Environmental impact of dairy cattle production systems

-an integral assessment-

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-an integral assessment-

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You can not live the future without acknowledging the past.

Marlies Thomassen

In het verleden,
ligt het heden.
in het nu,
wat worden zal.

Willem Bilderdijk

Abstract

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Most studies that assess the environmental impact of milk production focus on one environmental aspect or improvement options at farm level. Transfers between environmental pollutants, a phenomenon known as pollution swapping, can occur at farm level or between on and off farm pollution, and therefore, an integral assessment is needed. The general objective of the research presented in this thesis was to quantify the integral environmental impact of dairy cattle production systems in the Netherlands. The environmental impact of dairy cattle production systems can be assessed by indicators derived from Input-Output Accounting (IOA), Ecological FootPrint analysis (EFP), and Life Cycle Assessment (LCA). LCA indicators appeared to be most effective, because of their high relevance, good quality, and the fact that they focus on more than one environmental aspect and take into account pollutants throughout the production chain. Within LCA, two approaches were identified: attributional LCA (ALCA) and consequential LCA (CLCA). Different ways of how to handle co-products (mass allocation; economic allocation; system expansion) are applied within each method. LCA practitioners choose between ALCA and CLCA which is shown to result in differences in: total quantitative outcomes, environmental hotspots, degree of understanding, and sensitivity to uncertainties. It is recommended, therefore, to relate the choice of ALCA or CLCA to the research question. Different ways of milk production exist, such as milk produced in a conventional or organic dairy cattle production system. A comparison between the integral environmental impact of these two systems showed that, per kg of standardized milk, the organic dairy cattle production system had a lower energy use and eutrophication potential than the conventional system, whereas the conventional system had a lower land use. Acidification potential and global warming potential were similar for both systems. Purchased concentrates was an environmental hotspot for both the conventional and organic dairy cattle production system. To gain insight into the relation between economic and ecological sustainability of a dairy cattle production system, analysis of a large number of farms is required. This research showed that the Dutch Farm Accountancy Data Network (FADN) was suitable to perform an LCA of individual dairy farms. For 119 FADN dairy farms, LCA indicators were related to net farm income. Results showed that dairy cattle production systems with a high net farm income had a low on farm land use, total land use, energy use at the dairy farm, on farm and total climate change, all per kg standardized milk, but a high total and on farm eutrophication and acidification per hectare. The farm characteristics that influenced these relations were: farm size, Dutch livestock units per hectare, milk production per cow, purchased concentrates per 100 kg FPCM, and milk urea content. The LCA dairy model constructed within the research presented in this thesis proved to be a valid basis for further research to evaluate innovations and improvement options.

Key Words: Integral Assessment, LCA Indicators, Climate Change, Acidification, Organic, Conventional, Dairy Farming, Net Farm Income, The Netherlands

Voorwoord

Het begon allemaal met een mailtje van Imke de Boer tijdens mijn stage in Nieuw Zeeland in 2002: „Weet je wat LCA is?” De correspondentie ging over een afstudeervak dat ik na mijn stage mogelijk bij haar zou gaan doen. Ik was bezig met genetisch onderzoek naar schapen, PCR’s en gels maken op het laboratorium, zat middenin het rugby-seizoen en schapenscheerdersfeesten; LCA klonk me niet als muziek in de oren op dat moment. Bij terugkomst in Nederland en na een kennismakingsgesprek met Imke, was mijn LCA (levenscyclusanalyse) interesse echter gewekt. Samen met medestudente Trudy Straetemans hebben we de methodiek aangepakt en toegepast op biologische melkveebedrijven, wat jaren later resulteerde in mijn eerste publicatie.

Een jaar na de afronding van het LCA- afstudeervak studeerde ik af, en na een paar maanden gewerkt te hebben bij het Ministerie LNV voor de financiële afhandelingen van de vogelpest, kwam er een plek als toegevoegd docente vrij bij de leerstoelgroep Dierlijke ProductieSystemen (DPS). De coördinatie van BSc-vakken, en het lesgeven binnen de studie Dierwetenschappen en Biologische ProductieWetenschappen hebben mij veel nieuwe vaardigheden geleerd die ik later tijdens mijn promotie kon gebruiken. Tevens kwam ik in aanraking met mijn gemis aan diepgang tijdens het doceren, waardoor alles veel (meer) voorbereidingstijd kostte. Mijn keuze was gemaakt na bijna twee jaar doceren; ik wilde het onderzoek in! Ik was ‘besmet’ geraakt met LCA!

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Marlies Thomassen
Wageningen, januari 2008

Contents

Chapter 1

General introduction

1.1 Background and scope

Milk production on dairy farms in The Netherlands contributed to food production for centuries (Boekel, 1936). The way in which milk was produced changed after World War II, as a result of specialization, mechanization, and technological innovation (De Kroon, 1984; Bieleman, 2005). The Common Agricultural Policy (CAP) of the European Union (EU), established in 1957, stimulated intensification of agricultural production by price support. Scaling-up and intensification characterized the Dutch dairy cattle sector since 1960. In The Netherlands, animal intensity has always been higher than in other EU member states. From 1970 to 1984, animal intensity (expressed in number of dairy cows per hectare) increased by 38%, dairy herd size increased by 34%, while total number of dairy farms decreased by 50%. From 1975 to 1985, average milk production per cow increased by 15% (LEI, 2005). This intensification of milk production resulted in bulk production of butter. Milk quotas were introduced in 1984 to limit growth of milk production (Oenema, 2004). As a consequence of intensified agricultural production in The Netherlands, such as large-scale intensification of the dairy cattle production system, environmental side-effects became visible. Milk production on dairy farms causes ammonia emission, which contributes to acid deposition; leaching of nitrate and phosphate, which contribute to nutrient water enrichment; and carbon dioxide, methane, and nitrous oxide emissions, which contribute to climate change (Monteny, 2000; Ondersteijn *et al.*, 2002; Casey and Holden, 2005). To limit side-effects of intensified agricultural production, environmental policy measures were implemented (Henkens and Van Keulen, 2001; Oenema, 2004).

