Environmental Systems Analysis of Pig Production

Development and application of tools for evaluation of the environmental impact of feed choice

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Abstract

Strid Eriksson, I. 2004. *Environmental systems analysis of pig production - development and application of tools for evaluation of the environmental impact of feed choice.*
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The aim of this thesis was to develop the SALSA models (Systems AnaLysis for Sustainable Agriculture), and to apply them to studies for the benefit of more sustainable pig production.

Within the framework of environmental systems analysis, the SALSA models were constructed as substance and energy flow models using life cycle assessment methodology for impact assessment and scope definition. The pig production system studied included rearing of growing-finishing pigs (SALSA-pig model) and production of feed (SALSA-arable and SALSA-soybean models).

For energy use, global warming potential and eutrophication, the feed production sub-system had the largest environmental impact, whereas for acidification the pig sub-system was the dominant source.

Results from simulations using the SALSA-arable model showed that energy use, global warming potential and acidification increased with increasing nitrogen fertiliser rate, whereas eutrophication had a minimum around the current recommended rate.

When the pig production system was optimised regarding diet composition for different environmental targets, different diets were obtained. For acidification and eutrophication, a low protein diet was prioritised, which was achieved by high inclusion of synthetic amino acids. For energy use and global warming potential high levels of peas and rapeseed cake (a by-product from rapeseed oil production) were prioritised. The environmental optimiser almost entirely avoided soybean meal, due to its poor environmental record.

A main conclusion of the work was that feed choice had an impact on the environmental performance of pig meat production, not only via the features of the feed as fed to the pigs, such as the crude protein content, but also via the raw materials used, since the environmental impact from the production of these differed and since feed production generally had a large impact on the system as a whole.

Keywords: feed production, growing-finishing pigs, life cycle assessment (LCA), optimisation model, SALSA models, soybean meal

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To Emma, my sunshine

Time flies, make a statement, take a stand

(Titiyo, 2002)

Contents

List of Papers

This thesis is based on the following papers, appended and referred to in the text by their Roman numerals. Paper III is reproduced with kind permission of the publisher.

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. Strid Eriksson, I. & Nybrant, T. 2004. SALSA-pig – a simulation tool for environmental systems analysis of pig rearing. (Manuscript)

III. Strid Eriksson, I., Elmquist, H., Stern, S. & Nybrant, T. 2004. Environmental Systems Analysis of pig production: the impact of feed choice. (International Journal of Life Cycle Assessment, OnlineFirst, <DOI: http://dx.doi.org/10.1065/lca2004.06.160>)

IV. Strid Eriksson, I., Stern, S. & Nybrant, T. 2004. Optimisation of pig diets with respect to energy use, global warming, acidification and eutrophication. (Submitted to Agricultural Systems)

Notes on the authorship of the included papers:

In Paper I, the respondent developed parts of the SALSA-arable model (field operations, grain drying, nitrous oxide emissions and the impact assessment) and wrote parts of the text.

In Papers II-IV, the studies were to a very large extent planned, carried out and described by the respondent. The results were based on three models, of which the respondent developed the SALSA-pig and SALSA-soybean models and parts of the SALSA-arable model.

1. Introduction

1.1. Background

Agriculture and the environment

Meat and milk consumption is increasing in the world, leading to increased production of livestock. This livestock revolution is primarily driven by demand, caused by global population growth, urbanisation and income growth, and is projected to continue well into the new millennium (Delgado, 2003). World meat production has increased by 30% in the past decade, with the largest increase being recorded in the developing world (Table 1). Of the global production of cereals, oilseeds and tubers in 1990-1992, 40% was consumed as animal feed (de Haan, *et al.*, 1997).

Table 1. *Meat, total production of livestock (million tonnes)*[a]

Year	1993	1998	2003
World	194	224	254
Developed Countries	101	104	108
-Europe	55	53	53
-USA	31	36	39
Developing Countries	93	120	145
-Africa	9	10	12
-China	41	59	71
-India	4	5	6

[a] FAOSTAT, 2004

New incentives and policies for ensuring the sustainability of agriculture and ecosystem services will be crucial if we are to meet the growing global food demands without compromising environmental integrity or public health (Tilman *et al.*, 2002).

The agricultural sector plays an important role for some of the environmental problems in Sweden. Of total ammonia emissions, 84% is released from agricultural activities, mainly from animal housing and manure management (Statistics Sweden, 2003). Of the pollution load of nitrogen to coastal waters, 49% is attributed to agricultural activities, while 14% of greenhouse gas emissions, counted as carbon dioxide equivalents, are attributed to agricultural production, excluding emissions from manufacturing of synthetic fertilisers (Statistics Sweden, 2004). Direct energy use at farms is comparatively small, accounting for 2% of fuel and 1% of electricity of the total Swedish energy use (Statistics Sweden, 2002). However, energy required for the production of synthetic fertilisers and imported animal feeds used by the agricultural sector is not included in this figure.

The Swedish parliament has adopted 15 environmental targets with the common, overall objective: ‘to hand over to the next generation, a society in which all major environmental problems are solved’ (Ministry of the Environment, 1998). Some of these are strongly related to agricultural production: ‘A varied agricultural landscape’, ‘Zero eutrophication’, ‘Reduced climate impact’ and ‘Good-quality groundwater'. Further action is needed to achieve the goals for all of these targets (Environmental Objectives Council, 2004).

Within the Swedish agri-food production chain of milk and meat, primary agricultural production is responsible for the majority of the environmental impact, compared to transport, slaughter, packaging, retail and home cooking (Cederberg, 2003).

Pig feed and pig production

Pig meat is the most common type of meat consumed in Sweden, amounting to 35 kg pig meat of 80 kg total meat per person and year (SBA, 2004a). Most pig meat consumed in Sweden is produced within the country; the production corresponds to 3.3 million pigs per year (SBA, 2004b). However, there is a trend towards more imported pig meat in Sweden. In 1999, Swedish production was 325,000 tonnes and imports were 45,000 tonnes, whereas in 2003 domestic production had declined to 287,000 tonnes and imports had increased to 67,000 tonnes (SBA, 2004c).

Swedish pig production can briefly be described as consisting of two consecutive phases: 1) rearing of sows that produce piglets and 2) growing of piglets to produce slaughter pigs for the meat industry. This thesis is concerned with the production of slaughter pigs, also referred to as growing-finishing pigs.

Swedish pig feeds are usually based on cereals produced in Sweden. The supplementary protein feeds are either domestic (peas, rapeseed, by-products from the food industry, etc) or imported (mainly soybeans, but also rapeseed), Table 2.

Table 2. *Feed materials in compound feeds for pigs (tonnes/year)*[a]

Feed materials	Swedish	Imported	% of total
Cereals			
- Wheat	132700	8900	29
- Barley	85500	1400	18
- Oats	23600	400	5
- Wheat middlings	19500		4
- Wheat bran	18400		4
- Triticale	11700	500	2
Protein feeds			
- Soymeal		59600	12
- Rapeseed meal[b]		35700	7
- Peas, horse bean & lupins	17300	200	4
Other feed ingredients			15

[a] SBA, 2004d
[b] The current Swedish production of rapeseed is only enough for the production of heat treated (expro) rapeseed meal, which is fed to cattle (P. J. Herland, pers. comm.)

