Construction and application of an LP farm model with an integrated Life Cycle Assessment for the determination of sustainable milk production systems

Anke Möhring and Albert Zimmermann
Agroscope FAT Tänikon, Swiss Federal Research Station for Agricultural Economics and Engineering, CH-8356 Ettenhausen, Switzerland
Tel: +41 (0)52 368 31 31, Fax: +41 (0)52 365 11 90
E-mail: anke.moehring@fat.admin.ch, albert.zimmermann@fat.admin.ch

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Abstract

The increasingly stringent conditions underlying Swiss dairy production demand sustainable milk production systems that are economically optimised but also meet the ecological requirements of society. To determine such systems, a comparative-static LP model was constructed at farm level. Realistic production systems with coordinated herd management, buildings, feeding and mechanisation systems are reproduced in the model by means of binary variables. An Life Cycle Assessment (LCA) was integrated into the model to determine the environmental impacts of the farm. To this effect, the internal farm influences on production are illustrated in detail. An initial application of the model, in which a comparison of different income-optimised production systems was carried out, revealed some goal conflicts between economics and ecology. Systems involving full-time grazing achieved the best results in both aspects.

Keywords: Life Cycle Assessment (LCA), LP-model, dairy production, production system
JEL classification: C61, Q12, Q51

1. Introduction

The situation of dairy production in Switzerland – as in its adjoining European neighbours – is marked by intense pressure to adapt. Over the next few years further changes are anticipated – following the current negotiations within the WTO-Doha round, the implementation of bilateral treaties between Switzerland and the EU, and the abolition of milk quotas on 1 May 2009. The possibility of an early opt-out from milk quotas after 1 May 2006 gives Swiss dairy producers the chance to play an active part in shaping the transition.

Basically three adjustment strategies are possible at farm level: a) dairy producers try to absorb falling milk prices by more cost extensive production, b) they use existing production capacity to produce specialities or for alternative branches of farming or c) they drop out of production. If they choose the first option, the production costs per kg milk must be optimised by more cost-effective production methods or by an increase in milk volume. Under Swiss conditions, however, it is difficult for farms to grow, as there is a limit to the land available and the existing marketing channels for milk are already saturated. Producers are also subject to further restrictions. Society makes high demands on compliance with environmentally compatible and animal friendly production methods. Switzerland also has a long tradition of cheese production, especially the production of high quality raw milk cheese. The production of raw milk cheese is contingent on silage being omitted from the dairy cattle feed. Cost-cutting opportunities in the organisational and technical sphere are therefore of key importance to both silage and non-silage farms. The expectation is that no single production system can offer optimum adjustment potential, but that milk production systems geared to varying degrees of intensification are beneficial, depending on the given initial position of the farm.

The economic and ecological LP model presented here has two main objectives:
1) to study the impact of changed agricultural policy and economic conditions on farm production decisions and on organisational and technical adjustment measures on dairy farms and 2) to assess the associated environmental impacts using an integrated Life Cycle Assessment.

2. Methodical aspects of modelling at farm level

Economic research which includes the issues of technological choice is increasingly important in explaining economic growth (Allen, 2000). The linear optimisation method is not necessarily required to compare the economic aspects of different milk production systems. The use of this method is advantageous only when we need to know the optimum system combination of organisational and technical production system variables, particularly when research is being carried out into complex inter-

nal farm interrelationships and the interaction between technology, economics and ecology. An examination at individual farm level also permits consideration of the different initial conditions and location factors which affect farms in practice.

The literature already features numerous examples of this type of farm modelling, including several in the dairy farming sector (i.a. Ramsden et al., 1999; Valencia and Anderson, 2000; Anderson and Mayne, 2004).

In addition to the economic aspects, some models at farm aggregation level also include environmentally relevant aspects (i.a. Rigby and Young, 1996; Berentsen et al., 1992; Trunk, 1995; Zimmermann, 1997). Berge et al. (2000) and Ven (1996) use the Multiple Goal Linear Programming (MGLP) method.