Ammonia volatilized from animal manure increased as a result of large-scale intensification of livestock production systems, and contributed to acid deposition that caused damage of forest vegetation (Steinfeld *et al.*, 2006). The Fertilizers Act (1986) was implemented to control animal manure production by regulating the number of animals, whereas the Guideline for Ammonia and Animal Husbandry (1987) was implemented to control acidification in sensitive areas (Oenema, 2004; Starmans and Van der Hoek, 2007). The EU introduced the Air Quality Directive (1999) to limit ammonia and nitrogen oxides emissions into the atmosphere. To reduce acidification and eutrophication further, the National Emission Ceilings Directive (2001) was implemented based on the Gothenburg Protocol (Starmans and Van der Hoek, 2007). In this Directive, limits were set for each EU member state for the polluting components: sulphur dioxide, nitrogen oxides, ammonia, and volatile organic compounds (Starmans and Van der Hoek, 2007).

Nitrate and phosphate leaching of agricultural production systems increased as a result of the intensive use of nitrogen and phosphorus. This leaching contributed to the decline of the ecological quality of surface water and groundwater. The EU issued the Nitrate Directive, which is part of the Water Framework Directive, to establish a safety threshold of 50 mg nitrate per liter of groundwater (Henkens and Van Keulen, 2001; Oenema, 2004). The Dutch government ratified the Nitrate Directive in 1991. The Dutch manure policy focused from 1991 to 1998 on a stepwise decrease of the manure burden, which was extended to move towards balanced inputs of nitrogen and phosphorus from 1998 to the present (Henkens and Van Keulen, 2001). The MINeral Accounting System (MINAS) was introduced in The Netherlands in 1998 to comply with the Nitrate Directive. MINAS recorded all nitrogen and phosphorus inputs and outputs at farm level, based on a farm-gate balance, with levy-free standards for acceptable mineral losses (Schröder *et al.*, 2003). In 2003, the European Court of Justice rejected MINAS as policy instrument to meet the EC Nitrate Directive standards (Anonymous, 2004). Since January 2006, fertilizer application standards replaced MINAS legislation (De Hoop *et al.*, 2004).

As a result of large-scale intensification of agricultural production systems, carbon dioxide, methane, and nitrous oxide emissions increased. These increased emissions contributed to climate change (IPCC, 2006). The rising sea level and temperature due to greenhouse gases threatens the maintenance of future biodiversity (Steinfeld *et al.*, 2006). The Dutch Government ratified the Kyoto Protocol in 2002 and thereby agreed to reduce its emissions of greenhouse gasses by 6% in the period 2008-2012, compared with the level in 1990 (UNFCCC, 1997; Minnesma, 2003). No specific targets for agriculture were determined.

Environmental legislation does not stand alone; science and policy are interrelated (Van den Hove, 2007; Willems and de Lange, 2007). Research is needed to initiate, support and evaluate environmental legislation (Brink *et al.*, 2001; Pluimers, 2001; Starmans and Van der Hoek, 2007). The focus of legislation to reduce environmental pollution at farm level, promoted research at farm level. Environmental aspects were addressed individually in legislation, which stimulated research on individual environmental aspects.

Most research related to milk production focused on analysis or improvement of the environmental impact at dairy farm level. Nutrient balances were part of Dutch environmental legislation, which stimulated an efficient use of nitrogen and phosphorus (Erisman *et al.*, 2001; Ondersteijn *et al.*, 2003; Langeveld *et al.*, 2007). The experimental dairy farm De Marke, for example, was studied to gain insight into nitrate leaching to groundwater on sandy soils (Hack-ten Broeke *et al.*, 1999; Aarts *et al.*, 2000), whereas one of the goals of the Cows and Opportunities project was to optimize nutrient use at farm level (Hanegraaf and Den Boer, 2003). By focusing on nitrogen and phosphorus, insight was gained into emission of ammonia, nitrogen oxides, and nitrous oxide, besides leaching of nitrate and phosphate to surface water and groundwater. Additional research was carried out for ammonia volatilization of animal manure. Insight was gained into mitigation options, by using for instance different application technologies or housing designs (Monteny, 2000; Smits *et al.*, 2003; Mosquera *et al.*, 2006). Methane emission from enteric fermentation and manure management was modeled at farm and animal level to gain insight into possible mitigation options (Kebreab *et al.*, 2004; Monteny *et al.*, 2006; Mosquera *et al.*, 2006; Bannink *et al.*, In Press). Van Calker *et al.* (2004) modelled eutrophication, groundwater pollution, dehydration of the soil, acidification, climate change, and eco-toxicity at dairy farm level. Insight was gained into effects of farm management and environmental policy on the environmental impact at farm level.

Transfers between environmental pollutants, referred to as pollution swapping, can occur at farm level (Brink, 2003; Klimont and Brink, 2004). The amount of ammonia volatilized and the amount of nitrate leached, for example, interrelate at farm level (Wolf *et al.*, 2005). A good environmental performance at dairy farm level can imply a high environmental burden elsewhere in the production chain. Pollution swapping between on and off farm pollution can occur. It is important, therefore, to address several environmental aspects within the production chain. Life Cycle Assessment (LCA) is one approach to account for emissions and resources used during the entire life cycle of a product. LCA was used to study the environmental impact of the milk production chain in other countries (Cederberg, 2002; Høgaas Eide, 2002; Hospido *et al.*, 2003; Sonesson and Berlin, 2003; Casey and Holden, 2005). In The Netherlands, however, not much attention is paid yet to off-farm environmental impacts. An energy yardstick was developed, which enables one to quantify total energy use of farms (Mombarg and Kool, 2004). Furthermore, Schils *et al.* (2007) developed a dairy-farm model for greenhouse gas emission that includes emissions during production and transport of inputs, and explored this model by analyzing intensive dairy cattle production systems in The Netherlands (Schils *et al.*, 2006).