The SALSA research project

This thesis forms part of the SALSA (Systems AnaLysis for Sustainable Agriculture) research project, which is included in the systems analysis sub-programme of the FOOD 21 research programme (see http://www-mat21.slu.se).

FOOD 21 has been funded by The Foundation for Strategic Environmental Research (MISTRA) during 1997-2004. The overall goal for FOOD 21 is to find ways to an ecologically and economically sustainable Swedish food production. The program is multi-disciplinary and covers research on a number of different aspects of sustainable food production including production systems, product quality, and farmer and consumer aspects.

Other studies

The environmental impact of pig production in a life cycle perspective has previously been described by other authors. Among the Swedish contributions, two doctoral theses are found: Carlsson-Kanyama (1999) and Cederberg (2002). One of the main conclusions of Cederberg (2002) is that animals and crops need to be reintegrated to reduce the environmental burden of livestock production. Carlsson-Kanyama (1999) found that the human diet has a considerable impact on resource use and pollution levels, and that a sustainable diet is composed of non-exotic vegetable foods and only small amounts of meat. Cederberg & Darelius (2001) provide a comprehensive description of a life cycle assessment of Swedish pig meat production, in which it is stated that the most important measure for improved environmental performance of pig production systems is to have high nitrogen utilisation throughout the system.

Within the same research programme as the present thesis (FOOD 21), some other types of Swedish pig production systems have been studied. Organic pig production is described in Cederberg & Nilsson (2004). The authors conclude that an improved nitrogen utilisation in feeding and feed production would improve the organic pig production system from an environmental point of view, and that reduced feed consumption and lower inclusion of protein feeds would reduce land use and thereby nitrogen emissions. In Stern et al. (2004), a comparison of three future pig production scenarios is described. The study identified conflicting sustainability goals related to three scenarios studied: ‘Animal welfare’, ‘Environment efficiency’ and ‘High product quality’. A detailed report describing this study has also been published by Cederberg & Flysjö (2004).

Kumm (2003) describes different ways to reduce nitrogen pollution from Swedish pork production. On a hectare basis, the author found that catch crops and reduced mineral fertiliser rates to crops were efficient measures to reduce nitrogen leaching, whereas related to produced pig growth, reduced protein level in feed and healthy pigs (so called ‘Specific Pathogen Free’ pig production) had more important effects on reducing nitrogen emissions. The author further concludes that spatial allocation (within Sweden) of pig production can have a significant effect on the emission levels and the environmental damage caused by the released emissions.

A French study has used life cycle assessment (LCA) methodology to assess major environmental impacts associated with production and delivery of concentrated feed for pigs (van der Werf *et al*., 2004). In conclusion, the authors state that the environmental burdens associated with the production and delivery of pig feed can be decreased by: 1) optimising the fertilisation of its crop-based ingredients, 2) using more locally produced feed ingredients, 3) reducing the feed's Cu and Zn contents and 4) using wheat-based rather than maize-based feeds. Dourmad *et al*. (2002) have developed a model for prediction of the volume and composition of the effluents produced by pig farms. The model was used to analyse the influence of feeding strategies and housing systems on emissions from, and fertiliser value of, pig manure, and was validated using 19 experimental studies. The validation showed that the model was precise and robust for the prediction of slurry volume and nitrogen, phosphorus and dry matter contents.

In Denmark, a data-base has been built up, in which life cycle assessments of pig production can be performed (Nielsen *et al*., 2003). An environmental assessment of pig meat production has been conducted as an example of application of the model (Skodborg Nielsen & Nielsen, 2003). The authors conclude that there is probably a significant environmental improvement potential for exchanging soybeans for alternative protein sources (*e.g.* fungi-produced protein) in pig feeding.

Sandars et al. (2003) studied the influence of pig manure management practices using LCA methodology. In conclusion, the authors state that slurry injection, band spreading technique, anaerobic digestion and high utilisation of the nitrogen the in the manure were the most beneficial measures to keep the environmental impact from pig manure management low.

1.2 Objectives of the thesis

The main objective was to develop methods and tools for environmental systems analysis of pig production. Another objective was to apply the methods and tools developed to quantify some of the environmental improvement potentials of Swedish pig production. The tools and their delivered results aim to contribute to a more comprehensive understanding of the pig production system, bring to light some of the important issues, and guide to better decisions when taking measures for a more sustainable pig production.

1.3 Structure of the work

The work behind the thesis consisted of constructing the SALSA models and of performing environmental systems analysis (ESA) studies using the models. The SALSA-pig model and results from the SALSA-arable and SALSA-soybean models have also been integrated into an optimisation tool for pig feed. The thesis is based on four papers, which are related to each other as described in Figure 1.

The studies included analyse different aspects of pig production, spanning from the influence of individual parameters (I-II), via the influence of sets of parameters (scenarios; III) up to whole system optimisations (IV). The main issue investigated in each paper is listed below:

I) Environmental assessment of nitrogen fertiliser rate in crop production.

- What is the quantitative effect on the environmental indicators studied of reducing or increasing the use of mineral fertilisers?

II) Environmental assessment of crude protein level in pig production.

- What is the quantitative effect on the environmental indicators studied of reducing or increasing the crude protein intake?

III) Environmental assessment of feeding strategies in pig production.

- What is the quantitative effect on the environmental indicators studied of choosing different feed ingredients in a pig diet, e.g. exchanging imported protein feeds with domestic protein feeds or exchanging natural protein for synthetic amino acids?

IV) Optimisation of feeding strategies in pig production.

- What is the optimal combination of feed ingredients in a pig diet, in order to minimise different environmental targets during production of pig meat?
- How large is the deviation between the optimised target and the other targets?

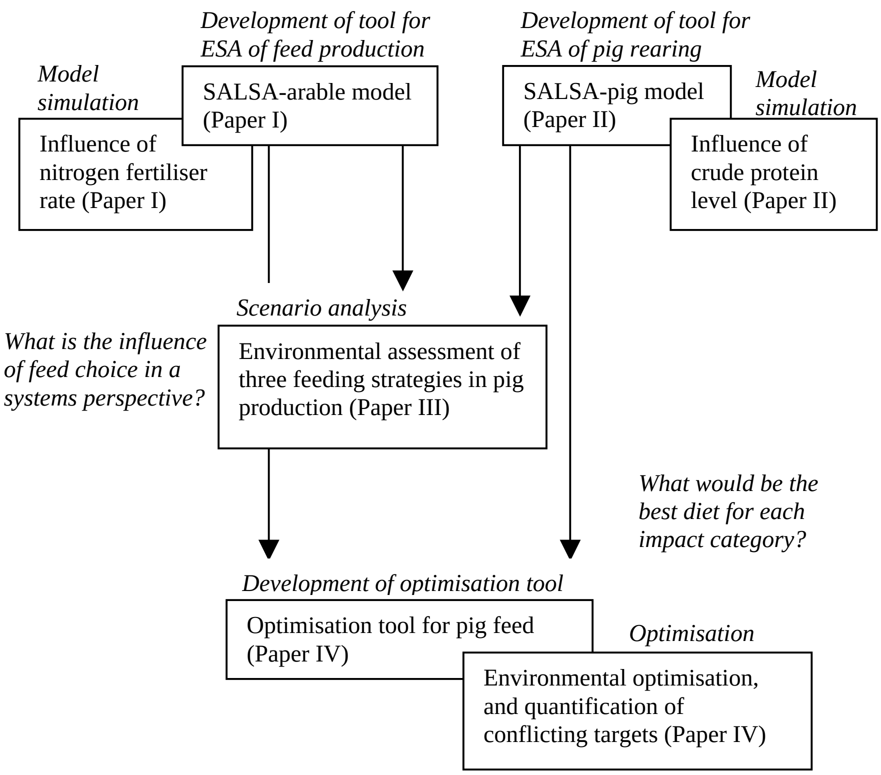

Fig 1. Structure of the work and relationships between the papers included in the thesis.

