001), while in a German thesis the LCA methodology for arable crop production has been developed using winter wheat production as an example (Brentrup, 2003). The whole production chain for production of wheat bread (Audsley *et al.*, 1997; Cowell, 1998; Andersson & Olsson, 1999) and rye bread (Weidema, Pedersen & Drivsholm, 1995) has been evaluated by several authors, including one study that focused on cereal-based baby food products (Mattsson & Stadig, 1999). The agricultural land use of three vegetable oil crops has been assessed in an LCA study in which Swedish-produced rapeseed is compared with Brazilian soybean and Malaysian palm oil (Mattsson, Cederberg & Blix, 2000). Another example of an LCA study including rapeseed oil production is one in which bio diesel is compared with rapeseed oil methyl ester (RME) for transportation (Reinhardt & Gärtner, 2002). Pig production has been studied by several authors (Carlsson-Kanyama, 1999; Cederberg, 2002; Kumm, 2003) and milk production has been studied by Cederberg & Mattsson (2000), Ledgard *et al.*, (2003) and Boer (2003).

Previous LCA studies have mainly focused on the environmental performance for different kinds of stock, farm type, locations, *etc*. To complement previous studies, there was a need to create a virtual farm, a farm model where input data were obtained from statistical data and general assumptions from other scientific studies. In this thesis such a farm model was constructed to analyse the emissions levels and energy use as a function of chosen management strategies and technologies.

1.4 Objectives and structure of the thesis

The overall objectives of this thesis work were to study the environmental impacts of agricultural production by developing a simulation model that described the physical flows for the on-farm production chain, from production of input materials until products were ready to be delivered from the farm. The products considered were: arable crops, pigs and milk/meat. The choice to build computer models was made to facilitate description of the complex farm production system and to permit analysis of different scenarios. By testing different scenarios, important key processes, interactions within the systems and central activities were to be found in order to identify where improvements could be made and conflicting goals could be found. This approach was expected to provide the potential to divide small impacts from large and to identify knowledge gaps in the area.

Results from simulations were intended to provide a basis for decision support for decisions at different levels, and also to provide general knowledge concerning the environmental consequences related to production. The time horizon considered lay between several decades and up to 100 years. Impact categories included in the work were potential contributions to eutrophication, acidification, global warming, energy use and land use.

The possibility to connect a physical flow model to a model of a farmer's strategic decision making was investigated to see how external factors such as the economy, subsidies *etc*. affected the environmental performance of the farm.

1.4.1 Specific objectives of the papers

- The objectives of the first study were to build a flexible model (SALSA arable) representing the physical flows during arable production, and to carry out a case study where the environmental consequences of different N application rates in grain production were investigated for the three crops wheat, barley and rapeseed.

- The objectives of the second study were to build an integrated model of the interwoven dependency between the physical system (SALSA arable) and anthropogenic system (decision-making farmer), in particular by a microsimulation modelling approach of the operations on an individual arable farm.

- The objectives of the third study were to develop the pig production model and to investigate the impact of feed choice on the environmental performance of growing-finishing pig production.

- The objectives of the fourth study were to develop the cow model and to investigate the environmental impact of three milk production levels and their corresponding meat production.

1.4.2 Overview and structure of this thesis

This thesis comprises four parts and the structure of the work, the relationships between the four studies and an overview are described in the following text and in Figure 2.

In the first study (Paper I) on grain production, the use of nitrogen was identified as a key management practice, which affected all environmental categories investigated as well as the yield. Experiences from the first study about the importance of yield regulation factors and the impact of nitrogen use were applied in the second study. The arable production was connected to a micro-simulation model in order to analyse the interwoven relationships between the farmer’s finances, environmental preferences and skills, in relation to environmental sustainability (Paper II). Two other alternative management strategies were added, *i.e*. pesticide dose level (no use, half dose and recommended dose) and two alternatives for fuel; diesel or biofuel made from oilseed rape. The manure used for organic production was assumed to be bought from a pig farm in the neighbourhood. One lesson learned from this study was that comparing organic and conventional agriculture production was complicated by difficulties in allocating environmental burdens between meat production and the manure on that pig farm.

Papers III and IV focus on livestock production and results from the first study on arable production were used for ingredients in the diet. The pig model (Paper III) included arable production and was expanded to also include imported feed concentrates for livestock production (soybean products and synthetic amino acids), energy use for operation of the buildings and emissions from animals and manure management to get a comprehensive picture. In crop production, the importance of yield variation proved to be significant since all emissions were divided by the yield. Here, the nitrogen was still the main focus since the feeding strategies affected both manure production and manure quality. Another issue was the significant impact from long-distance transport of soybean meal.

Paper II highlighted the difficulties in allocating emissions between the products and manure and this led to the dairy production study (Paper IV) being expanded to also include the subsequent meat production. Therefore the functional unit in Paper IV was set to a production of 1000 kg ECM[2] and the subsequent meat production from cattle stocks. The study on finishing pigs (Paper III) raised questions about the impact of breeding of the mother animals, which presumably had a higher influence in the cattle system due to a rather high replacement rate of cows in Swedish milk production. In addition, results and data from the arable production study (Paper I) and from the pig study (Paper III) regarding imported feed were used in the milk and meat study (Paper IV). The milk/meat model was then developed to include roughage production, the effect of palm oil expeller production, electricity use in dairy production, manure management, excretion of faeces and urine and emissions from cattle. The environmental consequences of three milk production levels and subsequent meat production were analysed.

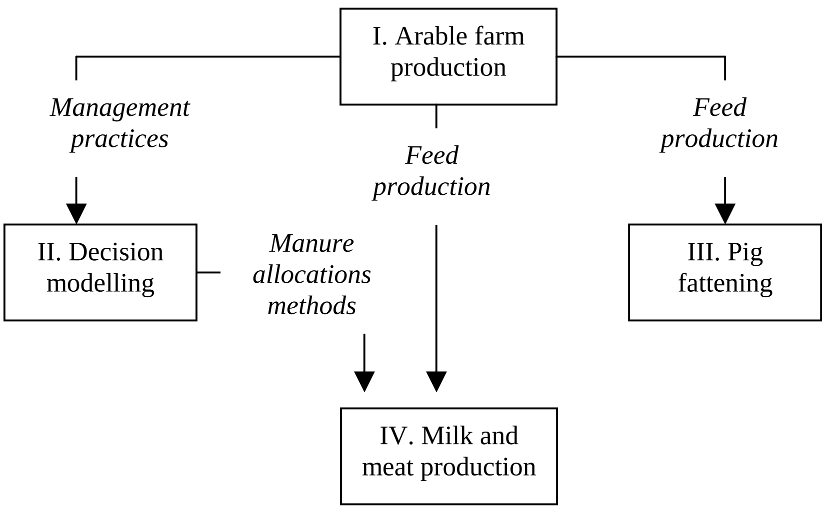

Fig. 2. The four papers in the thesis and how experiences and connections were related to each other.

[2] Energy corrected milk

Management practices were set somewhat differently in Paper II than in the other studies. In Papers I, III and IV, the scenarios and management strategies were designed from our own assumptions based on experiences of important environmental impacts during the model construction. In Paper II, the scenario was given as a set of alternatives where the farmer's production allocation depended on the farm's financial outcome, environmental preferences and the farmer's skills.

2. Materials and methods

To fulfil the objective – development and application of a simulation model that describes the physical flows for the on-farm production chain - a computer based modelling technique was used to facilitate description of the complex farm production system and to permit analysis of different scenarios.

Physical flow modelling is a way to calculate the flows of materials, substances and energy over time given a specified purpose. There are several approaches and simulation languages available for the construction of such models and the requirements specified for the present work were the following:

- Due to the complexity of the system to be modelled, a well structured modelling approach was judged to be necessary, both in the development of the models and in communication with other researchers and model users. This can be accomplished using a modular approach with the arable, pig and cow modules on the top level and further modularisation of the sub-models at lower levels.

- The modelling language should provide opportunities for different kinds of relations, including non-linear and dynamic relations. It is also desirable to have functions available for *e.g.* optimisation and statistical analysis.

Altogether this led to the choice of using MATLAB/Simulink (MathWorks, 2000) for implementation of the model. In this way previous experience from the development of the simulation model ORWARE (ORganic WAste REsearch model) could be used in the present work (Eriksson *et al.,* 2002). It also allowed the use of sub-models from ORWARE, like the biogas and composting models.

Another aspect of the choice of modelling platform was that in FOOD 21 there were a number of projects dealing with environmental systems analysis of the food chain after the farm gate, *i.e.* food industries, transport, retailers and consumption (Sonesson *et al.,* 2005). In that work MATLAB/Simulink was used and using the same language for agricultural production allowed future development of simulation models for the entire food chain.

The environmental impacts caused by agricultural production are represented by a great number of different substances. In order to interpret the simulation results, there is a need to aggregate of the data and also to relate the environmental impacts to production. For this purpose methods and approaches used in Life Cycle Assessment (LCA) were adopted.

Life Cycle Assessment is a method for studying the potential environmental impact of a product or service throughout its entire life cycle, from raw material to waste disposal (Lindfors *et al*., 1995; ISO, 1997, 1998, 2000a, 2000b; Guinée *et al*., 2001). Here, impact assessment methodology from LCA was used because a huge amount of work had already been done to supply impact factors, where the effect of substance flows had been classified and characterised into environmental impact categories. Other central concepts used that originate from LCA methodology are the concepts of a functional unit and economic allocation. The functional unit expresses the function of the studied product or service in quantitative terms and serves as a basis for calculations. It is the reference flow to which all other flows in the LCA model are related. In the ‘economic allocation’ the environmental loads are partitioned between products, which have more than one function, *e.g*. rapeseed grain from which both meal and oil is manufactured.

The development of this modelling approach contained a number of steps: statement of the objectives of the model; translation of the objectives into hypothesis; identification of the systems characteristic and causality, mathematical formulations of the system *i.e.* model construction; verification of the computer algorithms; simulation of different scenarios; sensitivity analyses of changes in some of the model parameters; analysis and evaluation of the model and finally analysis of results.

2.1 The physical flow models (SALSA arable, cow and pig)

The tool created to model both arable and animal production is called SALSA (<u>*S*</u>ystems <u>*A*</u>na<u>*l*</u>ysis for <u>*S*</u>ustainable <u>*A*</u>griculture). The Environmental Systems Analysis used in this study originates from the methods of using computer-based modelling to calculate the physical flows combined with LCA methodology.

The SALSA models were built to enable utilisation of different site-specific and management-related input data for simulations of different scenarios. The computer models were constructed in MATLAB-SIMULINK software (MathWorks, 2000) and EXCEL. Parameters were organised in vectors and matrices in MATLAB, and activities were organised in SIMULINK’s graphical interface. The graphical interface of SIMULINK enabled this complex farm system to be viewed as interacting sub-models in a hierarchical structure, which facilitated the comprehension of the system’s structure and behaviour.

To handle all substance quantities and energy flows a vector was constructed. In this substance flow vector, a specific position was dedicated to a quantity (kg) of a substance (H_2O, total N, NH_3, NH_4, NO_3, N_2O, organically bound N, P, K, SO_2, CO_2 of fossil origin and bio origin, CH_4), the energy use (MJ) or for information such as crop type, year in the crop rotation, whether the crop fixed nitrogen or not, *etc.* This substance flow vector is part of a three dimensional grid constituting one column, the second dimension represents activities or farm process-related emission points and the third dimension is reserved for time and organises the substance-activity grid for each simulated year, normally representing each crop in a crop rotation. The environmental impacts from different parts of the system are presented separately, which enables a comparison between sub-systems in order to find the sources behind the largest impacts. Results can be extracted from the matrix from different viewpoints such as environmental load from machinery operations, from production of input materials *etc.*

The main concepts of the SALSA models and details about the arable model can be found in a report by Elmquist, Lindgren & Mäkilä (2004). The conceptual framework for simulating the substance and energy flows for farm production by the SALSA models is illustrated in Figure 3. The box with dashed lines illustrates constraints used when the SALSA arable model was integrated with a decision model, which is called the integrated model in Paper II.

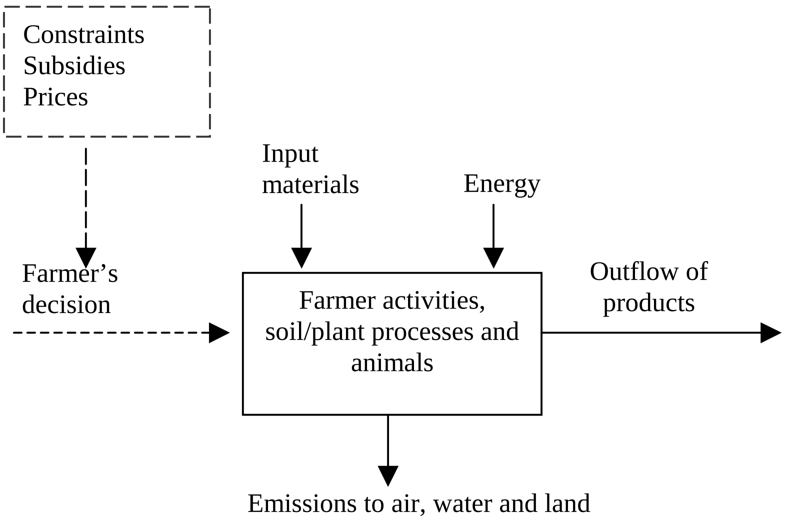

Fig. 3. The conceptual framework for simulating the substance and energy flows for farm production by the SALSA models (Papers I-IV). The dashed box shows the decision-making farmer's structural conditions influencing the business, which were included in the combined model (Paper II), including the farmer's choices of production allocation.

The arable production was the first model developed (SALSA arable). Simulation results from home feed production were later used as ingredients in feeds for pigs and cattle. Emissions and resource use from production of imported feeds and livestock emissions were added to the models and the two livestock models (SALSA pig and SALSA cow) were developed. Arable production (Papers I-IV) and meat/milk production (Papers III and IV) systems were studied from resource production until products were ready for delivery at the farm gate.

2.1.1 The SALSA arable model

The SALSA arable model consists of three parts; production of input materials, processes on the field and the farmer's management choices such as machinery operations, fertilising, drying of grain *etc*. An overview of the activities and processes included in the SALSA arable model as they are presented at the top layer in Simulink is shown in Figure 4. Boxes with vertical text show the sub-systems included for input materials; seed, diesel, electricity and fertiliser. The core system is the plant growing in the field, which is supplied with nutrients from the soil system. After harvest, the crop is transported from the field and dried at the farm. The arrows show flows of energy, materials and substances during farm production. The SALSA arable model and functions used for calculations are described in detail in a report by Elmquist, Lindgren & Mäkilä (2004).

There are two levels of input data; firstly, variables with specific data on management practices and site conditions (Table 2) and secondly, parameter data used for calculations in the sub-models (Table 3). Input variables of management practices and site conditions are valid for production on one hectare in one year. The tables do not cover all variable and parameters used but are examples of those most commonly used for simulation of the SALSA arable model. In order to visualise the effect from different scenarios, *i.e*. management practices, the specific parameters needed for each scenario simulation were kept separately, and organised in separate initiation files, and universal parameters of the model were loaded from a reference library.

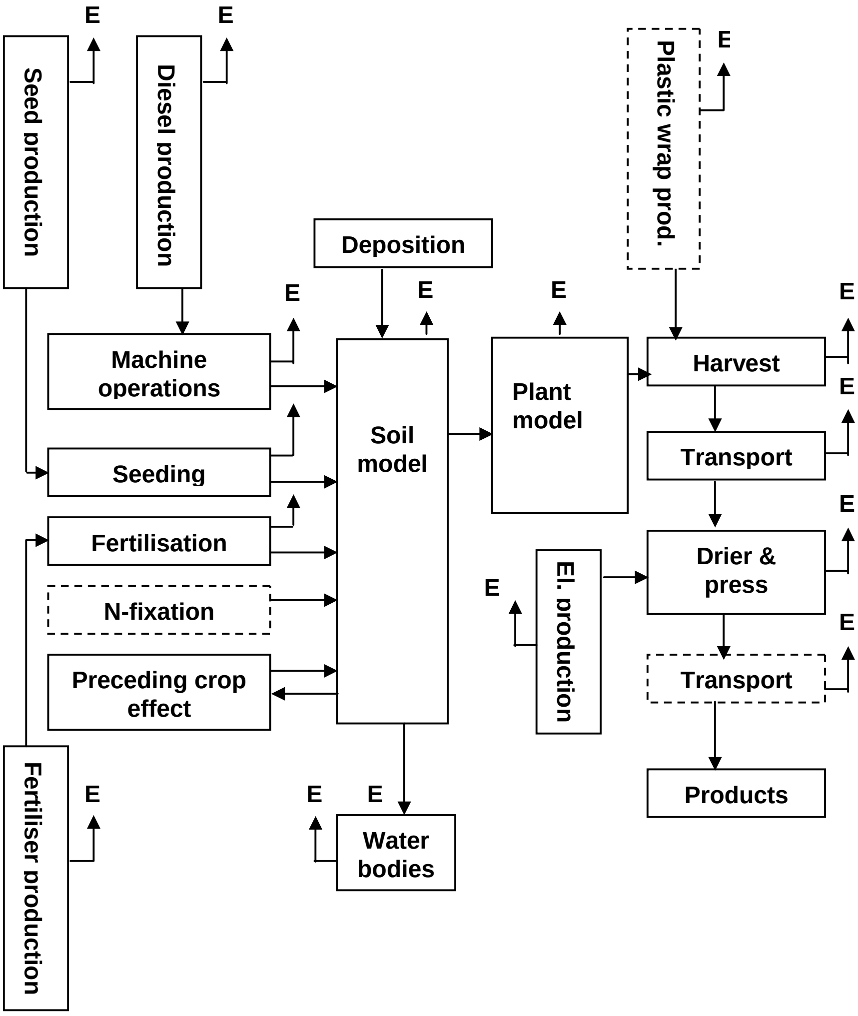

Fig. 4. Flow chart of the top level of the substance and energy flow model SALSA-arable, used for calculation of resource use, yield (Products) and emissions (E). Boxes with vertical text show the sub-systems included for input materials: fertilisers, diesel, electricity and seed. The arrows show flows of energy, materials and substances. The dashed boxes are included in the version developed for cow and pig production.