In conclusion, more knowledge is present about environmental impact of dairy cattle production systems at farm level than about off farm and total environmental impact. Insufficient knowledge is present about pollution swapping, so that an integral approach is needed. Nowadays around 10.5 million tons of milk are produced annually on about 20,000 specialized Dutch dairy farms that depend on many inputs, such as artificial fertilizer and concentrates (Binternet, 2006; Productschap Zuivel, 2007). An integral environmental impact assessment of the dairy cattle production system in The Netherlands is needed that takes into account the production chain, and that focuses on more than one environmental aspect. The aim of this thesis is to quantify the integral environmental impact of dairy cattle production systems in The Netherlands.

1.2 Objectives

The first goal is to inventory how the integral environmental impact of dairy cattle production systems can be assessed. Input-Output Accounting (IOA) is a process-oriented on-farm method frequently used to assess nutrient surpluses of agricultural production systems, whereas Ecological FootPrint analysis (EFP) and Life Cycle Assessment (LCA) are life-cycle-based methods that include impacts of the entire production chain. Indicators derived from these three methodologies are evaluated based on their relevance, quality, and availability of data to assess their effectiveness. An indicator is relevant when it provides relevant information about the system in question and if it is understandable to all stakeholders involved. An indicator is of good quality when it is reliable, sensitive, and when a trend or target value can be determined. An indicator should be based on available data, i.e., information, that is available currently or that can be gathered, so that data collection is technically and financially feasible.

Within LCA, two approaches were identified: attributional LCA and consequential LCA. LCA practitioners choose between attributional LCA and consequential LCA when assessing the integral environmental impact of a production system. Attributional

LCA describes the pollution and resource flows within a chosen system attributed to delivery of a specified amount of the functional unit. Consequential LCA estimates how pollution and resource flows within a system change in response to change in output of the functional unit. Different ways of how to handle co-products (mass allocation; economic allocation; system expansion) are applied within each method. Insight is needed into the effect of these choices within LCA on results. The second goal, therefore, is to assess differences between attributional LCA and consequential LCA when assessing the integral environmental impact of dairy cattle production systems.

After identifying effective indicators and assessing differences between attributional LCA and consequential LCA, the integral environmental impact of dairy cattle production systems can be assessed.

Different ways of milk production exist, such as milk produced in a conventional or organic dairy cattle production system. Dairy farmers are forced to look for different managerial ways to address environmental policy. One way to comply with future environmental legislation maybe to convert from a conventional to an organic dairy cattle production system, because organic farmers use fewer inputs. A comparison between conventional and organic systems is needed to address advantages and disadvantages of each system. The third goal, therefore, is to assess differences in integral environmental impact between conventional and organic systems, and to identify environmental hotspots[1] within these two systems.

Preferably, a large number of farms need to be taken into account when performing an LCA. Data collection, however, is often time-consuming and limited due to financial reasons. A need exists to identify of existing databases can be used to perform an LCA. The fourth goal, therefore, is to identify if the Farm Accountancy Data Network (FADN) can be used to perform an LCA of individual dairy farms.

The concept sustainability is built upon the three pillars: people, planet, and profit. Preferably, more than one pillar of sustainability should be addressed. By performing an LCA of dairy cattle production systems, insight is gained into environmental sustainability, the “planet”, of the dairy sector. No sector is sustainable without economic viable farms, the “profit”. Insight is needed into the relationship between environmental and economic performance of dairy cattle production systems. Subsequently, farm characteristics that influence this relationship must be identified, in order to gain insight into when net farm income is high and environmental burdens are low. The fifth goal, therefore, is to assess the relationship between LCA indicators and net farm income of dairy cattle production systems, besides the identification of farm characteristics that influence this relationship.

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[1] An identified environmental hotspot is an element that has a high contribution to the environmental burden of a product (Guinée et al., 2002)

The following research questions were formulated:

1. What are effective indicators to assess the integral environmental impact of dairy cattle production systems?
2. What are the differences between attributional LCA and consequential LCA when assessing the integral environmental impact of dairy cattle production systems?
3. What are the differences in integral environmental impact and environmental hotspots between conventional and organic dairy cattle production systems?
4. Is the Farm Accountancy Data Network (FADN) suitable to perform an LCA of individual dairy farms?
5. What is the relationship between LCA indicators and net farm income of dairy cattle production systems, and what are the underlying farm characteristics that influence this relationship?

1.3 Outline

The structure shown in Table 1.1 was used to answer the research questions. Chapters 2 and 3 focus on methodological choices, whereas Chapters 4 and 5 focus on application of the LCA methodology. In Chapter 2, indicators for environmental impact assessment derived from Input-Output Accounting (IOA), Ecological FootPrint analysis (EFP), and Life Cycle Assessment (LCA) are evaluated on their effectiveness by assessing the environmental impact of commercial organic dairy farms. Evaluation of effectiveness is based on an assessment of their relevance, quality, and availability of data. In chapter 3 attributional LCA and consequential LCA and different ways of how to handle co-products (mass allocation; economic allocation; system expansion) are compared by assessing the integral environmental impact of a conventional dairy cattle production system. There are four criteria used for this comparison: hotspot identification, comprehensibility, availability, and quality of data.