2. Methods

2.1 Environmental systems analysis

Environmental systems analysis (ESA) is a framework in which a number of methods are available. Some of the more common methods are described and compared in *e.g.* Wrisberg *et al*. (2002) and Moberg *et al.* (1999). The present thesis is based on the three distinguishable methods described below.

Substance flow modelling

In substance flow analysis (SFA), the flows of a selected number of substances are traced through a system. Most of the studies are performed to identify flows that are deemed most critical, either with respect to pollution control or to sustainable resource management (Wrisberg *et al*., 2002). A classical way to perform SFA is to analyse the inflows and outflows of a region, as was done in Stockholm during 1995, where flows of metals between the anthroposphere and the biosphere were analysed (Bergbäck *et al.*, 2001). In a thesis by Palm (2002), several examples of SFA applications are described. One example of an agricultural application of SFA is the field balance study of mineral nutrients and trace elements in dairy farming by Bengtsson, *et al.* (2003). Models for substance flow analysis have previously been developed, e.g. the ORWARE model, which was developed for environmental systems analysis of organic waste handling (Dalemo *et al*., 1997). The usefulness of this tool (e.g. Sonesson, *et al*. 1997, 2000; Jönsson, 2002) has demonstrated the advantage of combining the methods substance flow modelling and life cycle assessment.

Life cycle assessment methodology

Life cycle assessment (LCA) is a methodology developed for studies of environmental aspects and potential impacts of a product or service throughout its life, from raw material acquisition through production, use and disposal, *i.e.* from cradle-to-grave. The International Organisation of Standardisation has established a standardised framework for life cycle assessments (ISO, 1997).

LCA was first developed for industrial products, and aims to describe resource use, ecological considerations and impact on human health. The method is not new, but interest in it has increased dramatically since 1990 (Finnveden, 1998). A few years later the method was applied also on agricultural products. By 1997 the number of LCAs of agricultural products had increased, and the European Commission therefore arranged a Concerted Action for agricultural applications (Audsley *et al*., 1997).

In the LCA methodology, four mandatory phases can be identified: goal and scope definition, inventory analysis, environmental impact assessment and interpretation of results (Fig. 2.). A central concept within the LCA methodology is the use of a functional unit (*e.g.* per kg dried wheat), to which all results should be related. In this way, different systems can be compared as long as they produce the same function.

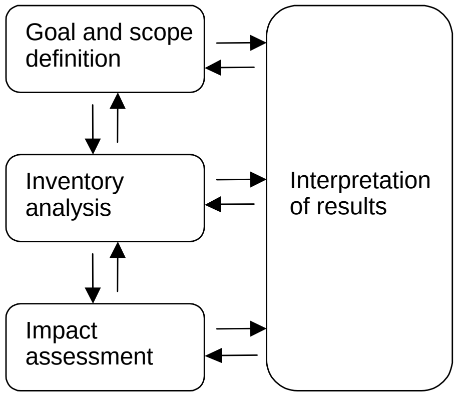

Fig 2. The phases of a life cycle assessment (ISO, 1997).

Optimisation with linear programming

The method of linear programming (LP) can be described as a mathematical way to calculate the amounts of a number of available resources that should be used in order to meet some defined requirements in the cheapest possible way, *i.e.*, to optimise the system for *e.g.* low economic cost. The method is described in detail in Hillier & Lieberman (1995). In Paper IV, the linear programming method was used to optimise pig diets according to different environmental targets. Azapagic & Clift (1998) have previously described linear programming as a powerful mathematical technique that can be successfully combined with Life Cycle Assessment. In a case study on boron production, the authors used LP to identify the opportunities for environmental improvements.

2.2 The SALSA models

A fundamental part of the work behind the thesis was to participate in the design and construction of the SALSA models. The SALSA models are constructed as substance and energy flow models using life cycle assessment methodology for impact assessments and scope definition. All SALSA models have been built in the software MATLAB/Simulink, in which parameters can be organised in vectors and matrices, thus allowing a narrow and structured format of the models (MathWorks Inc., 2000). The models are constructed from a bottom-up perspective where data on different processes are individually calculated and then aggregated to represent different farm activities. This hierarchical structure enables a comprehensive overview of the studied system at the top level of the model, meanwhile providing detailed information on processes at the lower levels.

At present, there are four existing SALSA models. SALSA-arable covers Swedish arable production of cereals, peas, rapeseed and hay (Elmquist *et al.*, 2004; Paper I). SALSA-soybean covers Brazilian soybean production, including extraction processes and transport to Sweden (described below). SALSA-pig was developed for analysis of growing-finishing pigs including manure management (Paper II), and SALSA-cattle covers milk and meat production (Elmquist, 2004; not included in this thesis).

Systems description and functional unit

The system studied in this thesis consisted of production of growing-finishing pigs including production of their feed. The system and the parts that are covered by different models are illustrated in Fig. 3. All flows of energy and emissions were related to a defined functional unit. For feed production, one kg dried feed ingredient was used, and for pig rearing one kg pig growth. In the whole-system studies (Papers III and IV), where both feed production and pig rearing were considered, one kg pig growth was used.

The impact categories considered were primary energy use, global warming potential (100 yr time horizon), acidification (maximum scenario) and eutrophication (aquatic; maximum scenario).

This thesis has focused on farming at a farm level perspective. The structural level of farming in Sweden, including location of farms and supply industries, *etc*, has not been studied in this research project.