The papers mentioned illustrate selected emissions of agricultural production. Foremost among these are nutrient losses and greenhouse gas emissions. This masks the danger that transfers to other environmental problems or to upstream or downstream sectors may occur. For example, although increased grazing reduces ammonia emissions, it can raise other nitrogen emissions. The replacement of self-produced fodder by bought-in feedstuffs does reduce emissions on the farm, but at the same time increases those in the upstream sector. One method of considering environmental impact as a whole is the Life Cycle Assessment. This method covers all the major environmental problems and looks at production systems from raw material production to waste disposal (Guinée, 2002). Until now the integration of the Life Cycle Assessment method into economic LP-models has been carried out only for selected industrial production systems (Azapagic and Clift, 1999; Vogstad, 2002). The present paper illustrates the Life Cycle Assessment method in a farm optimisation model geared to the processes of dairy husbandry and complementary arable farming.

3. Overview of the farm model

3.1 The illustration of a specialised dairy farm in the model

FARMO (**Far**m **Mo**del of Switzerland) is a static linear optimisation model. It was formulated in LPL (Linear Programming Language, Hürlimann, 2004). The farm type represented in the model is a dairy farm in the lowland region of Switzerland, in both silage and non-silage zone locations (Möhring et al., 2004). Totally new farms are used as the starting point, in other words the transformation costs for the change between production systems are not investigated. The farm model optimises dairy farms without their own breeding programme and with a limited supply of land. As an alternative to milk production the model farms can opt for the cultivation of market crops. The farm manager works full time on the farm. He can choose between milk production systems which differ technically and organisationally, between different crop management intensities, types of crop and feed rations, and can determine the scope of activity within the given land capacities. The optimisation computations carried out represent medium- to long-term strategic planning calculations. Individual farm provisions for the receipt of direct payments are taken into account in the model. This includes the conditions for compliance with Proof of Ecological Performance (Ökologischer Leistungsnachweis – ÖLN) and for proper animal welfare meeting the requirements for particularly animal-friendly housing systems (BTS scheme) and for regular open air access by domestic animals (RAUS scheme). With the goal function the model farm can optimise the income of the farm manager's family. However other target variables are also possible, for example the minimisation of environmental impacts when setting specific production volumes or combinations of various objectives by multiple goal optimisation methods.

3.2 Differentiating characteristics of the milk production systems and data base

In this paper four principle influencing factors are used to differentiate milk production systems. These are (cf. Table 1):

- **herd management**, determined in particular by breeding strategy and calving date;
- **feeding system**, with different winter and summer feeding strategies and a distinction between feed including and excluding silage in the ration;

- **building system**, the range of which is modelled mainly by the factors of housing shell, housing system, forage storage and feeding technology, milking technology, and
- **degree of mechanisation**, since the farm's stock of machinery and effectiveness varies as herd size increases.

Table 1: Variation ranges in milk production system modelling

Principle influencing factor	Differentiating characteristic	Variation
Herd management	breeding strategy	6000, 6500, 6700, 8000, 10 000 kg milk per year
	calving date	seasonal in spring, continual throughout the year
Feeding system	winter feeding (silage system)	grass silage, maize silage, meadow-dried hay
	winter feeding (non-silage system)	ventilated hay
	summer feeding (silage system)	Full-time grazing, fresh fodder/pasture, silage/pasture, all-year silage
	summer feeding (non-silage system)	full-time grazing, fresh fodder/pasture
Building system	housing shell	open stall housing, closed stall housing, open housing without stalls
	forage store	haystack, round bales, tower silo, horizontal silo
	feeding technology	- standard distribution with animal-feeding place ratio 1:1, - ad libitum distribution with animal-feeding place ratio 2:1, - self-feeding at horizontal silo
	milking technology	herringbone milking parlour, mobile milking parlour
Degree of mechanisation	combination of own mechanisation and contract work	3 stages for herd sizes of between 30 and 100 cows