Table 1.1 Overview of the structure of the thesis

Chapter	Characteristic	Data used	Scope
2	Method	Commercial farms	Indicators derived from IOA, EFP, and LCA were evaluated on their effectiveness by assessing the environmental impact of organic dairy farms.
3	Method	Average and marginal data	Attributional LCA and consequential LCA were compared by assessing the integral environmental impact of a conventional dairy cattle production system.
4	Application	Commercial farms	Two Dutch dairy cattle production systems, i.e. a conventional and an organic system, were compared on their integral environmental impact and identified environmental hotspots.
5	Application	Farm Accountancy Data Network	The relationship between economic and ecological performance of dairy cattle production systems was assessed, supplemented with identification of farm characteristics that influence this relationship.

Chapter 4 presents outcomes of LCA applied on conventional and organic dairy cattle production systems, using data from 21 commercial dairy farms. Differences in integral environmental impact and differences in environmental hotspots are identified and suggestions for mitigation options are given. In Chapter 5, the environmental sustainability approach presented in this thesis is related to the economic indicator net farm income. The integral environmental impact and net farm income are assessed for 119 conventional dairy farms that were included in the Farm Accountancy Data Network (FADN). Relations between LCA indicators and net farm income are investigated. Furthermore, farm characteristics that influence these relations are identified. Finally, Chapter 6 discusses methodological issues and results of the study, and presents the main conclusions. Main discussion issues include the choice of the dairy cattle production system, selection of methodology, choices within LCA methodology, implementation of the integral environmental impact assessment, and the focus on the pillar planet of sustainability. Recommendations for further research are given.

References

Aarts, H.F.M., Habekotté, B., Van Keulen, H., 2000. Nitrogen (N) management in the 'De Marke' dairy farming system. Nutrient Cycling in Agroecosystems 56, 231-240.

Anonymous, 2004. Mineralen beter geregeld; evaluatie van werking van de Meststoffenwet 1998-2003. Milieu en -Natuurplanbureau RIVM, Bilthoven, pp. 1-170.

Bannink, A., France, J., Lopez, S., Gerrits, W.J.J., Kebreab, E., Tamminga, S., Dijkstra, J., In Press. Modelling the implications of feeding strategy on rumen fermentation and functioning of the rumen wall. Animal Feed Science and Technology In Press, Corrected Proof.

Bieleman, J., 2005. Technological innovation in Dutch cattle breeding and dairy farming, 1850-2000. Agricultural History Review 53, 229-250.

Binternet, 2006. Het Bedrijven-InformatieNet van het LEI, Vol. 2007, www.lei.wur.nl/NL/statistieken/Binternet/.

Boekel, N.P., 1936. Eenige beschouwingen inzake de ontwikkeling van veehouderij en zuivelbereiding in de 19e eeuw tot de opkomst van het fabrieksmatig zuivelbedrijf. Rijkszuivelconsulent provincie Noordholland te Hoorn, Rijswijk, The Netherlands, pp. 1-16.

Brink, C., Kroeze, C., Klimont, Z., 2001. Ammonia abatement and its impact on emissions of nitrous oxide and methane - Part 2: Application for Europe. Atmospheric Environment 35, 6313-6325.

Brink, C. 2003. Modelling cost-effectiveness of interrelated emission reduction strategies - the case of agriculture in Europe, Wageningen University, Wageningen.

Casey, J.W., Holden, N.M., 2005. Analysis of greenhouse gas emissions from the average Irish milk production system. Agricultural Systems 86, 97-114.

Cederberg, C. 2002. Life Cycle Assessment (LCA) of animal production, Göteborg University, Göteborg.

De Hoop, D.W., Luesink, H.H., Prins, H., Daatselaar, C.H.G., van Bommel, K.H.M., Mokveld, L.J., 2004. Effecten in 2006 en 2009 van mestakkoord en nieuw EU-landbouwbeleid. LEI, Den Haag, pp. 1-182.

De Kroon, A.M.B.G., 1984. 100 jaar melk en zuivel in Venray e.o. DMV Campina bv; boterdivisie, Oirlo, gemeente Venray, The Netherlands.

Erisman, J.W., de Vries, W., Kros, H., Oenema, O., van der Eerden, L., van Zeijts, H., Smeulders, S., 2001. An outlook for a national integrated nitrogen policy. Environmental Science & Policy 4, 87-95.

FADN, 2007. Farm Accountancy Data Network, Vol. Available online (March 1st 2006), ec.europa.eu/agriculture/rica/index_en.cfm.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H., van der Ven, B.L., Weidema, B.P. (Eds.), 2002. Handbook on Life Cycle Assessment; Operational Guide to the ISO Standards. Centrum voor Milieukunde- Universiteit Leiden (CML); Kluwer Academic Publishers., Leiden, The Netherlands.

Hack-ten Broeke, M.J.D., Schut, A.G.T., Bouma, J., 1999. Effects on nitrate leaching and yield potential of implementing newly developed sustainable land use systems for dairy farming on sandy soils in The Netherlands. Geoderma 91, 217-235.

Hanegraaf, M.C., Den Boer, D.J., 2003. Perspectives and limitations of the Dutch minerals accounting system (MINAS). European Journal of Agronomy 20, 25-31.

Henkens, P.L.C.M., Van Keulen, H., 2001. Mineral policy in The Netherlands and nitrate policy within the European Community. Netherlands Journal of Agricultural Science 49, 117-134.

Høgaas Eide, M., 2002. Life Cycle Assessment (LCA) of Industrial Milk Production. International Journal of LCA 7, 115-126.