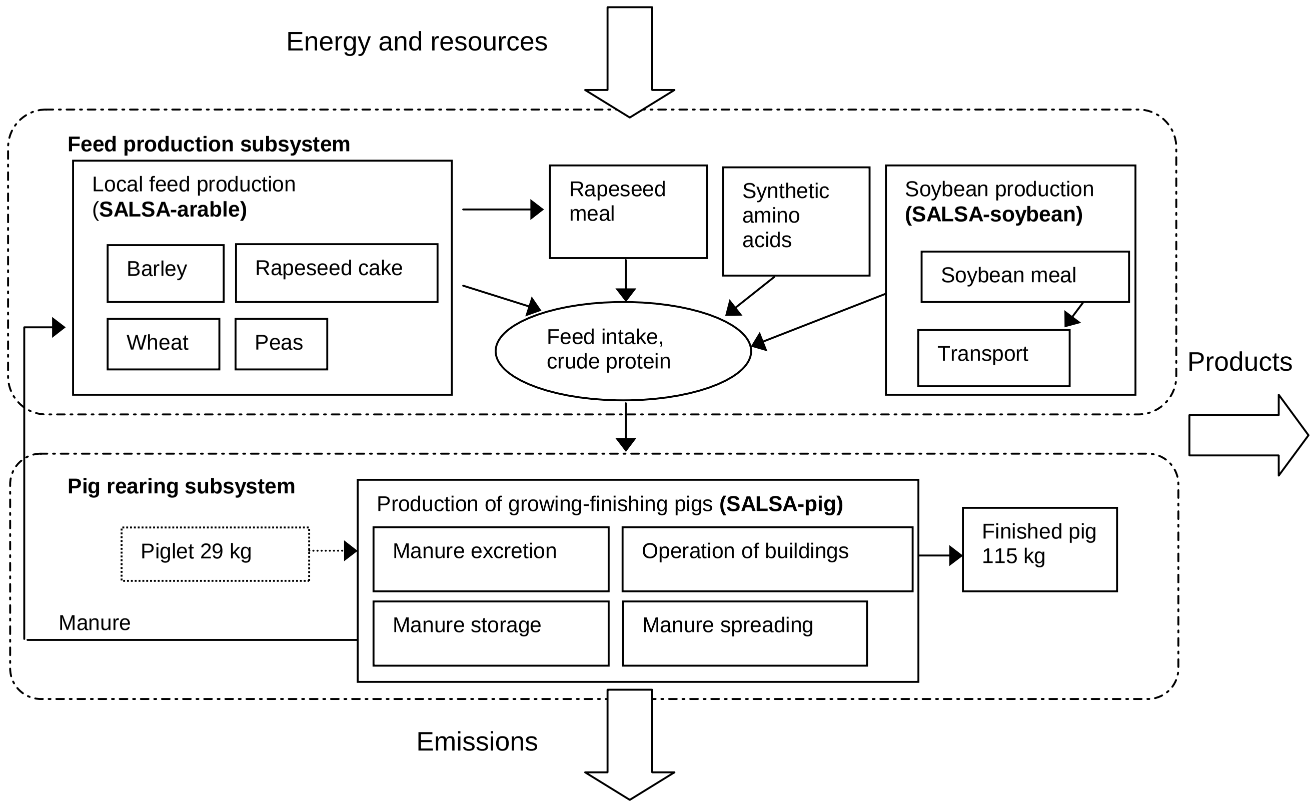

Fig 3. Systems description and the main structure of the interaction between the SALSA models.

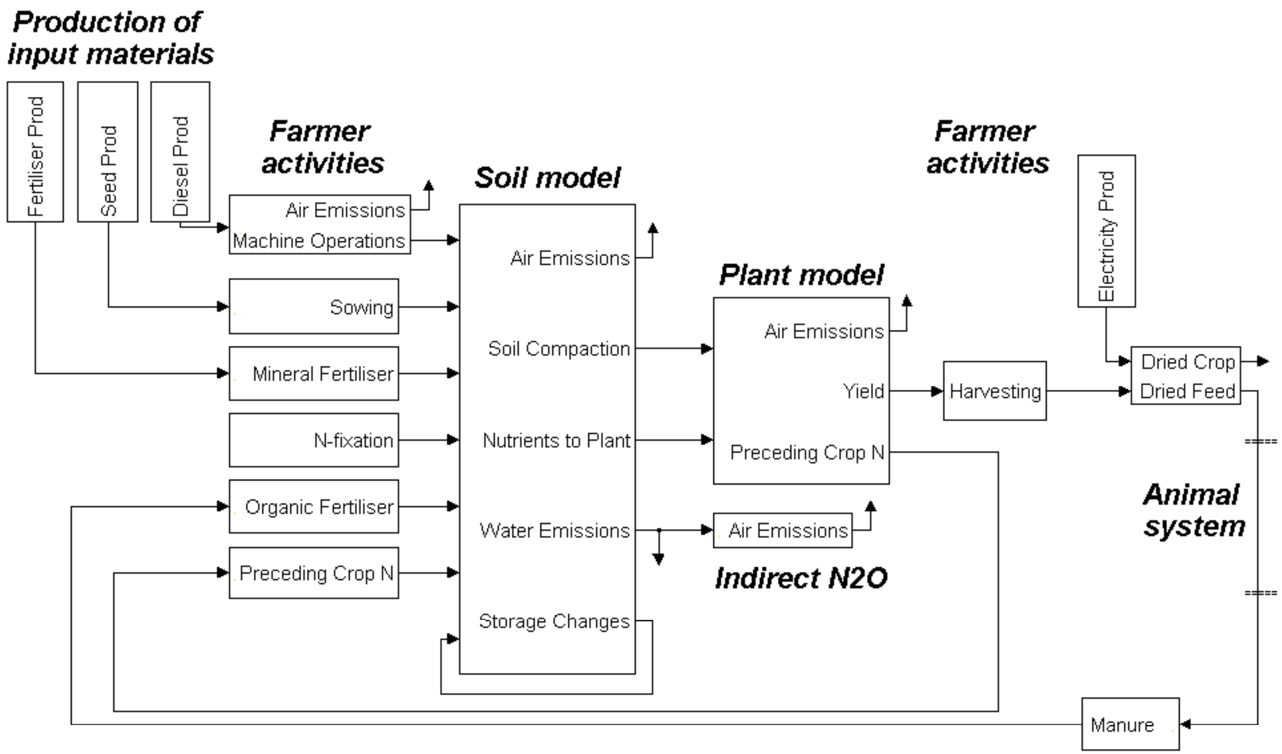

Fig. 4. The SALSA-arable model's top layer in Simulink describing the physical flows related to production of input material, farm activities and soil and plant processes.

SALSA-arable

Production of winter wheat, barley, peas and rapeseed was modelled in the SALSA-arable model (Fig. 4). Activities and processes modelled were field operations, air and water emissions from soil, air emissions from crops, indirect nitrous oxide emissions, drying of grain, pressing of rapeseed oil, electricity and diesel production, mineral fertiliser production, emissions from mineral and organic fertilising and seed production. The resulting energy use and emissions from different processes of each crop are classified and characterised into impact categories in post-simulation parts of the model.

The model considers nutrient aspects of crop sequences in two different optional ways. Then a crop (peas, rapeseed) has a positive fertilising effect on the succeeding crop, this could be credited, as an avoided use of mineral fertiliser nitrogen, to either the crop itself (Papers III and IV) or to the succeeding crop (Paper I). This will affect all environmental impacts related to the mineral fertiliser rate, such as environmental impacts from mineral fertiliser production, nitrogen leaching and nitrous oxide emissions from soil. Similarly, crop yields can either be calculated from nitrogen response functions (Paper I) or be determined by region specific values (Papers III and IV). In the latter case, mineral fertiliser rates are calculated from crop nitrogen demand according to current recommended levels (SBA, 2003a) minus nitrogen supplied from manure and possible preceding crop effects. The leaching sub-model is based on Aronsson & Torstensson (2003).