A large number of possible system combinations are found in practice. The model cannot illustrate all the possible system variants. Plausible production systems relevant to actual practice and to local Swiss conditions are therefore defined as part of preliminary selection (Gazzarin and Schick, 2004). The decision variables for the selection of production system and housing size are formulated in the model as binary variables. Detailed production processes within the production system, e.g. exact fodder portions based on the requirement of each animal depending on their respective lactation phase, are shown by the means of continuous variables. Logical constraints, which are translated into a mixed integer-valued formulation during input, are used for the representation of relationships between binary and continuous variables and for the avoidance of non-linearities.

The calculations of the relevant performance and cost items are based chiefly on planning and experimental data (i.a. Ammann, 2004; Gazzarin and Schick, 2004; Gazzarin and Hilty, 2002; Mosimann, 2001; ALP, 1999).

3.3 The integration of a Life Cycle Assessment

In FARMO the integration of the Life Cycle Assessment method takes place in a switch on/switch off submodel. The optimisation calculations can therefore be implemented with or without Life Cycle Assessments.

A Life Cycle Assessment encompasses four steps (Guinée, 2002): the definition of the objective and of the investigative framework of the study, the life cycle inventory, the impact assessment and the evaluation. Two elements of the first step are the system boundary and the functional unit. The „farm gate“ was set as the system boundary of the products produced on the model farm, applicable to both the economic and ecological variables. Product processing, distribution and consumption are therefore not taken into account. In the application presented the functional unit, as a reference variable for the results, is a kilogram of milk sold. The two calculation steps, the life cycle inventory and the impact assessment are integrated into the model. The main data base are the environmental inventories and emission models of the Swiss Agricultural Research Stations (Nemecek, 2003; Nemecek et al., 2004).

The life cycle inventory step includes the determination of the emissions and resource consumptions of the system. A distinction can be made between **direct** and **indirect** emissions: direct emissions originate on the farm itself, indirect emissions come from the provision or disposal of production factors. The resource consumptions considered are essentially fossil energy sources. They are methodologically treated as indirect emissions. The calculation of the life cycle inventory in the farm model requires the modelling of all the essential production factors in the differentiation required and formulation of the emission-relevant process conditions.

Modelling of the **indirect** emissions in the model takes place by linear linking of the environmental inventories with the corresponding production factors or activities. This will be illustrated using the example of bought-in fodder concentrate, only the differentiations necessary for understanding being shown:

$$EMI\,KF_{t,emi} = \sum_{kf,inv} KF_{t,kf} * kf\,inv_{kf,inv} * ef_{inv,emi} \qquad (1)$$

where: *EMI KF* model variable: indirect emissions of fodder concentrate purchased
KF model variable: fodder concentrate purchase
kf inv parameter: fodder concentrate link with associated environmental inventories
ef parameter: emission factors per volume unit of fodder concentrate (environmental inventories)
t, emi, kf, inv indices for the animal species (*t*), emissions (*emi*), fodder concentrates (*kf*), environmental inventories (*inv*)

The bought-in fodder concentrates are formulated as variables in the model. The link with the environmental inventories is made by way of parameters, which are defined for the associated combinations of fodder concentrates and environmental inventories. At the same time these parameters adjust any differing units. The environmental inventories contain the indirect emissions of the fodder concentrates. The variables for the resulting emissions are differentiated by animal species, so that where farms produce several products, the emissions can be allocated according to the animals' fodder concentrate requirement. If one species supplies several products, for example milk and meat, a further, economic allocation of emissions is made in a separate constraint according to the value of the products.