Hospido, A., Moreira, M.T., Feijoo, G., 2003. Simplified life cycle assessment of Galician milk production. International Dairy Journal 13, 783-796.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental panel on climate change; Greenhouse gas inventory reference manual. Volume 4.

Kebreab, E., Mills, J.A.N., Crompton, L.A., Bannink, A., Dijkstra, J., Gerrits, W.J.J., France, J., 2004. An integrated mathematical model to evaluate nutrient partition in dairy cattle between the animal and its environment. Animal Feed Science and Technology 112, 131-154.

Klimont, Z., Brink, C., 2004. Modelling of emissions of air pollutants and greenhouse gases from agricultural sources in Europe. International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1-69.

Langeveld, J.W.A., Verhagen, A., Neeteson, J.J., van Keulen, H., Conijn, J.G., Schils, R.L.M., Oenema, J., 2007. Evaluating farm performance using agri-environmental indicators: Recent experiences for nitrogen management in The Netherlands. Journal of Environmental Management 82, 363-376.

LEI, 2005. Landbouw Economisch Instituut. Land- en tuinbouwcijfers 2005. Jaarrapporten van het LEI en het CBS, Den Haag, The Netherlands.

Minnesma, M.E., 2003. Dutch climate policy: A victim of economic growth? Climate Policy 3, 45-56.

Mombarg, H., Kool, A., 2004. Telen met toekomst energie- en klimaatmeetlat. Plant research International B.V., Wageningen, pp. 1-52.

Monteny, G.J. 2000. Modelling of ammonia emissions from dairy cow houses. PhD, Wageningen University, Wageningen.

Monteny, G.J., Bannink, A., Chadwick, D., 2006. Greenhouse gas abatement strategies for animal husbandry. Agriculture, Ecosystems & Environment 112, 163-170.

Mosquera, J., Hol, J.M.G., Monteny, G.J., 2006. Gaseous emissions from a deep litter farming system for dairy cattle. International Congress Series 1293, 291-294.

Oenema, O., 2004. Governmental policies and measures regulating nitrogen and phosphorus from animal manure in European agriculture. Journal of Animal Science 82, E196-E206.

Ondersteijn, C.J.M., Beldman, A.C.G., Daatselaar, C.H.G., Giesen, G.W.J., Huirne, R.B.M., 2003. Farm structure or farm management: effective ways to reduce nutrient surpluses on dairy farms and their financial impacts. Livestock Production Science 84, 171-181.

Ondersteijn, C.J.M., Beldman, A.C.G., Daatselaar, C.H.G., Giesen, G.W.J., Huirne, R.B.M., 2002. The Dutch Mineral Accounting System and the European Nitrate Directive: implications for N and P management and farm performance. Agriculture, Ecosystems & Environment 92, 283-296.

Pluimers, J. 2001. An environmental systems analysis of greenhouse horticulture in The Netherlands; the tomato case, Wageningen University, Wageningen.

Productschap Zuivel, 2007. Melkverwerking en zuivelhandel, Vol. 2007, www.prodzuivel.nl.

Schils, R.L.M., Verhagen, A., Aarts, H.F.M., Kuikman, P.J., Sêbek, L.B., 2006. Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in The Netherlands. Global Change Biology 12, 382-391.

Schils, R.L.M., De Haan, M.H.A., Hemmer, J.G.A., Van den Pol-Van Dasselaar, A., De Boer, J.A., Evers, G.A., Holshof, G., Van Middelkoop, J.C., Zom, R.L.G., 2007. Dairywise, a whole-farm dairy model. Journal of Dairy Science 90, 5334-5346.

Schröder, J.J., Aarts, H.F.M., Ten Berge, H.F.M., Van Keulen, H., Neeteson, J.J., 2003. An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. European Journal of Agronomy 20, 33-44.

Smits, M.C.J., Monteny, G.J., Van Duinkerken, G., 2003. Effect of nutrition and management factors on ammonia emission from dairy cow herds: models and field observations. Livestock Production Science 84, 113-123.

Sonesson, U., Berlin, J., 2003. Environmental impact of future milk supply chains in Sweden: a scenario study. Journal of Cleaner Production 11, 253-266.

Starmans, D.A.J., Van der Hoek, K.W., 2007. Ammonia, the case of The Netherlands. Wageningen Academic Publishers, Wageningen, The Netherlands.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C., 2006. Livestock's long shadow; environmental issues and options. Food and Agricultural Organization of the United Nations, Rome, Italy.

UNFCCC, 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change, www.unfccc.int.

Van Calker, K.J., Berentsen, P.B.M., de Boer, I.J.M., Giesen, G.W.J., Huirne, R.B.M., 2004. An LP-model to analyse economic and ecological sustainability on Dutch dairy farms: model presentation and application for experimental farm "de Marke". Agricultural Systems 82, 139-160.

Van den Hove, S., 2007. A rationale for science-policy interfaces. Futures 39, 807-826.

Willems, P., de Lange, W.J., 2007. Concept of technical support to science-policy interfacing with respect to the implementation of the European water framework directive. Environmental Science & Policy 10, 464-473.

Wolf, J., Hack-ten Broeke, M.J.D., Rotter, R., 2005. Simulation of nitrogen leaching in sandy soils in The Netherlands with the ANIMO model and the integrated modeling system STONE. Agriculture, Ecosystems & Environment 105, 523-540.