Table 2. *Input variables of management practices and site conditions used in the SALSA arable model. The units are valid for production on one hectare*

Input variables of management practices and site conditions (SALSA arable):	*Unit:*
Crop choice	wheat, barley *etc*.
Choice of machinery operations, machinery type and number of operations	*e.g*. combi seeding machine, band slurry spreader *etc*., and number of the different operations
Fertiliser application rates	kg N, P, S *etc*./ha
Type of fertiliser	*e.g*. calcium ammonium nitrate
Time for fertiliser application	*e.g*. spring, summer, autumn *etc*.
Transport distance field to farm	km
Water content at harvest	%
Desired water content for the crops to be dried	%
Seed	kg
The choice of fuel type	biofuel or ordinary diesel
Location	*e.g*. an area in Sweden

Table 3. *Input parameters used in the SALSA arable model. (em. means emission)*

Input parameters (SALSA arable):	*Unit:*
Emission factor for NH_4-em. from plants	kg N ha, a crop specific value
Emission factor for NH_4-em. from fertilizing (mineral)	kg N/ha or % of total N application
Emission factor for NH_4-em. from fertilizing (organic)	% of NH_4-N applied
P-leaching	kg P/ha
N-leaching, basic value, average depending on location	kg N/ha
Emission factor for N_2O-em. from water bodies	% of total N input/ha
Emission factor for N_2O-em. from soil	% of total N input to soil/ha
Emissions vector for exhaust em. during fuel use	CO_2, NOx, (kg substance/MJ)
Emissions vector for em. during production of fertilizers	(CO_2, N_2O NOx, (kg /kg fertilizer)
Diesel use for different machine operations	MJ diesel/ha
Diesel use for drying of grain	MJ electricity and diesel/kg removed water
Diesel use for oil press	MJ electricity and diesel/kg rapeseed
Yield functions due to N application rate	kg applied plant available N
Yield factor related to pesticide level	% of yield
Yield factor related to a bad crop sequence	% of yield

2.1.1.1 The plant sub-model (SALSA arable)

Yield and emissions from the plants are calculated in the plant sub-model. Ammonia emissions from plants were calculated as a proportion of N fertilising rate (Joint EMEP/CORINAIR, 2001) or set as an average value for different crops (Rossvall *et al*., 1990; Holtan-Harwig & Bøckman, 1994). Depending on the purpose of the study, the yield is either a set value or a function of N-application rate, pesticide control level and crop sequence. Accordingly, the effect of varying weather was not considered and the average yield was considered.

The ability to respond in terms of yield to different N application rates was calculated from empirical data from Swedish field trials with different N application rates (Frö- och Oljeväxtodlarna, 1983-1994; Lantbruksstyrelsen, 1990; Mattson & Kjellquist, 1992). Three yield levels due to pesticide dose were applied; no dose, half dose or the manufacture's recommended dose. Data were obtained from an expert group's assessment of the yield consequences of applying different doses (Jordbruksverket, 2002). Crop sequences were considered and the model recognises which crops are being cultivated on a field. In Papers I and III, crop sequences were set according to the case studies and in Paper IV crop sequences frequently used in Swedish dairy production were applied (Maria Wivstad, pers. comm.). A cereal crop that follows ley, rapeseed, peas, *etc.* obtained a higher yield than after a cereal crop, since a following crop inherits some of the nitrogen applied to a previous crop. The environmental load from fertiliser production of the first crop is then credited to the crop that follows, which benefits from a previous fertilising. In the combined model SALSA arable and SALSA mind model (Paper II), the effect of monoculture was considered as yield reduction. For example, the cultivation of winter wheat two years in a row reduced the yield in the second year by 15%. The reduction in yield became even greater if the monoculture continued for further years.

2.1.1.2 The soil sub-model (SALSA arable)

The flow between the soil and plant system is complex and includes a large amount of substance and energy flows leading to environmental load. Thus, simplifications and approximations were necessary and the model was constructed to show a good enough picture of the system's behaviour and environmental performance. Therefore, existing models describing part of the system were implemented and, since the nitrogen flow gives effects during the whole production chain, the nitrogen flows was particularly studied. Nitrogen emissions from farmland were calculated using a model called 'STANK in Mind' or for the first studies a previous version called 'STANK farm model' was used (Hoffman *et al*., 1999; Aronsson & Torstensson, 2004). N leaching was calculated from data on average N-leaching, manure application, tillage time, crop type and fertiliser level relative to crop uptake *etc.* for the region. For phosphorous leaching, data depending on site were assumed (Carlsson *et al*., 2000). The 'soil memory effect' of organic nitrogen from N-rich crop residues or animal manure was carried over from one year to the next in the crop sequences. In the model this was considered as N-input to the crop, which resulted in a higher yield after some of the crops but also in extra N leaching, which was considered in the N leaching sub-model.

Nitrous oxide emissions from water bodies (indirect denitrification) and fields (direct denitrification) were calculated according to methodologies recommended by The Intergovernmental Panel on Climate Change (IPCC, 2001a), where N_2O emissions were assumed to be a proportion of the input of N to water bodies or fields.

2.1.1.3 Sub-models for production of input materials (SALSA arable)

(Seed, Diesel, Electricity, Fertiliser)

Environmental impacts from production of artificial fertiliser were estimated by multiplying the amount of the fertiliser used by an emission vector containing emission data per kg fertiliser produced. The emission vector was constructed from data from a Life Cycle Inventory (LCI) of fertiliser production (Davis & Haglund, 1999). Emissions and resource use for seed production were assumed to be the same on a hectare basis as for the crop production on the farm and were calculated as a percentage of total impact depending on seed rate. Production of energy carrier was recalculated to primary energy, *e.g*. production and distribution of the energy carrier was also included in the energy use (Brännström *et al*., 1996; Arnäs *et al*., 1997; Uppenberg *et al*., 2001a; Vattenfall, 2001; Sattari, 2002).

2.1.1.4 Sub-models for machinery operation (SALSA arable)

(Tillage, Seeding, Fertilisation, Harvest, Transport)

The exhaust emissions derived for different machine operations and grain transport were calculated from farm data on fuel consumption per hectare multiplied by an emission vector for different machine activities (Hansson & Mattson, 1999; Uppenberg, 2001b; Lindgren *et al*., 2002; Lindgren *et al*., 2003). Emission factors used for NOx emissions during diesel combustion varied for different machine operations whereas carbon dioxide (CO_2), nitrous oxide (N_2O), sulphur dioxide (SO_2) and methane (CH_4) emissions were the same for all operations.

2.1.2 The SALSA cow model

The SALSA cow model has been developed to study the environmental performance of milk and meat production from production of input materials until products are ready to be delivered from the farm. The choice of feed and manure handling are the most important measures influencing the environmental performance. The animal’s feed needs are set from the animal’s requirements due to production, health and type of animal (J. Linder pers. comm). Figure 5 shows the parts included in the SALSA cow model and how the cow model interacts with the SALSA arable model. Agricultural products coming from the SALSA cow model are milk and meat. Animals considered are cows for milk production and cows for meat production from suckling calves, bulls, heifers and other small calves. Culled cows are replaced with heifers reared on-farm.

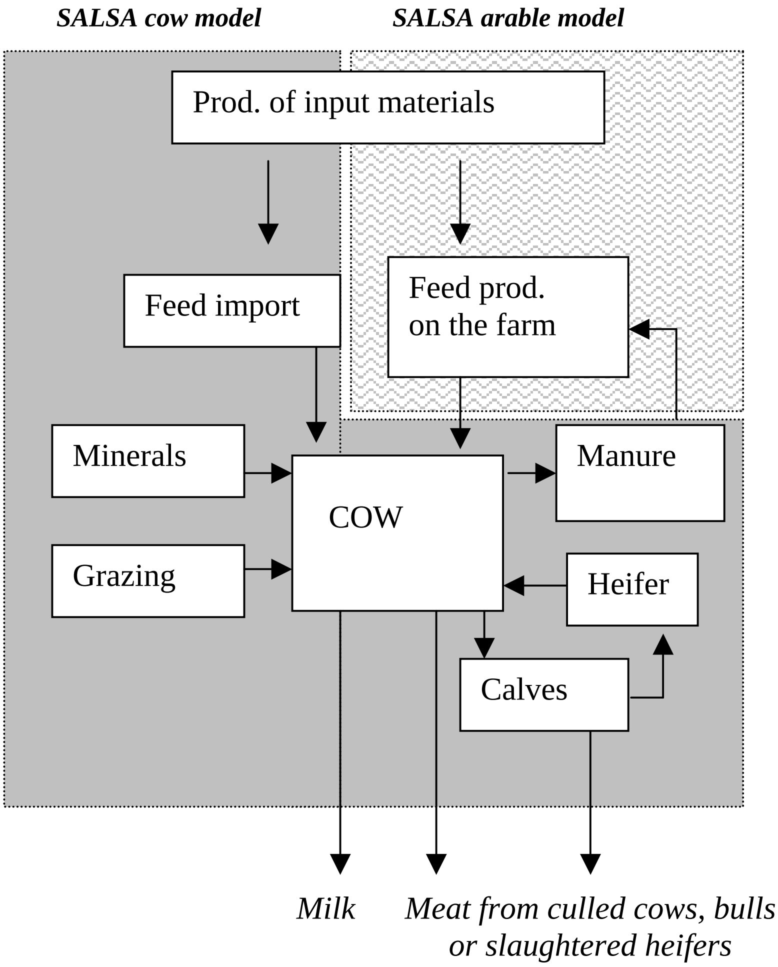

Fig.5. A conceptual picture of the SALSA cow model, including feed production, manure and heifer circulation within the system, and production of milk and meat. Emissions and resource use from livestock, production of concentrates and feed from grazing were calculated using the SALSA cow model, while roughage, barley, rapeseed and wheat production were calculated using the SALSA arable model.

The main input data to the cow model are shown in the Tables 4 and 5. Table 4 covers input data related to the farmer's management choices such as; feed, manure system and equipment used for milking. In Table 5, some parameters used for calculations of the emissions and energy use in the sub-systems in the SALSA cow model are listed.

Table 4. *Input variables of management practices used in the SALSA cow model*

Input variables of management practices:	*Unit:*
Feed use [a]	kg barley, roughage *etc.*/production period
Feed quality [b] (metabolisable energy)	MJ/kg feed in DM
Number of grazing days	No./year
Straw use	kg/day
Recruitment of heifers	% culled cows
Manure management system [c]	Slurry, deep litter, urine, covering of slurry tank *etc*.
Electricity use for milk equipment	MJ/cow
Proportion of manure to storage tank during the grazing period	%
The gross energy intake [d]	MJ/kg DM
VS (in manure storage) [e]	kg produced/animal

[a] Feed required for a specified animal production. [b] Calculated from data on ingredients in the feed. [c] Each system has its own ammonia emission factor. [d] The gross energy intake is calculated in the SALSA cow model from feed data and the value is used for calculations of methane emissions. [e] Volatile solids (VS) is the amount of total solids that volatilizes when ignited or heated to 550 ^{o}C, (in this study it is the organic matter in the faeces). VS was calculated from feed input data and is used for calculations of methane emission from slurry storage.

Table 5. *Input parameters used in the SALSA cow model. (Em. means emission)*

Input parameters:	*Unit:*
Emission factor for NH_4-em. from barn [a]	% of NH_4-N excreted
Emission factor for NH_4-em. from manure storage [b]	% of the NH_4-N content
Emission factor for NH_4-em. from spreading of manure [b]	% of NH_4-N applied
Dry matter of manure in storage tank [c]	%
Enteric fermentation factor (CH_4) [d]	%
Potential CH_4 production (B_o) (manure storage) [d]	m^3/kg VS
Methane conversion factor (MCF) (manure storage) [e]	%

[a] Steineck *et al*. (2000). [b] Karlsson & Rodhe (2002). [c] Calculated in the SALSA model. [d] IPCC (2001a). [e] Dustan (2002).

A flow chart of the substance and energy flow in the SALSA cow model is presented in Figure 6 showing the physical flow of substances and energy during production. There is a cascading structure throughout the model where the state in one sub-model depends on a previous one *etc*. For example, the amount and quality of the manure is calculated from feed data and the nutrient content of the manure available for plant production is calculated by considering ammonia losses from barn, storage and spreading. Solid arrows show physical flows and dashed lines show information flows used for calculations. Circles represent functions for flow calculations. The following sub-models in the SALSA cow are described below; feed, animal and manure. Other sub-models not shown in Figure 6 are energy use for milking equipment and fuel use for feeding.

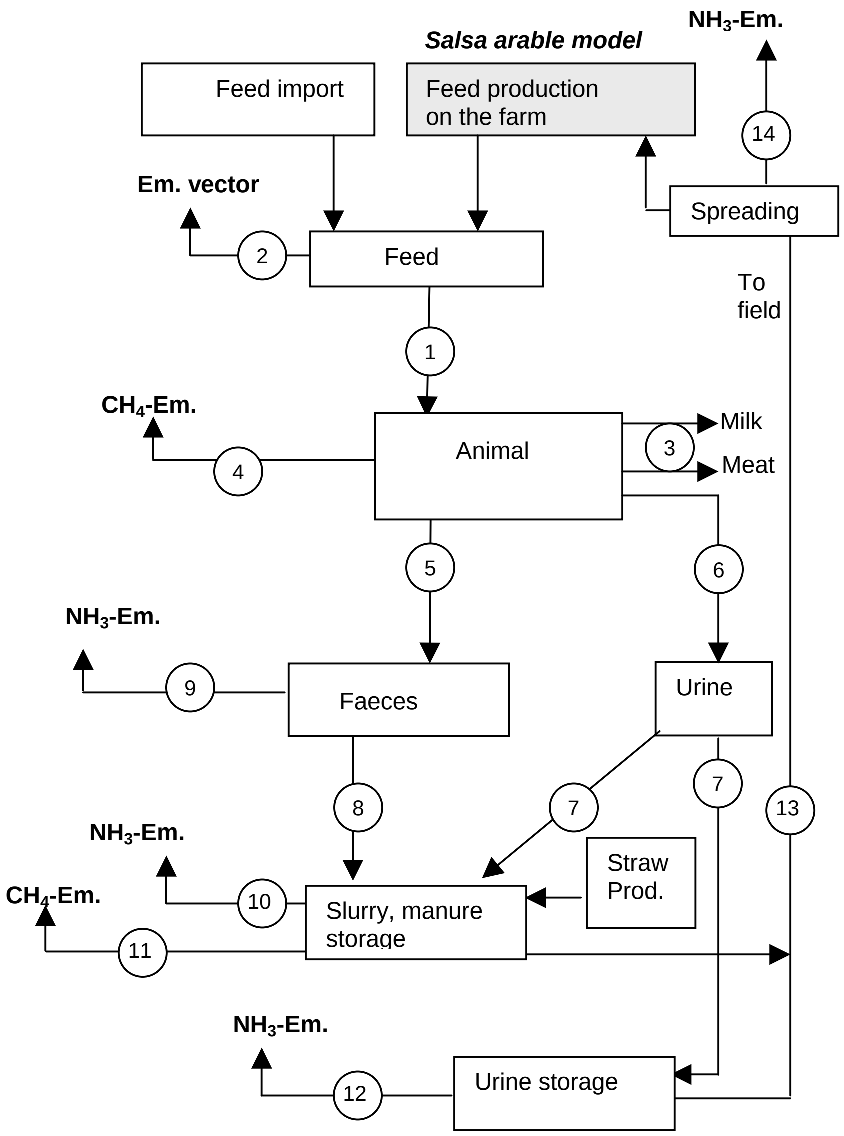

Fig.6. A flow chart of the substance and energy flow model, SALSA cow, used for calculations of emissions and resource use for production of milk and meat. From feed production several emissions are emitted (Em.vector), from animal and manure handling the major emissions are methane and ammonia (CH_4-, NH_3-Em). Solid arrows show flows of energy, materials and substances.