SALSA-soybean

The SALSA-soybean model calculates energy use for, and emissions from arable production of soybean and the subsequent extraction and distribution of soybean meal (Fig. 5). The background data were taken from a Brazilian farm described in Cederberg & Darelius (2001). The model is organised into twelve sub-models: diesel combustion at the farm (including diesel production), mineral fertiliser production, seed production, drying of beans, air and water emissions from soil and crop, indirect nitrous oxide generation, transport from farm to extraction plant, extraction, transport from extraction plant to harbour, ocean transport from Brazil to Germany, sea transport from Germany to Sweden and transport from Swedish harbour to farm. The model uses data from the database NTMcalc (NTM, 2002) for calculations of transport activities.

Since the extraction process gives rise to two co-products, soybean oil and soybean meal, there is a need for an allocation procedure to divide the environmental impact from the arable production between both co-products. The model uses an economic allocation base, to reflect the driving force behind the production. The factors used for allocation are 69% to soybean meal and 31% to soybean oil (Oil World Monthly, 2003).

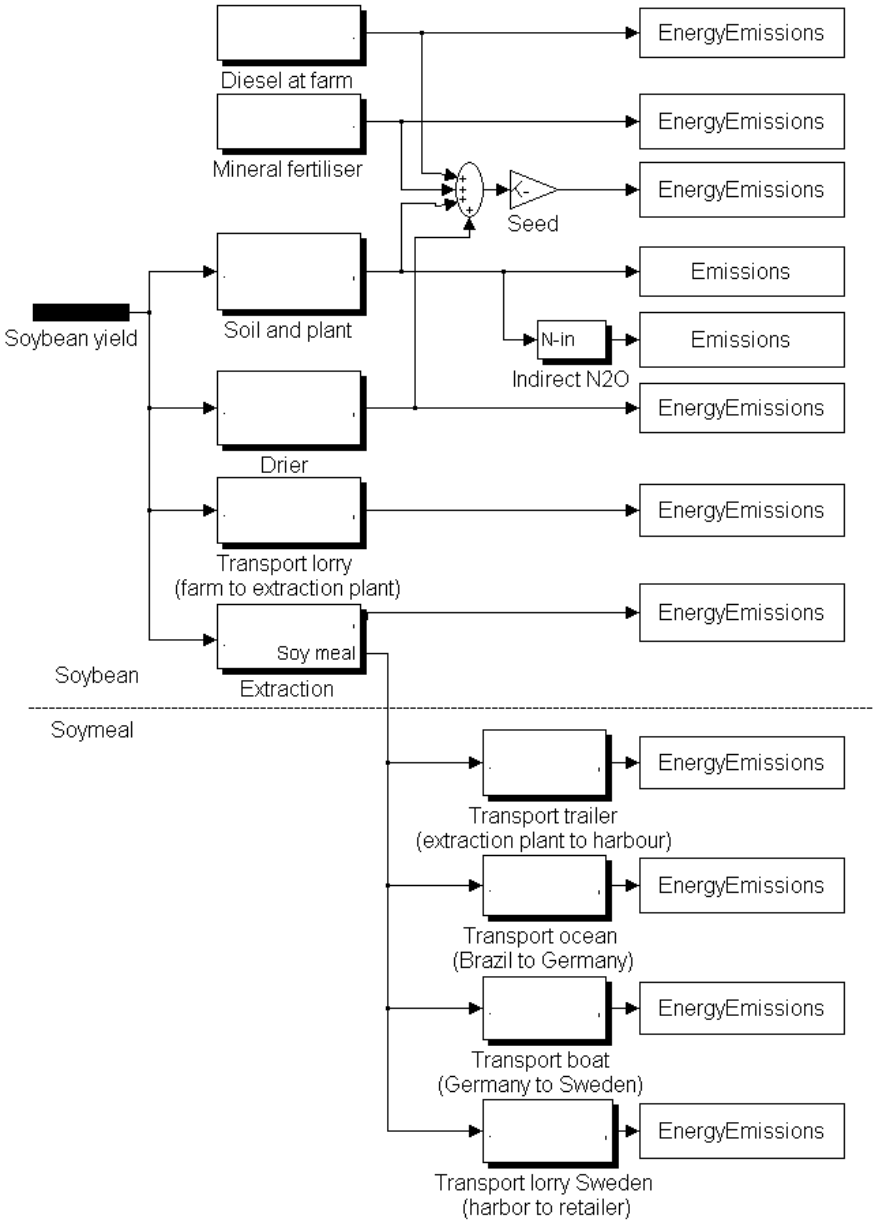

Fig. 5. Illustration of the SALSA-soybean model in Simulink. Input signal = black box, calculation sub-models = shadowed boxes, output signals = white boxes, 'EnergyEmissions' = primary energy use and emissions. Data above the dividing line are obtained per ha of soybean, later allocated with 69% to soybean meal. Data below the line are obtained per ha of soybean meal.

SALSA-pig

The SALSA-pig model includes the following processes taking place at a pig farm during fattening of growing-finishing pigs: energy use for operation of buildings; emissions originating from animals and excreta in the barn; emissions from manure storage; and emissions from manure application at fields, both from the manure itself and from tractor driving. The model also calculates the fertilising effect of the pig slurry, and converts this to avoided energy use and emissions from production of the corresponding amount of mineral fertiliser nitrogen. Furthermore, indirect emissions of nitrous oxides deriving from emitted ammonia and nitrate from the farm are included (IPCC, 2001). The SALSA-pig model is illustrated in Fig. 6.

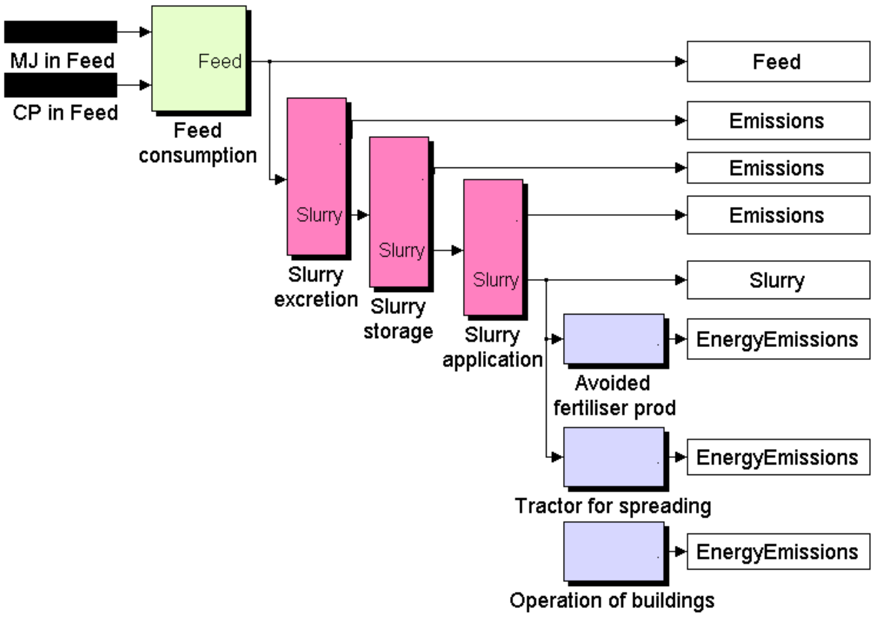

Fig. 6. Illustration of the SALSA-pig model in Simulink. Input signals = black boxes, calculation sub-models = shadowed boxes, output signals = white boxes. 'EnergyEmissions' = primary energy use and emissions; the emissions considered are listed in Paper II, Table 1.