Chapter 2

Evaluation of indicators to assess the environmental impact of dairy production systems

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Abstract

Current awareness of environmental pollution of animal production in Western Europe has triggered research on development of environmental indicators at farm level. Only when the environmental impact of commercial farms can be quantified effectively, important differences in impact can be demonstrated among contrasting systems, which subsequently can contribute to reducing the environmental impact from animal production. Therefore, the aim of this study was to evaluate the effectiveness of environmental indicators derived from three methods used widely in animal production, i.e., input-output accounting, ecological footprint analysis and life cycle assessment (LCA). Evaluation of the effectiveness of indicators was based on an assessment of their relevance, quality and availability of data. Such a systematic evaluation of these environmental indicators has never been performed yet. To evaluate the effectiveness of the thirteen environmental indicators, data from eight organic, commercial dairy farms in the Netherlands were used. Results show that indicators derived from input-output accounting are effective, because of their high relevance, good quality and easy availability of data. These indicators, however, do not include all environmental impact categories (e.g., land use, energy use, global warming potential), and focus on on-farm emission. The environmental indicator derived from ecological footprint analysis is not effective for land and fossil energy use, because of its limited relevance and low quality, whereas LCA resource-based indicators are effective because of their high relevance, good quality and availability of data. LCA indicators for global warming, acidification and eutrophication potential are effective also, because of their good relevance and good quality. Data of these LCA indicators are difficult to collect. To give a good insight into the environmental impact of a dairy production system, besides input-output accounting indicators, LCA indicators are required.

2.1 Introduction

In Western Europe, animal productivity per unit of land, labour and capital is high. This high productivity was obtained by effective introduction of 'land-saving-technologies', such as use of artificial fertilizer and imported feed stuffs, and 'labour-saving-technologies', such as large-scale mechanization, specialization and scaling-up (Bieleman, 1998).

In The Netherlands, the first warnings to indicate an imbalance between the rapidly growing livestock numbers and the agricultural area used for arable production, horticulture and fodder production were already noticeable at the end of the 1960s (Bieleman, 1998). Environmental legislation, however, was not enforced until after 1986 with the introduction of the Manure and fertilizer act, and the Soil protection act (Bieleman, 1998).

Current awareness of environmental pollution from animal production has triggered research on the interface between animal production and the environment, to assess the ecological sustainability of various animal production systems in an integrated manner (Cederberg and Mattsson, 2000; Van Dijk, 2001; Cederberg and Dalerius, 2000, 2001; Haas *et al.*, 2001; De Boer, 2003; Basset-Mens and Van der Werf, 2005). These studies, however, are based largely on data from a small number of experimental farms (Cederberg and Mattsson, 2000; De Boer, 2003) or "average production data" of production systems (Van Dijk, 2001; Basset-Mens and Van der Werf, 2005). To show differences in environmental performance among production systems, such as organic and conventional milk production, the environmental impact should be assessed not on a few *experimental* farms but rather on a number of *commercial* farms for each production system of interest (De Boer, 2003).

At present, a variety of methods are in use to assess the environmental impact of contrasting agricultural production systems at farm level (Van der Werf and Petit, 2002; Goodlass *et al.*, 2003). Differences exist among environmental assessment methods. Such methods can be process-oriented and merely include on-farm emissions (Halberg *et al.*, 2005). A process-oriented method used widely in agricultural production, is the input-output accounting approach (Halberg *et al.*, 2005). This approach computes the difference in, for example, nutrients entering and leaving the farm gate, while the farm itself is considered a black box. The difference between nutrient inputs and outputs (i.e., the nutrient loss) is assumed to be lost into the environment (Ondersteijn *et al.*, 2002a; Goodlass *et al.*, 2003).

Life cycle based methods evaluate global emissions and impacts from the entire production chain, in relation to types and amounts of products produced (Halberg *et al.*, 2005). Such methods compute the integrated environmental impact of an agricultural activity throughout its life cycle. Examples of life cycle based methods commonly used in agricultural production are ecological footprint analysis (Wackernagel and Rees, 1996) and life cycle assessment (Haas *et al.*, 2000).

The aim of this article was to evaluate the effectiveness of environmental indicators derived from process-oriented and life cycle based methods used commonly in animal production, i.e. input-output accounting, ecological footprint analysis and life cycle assessment. Evaluation of the effectiveness of various indicators was based on an assessment of their relevance, quality and availability of data to determine the environmental impact of commercial dairy farms. Only when the environmental impact of commercial dairy farms can be quantified effectively, important differences in the environmental impact can be demonstrated between contrasting dairy production systems. To evaluate the effectiveness of various environmental indicators, data from eight organic commercial dairy farms were used.

2.2 Material and methods

2.2.1 Data

To assess the effectiveness of environmental indicators, the environmental impact of eight organic commercial dairy farms was computed, using input-output accounting of nitrogen (N) and phosphorus (P), ecological footprint analysis, and life cycle assessment. These eight farms participated in a demonstration project of Dutch organic dairy farmers, the so-called BIOVEEM project (Meijs *et al.*, 2000). In this project, on-farm data were collected on a regular basis to improve farm performance. Additional on-farm and off-farm data were obtained by questionnaires and expert consultation. Table 2.1 provides some general characteristics of the organic dairy farms studied; data refer to year 2000. Annual inputs were corrected for supplies of manure and roughage.