2.1.2.1 Feed production (SALSA cow)

Regarding livestock production, the amount of feed was set according to recommendations for a specified production level *(flow number 1)*. Data for feed production on the farm (roughages, barley) were obtained from simulations of the SALSA arable model, which were complemented with production of plastic for silage covering, feed from grazing and fuel use for feeding. Production, manufacturing and transport of feed ingredients in concentrates (soybean meal, wheat bran, palm oil expeller, *etc*.) were added to the cow model (Cederberg 1998; Strid Eriksson *et al*., 2005). Emissions related to production of the LLDPE (Linear Low Density Polyethylene) plastic for silage production were calculated and energy obtained from recycling the plastic was considered (Bousted, 2003; Ringström *et al*., 2003). Regarding emissions and energy use for manufacturing and transport of the concentrates, the amount of fuel was multiplied by an emission vector specific for the fuel type. Finally, each feed ingredient obtained its own emission vector reflecting the environmental load and energy use per kg, and the total emissions from feed production (*flow number 2*) were calculated from the feed composition.

2.1.2.2 Animal sub-models (SALSA cow)

Outflow from the animal sub-model are milk and meat *(flow number 3)*, manure *(flow number 5)*, urine *(flow number 6)* and emission of methane (*(flow number 4)*. Milk production was a given value, and meat production was calculated depending on the choice of recruitment rate of cows and animal type for meat production. Methane emissions from enteric fermentation *(flow number 4)* from animals were calculated using IPCC Tier 2 model (IPCC, 2001a), where the gross energy intake (MJ/kg DM) was an important factor calculated in the SALSA cow model from the actual feed. Furthermore, the electricity use for milking equipment was assumed as a fixed value per cow.

2.1.2.3 Manure sub-models (SALSA cow)

Excretion of faeces and urine *(flows number 5 and 6)*, which leads to production of urine, slurry or manure, was calculated using a model presented in a report from the Swedish Board of Agriculture (Jordbruksverket, 1995). The nutrient content in faeces and urine was calculated from feed, straw input and production level for the animals. Furthermore, number of grazing days was considered in order to calculate the amount of manure, slurry *(flow number 8)* and urine that goes to storage *(flow number 7)*. When solid manure is assumed, part of the urine is collected in the solid bed and the rest is collected in the urine tank *(flow number 7)*.

The ammonia emissions from the barn *(flow number 9)*, storage *(flow number 10 and 12)* and during spreading of manure or urine *(flow number 14)* were calculated using ammonia emission factors specific for the management system chosen (Steineck *et al*., 2000; Karlsson & Rodhe, 2002). The actual nitrogen content of the manure during the flow from barn to field was calculated from emission data. The manure and urine were assumed to be spread on the field for feed production on the livestock farm *(flow number 13)*. The quality and quantity of the manure and urine and the expected yield of the crop determined the need for additional application of artificial fertilisers for crop production.

For methane emissions from storage of manure (*flow number 11)* the IPCC model was used, and the amount of emitted emissions was calculated using information on VS (kg volatile solids per kg DM) and DM in the manure, which was calculated from feed data, and some important factors (B_o, MCF, VS), see Tables 4 and 5 (IPCC, 2001a; Dustan, 2002). The method for calculating VS was obtained from a report by the Swedish Board of Agriculture (Jordbruksverket, 1995).

2.1.3 The SALSA pig model

The SALSA pig model is a tool for environmental systems analysis of pig rearing. The pig model is an expansion of the SALSA arable model to include pig production and the resulting interaction between arable and animal farming. The model traces energy and substance flows, calculating emissions at different stages from production of input materials up to a final agricultural product ready to be delivered from the farm gate (Figure 7). The SALSA pig model is described in detail in Strid Eriksson (2004). Examples of input data to the pig model are shown in Tables 6 and 7.

Table 6. *Input variables of management practices used in the SALSA pig model*

Input variables of management practices:	*Unit:*
Feed composition	kg barley, peas *etc.*
Feed quality [a]	MJ/kg DM
Mean metabolisable energy need/pig	MJ/kg pig growth
Manure management system	Slurry, deep litter, urine, manure, covering of slurry tank *etc*.
Electricity use for operation of farm building	MJ/pig
N intake per pig [b]	kg N/pig

[a] Calculated in the SALSA pig model from feed data. [b] Used for calculation of N excretion per pig.

Table 7. *Input parameters used in the SALSA pig model. (Em. means emission)*

Input parameters:	*Unit:*
Emission factor for NH_4-em. from barn	% of NH_4-N excreted
Emission factor for NH_4-em. from manure storage	% of the NH_4-N content
Emission factor for NH_4-em. from spreading of manure	% of NH_4-N applied
Enteric fermentation factor (CH_4) [a]	%
Dry matter of manure in storage tank [b]	%
Potential CH_4 production (B_o) (manure storage) [c]	m^3/kg of VS
Methane conversion factor (MCF) (manure storage) [d]	%
NOx emission factor (manure storage) [c]	kg N_2O-N per kg incoming N
VS in the manure [d]	kg per kg DM

[a] IPCC (1996). [b] Calculated in the SALSA pig model. [c] IPCC (2001a). [d] Dustan (2002)
[e] Volatile solids (VS) is the amount of total solids that volatilizes when ignited or heated to 550 °C, (in this study it is the organic matter in the faeces). VS in the pig manure was estimated according to Dustan (2002).

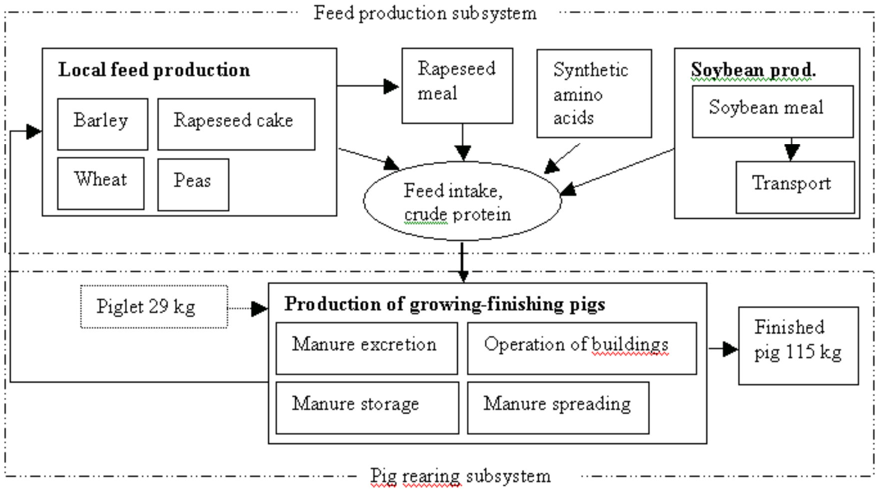

Fig. 7. The SALSA pig model pig included two sub-systems, production of feed ingredients and processes involved in pig rearing. (Figure from Strid Eriksson, 2004)

2.1.3.1 The feed production sub-model (SALSA pig)

Figure 7 represents the SALSA pig model, including local feed production (winter wheat, barley, peas and rapeseed), production of soybean meal, production of synthetic amino acids, pig rearing at the farm and manure handling. Outflows from the SALSA pig model are meat, manure and emissions to the environment. The amount of feed is calculated to fulfil the metabolisable energy (ME) requirements for one pig growing a specified growth interval (in Paper III one average kg in the range between 29 to 115 kg).

The soybean sub-model is similar to the other arable crops, but supplemented with the transport to and from extraction and transport by ship overseas. Data on distance, fuel and loadings are used to calculate the amount of emissions from such transport.

2.1.3.2 The manure sub-models (SALSA pig)

The manure excretion sub-model calculated the amount of manure produced, nitrogen excretion and the emissions occurring indoors from one pig. The amount of nitrogen excreted was dependent on nitrogen intake. The relationship between nitrogen intake and nitrogen excretion was taken from a Dutch study (Canh *et al*., 1998). Ammonia emissions due to ammonium nitrogen content in the excreted manure were also taken from Canh *et al*. (1998) after calibration to Swedish conditions of more frequent manure removals. Methane emissions from the pigs were calculated due to the pigs' energy intake in feed (MJ/kg DM) according to IPCC (1996).

2.1.3.4 Sub-models for emissions from the housing system (SALSA pig)

Methane emissions from manure storage were calculated according to IPCC (2001a). Emissions of methane from storage were estimated using the calculated manure quality data in the SALSA pig model (*i.e*. DM) and from factors described by IPCC (B_o, MCF, VS), see Table 7. Electricity use for operation of farm buildings was considered as a value per pig produced.

2.1.4 Output data from the SALSA models (arable, cow and pig)

Results from the SALSA models provide information suitable for various levels of evaluation and interpretation and the results can be presented for one crop, several crops, for a whole crop sequence or for meat or milk production.

There are three kinds of output data from the SALSA flow models; firstly, substance flows as separate substances (*e.g*. kg NO_3 to water), secondly substances aggregated into impact categories in the impact assessment phase (*e.g*. eutrophication) and thirdly, production-related output data (*e.g*. yield, manure production) (Tables 8, 9 and 10). The performance results from SALSA arable are used in SALSA cow and SALSA pig to calculate the environmental load from feed. Output data about the manure quality and quantity are used in the SALSA arable model to calculate the amount of artificial fertiliser that needs to be added.

Table 8. *Output data from the SALSA models presented as substances and energy flows per ha or per functional unit*

Environmental load and energy use:	*Unit:*
NO_3 to water	kg
P to water	kg
NH_3 to air	kg
NO_x to air	kg
CO_2 to air	kg
N_2O to air	kg
CH_4 to air	kg
SO_2 to air	kg
HCl to air	kg
Direct energy use [b]	MJ

[b] The energy use at the farm; diesel, electricity *etc*.

Table 9. *Output data from the SALSA models presented as impact categories per ha or per functional unit*

Outputs as impact categories:	*Unit:*
Eutrophication	kg O_2-equivalents
Global warming	kg CO_2-equivalents
Acidification	kg SO_2-equivalents
Primary energy use [a]	MJ
Land use	ha

[a] Primary energy includes production, distribution and energy converting losses of the energy carrier

Table 10. *Production-related output data from the SALSA models*

Production outputs:	*Unit:*
Crop yield	ton/ha
Animal production	kg ECM milk [a], kg bone and fatfree
Land use	ha per kg milk, meat or crop produced
Manure production	kg per functional unit
Manure application rates	ton per ha
Area needed for manure spreading	ha per functional unit

[a] ECM means energy corrected milk

Furthermore, the environmental impacts from different parts of the system and from different substances can also be presented separately, which enables a comparison between sub-systems in order to find the sources behind the largest impacts. The SALSA arable model uses 27 emission points to describe the system, including all field operations, soil, plant, indirect nitrous oxide, drying, pressing of rapeseed oil, diesel production, mineral fertiliser production and seed production.

For the SALSA pig and cow model, an additional 8 emissions points are used, including operation of buildings and equipment in the building, emissions direct from the animals, emissions from manure in the barn, during storage and during spreading, manufacturing of concentrates, plastic for silage covering and synthetic amino acids.

2.1.5 Interactions between arable and livestock production

Arable and livestock production systems interact, as can be seen in Figure 6 which shows the SALSA cow and SALSA arable model interactions. Livestock production depends on the feed quality/quantity, while arable production depends on the quality/quantity of the manure and urine excreted from the animal. Efficient nutrient management leads to a lower need for mineral fertilisers and the environmental loads from production of mineral fertilisers therefore decrease. This effect was significant in Paper IV, where lower amounts of manure were produced at the high milk production level than at the low production level (per kg milk produced). In the model, the mineral fertiliser application rates are used to replace outflow of nutrients in the products sold from the farm and to replenish losses from storage and spreading of manure. Consequently, the additional application of mineral fertiliser on the livestock farm was calculated as the difference between the nutrient requirements in the crop production and the nutrient value of the manure and slurry obtained from the livestock system.

2.2 The combined model (SALSA arable and SALSA mind)

A combined model was constructed to link the physical flows at the farm to structural preconditions like the economy and legislation, as well as to the farmer as a decision-maker. In the combined model, the results from the SALSA arable model are integrated with the farmer's decision model SALSA mind. The decision is a result of the cost and income per crop choice, the farmer's environmental interest and the farmer's decision preferences. It is a one-person simulator (one farmer at one farm). The simulation is an interactive process going on until the given constraints in the scenarios are satisfied. The combined model is used in Paper II, where it is called 'the integrated model'. The model is also described thoroughly in a report by Elmquist, Lindgren & Mäkilä (2004). Figure 8 shows the conceptual framework of the combined model.

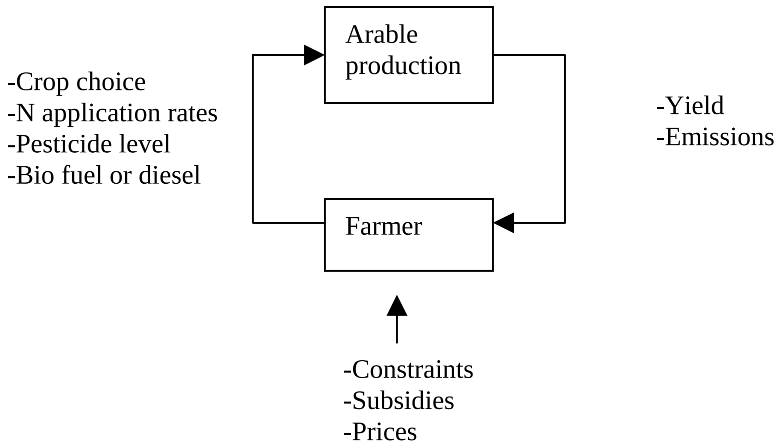

Fig. 8. A conceptual model of the combined simulation model consisting of the SALSA arable model and the SALSA mind model.

Four types of theoretical decision models were applied and tested for the individual action of a farmer's decision on production allocations. Two extreme variants were used as reference points, one extreme rational farmer '*pure rationality*' who had access to all prices and outcomes of all production alternatives and had the ability to decide the best available option in every decision. The other extreme was the farmer who made random decisions '*garbage can*'. There were also two intermediate types of farmer, which were probably more like a real farmer in terms of decision-making. The '*bounded rational*' decision-maker settled for a satisfying behaviour drawn on experience. He/she evaluated all possible alternatives of production allocation for a limited set of alternatives. The additional alternative was the '*incremental*' decision-maker, who changed operations by small steps and relied on traditional knowledge and experience.

In the combined model where the crop sequences are simulated (Paper II), some practical obstacles and constraints are automatically included. For example, no more than 60% of the crops can be winter wheat because of machinery capacity constraints, while winter crops cannot follow some of the spring crops due to late harvest. In order to get the EU area subsidy, 10% of the arable land has to lie fallow every year.

2.3 Systems boundaries and allocations

Arable production (Papers I-IV) and meat/milk production (Papers III and IV) systems were studied from resource production until products were ready for delivery at the farm gate. Energy use and emissions were calculated for each activity or process related to the production.

Feed production was studied including production of input materials; seed, diesel, electricity, fertiliser, plastic for silage covering and then through processes and activities for feed production on the farm; field operations, emissions during spreading of mineral fertiliser, soil and plant emissions, harvest, drying, and transport of products from field to farm. (Transport of cereals to the mill was included in Paper II). Production and transport of feed ingredients for production of concentrate were also included, such as synthetic amino acids used and soybean meal, *etc*. Processes from livestock production included excretion of manure and urine and emissions from animals, storage and from spreading of organic fertiliser.

Production of machines and buildings was excluded from the studies for two reasons; first, there was no difference between the scenarios and second, there are difficulties in allocating the use of capital goods among all the activities on the farm as well as in deciding the lifetime of machines and buildings. Transport of mineral fertiliser to the farm and energy use for production of pesticides was not included because of its minor importance (Bernesson, 2004). The ecological effect of pesticide use was excluded because of lack of methods for evaluating such effects.

For soybean and rapeseed, which give rise to two co-products, the environmental impacts needed to be divided among the products. In order to apportion the feed production between feed and oil, an economic allocation was used for soybean and rapeseed production. For soybean meal, 69% was allocated to the meal and for rapeseed meal, 30% was allocated to the meal (Oil World Monthly, 2003; Strid Eriksson, 2004).