3. Description of papers included

3.1 Paper I

The first paper describes the SALSA-arable model, which was developed for environmental assessment of local feed production. The model includes processes from the feed production chain, from manufacturing of mineral fertilisers and diesel, through tractor operations and drying, to emissions from crops and the soil. The nutrient perspective of crop sequences was considered through crop-specific N response functions that were adjusted to different preceding crops.

Paper I also presents results from a study on the influence of mineral nitrogen fertiliser rate on crop yield and environmental impacts from production of wheat, barley and rapeseed. Eutrophication, acidification and global warming potential were analysed for different soil types (clay and sand). The results showed that higher nitrogen rates gave higher energy use, global warming potential and acidification potential per kg crop, despite the higher yields that were produced per ha. For eutrophication, lower rates were only effective down to a certain level, where the reduced yield started to have a larger impact on the overall result. Optimal fertiliser rates for eutrophication were recorded at or slightly below current recommended fertiliser rates.

3.2 Paper II

The second paper covers the description of the SALSA-pig model, which was developed for and used in subsequent studies to generate environmental inventory data and impact assessment results for rearing of growing-fishing pigs. The model calculates feed intake and manure production, data that are necessary when the model is connected to the SALSA-arable model. It also includes sub-models for estimation of manure emissions throughout the system and for energy use and emissions from operation of buildings and driving of tractor for manure spreading.

Paper II also presents results from a study on the influence of crude protein (CP) level in the feed on the environmental impacts from the pigs. Eutrophication and acidification increased with increasing CP levels, whereas energy use and global warming decreased. The latter result was explained by the avoided mineral fertiliser production that was an effect of the higher fertiliser value of the manure produced. Feeding the pigs high levels of protein thus causes increased emissions of ammonia, but is an investment in useful fertilisers saving energy and emissions of nitrous oxides. Paper II further includes a normalisation of the results in relation to Swedish total environmental burdens, where acidification was identified as the most important environmental impact.

3.3 Paper III

Paper III is a case study of three scenarios with different feeding strategies for growing-finishing pig production. In this paper, results from the three SALSA models are used together to allow the influence of feed choice in a systems perspective to be studied. The scenarios were designed to reflect different trends in pig feeding, including increased soybean use (SOY), increased use of domestic crops (peas and rapeseed) (PEA) and increased use of domestic crops and synthetic amino acids (SAA). The last two scenarios had environmental advantages, PEA for energy use and global warming and SAA for eutrophication and acidification (Figs. 3-6 in Paper III).

The experiences from this study led to the questions: Can the environmental impact of pig feeding be further decreased? What would be the best feed for each impact category? The need for an optimisation tool was recognized.

3.4 Paper IV

In the fourth paper an optimisation model is presented, which allows pig diets to be optimised for lowest environmental impact for the entire system, including both feed production and animal husbandry. The paper presents five different optimised diet compositions (for minimal cost, energy use, global warming, acidification and eutrophication), the environmental impacts caused by these and degree of conflict between the targets. For energy use, global warming and eutrophication, the feed production sub-system was the dominating source, whereas for acidification, the animal rearing sub-system contributed the majority of the impact. An important conclusion from the study was that there was a conflict between energy use and global warming on one hand and eutrophication and acidification on the other. However, diet formulations without imported soybean meal were preferable for almost all environmental impact categories analysed.

4. Discussion

4.1 Advantages and drawbacks of the tools used

One of the most valuable outcomes of the SALSA research project was the knowledge about the system, built up and assembled in the models through the model construction phase.

The flexibility and rapidity with which new scenarios can be tested are two of the main advantages of the SALSA models. Once the models are constructed, new values of parameters can easily be inserted to incorporate new knowledge or to perform *e.g.* sensitivity analyses. The main drawbacks with the models are the considerable investment made in the model construction and, from a transparency perspective, the aggregated structure of the results. The technical platform and the general approach of the SALSA models are uniform with the ORWARE model, which offers many possibilities for combined agriculture-organic waste studies, *e.g.* where SALSA-pig is connected to biogas or compost sub-models.

In Denmark, a data-base (LCA food) has been constructed with a similar purpose as the SALSA models, *i.e*. to study the environmental impact of food production (Nielsen *et al*., 2003). The data-base (available as a website) has a process mode and a product mode. In the process mode the data-base provides input/output data on a variety of processes in the Danish food sector and in the product mode it provides estimates of environmental impacts associated with a variety of food products at different stages of the production chain. Data on production in agriculture and fishery have been determined by a 'top-down' approach where statistical data on a national level have been broken down to represent specific processes.

Compared to the Danish data-base, the SALSA models are farm management orientated and focus on the farm level, while the LCA food data-base has a national perspective and is orientated towards changes in market demand for different food items. The SALSA models provide more possibilities to study the influence of individual parameters, since SALSA to some extent uses mechanistic relationships between input data and output data. One example of this is the tractor emissions from field operations, which are determined by calculating the crop-specific diesel consumption for the operation, and then multiplying this by an operation-specific emission vector. If another fuel is to be tested, *e.g*. bio-fuel, the emission vector can be adjusted to match this new fuel. On the other hand, the Danish data-base may better represent the absolute figures on a national level than would be the case if the SALSA models were simply scaled up. In addition, the Danish data-base contains a higher number of food products than the SALSA models presently cover.

Compared to commercial LCA tools, e.g. SimaPro (PRé Consultants, 2004), the SALSA models are research tools, constructed with the purpose to change background parameters and variables. In a commercial tool, background data are often fixed and the variation introduced by the LCA practitioner usually concerns the processes that should be included in a production chain. The SALSA-models thus require more knowledge about the simulated system to verify the plausibility of variable values.

4.2 Results from applications of the tools

Production of feed ingredients

Production intensity

In Paper I, it was found that extensive crop production (lower mineral fertiliser application and lower yield) was more favourable than intensive production, for the environmental impacts investigated. An exception was eutrophication that increased both at high and low nitrogen rates, thus forming an optimum N-rate at or slightly below the current recommended rate. In a German study, it was similarly concluded that fertiliser rates below the economical optimum were preferable for all impact categories studied, except land use (Brentrup *et al.*, 2004). For energy use, acidification and to some extent global warming potential the increased environmental burden at higher fertiliser rates was mainly an effect of the increased environmental burdens of mineral fertiliser production. Contrary, for eutrophication the effect was mainly coupled to the level of N input to the soil. The increased yields at higher N rates did not compensate for the accelerated environmental impacts related to high N rates. However, for eutrophication also the loss of yield at low N rates had a markedly negative impact.

In Paper III, an observation was that crop yield per hectare generally had a high impact on the environmental load per kg feed ingredient, as many impacts were more related to the cropped area than to the amount of yield-related inputs (mineral fertiliser, grain drying, *etc*.). High-yielding crops had lower environmental burdens per kg product than low-yielding crops (note that all these crops were assumed to be fertilised with recommended rates).