Table 2.1 General characteristics of organic dairy farms in the study

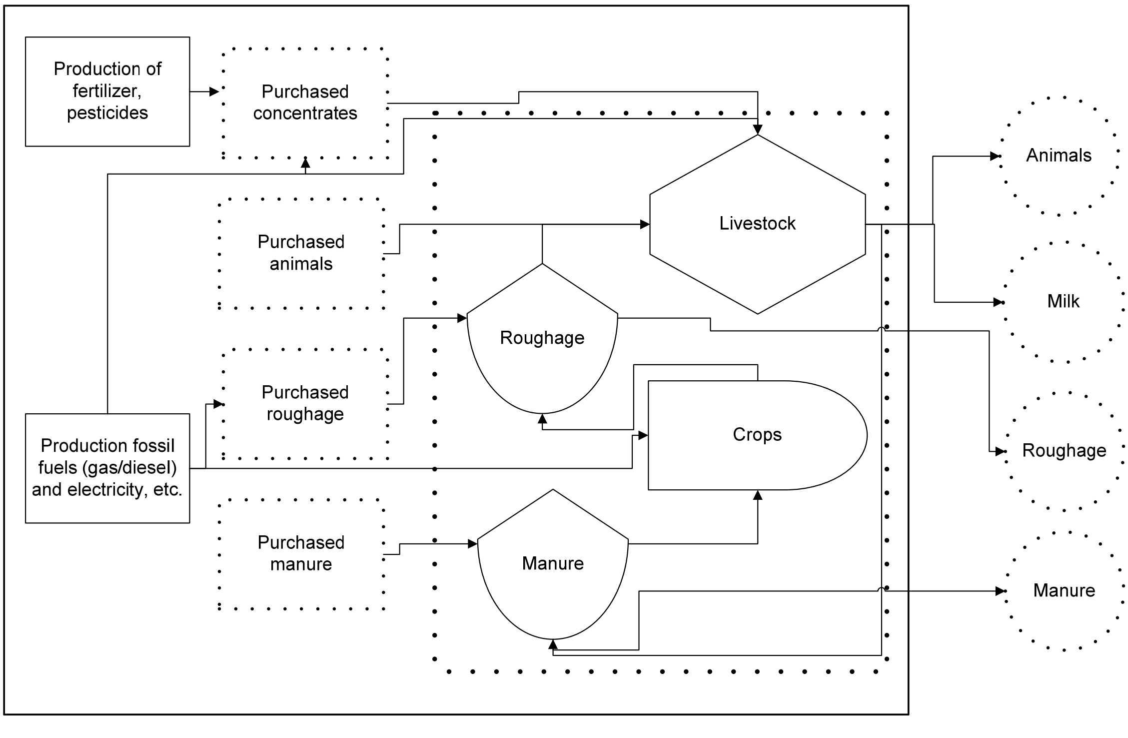
Parameters	Dimension	Farms							
		A	B	C	D	E	F	G	H
Grassland	ha	25.5	31.7	50	34.3	37.3	36.3	37.4	35
Arable land	ha	0	8	6	0	2.5	9.2	4.3	20
Stable type[a]		C	C	H	C	C	C	M	C
Dairy cows	n	38	65	60	44	44	70	42	72
Density	LU/ha[b]	1.72	2.01	1.25	1.66	1.43	1.88	1.13	1.69
Production	kg/cow per yr	7600	6219	5405	7675	6359	6546	4723	6463
Production	tonne milk/ha	11.3	10.2	5.8	9.9	7.0	10.1	4.8	8.5
Clover fixation	kg N/ha	26	129	50	61	125	62	67	47
Purchased manure	tonne	198	0	0	0	221	0	0	302
Purchased roughage	tonne WW[c]	89	290	0	140	134	6	0	60
Purchased straw	tonne	0	0	120	0	0	0	0	0

[a] C = Cubicle stable; H = hill chamber stable; M = mix of cubicle stable and chamber stable.
[b] LU = Dutch Livestock Units (Bureau Heffingen, 2001). 1 LU = the yearly phosphate excretion of one milking cow (41 kg). Other animal categories are related to this LU dependent on their yearly phosphate excretion, e.g. one heifer = 0.44 LU (Phosphate production = 18/41).
[c] WW = Wet weight.

2.2.2 Input-output accounting of nutrients

For each dairy farm, the annual farm surplus of N and P was computed using input-output accounting at farm level. This surplus was derived from the difference between farm inputs and outputs; the farm itself was considered a black box (Ondersteijn *et al.*, 2002a,b). The difference between nutrient inputs and outputs is called "farm surplus", expressed per ha farm area, and is assumed to be lost into the environment. Definition of the system boundaries is illustrated in Figure 2.1.

Relevant inputs and outputs and the computation procedure are shown in Table 2.2. The N input through purchased concentrates, for example, was computed by multiplying the amount of each concentrate purchased by a farm, by its nutrient content. The nutrient content was obtained from the feed industry or estimated from concentrate composition and related nutrient contents. N-fixation per farm was estimated by assessing the gross clover yield DM per grassland area (based on an average estimate in spring and late summer), assuming an N-fixation of 50 kg N per tonne clover (Meijs *et al.*, 2000). Similarly, N output was computed by multiplying amount of each product sold, such as animals, milk, manure and roughage, by its nutrient content. Finally, the annual farm surplus of N was derived from the difference between N input and N output (see Table 2.2), and expressed per farm area. This annual farm N surplus, however, included N losses into the environment due to emission of NH_3, NO_x, and N_2O, and to leaching of NO_3^- (Bentrup *et al.*, 2000). The amount of organic N in the soil was assumed to be constant, implying equal mineralization and immobilization rates. To specify further the annual N surplus of a farm, we corrected it for the annual emission of NH_3 (see Table 2.2). The final N surplus per ha farm area, therefore, included N losses into the environment due to emission of NO_x and N_2O, and to leaching of NO_3^- only.



• • • System boundary input-output accounting
—— System boundary 'cradle to farm-gate' methods like EFP and LCA

Figure 2.1 System boundaries

The annual NH_3 emission of a farm consisted of the annual animal-based NH_3 emission plus the annual area-based NH_3 emission. The annual animal-based NH_3 emission included emission from the barn, from manure storage facilities and from grazing, and was computed by multiplying animal numbers by its reference value (Oenema *et al.*, 2000). The annual area-based NH_3 emission included emission during on-farm application of animal manure, and was computed by multiplying the amount of mineral N applied (Mooij, 1996) by relevant NH_3 emission factors (Van der Hoek, 2002). Input-output accounting of nutrients, therefore, yielded three environmental indicators; annual NH_3 emission per ha farm area, surplus of N (kg) per ha farm area, and surplus of P (kg) per ha farm area.