2.4 Impact assessment

2.4.1 Impact categories included

In order to classify and characterise substances depending on their impact, methodology developed in Life Cycle Assessment (LCA) was used. The aim of the LCA was to assess the environmental impacts of the substance flows and it was performed using the following impact categories:

Ecological effects:

- Eutrophication of water (N and P)
- Global warming potential (GWP) (from a 100-year perspective)
- Acidification (in terrestrial systems)

Resources:

- Primary energy use (fossil origin and electricity)
- Land use (cultivated area used for production)

These impact categories were chosen because of their significant impacts for farm production (Table 1). Other relevant impacts of farm production include changes in biodiversity and aesthetic aspects of an open landscape, but those effects were not included in the analysis since they are difficult to quantify and include in physical flow simulations.

The equivalence category factors for environmental impact per kg substance for eutrophication (O_2-equivalents), acidification (SO_2-equivalents) and global warming potential (CO_2-equivalents) are given in Table 11 and a brief description of the underlying concept follows. Results from simulations are given as kg O_2-, SO_2-, CO_2-equivalents and MJ primary energy per functional unit, according to LCA practice (Baumann & Tillman, 2004).

Table 11. *The impact factors for eutrophication (O_2-eqv), global warming potential (CO_2-eqv) and acidification (SO_2-eqv) used in the studies*

Type		Effect or resource use	O_2-eqv/kg	CO_2-eqv/kg	SO_2-eqv/kg
Eutrophication		NO_3 to water[a]	4.4	-	-
		P to water[a]	140	-	-
	(II, III)	NH_3 to air[a]	16	-	-
	(I, IV)	NH_3 to air[b]	20	-	-
		NO_x to air[a]	6	-	-
Global warming		CO_2 to air[c]	-	1	-
		N_2O to air[c]	-	296	-
		CH_4 to air[c]	-	23	-
Acidification[a]	(II, III)	NH_3 to air	-	-	1.88
		SO_2 to air	-	-	1.0
		NOx	-	-	0.7
		HCl	-	-	0.88
Acidification[d]	(I, IV)	NH_3 to air	-	-	4.4
		SO_2 to air	-	-	3.8
		NOx	-	-	1.3

[a]Lindfors *et al*. (1995). [b]Primary oxygen consumption included according to Kärrman & Jönsson (2001). [c]IPCC (2001b). [d]Huijbregts *et al.* (2000).

2.4.2 Eutrophication

All flows which give rise to eutrophication (nitrate leaching from soil, phosphorus runoff or leaching from soil, NH_3 emissions from manure management and NOx-emissions from tractor operations) were characterised according to their potential impact and presented as O_2-equivalents. The impact factor used for estimating the potential effect to eutrophication was obtained from Nordic Guidelines (Lindfors *et al.*, 1995) with an additional factor for primary oxygen consumption in oxidation of ammonia in aquatic systems (3.8 g O_2 per 1 g NH_3) from Kärrman & Jönsson (2001) (see Table 11). O_2-equivalent refers to the oxygen needed to degrade the eutrophication substances in water bodies. The impact index is based on the composition of carbon, nitrogen and phosphorous in phytoplankton (Lindfors *et al*., 1995). This is an overestimation but to make the results general, the eutrophication maximum-scenario was used, which means that P and N together were included as potential affecting substances (Lindfors *et al.*, 1995). At present, terrestrial eutrophication is usually not covered by current LCA (Udo de Haes *et al*., 2002).

2.4.3 Acidification

In order to assess the studied system's contribution to acidification, outflows of acidifying substances were calculated. The acidification impact in terrestrial systems (SOx-equivalents) was considered in the studies. Nitrogen as NO_x and NH_3 was assumed to contribute to acidification, together with SO_2 and HCl. Soil acidification is an excess of hydrogen ions originating from the removal of negatively charged ions by leaching or other biochemical processes. The characterisation factors were based on their potential to release hydrogen ions. However, the final acidification effect, from nitrogen, depends on the amount of nitrogen leached from the system. Finnveden *et al.* (1992) suggest an approach of a doubled scenario presenting both min and max effect. The min scenario is when the contribution from nitrogen compounds is zero and the max scenario is the theoretical maximum.

Impact factors for the (terrestrial) acidifying effect assuming the max scenario approach were used in Papers II and III (Lindfors *et al.*, 1995). These equivalency factors probably give an overestimation of the importance of nitrogen relative to sulphur because of the assimilation of nitrogen by ecosystems. The amount of nitrogen leached compared to the input is typically less than 15% in Scandinavia (Grennfelt, Hov & Derwent, 1994) so the actual effect is probably somewhere between the min and max scenarios. Site-specific factors presented by Huijbregts *et al.* (2000) were used in Papers I and IV and the worst-case scenario was chosen for those site-specific factors in which above- and below-threshold marginal changes in the hazard index were summed. A model called RAINS was used and the relative acidification risk was calculated using the ratio between deposition and critical load (Huijbregts *et al.*, 2000). The regional factor is relative to the potential of 1 kg SO_2 released from a reference scenario in Switzerland.

2.4.4 Global warming potential

Gases that have a potential effect on global warming are N_2O, CO_2 and CH_4. Nitrous oxide is emitted from soil and during mineral fertiliser production. Fossil carbon dioxide originates from machine operations, while methane is emitted directly from livestock and from manure storage tanks. Substances that lead to global warming (GWP) were multiplied by equivalence factors according to IPCC (2001b). The GWP characterisation factors are based on the ability of the compound to absorb IR radiation and the lifetime of the substance in the atmosphere. The GWP factors differ with horizon time and in this study a perspective of 100 years was chosen. This time perspective is often used in LCA studies, and was also proposed in a report by Naturvårdsverket (1991).

2.4.5 Primary energy

To enable the energy use from different energy carriers to be aggregated, the primary energy concept was used. This concept is mentioned by Lindfors *et al.* (1995) as a method for aggregating the energy use into one category. Primary energy is a concept to include direct energy use and the energy use during production and distribution of the energy carrier (Figure 9). This approach resulted in a conversion factor (by which the direct electricity use is multiplied) of 2.2 for a

Swedish average electricity mix and 1.1 for Brazilian electricity mix (Sattari, 2002). For diesel use, 6% extra energy was added to include the production and distribution costs (Uppenberg *et al*., 2001a; Uppenberg *et al*., 2001b).

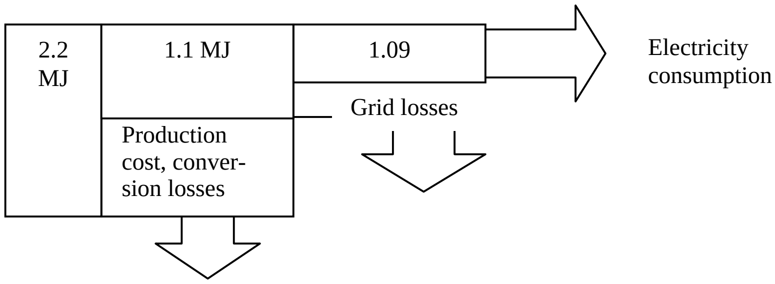

Fig. 9. The assumptions for calculation of the primary energy factor for a Swedish electricity mix, which includes energy use for production and distribution, energy losses during energy conversion for the nuclear part and grid losses.

For energy use for production of plastic silage wrap, the energy generated by the plastic material waste collected, which replaces virgin energy sources for plastic production, was subtracted from the total energy use (Ringström, Fröling & Hallberg, 2003).

2.4.6 Land use

There have been several attempts to develop methods for land use assessment in LCA methodology. Methods can be based on a comparison of a natural ecosystem and the effect of the cultivated agricultural land. However for Swedish conditions, the impact of cultivation of agricultural land is not clear-cut, since arable land is not always a limited resource and agricultural production can be more favourable for a biodiverse landscape than the natural ecosystem. Because of these methodological difficulties, the impact of land use was considered as area farmland used (ha) per functional unit (f.u.).

2.5 Verification and validation of the models

To ensure that the models operate as intended, the sub-models were tested independently. This means that they were technically validated as well as verified in the sense that they produce realistic results, *e.g.* compared to results found in the literature or from experience. It can then be concluded that the entire model produces reasonable results. It is in principle impossible to validate the SALSA models in a strict meaning. For example, it is not possible to validate contributions to the greenhouse effect in a 100-year perspective, or the maximum eutrophication *i.e.* the eutrophication effect from both nitrogen and phosphorous in a water body, simply because there are no such measurements available for the whole production system. Besides, the methods used for impact assessment are based on the potential impacts and not estimated true values (Udo de Haes *et al*., 2002).

3. Results

3.1 Results from Paper I (arable production)

In Paper I the environmental consequences of using different nitrogen application rates were studied for cultivation of spring rapeseed, spring barley and winter wheat. The results per kg spring barley produced are presented in Figures 10-12. Figure 10 shows the primary energy use and Figure 11 shows the contribution to global warming for normal application rates. In Figure 12, results of simulated leaching for different nitrogen application rates and for phosphorus are presented.

High N application rates gave the highest environmental impacts per kg product for three of the four categories (Figures 4, 6, 7 in Paper I), while eutrophication appeared to have a minimum impact below the application rates generally used on Swedish farms (Figure 5 in Paper I). The environmental impacts are highly dependent on the yield, which is *inter alia* a result of the nitrogen application rates per hectare. The yield response functions of the three crops related to the nitrogen application rates are presented in Figure 3 in Paper I. Wheat and barley have a similar function in a feed mix and can be compared, apart from the fact that wheat is slightly more energy-rich than barley. Rapeseed is not used for the same purposes as the two other cereals and thus cannot be directly compared with them. Rapeseed responds weakly to nitrogen fertilisation and that can be explained by the fact that much of the nitrogen supplied is used for the tap-root. However, the nutrient rich residues from the rapeseed crop have a fertilising effect on the following crop that can be accounted for as avoided environmental burden for mineral fertiliser production in the crop that follows.

Energy use for mineral fertiliser production was the largest energy contributor, followed by field operations and drying (Figure 10). The energy use for mineral fertiliser production originated mainly from the production of ammonia, which is the most energy-demanding production step. For energy use for drying, average conditions were assumed and hence for bad conditions with much rain during harvest, more energy is used for the drying. Energy use for field operations were obtained from a case farm with arable production.

Contributions to global warming came from three main sources: mineral fertiliser production, air emissions from soils and indirect air emissions from recipients (Figure 11). Both N_2O and CO_2 are emitted during mineral fertiliser production. Both N_2O emissions from soil (direct N_2O emissions) and from recipients (indirect N_2O emissions) have large variation due to soil type, nutrient status and climate.

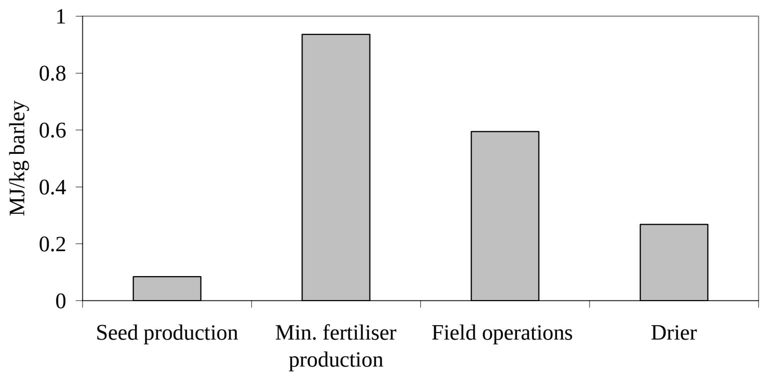

Fig. 10. Simulated primary energy use (MJ/kg spring barley) per activity or process during the production chain of spring barley. Normal rates of mineral fertiliser (87 kg N/ha), recommended pesticide dose and ordinary diesel fuel were assumed (Paper I).

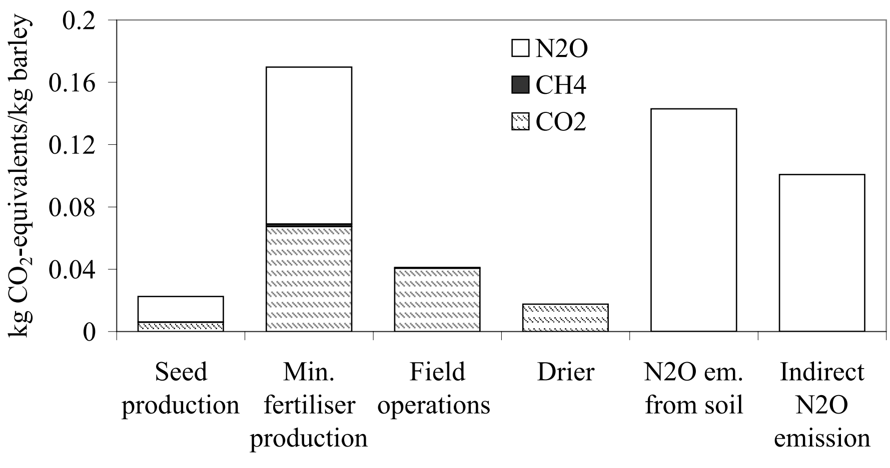

Fig. 11. Simulated global warming potential (CO_2-equivalents/kg spring barley) per substance and per activity or process during the production chain of spring barley. Normal application rates of mineral fertiliser (87 kg N/ha), data for field operations from the case study and the average water content in grain during harvest were assumed (Paper I).

Losses from soil of phosphorous (P) and nitrogen (N) were found to be of significance for the eutrophication impact since all other emissions were very small from arable production. Leaching levels from different nitrogen application rates are presented in Figure 12. The eutrophication caused by NO_3 leaching from soil, as kg O_2-equivalents per kg product, was shown to be largest for low and high N application rates. For application rates more than recommended the N leaching increased slightly with N application rates.

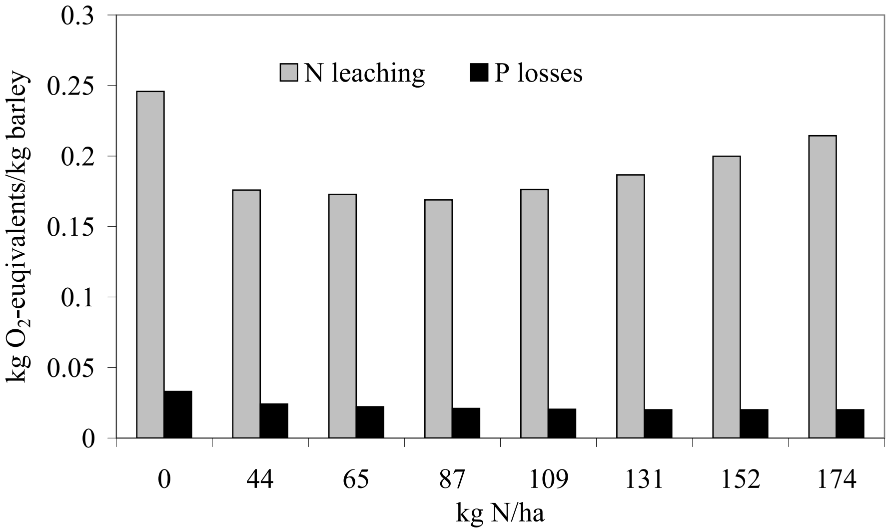

Fig. 12. Simulated leaching (O_2-equivalents/kg spring barley) per substance and per activity or process during the production chain of spring barley for N-application rates from 0-174 kg N/ha. A clay soil assumed (Paper I).

3.2 Results from Paper II (arable production including the decision model)

Paper II deals with simulations with the combined arable and decision models for arable production for one year of production on a farm cultivating 167 hectares. Results of simulations for two of the environmental categories (GWP and acidification) across decision models and accepted environmental loadings are presented in Figures 13-14. These figures are simulation results of the farmer's production allocation depending on acceptance of environmental loadings, skills, prices and subsidies. Four theoretic models for skills were used, namely a '*rational*' decision-maker, a '*bounded rational*' decision-maker, an '*incremental'* decision-maker and decision-maker driven by pure chance '*garbage can*'. Six levels of acceptance of environmental loadings; *unlimited-, much-, medium-, little-, limited-loadings* and *organic production* were assumed.

Regarding economic aspects of the simulation, organic farming appeared to be more profitable than conventional farming (Figure 3 in Paper II). The conventional farmers trying to minimise environmental loadings were those who did worst from an economic perspective, some of them showing zero results or even losses. The development of the combined simulation model consisting of the SALSA arable model and a microsimulation model representing the decision-making at the farm demonstrates the possibility of operationally amalgamating research from the social sciences and the natural sciences.

For the GWP category, the results show that the potential impact increases as the farmer's environmental awareness decreases, which is due to the close relationship with high nitrogen fertiliser rates and high GWP (Figure 13).