The formulation of **direct** emissions is based on specific emission models, the transfer to the linear model necessitating certain adjustments. For example, in the formula for ammonia emissions in slurry spreading (equation 2, Katz, 1996) the variable factors do not have a linear link with each other and partly represent relatives of two magnitudes, both shown as variables in the model:

$$EMI\,NH3 = (-9.506 + 19.408 * NH4 + 1.102 * SD) * (0.021 * GHA + 0.358) \qquad (2)$$

where: *EMI NH3* ammonia loss [kg N/ha]
NH4 ammonia content of the slurry [g N/kg fresh matter]
SD water saturation deficit of the air [mbar]
GHA amount of slurry per unit of area [t/ha]

For inclusion in the farm model this formula was approximately linearised, so that the emission-influencing factors – starting from the amount of slurry spread and a base-emission factor – are taken into account by means of separate parameters. At the same time certain factors not illustrated in the model must be estimated on the basis of other variables, for example the amount of slurry spread per area based on the number of animals per hectare. A possible reduction in emissions due to the spreading technique was also taken into consideration.

$$EMI\ NH3_t = \sum_{hd,k,p,tb,ps} HD_{t,hd,k,p} * GEHALT_{hd} * NH3_{hd} * VER_{hd} * SD_p * GHA_{tb} * ST_{ps} \quad (3)$$

where: *EMI NH3* model variable: direct ammonia emissions of slurry spreading
HD model variable: amounts of farm manure spread
GEHALT parameter: ammonia content of the farm manure
NH3 parameter: base-emission factor
Correction factors (parameters):
VER slurry dilution
SD water saturation deficit
GHA amount of slurry per area
ST spreading technique
t, hd, k, p, tb, ps indices for the species (*t*), manure types (*hd*), crop types (*k*), periods (*p*), animal number per hectare (*tb*), production systems (*ps*)

The indirect and direct emissions are summed up in a separate equation for each species and then allocated to the products produced by the species. The assessment of the impacts of altogether over 100 emissions on relevant environmental problems (for instance greenhouse potential, eutrophication) is carried out in the impact assessment. In the impact models used the connections between the emissions and the potential environmental impacts are linear and can therefore be shown by a simple constraint:

$$UMWI_{pr,umwi} = \sum_{emi} EMI_{pr,emi} * wf_{emi,umwi} \quad (4)$$

where: *UMWI* model variable: environmental impacts
EMI model variable: emissions
wf parameter: impact factor (potential environmental impact per emission unit)
pr, umwi, emi indices for the products or product groups (*pr*), environmental impacts (*umwi*), emissions (*emi*)

4. Comparison of different milk production systems

As an example of one application of the farm model, Figure 1 shows the costs and three environmental impacts of six different milk production systems. The values are referred to one kilogram of milk sold, the results of the farm with tethered housing were set at 100 %. Normally the model selects an optimum production system in each case. However, to allow comparisons, the appropriate production system was selected in advance for these calculations. The production systems differ in particular with regard to herd management, feeding system and building system. Other factor capacities such as land supply and available family workforce were specified identically in all the model farms.