These two apparently contradictory statements may need to be explained. For a single crop, a low intensity fertiliser strategy was shown to be favourable. Higher inputs of mineral fertiliser (above recommended rates) did not pay off in terms of higher yields to compensate for the higher environmental burdens caused by the production and use of the fertiliser. On the other hand, when comparing different crops, *e.g.* wheat and barley, high yield was beneficial for many of the environmental impacts, even when the higher yielding crop (wheat) used more mineral fertiliser per hectare than the lower yielding crop (barley). Based on this, one conclusion may be drawn: encourage the use of high-yielding crops, but do not over-fertilise them.

Production efficiency and production volume

The studies underlying this thesis all assess the environmental impacts per kg production (kg crop or kg pig growth). Lifting the thoughts on production efficiency to the next system level leads to the following discussion. The rationale behind the statement that a high efficiency is desirable is based on the implicit fact that less material can be consumed for the same good. However, if this only leads to an increase in production volume, have we then gained anything? This question can be exemplified by the eutrophication issue (also described in Paper III).

From a eutrophication point of view, environmental impact per kg product may not be sufficient for making a fair decision. Cederberg (2002) suggests that assessment of eutrophication in animal production systems should be made both per unit product and per hectare. In a watershed area, all land use affects the nutrient status of the recipient (*e.g.* coastal waters). If a pig-farm in the area increases its efficiency and produces sufficient amounts of feed on fewer hectares, what happens with the set-aside land? Will this be used for cash crop production (*e.g.* wheat), bio fuel production or permanent fallow? The only alternative that will lead to an improved eutrophication status of the recipient is probably the latter. Growing more wheat (increasing the production volume) may increase the eutrophication load of the recipient waters, despite the pig farm reducing its eutrophying emissions. The alternative of growing bio-fuels might also increase the eutrophication, but meanwhile reduce resource use on a global scale, hence switch from one type of environmental burden to another. The extent to which a recipient can tolerate more nutrient stress differs, often with spatial location. So, whether the trade-off between more eutrophication and less use of fossil fuels in the bio-fuel alternative is worth its price depends on the sensitivity of the recipient and has to be discussed from a regional or national perspective.

Despite this complex situation, it is questionable whether the pig production system should be held responsible for the fate of the abandoned land.

Domestic feed production

Production and distribution of domestic feed ingredients had a lower environmental impact per kg than soybean meal (Table 3). Similar results were obtained in a French study, where soybean meal was shown to have higher environmental impacts than most other tested feed ingredients (van der Werf *et al.*, 2004). When also taking into consideration the feeding value, diets based on domestic crops still had better environmental records providing they were fortified with synthetic amino acids (see Paper III).

Table 3. *Environmental impact per kg feed ingredient (from Paper IV)*

Feedstuff	Energy	GWP	Acid	Eutro
	[MJ/kg]	[kg CO_2-eq/kg]	[g SO_2-eq/kg]	[kg O_2-eq/kg]
Barley	1.9	0.38	1.2	0.13
Peas	1.1	0.31	1.0	0.21
Rapeseed cake	2.2	0.41	1.3	0.15
Rapeseed meal	3.2	0.55	2.1	0.18
Soybean meal	5.0	0.73	8.3	0.42
Winter wheat	1.8	0.39	1.2	0.10
Synthetic amino acids	86	3.6	41	0.04

Pig rearing

Pig rearing is a sub-system of the larger pig production system, and is described in detail in Paper II.

Manure management

Swedish manure management is controlled by regionally adjusted legislation (SBA, 2003b). It is based on animal density and takes into consideration, in sensitive areas, nitrogen uptake, spreading time, spreading technique and winter crop coverage.

When studying the pig rearing sub-system (papers II-IV) we could confirm that the nitrogen input of the system (crude protein in feed) took several pathways on its way out. Some was retained in the produced meat, some was lost as emissions and the rest was left in the manure. The fate of the last pool was important from an environmental point of view. A fundamental assumption of the studies was that this manure was used for crop production, replacing mineral fertilisers. In this way, the input nitrogen, deriving from the feed, could be regarded as an investment. But, this effect was only valid from an energy use and GWP perspective, since both these impact categories were negatively correlated with crude protein level (paper II). From an acidification and eutrophication perspective, the nitrogen emissions of the pig rearing sub-system were much more important than the small amounts saved through avoided mineral fertiliser use, so high levels of nitrogen input could not be seen as a wise investment. For acidification and eutrophication it was important to have a low nitrogen turnover, *i.e.*, to feed the pigs low protein diets in order to get low nitrogen emissions during all stages of manure management. There are many studies confirming that low crude protein diets leads to reduced nitrogen excretion (*e.g.* Canh *et al.*, 1998; Hayes et al., 2004).

Feed conversion

In paper III, a sensitivity analysis was performed on the feed conversion factor of the pig, which in practical situations can be improved by e.g. successful breeding. The assumption of 35 MJ metabolisable energy (ME) per kg pig growth was reduced by 10% to 31.5 MJ ME. This reduced the nitrogen excretion by 15% and acidification by 20%, assuming the nitrogen retention was the same. More efficient pigs hence had positive effects on the emissions from the pig rearing phase, and a reduction of the feed intake also reduces environmental impacts from production of the feed ingredients. This twofold effect showed that efficient pigs contributed to savings in the whole system.

Impact of feed choice

As stated in Paper III, feed choice had an impact on the environmental performance of pig meat production, not only via the features of the feed as fed to the pigs, such as the crude protein content, but also via the raw materials used, since the environmental impact from the production of these differed and since feed production had a large impact on the system as a whole. In this respect, it is important to make a careful decision on what feed ingredients to use.

However, there is a dilemma. To decide what is 'environmentally friendly' is an impossible task, since the environmental impact categories have conflicting solutions. Some example of this can be taken from paper IV. When optimising the system for minimal acidification and eutrophication, peas were avoided. Contrary, when optimising for low energy use and global warming potential, peas were one of the best crops. To overcome this problem, some authors have suggested weighting methods to decide what environmental impacts are most important (Steen, 1999; Bengtsson & Steen, 2000; Goedkoop & Spirensma, 2001; Erlandsson, 2003). Weightings are usually performed on normalised results.

Normalisation

Normalisation denotes a method where the environmental impact of a studied system is compared with the impact of a whole region or nation (*e.g.*, Lindfors *et al.*, 1995). If no weighting method is added to the normalised results, all categories are implicitly considered equally important. Compared to other sectors in Sweden, agriculture contributes a lot to eutrophication and ammonia emissions, and less to energy use and emissions of greenhouse gases. One argument is then that agriculture should mainly focus on reducing its ammonia and eutrophying emissions. However, if sustainability is mainly threatened by global warming, all sectors should prioritise measures to reduce emissions of greenhouse gases. This question contains a high degree of personal judgement, and can therefore not be answered with scientific methods.

Despite the ethical dilemma that it is impossible to decide what impact category is most important, decisions on feed choice will have to be taken. In the case of acidification and eutrophication, which are more site dependent than energy use and global warming, the sensitivity of the recipient will be a guide. In sensitive areas it may be better to avoid further nitrogen load than to, *e.g.* prioritise energy saving.