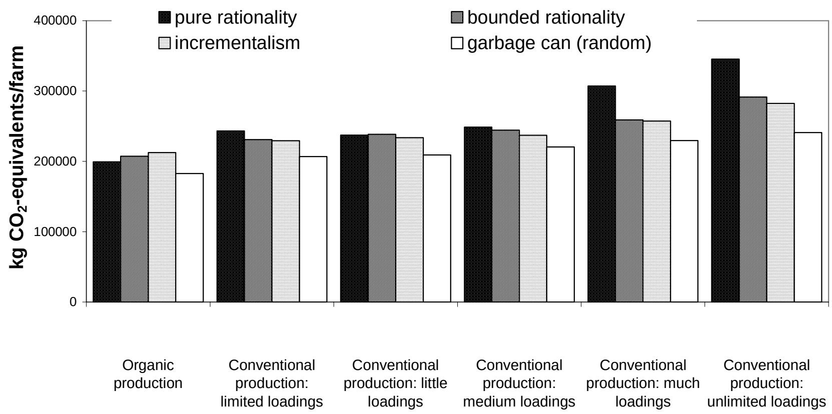

Fig. 13. Emissions of CO_2-equivalents (GWP) across the four decision models (pure rationality, bounded rationality, incrementalism, random) and the six levels of acceptance of environmental loadings (unlimited to limited conventional and organic production) (kg/farm and year).

The variation in acidification across alternatives depends on nitrogen application rates and crops chosen by the farmer to be cultivated on the farm in the actual year (Figure 14). Losses during spreading of organic fertiliser were only included in the organic alternative due to the decision to use the farm gate as the system boundary. This assumption belongs to a farm accounting budget methodology[3], which makes the comparison for acidification only adequate within the conventional production category. This is due to the fact that there is no large difference in the amount of ammonia emitted to the air regardless of whether the manure is used on a conventional or organic farm.

3 The accounting type of LCA answers questions of the type 'What environmental impact can this product be held responsible for? The change-orientated type of LCA compares the environmental consequences of alternative courses of action (Baumann & Tillman 2004).

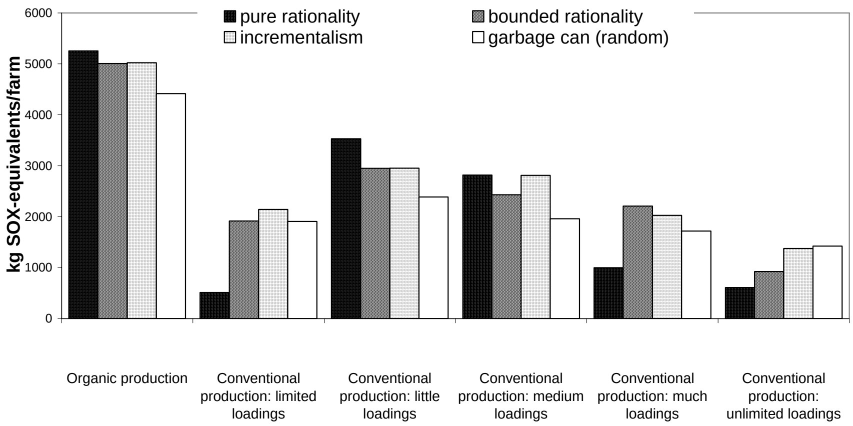

Fig. 14. Emissions of SO_x-equivalents (acidification) across the four decision models (pure rationality, bounded rationality, incrementalism, random) and the six levels of acceptance of environmental loadings (unlimited to limited conventional and organic production) (kg/farm and year), Paper II.

One alternative open to the decision-making farmer was to use biofuel such as RME (rapeseed methyl ester) instead of ordinary diesel for machinery work and drying. Environmental impacts such as eutrophication, GWP, acidification and energy use per kg winter wheat produced are presented in Table 12. As can be seen in Table 12, the environmental loadings did not decrease when RME was used instead of ordinary diesel. The larger loadings for RME are a consequence of the emissions during the production of mineral fertiliser and the use of more land for rapeseed production.

Table 12. *Simulated results of environmental impacts from Paper II for the basic scenario for winter wheat production comparing RME or diesel for machinery work. Results are presented per kg product as kg CO_2-equivalent (GWP), kg O_2-equivalent (eutrophication), kg SO_2-equivalent (acidification) and MJ as primary energy use*

Fuel type	O_2-eqv/kg[a]	CO_2-eqv/kg[b]	SO_2-eqv/kg[a]	MJ/kg
RME	0.075	0.39	0.0009	2.1
Diesel	0.064	0.38	0.0007	1.7

The impact categories used for the simulations were from [a]Lindfors *et al*. (1995), Kärrman & Jönsson (2001) and from [b]IPCC (2001b) assuming a 100-year horizon.

3.3 Results from Paper III (pig production)

In Paper III, pig growth taking place in the interval 29-115 kg live weight for three feed choices was investigated and the functional unit was kg pig growth in that interval. The three scenarios of feed choice were selected with the purpose of reflecting the effects of different feedstuffs and different crude protein levels. Cereals are the main ingredients in the feed, 84% for scenario SOY, 63% for scenario PEA and 80.7% for scenario SAA. In scenarios PEA and SAA, the protein sources from crops were peas and rapeseed. In scenario SAA, synthetic amino acids were also included.

The scenario SOY is regarded as a reference case to reflect an example close to current practice. The scenario PEA is based on organic pig feed and scenario SAA is a domestic feed where soybean is replaced by synthetic amino acids. (Results presented in Appendix in Paper III). The scenario PEA resulted in 20% less energy and 9% less GWP, but 5% more acidification and 2% more eutrophication compared to scenario SOY. The scenario SAA showed less environmental impacts for all categories compared to scenario SOY, with 10% less energy used, 7% less GWP, 20% less acidification and 17% less eutrophication.

Contributions to global warming and eutrophication for the three scenarios and for different activities are shown in Figures 15-16. The following activities are included: The protein sources (prot.) in feeds deriving from soybean meal (S), synthetic acids (SA), rapeseed meal or cake (R) and peas (P). Cereals are barley (B) or wheat (W). The manure management system creates emissions from excretion of faeces and urine in the barn (Ex), from storage of slurry (St) and from spreading of slurry (Sp). Electricity use on the farm is marked with (E) and energy use for spreading of slurry (T).

Production of the protein ingredients gave generally more environmental impacts per kg feed than production of cereals. Soybean meal was included at 12% in scenario SOY and contributed significant energy use due to long distance transportation (Figure 15).

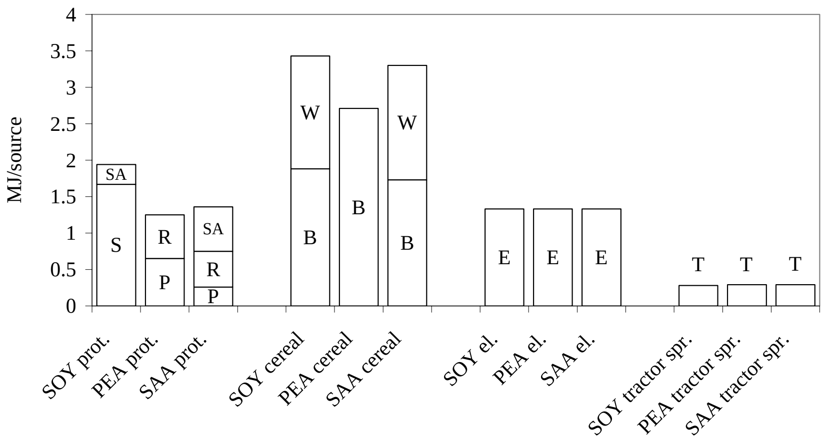

Fig. 15. Energy use (primary) per kg pig growth for the three feeding scenarios allocated to sources (Paper III). SA=Synthetic amino acids, S=Soybean meal, R=Rapeseed meal or rapeseed cake, P=Peas, B=Barley, W=Wheat, E=Electricity, T=Tractor use for spreading of animal manure.

Acidification originated mainly from ammonia emissions from the barn and from storage and spreading of manure. Substances contributing to eutrophication were mainly related to feed production, where leaching of nitrogen was the most important source (Figure 16). Remaining eutrophication originated from ammonia emission from the animal system (emissions from barn, storage and from spreading).

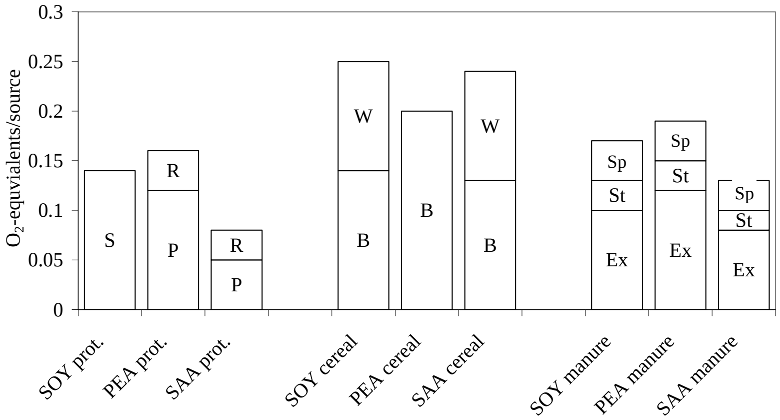

Fig. 16. Eutrophication per kg pig growth for the three feeding scenarios allocated to sources (Paper III). SA=Synthetic amino acids, S=Soybean meal, R=Rapeseed meal or rapeseed cake, P=Peas, B=Barley, W=Wheat, Sp=Spreading of animal manure, St=Storage of animal manure, Ex=Emissions of excreted faeces and urine in the barn.

3.4 Results from Paper IV (milk and meat production)

In Paper IV, three milk producing intensities (LOW, MED, HIGH) were studied. LOW corresponded to a yearly production of 6000 kg ECM/cow, MED to 8000 kg ECM/cow and HIGH to 12000 kg ECM/cow. The functional unit consisted of 1000 kg ECM milk and the corresponding meat production (28 kg bone- and fat-free meat). The systems were expanded with meat production from suckling cows to obtain the same amount of meat in all scenarios. Global warming potential and eutrophication for the three scenarios are presented in Figures 17-18, allocated to different animal types and sources. Animals from the dairy system were dairy cows (C), heifers and calves (H), 12 month-old beef bulls (B) and all animals in the suckling system (cows, heifers, calves and bulls) (S). Sources were home feed production (ley and barley), imported feed (soybean meal, rapeseed meal, palm oil expels and other concentrate ingredients) and the manure management systems (emissions from barn, storage and from spreading).

The results showed small differences between the scenarios but there was a relatively clear tendency for less environmental impacts and energy use from the scenario HIGH compared to scenario LOW (Figures 4-7 in Paper IV). As can be seen in the figures, most of the impacts originated from the dairy production system. This can for example be seen in Figure 17, which shows the contributions from GWP gases originating mostly from the dairy cow system (C, and H). For the scenario MED, approximately 90% of all the environmental impacts originated from the dairy system, while for the scenario HIGH the corresponding value was approx. 75%. The remainder came from emissions mainly from the complementary feed production. The higher milk production contributed to lower environmental impact per kg milk but the benefit was nearly replaced by environmental impacts for the complementary meat production. Eutrophication originated mainly from spreading of manure and on-farm feed production (Figure 18). The greatest contribution to acidification came from ammonia emissions from spreading of manure on ley. The main energy uses for the milk and meat production were electricity in the dairy system, energy use for mineral fertiliser production, diesel fuel for machinery work, drying of grain, diesel use for feeding of the suckling animals and fuel for long distance transport by ship. Energy use for production of plastic wrap for covering silage was approx. 20% of the energy use for producing silage.

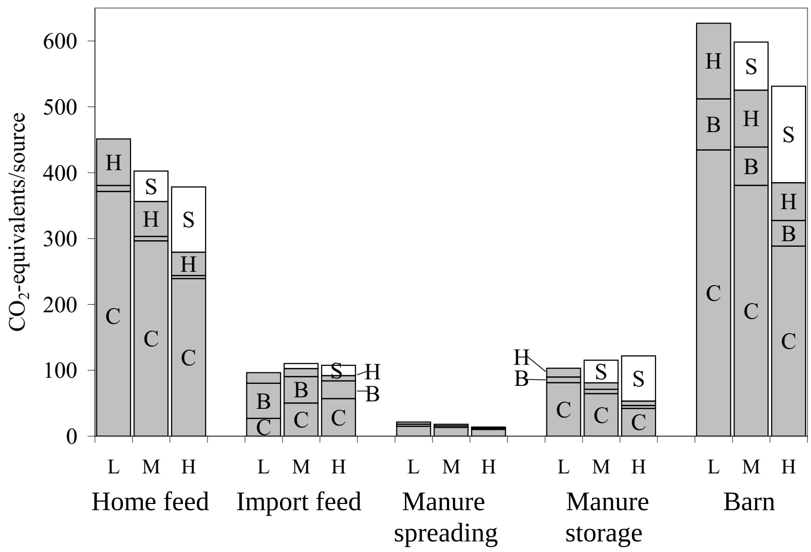

Fig. 17. GWP per functional unit (1000 kg milk and 28.2 kg meat) for the three feeding scenarios (LOW, MED and HIGH) allocated to animals and main sources; home feed production (ley, barley, grazing), imported feed (soybean meal, rapeseed meal, palm oil expeller), manure spreading, manure storage, and enteric fermentation from the animal. C=dairy cows, B=bulls in the dairy system, H=heifers in the dairy system, S=all animals in the complementary meat production (suckler cows, calves, heifers, bulls). Figures from Paper IV.

Land use per scenario (ha per f.u.) is presented in Figure 19. Compared to the scenario MED, 14% more land was used for the scenario LOW and 10% less land for the scenario HIGH. The imported feed consisted of soybean meal imported from Brazil and rapeseed meal assumed to be cultivated outside the livestock farm in Sweden or in another country in Europe. The same allocation factors used for simulations of the emissions were used to calculate the land use for the soybean meal and rapeseed meal. The LOW scenario used most land for ley production and the HIGH scenario used most land for grazing.

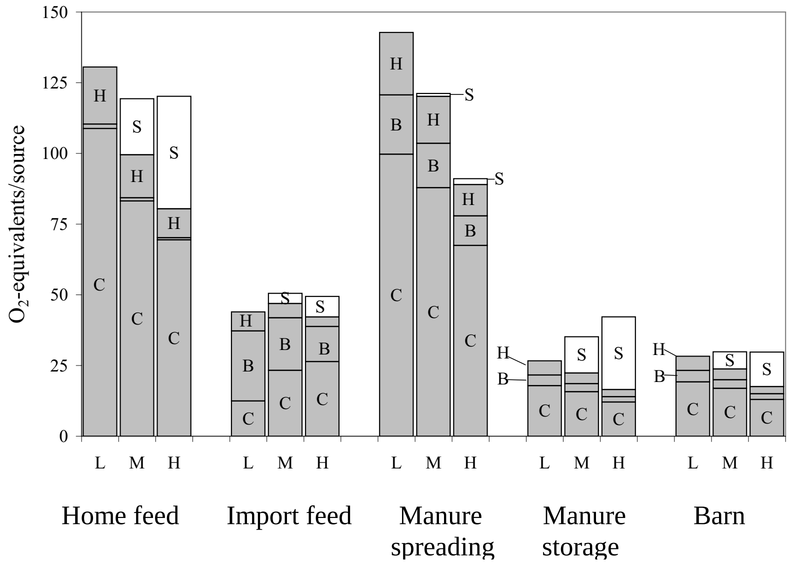

Fig. 18. Eutrophication per functional unit (1000 kg milk and 28.2 kg meat) for the three feeding scenarios (LOW, MED and HIGH) allocated to animals and main sources; home feed production (ley, barley, grazing), imported feed (soybean meal, rapeseed meal, palm oil expeller), manure spreading, manure storage, and emissions from the barn. C=dairy cows, B=bulls in the dairy system, H=heifers in the dairy system, S=all animals in the complementary meat production (suckler cows, calves, heifers, bulls). Figures from Paper IV.

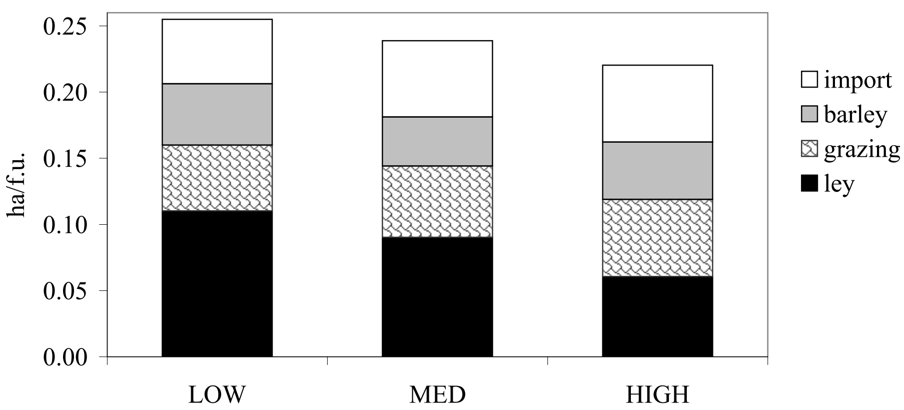

Fig. 19. Agricultural land use per functional unit (1000 kg milk and 28.2 kg meat) for the three feeding scenarios (LOW, MED and HIGH) allocated to feed ley, barley, grazing, and imported feed (soybean meal, rapeseed meal). Figures from Paper IV.