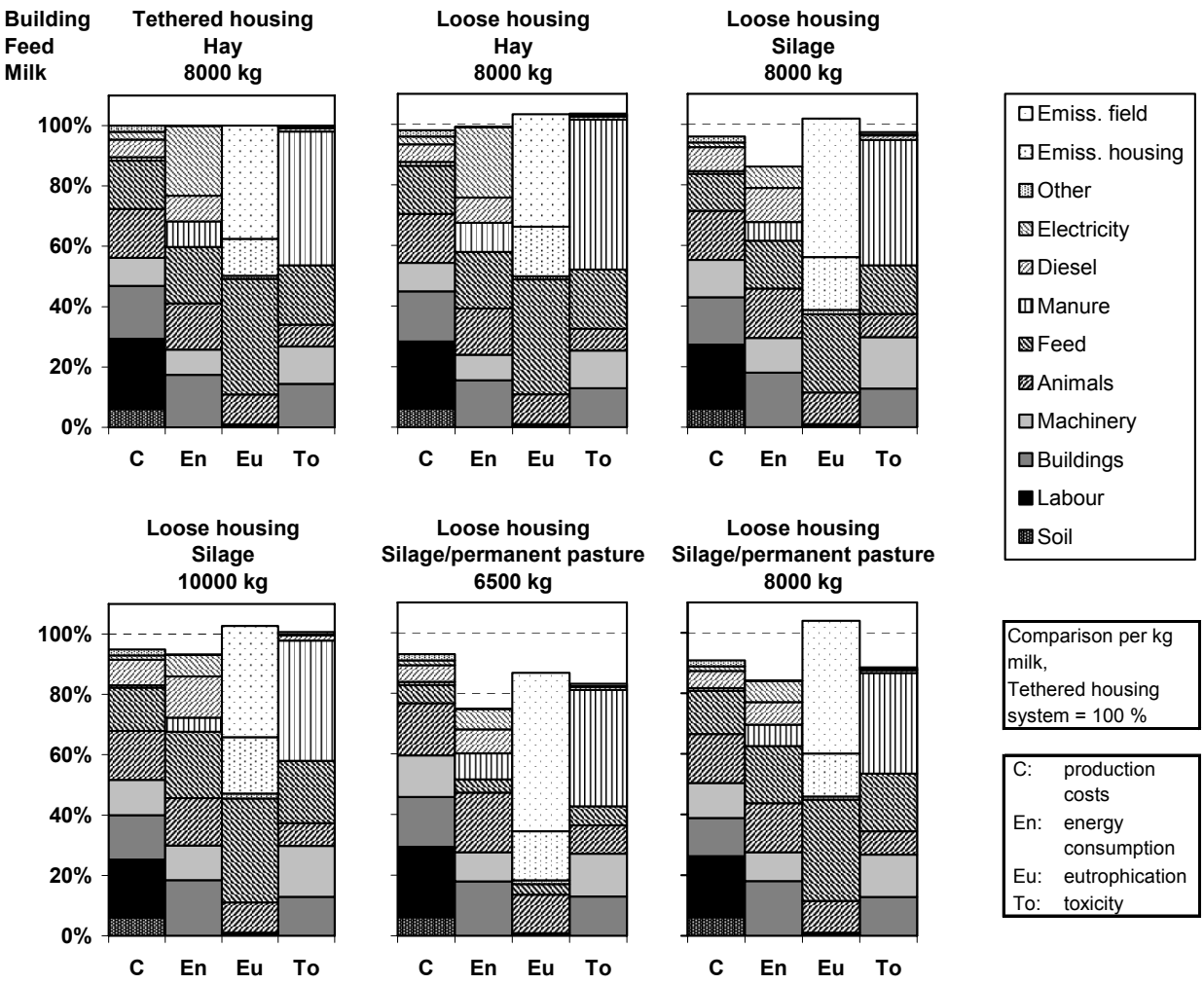

Figure 1: Costs and environmental impacts of different milk production systems

The specialised dairy farms have a quota of maximum 400 000 kg milk. The income of the farm manager's family was maximised with the objective function. Within the framework of the given production system the model thus optimised land use and the combination of production methods as well as the number of animal housing places. The model calculations were followed by a deduction of opportunity costs, so that the comparison of results would also take into account differences relating to the requirement for the farm's own factors (labour, soil, capital).

The production costs per kg milk thus determined are somewhat lower for loose housing than for the tethered housing system thanks to lower building and labour costs. Again slightly lower costs are incurred by the production system using silage instead of dry hay as winter feed. The higher technology costs of silage production are offset by lower supplementary feed costs. However model calculations for farms with lower milk volumes give higher production costs for silage systems than for dry hay due to poorer capacity utilisation of the production factors. Also, under Swiss conditions, milk from farms with silage feeding fetches lower prices, further increasing the advantages of the dry hay system. The production system still more intensively geared to silage feeding and to a high milk yield of 10 000 kg per cow can again slightly cut production costs with the high volume of milk implied. However the lowest production costs are achieved by production systems with consistent full-time grazing and seasonal calving. This is conditional on well rounded grazing areas. Particularly the system with full-time grazing and a simultaneous high milk yield makes great demands on management. Even greater potential savings than the choice of production system affords increasing herds.