Taking into consideration the subjectivity of comparing different impact categories against each other, a normalisation of the results from pig rearing and feed production has still been made in this thesis (see also Paper II). The figures from an average situation of pig production (scaled up to 1000 kg pig growth to get manageable figures) were compared to the total Swedish per capita environmental burden, to illustrate the relative difference between the studied impact categories (Table 4). The pigs were assumed to eat 2.8 kg feed per kg growth and the feed to contain 14.5% crude protein. If all environmental impacts are equally important, some conclusions can be drawn. For the pig-rearing phase, acidification was the most significant environmental impact, followed by eutrophication. For feed production, eutrophication was the dominant impact category, while acidification and global warming potential were equally important. In no sub-system energy use had a large impact. When pig rearing and feed production were combined to find the total system impact, eutrophication turned out to be most important impact followed by acidification.

Table 4. *Normalisation of the results from pig rearing and feed production compared to the Swedish per capita environmental burden*

Impact category	Total Swedish environmental impact	Impact per capita (IPC)	1000 kg pig growth	Feed to supply 1000 kg growth	1000 kg pig growth /IPC (%)	Feed for 1000 kg pig growth/IPC (%)	1000 kg pig growth including feed production/IPC (%)
Energy	2260 PJ	251 GJ	650 MJ	5761 MJ	0.3%	2.3%	2.6%
GWP (CO2-eq)	70000 ton	7800 kg	310 kg	1105 kg	4%	14%	18%
Acid (SO2-eq)	336800 ton	37 kg	18 kg	4.8 kg	49%	13%	62%
Eutro (O2-eq)	5091000 ton	566 kg	160 kg	399 kg	28%	70%	98%

Sources: Brandt & Ejhed, 2002; Lindfors *et al*., 1995; SEA, 2004; SEPA, 2002; SEPA, 2004; Statistics Sweden, 2003

5. Concluding remarks

5.1 Methodological aspects

The SALSA models offer a structured way of translating assumptions about a system into operational inventory data, beneficial in, for example, subsequent life cycle assessments. Variables can easily be changed, which make the models flexible and suitable for experimenting on different farming conditions by computer simulations.

The scenario analyses carried out here, which compared a number of parallel life cycle assessments on projected systems, gave insights into the processes that had large impacts on the system as a whole and to what extent differences in feed choice influenced the results.

The optimisation tool, developed at the end of the research project extended the possibilities of understanding the influence of feed choice on the environmental impacts of the system, and introduced a possibility to compose optimal diets for different environmental targets.

5.2 Environmental improvement potential of pig production

Present pig production can be improved by lower, better balanced protein supplies leading to lower nitrogen excretion. In this respect, the use of synthetic amino acids appears to be beneficial from an environmental point of view. The advantages with synthetic amino acids have been described by *e.g.* Fickler & Limper (1997). One of the main problems with synthetic amino acids is their high economic cost for the farmer, however. Economic incentives or restrictions on nitrogen excretion may be two ways to improve this in practice.

Furthermore, the use of pig breeds with high feed conversion rates would reduce environmental impact both from pig rearing itself and from feed production. These positive effects need to be weighed against possible negative effects on animal welfare.

The environmental impact of pig production would also greatly benefit from exclusion of imported soybean from the feed. The production and transportation of soybean takes a disproportionately large share of the environmental impact of pig production. Furthermore, soybeans represent a recent and powerful threat to biodiversity in Brazil (Fearnside, 2001). A shift towards domestic protein sources would improve the environmental performance of the pig production sector. In a recently published thesis by Deutsch (2004), the author concludes that future resilience in food production systems will require more explicit links between consumers and the work of supporting ecosystems, locally and in other regions of the world. Deutsch further states that global trade in its present form seems to accelerate negative ecological changes.

Peas are a domestic crop that could be used for pig feed. Besides their value as a feedstuff, they also have a beneficial effect in the crop sequence of a farm. The growing of peas reduces the need for mineral fertilisers for the succeeding crop (approx. 30%), thus saving energy and emissions of greenhouse gases (at the expense of more eutrophication, however). Yet, there are also economic and practical problems associated with pea production, besides that pigs cannot eat unlimited amounts of peas per day. Cultivation methods for peas that reduce eutrophication, *e.g.* intercropping with cereals, appear to be an essential measure for improvements in pea production.

Crop production in general should focus on avoiding over-fertilising of crops, and for eutrophication also very low nitrogen rates limiting crop growth, should be avoided. In this respect, a careful management and an effective use of the produced pig manure is important, both to restrict the need for mineral fertilisers and to avoid excess nitrogen inputs to soil.

The use of more domestic feed sources is at present counteracted by the high availability of cheap soybean meal. The increasing importation of soybean meal is a common problem for all of Europe, and to find a solution to the problem, other European countries would probably need to be involved. Positive incentives for the Swedish producers would also arise if Swedish consumers started to demand pig meat produced without soybean meal.

This thesis mainly focuses on the ecological aspects of sustainability, and the social and economical aspects are not carefully examined. However, the proposed solutions may not be sufficient even from an ecological point of view. Comparisons and discussions are only made to see the improvement potentials within a defined system. The relevant question of the existence of the system as such, or of how much pig meat can be consumed in a sustainable way, is outside the scope of this work.

5.3 Future research

Other feed ingredients

This method for studying the environmental impact of pig production could be improved by increasing the number of available feedstuffs. At present, we have background data on seven feed ingredients. Although these cover a large proportion of the commonly used feeds, a higher number of ingredients to choose from would lead to both higher accuracy of the studies and, even more important, a higher potential to find the really efficient feed ingredients. Some feed ingredients that could be of interest to study are potato protein, triticale and by-products from the food industry. By-products can have a considerably lower environmental impact than feed ingredients solely produced for animal feeding, when the alternative value of the avoided land use is considered (Wittgren *et al.*, 2004).

In the Netherlands a research programme (PROFETAS) is in progress in which novel food proteins for humans are under study (Aiking, 2000). The underlying objective is that some of the meat consumed today could be exchanged for vegetable derived proteins of different kinds. A possible spin-off effect from that research programme could be to evaluate their new vegetable protein sources also from an animal feed aspect. However, feeding pigs protein sources that are suitable for human consumption can be questioned from an ethical perspective.

Other pig production systems

At present, there is a trend towards more imported meat in Sweden. For a long time, Swedish consumers mainly bought Swedish meat, but during recent years the consumption of imported meat has increased from 12% to 19% (SBA, 2004c). Most of this meat comes from Denmark, Finland and other EU countries. An interesting study would be to compare pig meat from Swedish pig production systems with imported meat from other countries.

As discussed in Paper II, there are also potentially interesting studies to be carried out where the SALSA-pig model is expanded with the biogas sub-model in the ORWARE model, especially if SALSA-pig is first improved regarding the relationship between diet and methane formation. A possible result from this kind of study would be to find favourable diet formulations for both biogas and pig meat production.

Finally, if the SALSA models are converted into a user-friendly format, these tools can be used by farmers, the feed industry and other decision-makers for improving the environmental impacts of the pig production sector.

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