4. Discussion

Several types of experiences emerged from the work constructing the SALSA simulation model; one was the results obtained from the simulations, while another was an increased insight into system characteristics and the relationships between important factors within the system. This section begins with a discussion about the impact of different management strategies, followed by a discussion of the main potential environmental impacts found in the results. The section concludes with a general discussion about the model, the validity of the results and the needs and possibilities for future developments.

4.1 Management strategies

4.1.1 The impact of crop yield and crop sequence

Crop yield is a result of management strategies, local conditions and the actual weather and since emissions and resource use in the present work were appointed to a functional unit, the size of the yield was an important factor. This fact was shown in two of the four studies (Papers I, II), where the yield was tested for different input of resources. In Paper I, the yield response to different fertiliser application rates was investigated, while Paper II investigated the yield due to three management factors; nitrogen fertiliser rates, pesticide doses and reduction due to an unfavourable crop rotation. The results from the studies demonstrated the importance of studying the effects of non-linear relationships, such as yield response to different nitrogen application rates. The SALSA model proved to be a good tool for studying these non-linear relationships between management and environmental impact per functional unit.

Barley and wheat are the most commonly used cereals in animal feeds in Sweden and they basically fulfil the same function in the diet of supplying the animals with metabolic energy. In Papers III and IV, different cereal crops were used in feeds and the choice of cereal in the feed affected the final result. Environmental impacts per kg product from winter wheat were considerably less than from spring barley due to differences in yield per hectare, which was also shown in Paper I. This can be explained by the winter wheat's longer growing period and higher harvest index[4].

However, this effect cannot be attributed to winter wheat alone, since this crop is often placed in the most favourable position in the crop sequences, where it obtains a benefit from the preceding crop. In Paper I, a sensitivity analysis is presented on the effect of the residual nitrogen fertilising effect from a rapeseed crop on the following crop. Other authors also highlight the importance of allocating environmental loads due to fertilisation according to the uptake and uptake efficiency per crop (Zeijt, Leneman & Wegener Sleeswijk, 1999). Furthermore, a larger yield for cereals that follow an oilseed crop or ley is caused by both high nutrient status in the soil and by a sanitation effect on soil-borne

[4] $\frac{\text{Grain yield} * 100}{\text{Total above-ground biomass}}$

pathogens. Consequently, this interlinkage between crops in a crop sequence needs to be considered. To obtain a more fair comparison between the crops in a crop rotation, the mineral fertiliser production avoided due to preceding crop effect should be allocated to the crop that caused it.

The effects of reduced yield due to unfavourable crop sequences were demonstrated in Paper II. The results showed that the most economically orientated and rational farmer (who had access to the best alternatives and could choose the economically most favourable alternative) never chose monoculture despite better prices and higher yield for some of the crops. An extension officer with long-term experience of pesticide control claims that ‘a good crop sequence (where cereals are alternated with oilseed, peas, *etc.*) is more economically beneficial than monoculture in a long-term perspective due to higher yields’ (Peder Waern, pers. comm.).

4.1.2 Nitrogen application rates

The impact of nitrogen application rates was tested for crop production in Papers I and II. The results showed that nitrogen fertiliser application rate is a key factor affecting the environmental impacts from the production chain, as well as the yield. The results in Paper I showed that N application rates below the economic optimum were more environmentally friendly for three of four categories studied than the economically optimal nitrogen application rate (GWP, acidification and primary energy use). An exception was the risk for eutrophication (per kg product), which increased at N application rates both lower and higher than the optimum. Similar results have been shown in a German study where lower environmental impacts were obtained by using a more extensive production than the economic optimum (Brentrup, 2003).

The economic optimum for nitrogen application rates is a result of the biological nitrogen response function, the actual prices and costs for fertilisers and for spreading. However, according to several investigations (Naturvårdsverket, 1997c; Joelsson *et al.*, 1999; Kihlberg, 2002), farmers use more nitrogen than the economic optimum calculated by the Swedish Board of Agriculture (SJV). In their optimisation, costs for fertilisers and spreading are included, which is about 20% of the total cost per hectare (Paper II). The reason why farmers use more than the SJV economic optimum is that they consider all costs they have for the crop production per hectare. They have more to risk in loss of income due to a reduction in yield or crop quality than to lose in extra costs for fertilisers. On the basis of these results, a Danish action to reduce leaching seems to be interesting (Ministeriet for Fødevarer, Lantbrug och Fiskeri, 2004). Danish farmers in leaching-sensitive areas are compensated for their financial losses if they use less nitrogen fertiliser than the economic optimum application rates.

In Paper I, leaching from different N application rates was investigated. The N flows not accounted for turned out to be remarkably large, particularly for high nitrogen N application rates. It can be questioned whether the N-leaching model (Aronsson & Torstensson, 2004) used in this study mirrors what happens for large N application rates. The model is based on the assumption that N leaching arising from surplus application increases linearly with increasing application rate.

However, when both the crop and the microorganisms have fulfilled their N needs, emissions and losses of N are expected to increase. It seems that the leaching model cannot be used for extrapolations outside the normal range for N application rates. In a field study in southern Sweden, N leaching from a clay soil in response to different N application rates to spring-sown cereals was investigated. It was found that the increase in nitrate leaching was moderate when N fertilisation was below the optimum for the crop, after which it increased rather sharply (Bergström & Brink, 1986). Other authors have pointed out that for high application rates, 'higher than normal' or 'higher than the crop needs', nitrate leaching increased significantly (Simmelsgaard & Djurhuus, 1998; Hessel Tjell *et al.*, 1999; Larsson & Johnsson, 2003). It is not likely that surplus applications of soluble N can remain in the soil and be available as a fertiliser to the crop in the following season. This study focused attention on the need for better N leaching models covering different N application rates, particularly when N is applied in surplus.

4.1.3 Self sufficiency in feed for pig production

The domestic feeds, scenario PEA, (Paper III) proved to be more environmentally friendly for some of the impact categories investigated for pig feed choice (global warming potential and energy use) compared to the scenario based on imported feed SOY. Peas had the lowest energy requirement due to their nitrogen fixing ability, which reduced the need for mineral fertiliser in the crop sequence. However, a disadvantage is the increased nitrogen leaching after a pea crop and the excess use of crude protein content which proved to lead to more losses in the consecutive flow steps of manure storage and manure spreading. The alternative scenario with replacement of soybean meal by peas and rapeseed meal in combination with synthetic amino acids resulted in even more improvements where 10% of the energy, 7% of the GWP and 17% of the eutrophication was avoided. However, there are also other negative effects from soybean production that need to be considered such as loss of biodiversity, the effect of pesticide use *etc.* and more environmental impact categories need to be included to get a better picture of the total environmental effect from imported *versus* domestic feed choice.

4.1.4 The impact of milk production intensity

The milk yield level is a result of management practices such as feed choice, *etc.* and the stock's genetic capacity for milk production. A high quality supply of metabolic energy per kg dry matter (MJ/kg DM) is important for high milk production levels. In Paper IV, a tendency for lower environmental impacts from the high producing dairy cows was shown. However, in another study by Cederberg & Flysjö (2004), it was shown that in practice, farmers use more concentrates for high level milk production than was assumed in this study, which would probably lead to smaller differences in the environmental impacts between the LOW, MED and HIGH scenarios.

In the LOW scenario studied here, 72% roughage was applied. Another interesting scenario to investigate would be to simulate the environmental effects of a low producing milk system based almost entirely on roughage. In a Swedish experiment, it has been shown that low level milk production can be almost exclusively based on roughage without compromising animal health (Birgitta Johansson, pers. comm.).

The impact from maintenance and breeding of heifers was shown to be a significant proportion of the total environmental impacts. A high recruitment rate is a waste of the resources invested in the heifer. In a study by Strandberg (1993), it was shown that after the sixth lactation the investment for the heifers was repaid. However, the recruitment of heifers depends on whether the cows have been in calf or not. This indicates that the recruitment percentage for cow replacement purposes is an important factor both for the farmer's finances and for the total environmental load and that by using a lower replacement rate some of the negative environmental impacts can be avoided.

4.1.5 Farmers' decision-making (Paper II)

Farmers' strategies for sustainable production are not simple, since farmers must choose individually to sustain themselves economically. In Paper II, the structural influence from the political changes regarding subsidies was shown to have a major influence on the farm economy. Results in Paper II indicate that the economic potential for making 'better' production-related choices for a conventional farmer is much less than the gains of converting to organic production, everything else being equal. The farmer can choose between two relatively economically sustainable strategies; either he/she can specialize in organic production (benefiting from higher subsidies and output prices) or he/she can continue with conventional cultivation and use larger amounts of pesticides and fertilisers (benefiting from large yields). The next question to arise is how real farmers can improve their choice of production allocation and increase profits in reality. This study was a result of simulation using theoretical decision models for farmers and therefore cannot answer that question. Expenditure on machinery is the largest expense for the agricultural business (excluding wages and taxes). In a study investigating the timeliness costs related to machinery operations, it was found out that significant savings could be made by using some sort of machinery co-operation (de Toro, 2004). However, there is obviously a need for more investigations on that subject.

4.2 Main potential environmental impacts

Several factors can be identified as making large contributions to the environmental impacts; mineral fertiliser production, emissions from manure management, emissions direct from the animals, primary energy use, losses of nitrous oxide emissions from soil and water bodies, and long distance ship transport.

4.2.1 Mineral fertiliser production

Production of mineral fertiliser was the largest energy user, and emissions of the GWP gases N_2O and CO_2 originated to a large extent from mineral fertiliser production. Other studies have also shown the significant contribution of GWP emissions from mineral fertiliser production (Brentrup, 2003). In order to reduce the N_2O emissions originating from fertiliser production, efforts should be made to introduce scrubbing techniques during fertiliser manufacture (Laegreid, Bockman & Kaarstad, 1999).

One example of the significant effect of mineral fertiliser production was shown in Paper II, where one of the farmer's alternatives was to choose bio-fuel instead of ordinary diesel for machinery work. RME is a refined product from rapeseed oil, which can be used as fuel in an ordinary diesel engine. The use of a bio-produced product instead of diesel fuel implies that fossil fuel can be replaced and carbon dioxide emissions avoided. However, the bio-fuel alternative generated even larger contributions to global warming potential (Table 12). This can be explained by the large use of mineral fertilisers for growing of the rapeseed oil crop. In a study by Bernesson (2004), it was shown that RME could give lower GWP impacts for a high-yielding winter rapeseed crop when the indirect air emission of nitrous oxide was excluded from the study. In the study presented in Paper II, the IPCC (2001a) method for calculations of indirect air emissions and emission factors for nitrous oxide emissions was used. The uncertainty of that method is discussed in a study by Kasimir-Klemedtsson (2001) and for Swedish conditions a lower emission factor is proposed. The conclusion that can be drawn from this is that RME can give lower environmental impacts for high-yielding crops but the results are highly sensitive to assumptions of nitrous oxide emissions from soil and recipient waters and of yield.

4.2.2 Emissions from manure management

Emissions from storage and spreading of manure were the main acidification contributor from livestock farming. The choice of manure management is a key factor because it affects the amount of emissions from the system and because of the fact that if the manure can be handled with high nutrient use efficiency, the need for artificial fertiliser decreases.

It can be rather hard for farmers to find time to spread all manure in an efficient way and the manure is then treated more as a waste than as a resource. Nitrogen is often used in excess of crop uptake, especially on animal farms (Johnson & Hoffman, 1997; Joelsson *et al.*, 1999; Kihlberg, 2002). However, Swedish legislation restricts when and how to spread animal and mineral fertilisers in an appropriate way (Swedish Board of Agriculture).

The manure management choice was particularly important for beef production in the milk/meat production study (Paper IV), due to ammonia emissions originating from the solid manure system. Another important factor is the farm's own land available for manure spreading. When a large proportion of the feed is imported to the livestock farm, there is less incitement to invest in nutrient efficient techniques. In organic production the demand for a high proportion of feed production on-farm is one of the fundamental principles. When livestock production is more closely related to the feed production areas, there is probably better nutrient recycling efficiency in both systems. Another study pointed out significant economic savings in a study of cooperation between a milk producer and a feed producer (Samuelsson, 2003) due to improved yields arising from a more diversified crop sequences, more effective use of manure, *etc*. In conclusion, if a manure management system that gives low ammonia emissions is used, less mineral fertiliser is needed and environmental load for the mineral fertiliser production phase can be avoided.

4.2.3 Methane emissions from animals

Direct emissions of methane from animals are significant, for ruminants in particular. The lifetime of the animals is important for the total emissions from the animals. For example, bulls grow to the same weight as steers in about half the time. This leads to a doubling of the CH_4-emissions per kg meat for steers. In Paper IV, the choice to assume fattening bulls for the complementary beef production with growth to 480 kg was important and if steers had been chosen instead more methane emissions would have been emitted. But steers are held to keep the landscape open with grazing animals, a service that cannot be obtained from bulls to the same extent without large fences. This is an example of an issue that conflicts with the target of reducing GWP emissions per kg meat produced.

4.2.4 Primary energy use

It seems obvious that the most energy saving action in arable production is to plan for efficient nitrogen use, since such large amounts of energy are used for mineral fertiliser production (Figure 7). For milk production, a considerable amount of fuel is used by machinery during ley harvesting. Energy use for plastic silage wrap production was a significant contributor to the primary energy use for silage production. At present only 30% of the plastic wrap is collected for re-use, replacing raw materials or energy purposes. Another activity for where energy use can be significant is drying of grain during wet years. Diesel consumption at farms varies a lot and the tractor is used for many other unspecified activities on farms.

4.2.5 Nitrous oxide emissions from soil and water bodies

There were considerable emissions of nitrous oxides (N_2O) from both soil and water bodies. However, these calculations are probably the most uncertain results because of the rough method for estimation of N_2O-emissions based on the total inflow of nitrogen to the soil (IPCC, 2001a). Emissions of N_2O also depend on the availability of organic material in the soil and on other factors such as whether the soil profile is water saturated. Kasimir-Klemedtsson (2001) showed that N_2O emissions increase exponentially with applications of nitrogen and organic materials.

4.2.6 Long distance ship transport

Transport of the soymeal had a significant influence on environmental impacts in the pig growth study (Paper III). More than half of the energy use and 75% of the acidification were due to long distance transportation of soybean ingredients for pig growth. However, whether SO_2 emissions from the ocean-going ships delivering soybean to Europe contribute to acidification is debatable, because a major proportion is considered to be deposited off-shore and be absorbed by the enormous sea volume, which is less sensitive to acidification. That argument needs to be considered carefully and should be analysed from a sceptical view because recent history has taught that we were wrong before when we thought that the seas and atmosphere could absorb all emissions without being affected.

4.3 Applicability of the model

4.3.1 The SALSA model

The SALSA models proved to be useful tools where the agricultural production perspective was combined with environmental aspects. The life cycle perspective for considering the process from resource production until the product is ready to be delivered makes it possible to consider the whole production chain and the simulation model turned out to be a good tool for studying the effects of several substances and numerous activities on different scales simultaneously. The non-linear relationship between milk production level and environmental loads was demonstrated using the SALSA cow model developed (Paper IV). One important factor concerning environmental impacts was the amount and quality of the manure produced, which differed between the scenarios. Animal size and productivity, diet, water intake, housing and seasonal weather conditions are all factors that influence the total quantity and nutrient content of livestock excreta (Smith & Frost, 2000).

Consequently, results from the environmental systems analysis are useful in decision support for stakeholders on several levels, for the farmer's production allocation on the farm, during the drafting of legislation or when subsidies for sustainable production are being developed. The SALSA models were developed to be a flexible tool for studies from several viewpoints. However, other tools are needed for quality analysis of the impact on biodiversity and the aesthetic values of an open landscape.

The uncertainty and variability of the input data used for simulations need to be considered in this type of model construction and there is a need for development of methodologies to perform such studies. Huijbregts (2001) presented a general framework for uncertainty and variability in LCA studies on several levels due to; parameter uncertainty, model uncertainty, uncertainty due to choices, spatial variability, temporal variability and variability between objects/sources. One example of large variation in management and environmental impacts between farms is shown in a life cycle inventory of 23 Swedish dairy farms by Cederberg and Flysjö (2004), and the authors claimed a need for a better knowledge of these variations and their causes. The sensitivity analysis in Paper IV showed the importance of testing parameter settings including different emissions factors, since a small difference in the parameter can lead to large differences in the results. An important factor identified which was used for calculations of the methane emissions from animals is the energy content per kg feed (Paper IV).