By comparison with farms producing 200 000 kg of milk (Möhring and Zimmermann, 2004), the production costs per kilogram of milk are around 30 % lower in the model calculations illustrated here.

The three selected environmental impacts differ only slightly between the production systems using tethered or loose housing. In loose housing the direct ammonia emissions contributing to eutrophication are somewhat higher. The systems with silage in particular have lower energy consumption than the systems with ventilated hay, despite the greater need for mechanisation and plastic film. The systems with full-time grazing achieve comparatively low environmental impacts, especially when, with a lower milk yield per cow, they are linked to feed geared to a basic ration or the purchase of a small amount of feed supplement. Although grazing results in higher nitrate emissions, eutrophication overall is reduced thanks to lower ammonia emissions and, in particular, to the purchase of less fodder concentrate, with correspondingly lower indirect emissions. Herd size chiefly influences environmental impacts caused by fixed production factors. Thus the energy consumption per kg milk, linked partly to the stock of buildings and machinery, is around 20 % lower in comparison to model calculations with 200 000 kg of milk produced (Möhring and Zimmermann, 2004), but the eutrophication per kg milk hardly changes with herd size because it is chiefly linked to variable factors like manure volume and feed purchase.

Some production systems therefore either have advantages in respect of cost or in respect of specific environmental impacts. The systems with full-time grazing achieve comparatively good results on all points. However goal conflicts occur even in these systems: a high milk yield per cow is desirable from the economic viability point of view, but the associated requirement for supplementary feed aggravates several environmental impacts.

5. Model discussion and outlook

The detailed formulation of the internal farm interrelationships in an optimisation model makes it possible to investigate impacts of changed underlying conditions on the choice of the production methods and to assess the advantages and disadvantages of different production systems. This procedure also facilitates the integration of the Life Cycle Assessment calculation methods into the model. The advantage of the Life Cycle Assessment method over the modelling of individual substances or indicators is that consideration is given to a comprehensive examination of the environmental impacts from raw material production to the „farm gate“ as well as to the interrelationships between the various environmental impacts. The simultaneous representation of both economic and ecological variables in the model allows the use of different target variables and the application of multiobjective optimisation methods.

The model makes very high demands of a detailed data base. However the expense of such a model is justified, as a consideration of the interactions between technology, economics and ecology opens up new potential for individual farm optimisation.

6. Bibliography

Allen, B. (2000): The Future of Microeconomic Theory. *Journal of Economic Perspectives* 14 (1): 143-150.

ALP (1999): Fütterungsempfehlungen und Nährwerttabellen für Wiederkäuer. Agroscope Liebefeld-Posieux, Eidgenössische Forschungsanstalt für Nutztiere und Milchwirtschaft, 4. Auflage. LMZ, Zollikofen.

Ammann, H. (2004): Maschinenkosten 2005. Kostenansätze Gebäudeteile und mechanische Einrichtungen. *FAT-Berichte* (621).

Anderson, D. and Mayne, S. (2004): Incorporating Niche Marketing Contracts into the Farm Model: An Example from Dairy Industry. Paper presentation. 78. Annual Conference of the Agricultural Economics Society. 2.-4. April 2004.

Azapagic, A. and Clift, R. (1999): Life Cycle Assessment and multiobjective optimisation. *Journal of Cleaner Production* 7: 135-143.

Berentsen, P.B.M., Giesen, G.W.J. and Verduyn, S.C. (1992): Manure legislation effects on income and on N, P and K losses in dairy farming. *Livestock Production Science* 31: 43-56.