4.3.2 System boundaries and allocation

The choice of system boundaries is always debatable, since any boundary inevitably omits important activities and processes from the system studied. The critical issue in making comparisons between different systems is to choose suitable system boundaries so an adequate comparison can be made. Three milk production levels were compared in Paper IV (6000, 8000 and 12000 kg ECM/year) and there were small differences in emissions depending on the feed used. If the milk level alone had been considered, the highest production level would have been the most favourable from an environmental point of view. However, the pattern changed because both milk and meat production were considered. This shows the importance of well-defined system boundaries as well as the additional information obtained from choosing expanded system boundaries. The same conclusion regarding milk and meat production was reached by Cederberg and Stadig (2003) who pointed out that the milk and meat production systems are interlinked to each other and need to be studied simultaneously.

One lesson learned from Paper II was the problem in setting an adequate system boundary to allow conventional and organic farming to be compared. Mineral fertiliser was used in the conventional system and slurry assumed to be bought from a pig farm in the neighbourhood was used in the organic alternative. Since there was no obvious solution on how to set the system boundary at the beginning of the project, the farm gate was set as the system boundary, *i.e*. inflows and outflows of the arable farm were investigated and the share of different parts was the main focus. Emissions from slurry spreading were included in the organic alternative but not in the conventional alternative. However, this way of setting system boundary can be questioned, since the total size of ammonia emissions that will reach the recipient due to slurry management depends on the choice of slurry management technique and not on whether an organic or conventional system is used on the specific farm. Losses during storage and spreading of slurry should be either included or excluded for both conventional and organic systems, since there is no difference in the total emissions of ammonia to the environment between the systems.

Moreover, the slurry used in the organic alternative did not simply materialize from nowhere and, consequently environmental impacts from 'upstream' slurry production need to be included for mineral fertiliser production. (The pig production farm was assumed to be conventional). However, there is no obvious way to allocate the environmental impacts from mineral fertiliser production between pig meat and slurry productions since they have such different physical characteristics and economic values. The conclusion that can be drawn from Paper II was that an expanded system was needed in that case, including both meat and crop production, to enable conventional and organic farming to be compared.

4.4 Future development

The studies in this thesis included four or five impact categories and other important factors that need to be considered are the ecologic impact of pesticide use and the impact on biodiversity of different production systems. For example, less pesticide was used for roughage production than for cereal production, a fact not considered in the milk/meat production study or for feed production on-farm compared to imported feed in the pig production study. A further development of the model should include impact assessment of the potential effects of pesticides on the environment. Further work should also include effects of imports of other substances such as cadmium and the consequences of the import via feed.

Another question that needs to be further investigated is phosphorous leaching due to the large amount of phosphorus imported via feed. It is important to determine whether phosphorous losses increase from soils with high phosphorus content and what the long-term ecological consequences are of outflow of phosphorous via feed from crops cultivated on the other side of the world?

Since the choice of crop sequences has such a large influence on yield and environmental impact, the effect of different crop sequences needs to be studied in greater depth. The effect of more cooperation between arable and livestock farm for better nutrient recycling and more varied crop sequences would be an interesting area for further investigation.

The variation in yield due to weather and management choices is a typical characteristic for farm production. Here, an average weather situation for different districts was assumed in this first version of the SALSA models. Variation due to weather is an aspect that should be improved in future versions of the model. This is particularly important concerning yield variations and losses of phosphorus and N_2O from the soil. In order to get more reliable results and to get figures on the variations, the uncertainty analysis could be developed to include different assumptions for more of the input data used.

In addition, questions of environmental impacts need to be put in a larger context including both animal welfare and the farm business. The studies showed significant land use abroad for production of feeds for pig and milk/meat production, a fact that needs to be further analysed. As regards food production, ecological, economic and social criteria of sustainability must be fulfilled (Öborn *et al.*, 2002). Therefore, stewardship of both natural and human resources is of prime importance.

A further development of the SALSA model could include a user-friendly format for decision-makers on different levels and the results of different decisions could be tested by simulations before a new management system is implemented.

5. Conclusions from the farm system studies

5.1 Methodological aspects

- Simulations with the SALSA models allowed scenarios to be studied and the result of different management strategies for arable production and livestock production to be viewed concurrently. The systems analysis approach made it possible to study several substance flows simultaneously and an improvement for one activity did not necessarily lead to a total improvement concerning the whole system.
- The SALSA model demonstrated the importance of including non-linear relationships in this type of environmental systems analysis study. This fact was important for crop yield and amount of meat/milk produced, for N_2O-emissions from soils and recipients, for manure quality and quantity, for CH_4-emissions due to the energy content in feed and for emissions from the manure management system.
- The choice of system boundaries and allocation methods had a large influence on the results. Interrelationships between different production systems such as milk and meat or feed production need to be considered, for example by using an expanded system approach.
- Variability and uncertainty in input data and in model assumptions need to be included in this kind of environmental systems analysis.
- The development of the combined model consisting of the SALSA arable model, the decision-making farmer and the structural conditions influencing the farmer showed the interwoven dependency between the physical and anthropogenic systems.
- This thesis focused attention on the need for better N leaching and N_2O emission models covering different N application rates, particularly when N is applied in surplus.

5.2 Environmental aspects

a) The impacts concerning production and production levels

- Since the environmental load and energy use values obtained by simulations were divided by the amount of crop, milk, meat, *etc.* produced, the size of the production had a major influence on the final result.
- High level milk production complemented with meat production from a suckler cow system gave slightly lower environmental impacts for the four impact categories studied than low level milk production. This can be explained by the higher milk production efficiency from more concentrates in the feed.

- In achieving more sustainable agricultural production, the results showed the importance of society supporting and stimulating production to be more environmentally friendly.

b) The impacts concerning fertilisation

- The use of nitrogen is a key factor affecting both yield and all environmental categories. In the simulation with the combined model (Paper 2), more nitrogen than recommended was frequently applied, which seems to be related to the relatively low cost of nitrogen compared to its yield-increasing potential.

- The choice of manure management system is important since it affects the total environmental impacts from the livestock production systems as well as the need for mineral fertiliser to replace for N losses occurring from barn, from storage and during spreading.

c) The choice of feed

- Regarding crops and feed ingredients, there are considerable differences in terms of their environmental effect.

- The results from the pig growth study showed that by choosing feedstuffs with a low environmental impact during production, some of the environmental burdens could be avoided. Feed produced on-farm in combination with synthetic amino acids was environmentally favourable for pig production.

- For feeds for milk production, there was no clear-cut difference between the feeds as regards impact, since they had such different effects on the production level.

d) Energy requirement

- Significant primary energy uses in crop production include mineral fertiliser production, fuel use for machinery operations and drying for the dairy and pig system, electricity use for operating the buildings and for the milking equipment, long distance ship transport for soybean meal, production of plastic cover for silage and diesel fuel for feeding in the suckling system.

References

Andersson, K. & Olsson, T. 1999. Life Cycle Assessment of bread produced on different scales. *Int J LCA* 4, 25-40.

Arnäs, P-O., Blinge, M., Bäckström, S., Furnander, Å. & Hovelius, K. 1997. *Livscykelanalys av drivmedel - En studie med utgångspunkt från svenska förhållanden och bästa tillgängliga teknik* (Life Cycle Assessment of Motor Fuels - A Study Based on Swedish Conditions and on Best Available Technology). Meddelande nr. 95, Dept of Transportation and Logistics, Chalmers Univ Technol, Göteborg, Sweden

Aronsson, H. & Torstensson, G. 2004. *Beräkning av olika odlingsåtgärders inverkan på kväveutlakningen - Beskrivning av ett pedagogiskt verktyg för beräkning av kväveutlakning från enskilda fält och gårdar* (Description of an Empirical Model for Estimation of Nitrogen Leaching from Fields and Farms). Uppsala: Technical Report 78, Division of Water Quality Management, SLU.

Audsley, E., Alber, S., Clift, R., Cowell, S., Crettaz, P., Gaillard, G., Hausheer, J., Jolliet, O., Kleijn, R., Mortensen, B., Pearce, D., Roger, E., Teulon, H., Weidema, B. & van Zeijts, H. 1997. *Harmonisation of Environmental Life Cycle Assessment for Agriculture.* Final Report Concerted Action AIR3-CT94-2028. European Commission DG VI Agriculture.

Baumann, H. & Tillman, A-M. 2004. *The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application.* Studentlitteratur, Lund.

Bernesson, S. 2004. *Farm-scale Production of RME and Ethanol for Heavy Diesel Engines-with Emphasis on Environmental Assessment.* PhD thesis. Swedish University of Agricultural Sciences, AGRARIA 497. Uppsala.

Bergström, L. & Brink, N. 1986. Effects of differentiated applications of fertiliser N on leaching losses and distribution of inorganic N in the soil. *Plant and Soil* 93, 333-45.

Bertilsson, J. 2002. *Bra foderstater på närproducerat foder.* (Locally produced feed with high quality). Djurhälso- och utfodringkonferens Karlstad 20-22 August 2002, Svensk Mjölk.

Björklund, A. 2000. *Environmental Systems Analysis of Waste Management.* PhD thesis, Division of Industrial Ecology, Royal Institute of Technology, Stockholm.

Brentrup, F. 2003. *Life Cycle Assessment to Evaluate the Environmental Impact of Arable Crop Production.* PhD thesis. Hannover: University of Hannover, Cuvillier verlag, Göttingen.

Brännström-Norberg, BM., Dethlefsen, U., Johansson, R., Setterwall, C. & Tunbrant, S. 1996. *El & Miljö - Livscykelanalys för vattenfalls elproduktion.* (Electricity and the Environment - LCA of Vattenfalls Electricity Production). Report, Vattenfall AB. Stockholm, Sweden

Boer, I. 2003. Environmental impact assessment of conventional and organic milk production. *Livestock Production Science* 80, 69-77.

Boustead, I. 2003. *ECO Profiles of the European Plastics Industry POLYOLEFINS.* Report APME, Bryssel. www.apme.org/lca

Canh, TT., Aarnink, AJA., Schutte, JB., Sutton, A., Langhout, DJ. & Verstegen, MWA. 1998. Dietary protein affects nitrogen excretion and ammonia emission from manure of growing-finishing pigs. *Livestock Production Science* 56 (3), 181-191.

Carlsson, C., Kyllmar, K., Ulén, B. & Johnsson, H. 2000. *Typområden på jordbruksmark – Avrinning och växtnäringsförluster för det agrohydrologiska året 1998/1999* (Nutrient Losses From Arable Land in 1998/1999, Results from the Water Quality Monitoring Programme 'Typområden på jordbruksmark'). Ekohydrologi, Report no 55, Swedish Univ AgricSci (SLU) Uppsala

Carlsson-Kanyama, A. 1999. *Consumption Patterns and Climate Change: Consequences of Eating and Travelling in Sweden.* PhD thesis, Dept of Systems Ecology, Stockholm University, Sweden.

Cederberg, C. 1998. *Life Cycle Assessment of Milk Production – A Comparison of Conventional and Organic Farming*. Göteborg: Swedish Inst Food Biotechnol SIK report No 643.

Cederberg, C. 2002. *Life Cycle Assessment (LCA) of Animal Production.* Doctoral Thesis. Department of Applied Environmental Science, Göteborg Unversity.

Cederberg, C. & Mattsson, B. 2000. Life cycle assessment of milk production – a comparison of conventional and organic farming. *Journal of Cleaner Production* 8, 49-60.

Cederberg, C. & Stadig, M. 2003. System expansion and allocation in life cycle assessment of milk and beef production. *International Journal of LCA* 8(6), 350-356.

Cederberg, C. & Flysjö, A. 2004. *Life Cycle Inventory of 23 Dairy Farms in South-Western Sweden.* The Swedish Institute of Food and Biotechnology, SIK report No 728.

Cowell, S. 1998. An LCA study of breadmaking wheat production. In: *Environmental Life Cycle Assessment of Agricultural Systems: Integration Into Decision-Making*. PhD thesis. Guildford: Centre for Environmental Strategy, University of Surrey.

Davis, J. & Haglund, C. 1999. *Life Cycle Inventory (LCI) of Fertiliser Production. Fertiliser Products Used in Sweden and Western Europe.* Göteborg: Swedish Inst Food Biotechnol, SIK Report No. 654,

de Toro A. 2004. *Assessment of Field Machinery Performance in Variable Weather Conditions Using Discrete Event Simulation.* PhD Thesis. AGRARIA No 462. Swedish University of Agricultural Sciences, Uppsala.

Dustan, A. 2002. *Review of Methane and Nitrous Oxide Emission Factors for Manure Management in Cold Climates.* JTI Report 299. Swedish Inst Agric Environmental Engineering, Uppsala.

Elmquist, H., Lindgren, U. & Mäkilä, K. 2004. *Decision-Making and Environmental Impacts – A dynamic simulation model of a farm business.* Dept. of Biometry and Engineering, SLU, Report - Environment, Technology and Agriculture 2004:02, SLU, Uppsala.

Eriksson, O., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J-O., Granath, J., Carlsson, M., Baky, A., Thyselius, L. 2002. ORWARE – a simulation tool for waste management. *Resources, Conservation and Recycling* 36, 387-307.

Finnveden, G., Andersson-Sköld, Y., Samuelsson, M-O., Zetterberg, L. & Lindfors, L-G. 1992. Classification (impact analysis) in connection with Life Cycle Assessments - A preliminary study. In '*Product Life Cycle Assessment*', 172-231.

Frö- och Oljeväxtodlarna. Försöksverksamhet Oljeväxtodling 83-94. 1983-1994 (Oilseed Crop Cultivation 84-94. Results of Trials). Malmö: Frö- och oljeväxtodlarnas Service AB, Sweden.

Grennfelt, P., Hov, O. & Derwent, R.G. 1994. Second generation abatement strategies for Nox, NH3, SO2 and VOC. *Ambio* 23**,** 425-433.

Guinée, J., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H., de Bruijn, H., van Duin, R. & Huijbregts, M. 2001. *Life Cycle Assessment – An Operational Guide to the ISO Standards*. Ministry of Housing, Spatial Planning and the Environment (VROM), and Centre of Environmental Science, Leiden University (CML).

Hansson, PA. & Mattson, B. 1999. Influence of derived operation-specific tractor emission data on results from an LCI on wheat production. *Int J LCA* 4, 202-6.

Hessel Tjell, K., Aronsson, H., Torstensson, G., Gustafson, A., Lindén, B., Stenberg, M. & Rydberg, T. 1999. *Mineralkvävedynamik och växtnäringsutlakning i handels-stallgödslade odlingssystem med och utan fånggröda.* (The mineral dynamic flows and leaching of nutrients from artificial and manure fertilised crop systems with and without catch crops). Division of Water Quality Management, Report 50, SLU, Uppsala.

Hoffman, M., Aronsson, H., Aronsson, P., Nilsson, H. & Albertsson, B. 1999. *Gårdsmodellen – en empirisk modell för kväveutlakning,* (Farm-model – An Empirical model for Estimation of Nitrogen Leaching). Technical report 48, Division of Water Quality Management, SLU, Uppsala.

Holtan-Harwig, L. & Bøckman, O. 1994. Ammonia exchange between crops and air. *Norwegian J Agric Sci Supplement* no 14.

Huijbregts, MAJ., Schöpp, W., Verkuijlen. E., Heijungs, R. & Reijnders, L. 2000. Spatially explicit characterisation of acidifying and eutrophying air pollution in life-cycle assessment. *J. Indus. Ecol.* 4 (3), 125-142.

Huijbregts, M.A.J. 2001. *Uncertainty and Variability in Environmental Life-Cycle Assessment.* PhD thesis, University of Amsterdam, The Netherlands.

ISO. 1997. Environmental management - Life cycle assessment - Principles and framework. *ISO* 14040:1997, *European Committee for Standardization*, Brussels, Belgium.

ISO. 1998. Environmental management - Life cycle assessment - Goal and scope definition and inventory analysis. *ISO* 14041:1998(E), *International Organization for Standardization*, Geneva, Switzerland.

ISO. 2000a. Environmental management - Life cycle assessment - Life cycle impact assessment. *ISO* 14042: 2000(E), *International Organization for Standardization*, Geneva, Switzerland.

ISO. 2000b. Environmental management - Life cycle assessment - Life cycle interpretation. *ISO* 14043: 2000(E), *International Organization for Standardization*, Geneva, Switzerland.

IPCC. 1996. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Reference Manual, Chapter 4- Agriculture.* Houghton J T, Meira Filho L G, Lim B, Treanton K, Mamaty I, Bonduki Y, Griggs D J, Callender B A (Eds). IPCC, UK Meteorological Office, Bracknell.

IPCC. 2001a. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* Chapter 4 - Agriculture, (Internet address: www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm).

IPCC. 2001b. *Climate Change 2001: The Scientific Basis.* Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, UK and New York, USA, 2001. (Internet address: www.grida.no/climate/ipcc_tar/wg1/index.htm)

Joint EMEP/CORINAIR *Atmospheric Emission Inventory Guidebook, Third Edition.* 2001. Copenhagen: European Environment Agency, (Internet address: http://reports.eea.eu.int/EMEPCORINAIR3/en)

Joelsson, A., Kyllmar, K., Lindstrom, S. & Wijkmark, L. 1999. *Utveckling av jordbruket mot miljömålen. (The Agricultural Sector's Development To Achieve The Environmental Goals.)* Länsstyrelsen Halland, Report 23, Halmstad.

Johnson, H. & Hoffman, M. 1997. Kväveläckage från svensk åkermark - Beräkningar av normalutlakning för 1995 och 1999. *(Nitrogen Losses from Swedish Arable Land, Calculations of Normal Leaching in 1995 and 1999).* Swedish Environmental Protection Agency, Report No 5248.

Jordbruksverket. 1995. *Gödselproduktion, lagringsbehov och djurtäthet vid nötkreaturshållning.* (Manure Production, Storage Requirements and Animal Density in Cattle Production). Jordbruksverket, Report 1995:10, Jönköping, Sweden.

Jordbruksverket. 2002. *Förslag till handlingsprogram för användningen av bekämpningsmedel i jordbruket och trädgårdsnäringen till år 2006.* Report 2002:7, SJV, Jönköping, Sweden.

JTI. 2001. Element Balances as a Sustainability Tool. JTI rapport Lantbruk & Industri 281. Workshop in Uppsala March 16-17, 2001. Swedish Institute of Agricultural and Environmental Engineering (JTI), Uppsala.

Karlsson, S. & Rodhe, L. 2002. *Översyn av Statistiska Centralbyråns beräkning av ammoniakavgången i jordbruket - emissionsfaktorer för ammoniak vid lagring och spridning av stallgödsel.* (A Review of the Agricultural Emissions of Ammonia as Calculated by Statistics Sweden – Emission Factors for Ammonia at Storage and Application of Animal manure). Swedish Inst Agric Environ Eng (JTI), Uppsala

Kärrman, E. & Jönsson, H. 2001. Including oxidization of ammonia in the eutrophication impact category. *Int J LCA* 6, 29-33.

Kasimir-Klemedtsson, Å. 2001. *Metodik för skattning av jordbrukets emissioner av lustgas.* (Methods to estimate emissions of nitrous oxide from the agriculture sector). Underlag för Sveriges nationalrapport till Klimatkonventionen, Swedish Environmental Protection Agency, Report No 5170, Stockholm.

Katajajuuri, J.M. & Loikkanen, T. 2001. Enhancing competitiveness through green innovation. Finnish food industry committed to environmental data production - LCA pilot case for barley. In: *Proceedings of 9th International Conference of the Greening of Industry Network, Sustainability at the Millennium: Globalisation, Competitiveness, and the Public Trust,* Bangkok (Thailand).

Kihlberg, J. 2002. *Avvikelse från kväveoptimum hos lantbrukare i Skåne - en enkätundersökning. (Deviation from Nitrogen Optimum for South Swedish Farms - A Questionnaire).* Uppsala: Seminarier och examensarbeten No 43. Dept. Of Water Quality Management, Swedish University of Agriculture Sciences.

Kumm, K.I. 2003. Ways to reduce nitrogen pollution from Swedish pork production. *Nutr Cycl Agroecosys* 66 (3), 285-293.

Lantbruksstyrelsen. 1990. *Kvävegödsling. Hur påverkas gödslingsbehovet av ny livsmedelspolitik?* (Nitrogen Fertilisation. How are Fertiliser Requirements Affected by New Food Policies?). Lantbruksstyrelsen Report 1990:12.

Larsson M.H., & Johnsson, H. 2003. Simulation of nitrate leaching using a modeling system with automatic parameterisation routines. *Soil Use and Management* 19, 172-81.

Laegreid, M., Bockman, O.C. & Kaarstad, O. 1999. *Agriculture, Fertilisers and the Environment. Wallingford*, UK: CABI Publishing. 234 pp.

Ledgard, S.F., Finlayson, J.D., Patterson, M.G., Carran, R.A. & Sedderburn, M.E. 2003. Effects of intensification of dairy farming in New Zealand on whole-system resource use efficiency and environmental emissions. *Proceedings from the 4th International Conference,* October 6-8, 2003, Bygholm, Denmark. Halberg (ed.) 226-229.

Lindfors, L-G., Christiansen, K., Hoffman, L., Virtanen, Y., Juntilla, V., Hanssen, O-J., Rønning, A., Ekvall, T. & Finnveden, G. 1995. *Nordic Guidelines on Life-cycle Assessment*. Nord 1995:20. Nordic Council of Ministers, Copenhagen, Denmark.

Lindgren, M., Pettersson, O., Norén, O. & Hansson, P-A. 2003. Operation specific engine load pattern and exhaust gas emission data from vehicles used in typical agricultural operations. Proc 4th Int Conf Life Cycle Assessment in the Agri-food sector - Linking Environmentally Friendly Production and Sustainable Consumption. Danish Inst Agric Sci, Bygholm Park Hotel, Denmark Oct 6-8, 2003

Lindgren, M., Pettersson, O., Norén, O. & Hansson, P-A. 2002. *Engine Load Pattern and Engine Exhaust Gas Emissions from Off-Road Vehicles and Methods to Reduce Fuel-Consumption and Engine Exhaust Gas Emissions.* Swedish Inst Agric Environ Eng JTI report 308. Uppsala

MathWorks. 2000. *SIMULINK Dynamic System Simulation for MATLAB Version 4.* The MathWorks Inc. Natick, Massachusetts, U.S, November 2000.

Mattsson, B. & Stadig, M. 1999. Screening life cycle assessment of organic and conventional production of cereal-based baby food product. In: *Environmental Life Cycle Assessment (LCA) of Agricultural Food Production*. PhD thesis. Alnarp: Swedish University of Agricultural Sciences, AGRARIA 187.

Mattsson, B., Cederberg, C. & Blix, L. 2000. Agricultural land use in life cycle assessment (LCA): Case studies of three vegetable oil crops. *J Cleaner Prod* 8, 283-92.

Mattson, L. & Kjellquist, T. 1992. *Kvävegödsling till höstvete på gårdar med och utan djurhållning.* (Nitrogen Fertilisation of Winter Wheat on Farms With and Without Animals). Uppsala: Report 189. Div. of Soil Fertility and plant Nutrition, SLU.

Naturvårdsverket. 1991. *The Greenhouse Gases: Emissions and Countermeasures in an international perspective.* Swedish Environmental Protection Agency, Report No 4045. Solna. Sweden.

Naturvårdsverket. 1997a. *Kväve från land till hav.* Report No 4735, (Nitrogen from Land to Sea). Swedish Environmental Protection Agency, Stockholm.

Naturvårdsverket. 1997b. *Förluster av fosfor från jordbruksmark.* Report 4731. (Losses of Phosphorous from Agricultural Land). Swedish Environmental Protection Agency, Stockholm.

Naturvårdsverket. 1997c. *Kväveläckage från svensk åkermark.* (Nitrogen Leaching from Swedish Arable land). Swedish Environmental Protection Agency, Report 4741, Stockholm.

Öborn, I., Sonesson, U., Stern, S., Berg, C., Gunnarsson, S. & Lagerkvist, C-J. 2002 *Uthållighetsbrister I livsmedelskedjan - en intervjuundersökning*. (Identifying weak links in the sustainable food chain - an interview survey). Report MAT 21 No 6. Uppsala.

Oenema, O., Kros, H. & de Vries, W. 2003. Approaches and uncertainties in nutrient budgets: Implications for nutrient management and environmental policies. *European Journal of Agronomy* 20, 3-16.

Oil World Monthly. 2003. Lowest asking prices for the nearest forward shipment. *Oil Worlds Monthly*, 48 (46).

Reinhardt, G. & Gärtner, S. 2002. Biodiesel or pure rapeseed oil for transportation: Which one is best for the environment? In: *Proceedings of 12th European Conference on Biomass for Energy, Industry and Climate Protection*, 17-21 June 2002, Amsterdam (The Netherlands)

Ringström, E. Fröling, M. & Hallberg, L. 2003. *Samhällsekonomisk analys av hantering av lantbrukets ensilageplast*. (A Societal Economical analysis of the management of plastic silage covering used in agriculture). Rapport från CIT Ekologik AB Chalmers Industriteknik.

Rosswall, T., Andrén, O., Lindberg, T. & Paustian, K. 1990. *Ecology of Arable Land - Organisms, Carbon and Nitrogen Cycling*. Ecol Bull 40. Munksgaard Int Booksellers, Copenhagen

Samuelsson, J. 2003. *Samverkan mellan mjölk- och spannmålsproducenter – vilka ekonomiska incitament föreligger? Economic benefits of partnership arrangements between dairy and crop farms – what is the role of incentives?* Department of Economics, Examensarbete 323, SLU.

Sattari, J. 2002. Forschungsprojekt Energiepolitik. Atomenergie in Brasilien Übersicht, (Internet adress: www.anti-atom.de/akwbras.htm) 9th December 2002.

SBA. 2001. *Market overview – Animal products*, Report 2001:21. Swedish Board of Agriculture, Jönköping.

SBA. 2002. *Animal production, monthly statistics – 2002:5*. Swedish Board of Agriculture, Jönköping.

SCB. 2000a. *Utsläpp till luft av ammoniak i Sverige 1999*. (Emission to Air of Ammonia in Sweden from Agriculture and other Anthropogenic Sources in 1999). Report MI 37 SM 0001, Statistics Sweden, Örebro

SCB. 2000b. *Utsläpp till luft i Sverige - Svaveldioxid, käveoxider, koldioxid, metan, dikväveoxid, kolmonoxid och flyktiga organiska ämnen 1999*. (Emissions to air in Sweden: Sulphur dioxide, Nitrogen oxides, Carbon dioxide, Methane, Nitrous oxide, Carbon monoxide and Volatile Organic Compounds, 1999). Statistics Sweden, Report MI 18 SM 0001, Örebro

SCB. 2001. *Miljöräkenskaper 1993-1998*. (Environmental Accounting 1993-1998). Statistics Sweden, Report MI 53 SM 0101

SCB. 2003. *Jordbruksstatistisk årsbok 2003*. Statistics Sweden, Örebro.

SCB. 2004. *Animalieproduktion Års- och månadsstatistik – 2004:5 (Animal products – Annual and Monthly Statistics –2004:5)* Statistics Sweden, Report JO 48 SM 0407, Örebro.

Simmelsgaard, S.E. & Djurhuus, J. 1998. An empirical model for estimating nitrate leaching as affected by crop type and the long-term N fertiliser rate. *Soil Use and Management* 14, 37-43.

Smith, K.A. & Frost, J.P. 2000. Nitrogen excretion by farm livestock with respect to land spreading requirements and controlling nitrogen losses to ground and surface waters. Part 1: Cattle and sheep. *Bioresource Technology* 71, (2), 173-181.

Sonesson, U., Mattsson, B., Nybrant, T. and Olsson, T. 2005. Industrial processing versus home cooking – An environmental comparison between three ways to prepare a meal. *Accepted for publication in AMBIO*, vol 34, no 4-5.

Steineck, S., Gustafsson, A., Richert Stintzing, A., Salomon, E., Myrbeck, Å., Albihn, A. & Sundberg, M. 2000. *Växtnäring i kretslopp*. (Crop Nutrient Recycling). Report SLU Kontakt nr 11, Uppsala

Strandberg, E. 1993. Livstidsproduktion som avelsmål för mjölkkor. (Lifetime production as breeding goals for dairy cows). Husdjurskonferensen, 27-28 januari. *SLU-Info Rapporter, Allmänt* 181, 197-202. SLU, Uppsala.

Strid Eriksson, I., Elmquist, H., Stern, S. & Nybrant, T. 2005. Environmental Systems Analysis of pig production: the impact of feed choice. *International Journal of Life Cycle Assessment*, vol 10 no 2, 143-154.

Strid Eriksson I. 2004. *Environmental Systems Analysis of Pig Production. Development and application of tools for evaluation of the environmental impact of feed choice.* PhD Thesis. AGRARIA 491, Swedish Univ Agric Sci (SLU) Uppsala.

Svensk Mjölk. 2004. *Anslutning och medelavkastnings officiell kokontroll.* (Statistics of farmers associated to the official cow control programme and the average milk production) http://www.statistik.svenskmjolk.se/search.asp, 19th August 2004.

Swedish Government. 1997. *Svenska miljömål. Miljöpolitik för ett hållbart Sverige.* (Swedish Environmental Quality Objectives - An Environmental Policy for a Sustainable Sweden). Swedish Government Bill, 1997/98:145.

Udo de Haes, H., Finnveden, G., Goedkoop, M., Hauschild, M., Hertwich, E., Hofstetter, P., Jolliet, O., Klöpffer, W., Krewitt, W., Lindeijer, E., Müller-Wenk, R., Olsen, S., Pennington, D., Potting, J. & Steen, B. 2002. *Life-cycle Impact Assessment: Striving Towards Best Practice*. SETAC press, (Internet address: www.setac.org.)

Uppenberg, S., Almemark, M., Brandel, M., Lindfors, LG, Marcus, HO., Stripple, H., Wachtmeister, A. & Zetterberg, L. 2001a. *Miljöfaktabok för bränslen. Del 1. Huvudrapport. (Environmental Data on Fuels. Main Report).* IVL Report B1334-2B, Swedish Environmental Research Institute Ltd. Stockholm.

Uppenberg, S., Almemark, M., Brandel M., Lindfors, L-G., Marcus, H-O., Stripple, H., Wachtmeister, A. & Zetterberg, L. 2001b. *Miljöfaktabok för bränslen. 2001. Del 2. Teknisk bilaga. (Environmental Data on Fuels. Background Data and Technical Appendices)*. IVL Report B1334-2A, Swedish Environmental Research Institute Ltd. Stockholm.

Vattenfall, 2001. *Livscykelanalys av vattenfalls el.* (Life Cycle Analysis of the Electricity supplied by Vattenfall). Vattenfall AB andExplicare AB, www.vattenfall.com

von Malmborg, F. 2003. Back to basics with environmental systems analysis: Lessons from systems theory and decision-making theory. Manuscript presented at the 2nd *Conference of the International Society for Industrial Ecology*, 29 June – 2 July 2003. University of Michigan, Ann Arbor, MI.

Weidema, B., Pedersen, R. & Drivsholm, T. 1995. *Life Cycle Screening of Food Products - Two Examples and Some Methodological Proposals*. Report from the ATV project: Life Cycle Assessment on Food - Development of a Method to Apply the Life Cycle Concept on Products within the Food Sector. Lyngby: Danish Academy of Technical Sciences.

Wrisberg, N. & Udo de Haes, H. 2002. *Analytical Tools for Environmental Design and Management in a Systems Perspective.* Kluwer Academic Publishers, Dordrecht.

Zeijt, H., Leneman, H. & Wegener Sleeswijk, A. 1999. Fitting fertilization in LCA: allocation to crops in a cropping plan. *Journal of Cleaner Production* 7, 69-74.

Interviews and other sources:

EUROPA - Activities of the European Union – Agriculture (europa.eu.int/pol/agr/index_en.htm) 2004-05-14

FOOD21, (Internet address: www-mat21.slu.se) 2005-05-01

Johansson Birgitta, Department of Animal Environment and Health, SLU, Skara. 2004-12-03

Linder Janne, Swedish Board of Agriculture. 2003-01-17

Ministeriet for Fødevarer, Lantbrug och Fiskeri, (Internet address: www.dffe.dk/Default.asp?ID=10887) 2004-03-09

Swedish Board of Agriculture, (Internet address: www.jordbruksverket.se/startsida/forfattningar.4.7502f61001ea08a0c7fff120602.html,) 2005-01-03.

Waern Peder, Extension officer, Swedish Board of Agriculture, SJV, Växtskyddscentralen, Uppsala SLU, 2004-10-18.
Wivstad Maria, research assistant, Department of Ecology and Crop Production Science, SLU, 2003-06-05.

Abbreviations used:

CO_2 – carbon dioxide
CH_4 – methane
ECM - energy corrected milk
f.u. - functional unit
GWP - Global warming potential
LCA – Life Cycle Assessment
N_2O - nitrous oxide
NO_3 – nitrate
NO_x – nitrogen oxides
RME - rapeseed methyl ester
SALSA - *S*ystems *A*na*l*ysis for *S*ustainable *A*gricultural Production
SO_2 – sulphur dioxide