Berge, H.F.M. ten, Ittersum, M.K. van, Rossing, W.A.H., Ven, G.W.J. van de, Schans, J. and Sanden, P.A.C.M. van de (2000): Farming options for the Netherlands explored by multiobjective

modelling. *European Journal of Agronomy* 13: 263-277.
Gazzarin, C. and Hilty, R. (2002): Stallsysteme für Milchvieh: Vergleich der Bauinvestitionen. *FAT-Berichte* (586).
Gazzarin, C. and Schick, M. (2004): Milchproduktionssysteme für die Talregion. Vergleich von Wirtschaftlichkeit und Arbeitsbelastung. *FAT-Berichte* (608).
Guinée, J.B. (ed) (2002): Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. Kluwer, Dordrecht: 704 S.
Hürlimann, T. (2004): Reference Manual of the modeling language (Version 4.43). Universität Fribourg.
Katz, P. (1996): Ammoniakemissionen nach der Gülleanwendung auf Grünland. Diss. ETH Zürich (11382).
Möhring, A., Gerwig, C., Zimmermann, A. and Hürlimann, T. (2004): Landwirtschaftliches Betriebsoptimierungsmodell der Schweiz, Farm Model of Switzerland (FARMO). Modelldokumentation. Internes Arbeitspapier. Agroscope FAT Tänikon, Eidgenössische Forschungsanstalt für Agrarwirtschaft und Landtechnik und ETH Zürich, Institut für Agrarwirtschaft.
Möhring, A. and Zimmermann, A. (2004): Milchproduktionssysteme für die Talregion. Vergleich unter verschiedenen Szenarien. *FAT-Berichte* (609).
Mosimann, E. (2001): Croissance des herbages. *Revue suisse Agricole* 33 (4): 163-167.
Nemecek, T. (2003): SALCA-Templates. Swiss Agricultural Life Cycle Assessment Database, Beschreibung der Mustersysteme „SALCA-Betrieb“ und „SALCA-Kultur“, Version 1.31, August 2003. Eidg. Forschungsanstalt für Agrarökologie und Landbau (FAL), Zürich-Reckenholz.
Nemecek, T., Heil, A., Huguenin, O., Meier, S., Erzinger, S., Blaser, S., Dux D. and Zimmermann A. (2004): Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 (15). Eidg. Forschungsanstalt für Agrarökologie und Landbau (FAL), Zürich-Reckenholz.
Ramsden, S., Gibbons, J. and Wilson, P. (1999): Impacts of changing relative prices on farm level dairy production in the UK. *Agricultural Systems* 62: 201-215.
Rigby, D. and Young, T. (1996): European environmental regulations to reduce water pollution: An analysis of their impact on UK dairy farms. *European Review of Agricultural Economics* 23: 59-78.
Trunk, W. (1995): Ökonomische Beurteilung von Strategien zur Vermeidung von Schadgasemissionen bei der Milcherzeugung - dargestellt für Allgäuer Futterbaubetriebe. Diss. Univ. Hohenheim, Studien zur Agrarökologie Bd. 15: 175 S.
Valencia, V. and Anderson, D. (2000): Choosing optimal Milk Production systems in a changing economic environment. *Farm Management* 10 (10): 618-631.
Ven, G.W.J. van de (1996): A mathematical approach to comparing environmental and economic goals in dairy farming on sandy soils in the Netherlands. PhD Thesis, Wageningen Agricultural University.
Vogstad, K.O., Strømman, A.H. and Hertwich E. (2002): Multiple Product Systems Environmental Assessment - Combining Hybrid LCA & Linear Programming. Platform presentation at the SETAC conference 2002, 13.-16. May 2002, Vienna, Austria.
Zimmermann, A., Hausheer, J. and Pfefferli, S. (1997): Ammoniak: Kosten der Emissionsminderung. Betriebswirtschaftliche Beurteilung der Möglichkeiten zur Reduktion der Ammoniak-Emissionen in der Schweiz. *FAT-Schriftenreihe* (44): 130 pp.