Table 2.2 Input-output accounting of nutrients at an organic dairy farm

Element	Computation[a]	References
Input		
Purchase of concentrates	Q × nutrient content purchased concentrates	CVB (2000)
Purchase of roughage	Q × nutrient content purchased roughage	CVB (2000)
Purchase of animals	Q × standardized nutrient content animals	Bureau Heffingen (2001)
Purchase of manure	Q × standardized nutrient content manure	Bureau Heffingen (2001)
Atmospheric deposition	Average value of relevant region	RIVM (2002), De Koeijer and Wossink, (1990)
Clover fixation	On-farm estimated N-fixation	Meijs *et al.* (2000)
Output		
Sale of animals	Q × standardized nutrient content animals	Bureau Heffingen (2001)
Sale of milk	Q × nutrient content milk sold (dependent on protein %)	CVB (2000)
Sale of manure	Q × nutrient content manure sold	Bureau Heffingen (2001)
Sale of roughage	Q × nutrient content roughage	CVB (2000)
Surplus	($\sum$ inputs – $\sum$ outputs) / total farm area – NH_3 emission/farm area	
Correction NH_3 emission per farm area	No. animals × reference values annual NH_3 emission +NH_3 emission from manure application	Oenema *et al.* (2000),Van der Hoek (2002), Mooij (1996)

[a] Q = actual amount of product purchased or sold, obtained from technical farm data for year 2000 (in kg or numbers).

2.2.3 Ecological Footprint Analysis

For each dairy farm, an ecological footprint was computed. The ecological footprint of a farm is the biologically productive area (BPA) required to produce all inputs used and to absorb waste (i.e., CO_2 from fossil fuel combustion) generated by the farm (Wackernagel and Rees, 1996). Hence, BPA includes actual land use and land required to absorb all CO_2 from combustion of fossil fuels. To compute the ecological footprint of a dairy farm, therefore, BPA of all inputs of the farm were tracked. Relevant information and the computation procedure are in Table 3. Definition of the system boundaries is illustrated in Figure 2.1.

Table 2.3 Ecological footprint analysis at an organic dairy farm

Element	Computation[a]	References
Off-farm resources		
Purchase of concentrates	Q × BPA/kg concentrates	Thomassen (2003)
Purchase of roughage	Q × BPA/kg roughage	Thomassen (2003)
Purchase of manure	Q × BPA/manure	Brand and Melman (1993)
Purchase of animals	Q × BPA/animal	Brand and Melman (1993)
External labour	Q × BPA/l diesel	Michaelis (1998)
On-farm resources		
Land use	Actual use of land (in m^2)	Meijs *et al.* (2000)
Use of diesel	Q × BPA/l diesel	Michaelis (1998)
Use of oil	Q × BPA/kg oil	Michaelis (1998)
Use of electricity[b]	Q × BPA/kWh electricity	Michaelis (1998), EIA (2001)
Use of gas	Q × BPA/m^3 gas	Michaelis (1998)
Allocation[c]		
Sale of milk (kg FPCM[d])	Q × milk price	LEI (2003), Snoek *et al.* (2000)
Sale of animals	Q × animal price	Snoek *et a*l.(2000)
Sale of roughage	Q × price of roughage	Van Delen (2003)
Sale of manure	Q × price of manure	Wagenaar (2003)

[a] Q is actual amount of product obtained from technical farm data and BPA is Biologically Productive Area (in m^2).

[b] The composition in which different energy carriers (like oil, coal, natural gas, nuclear and renewable sources) are used to produce electricity, is based on a Power Mix of 1999 with related emissions based on a study done on continental European energy systems.

[c] The average distribution of final economic allocation of the eight farms is 88.8% milk; 10.7% animals; 0.4%; roughage; 0.1% manure.

[d] FPCM is Fat and Protein Corrected Milk, i.e., 0.337 + 0.116 × %fat + 0.06 × %protein × kg milk produced (CVB, 2000).

Off-farm BPA was determined by the amount of resources, including purchased concentrates, roughage, manure, animals and external labour (Q; see Table 2.3), and the BPA requirement of these resources. The BPA requirement of one kg of concentrates, for example, was computed from information on feed composition and from BPA requirements of at least 75% of its main feed ingredients, depending on information made available by feed suppliers. The BPA requirement of one kg feed ingredient is the sum of its actual land use and its energy requirement for cultivation and transport (i.e., CO_2 waste production). Land and energy requirements of each feed ingredient are summed into BPA by assuming that 1 ha of woodland absorbs all CO_2 released during combustion of 100 GJ of energy (Wackernagel and Rees, 1996). Most feed ingredients are grown not only for their use in cattle feed, but they are co-products of the sugar or oil industry for example. To determine land and fossil energy use of a co-product, economic allocation was used (De Boer, 2003). The BPA requirement of external labour includes fossil fuel use during contract work.

On-farm BPA is determined by actual farm land used and by BPA from on-farm combustion of fossil fuels (Table 2.3). The BPA requirements per amount of fossil fuel used are from Michaelis (1998) (Table 2.3).

Finally, to compare the ecological footprint of farms, that differ in size (i.e., total milk production), total BPA was ascribed economically to the main farm output, i.e., fat and protein corrected milk production (FPCM), and expressed per kg of FPCM. This final economic allocation differed by farm and varied between 85% and 93%, depending on the amount of products sold (Table 2.3). Ecological footprint analysis, therefore, yielded one environmental indicator; BPA (in m^2) per kg of FPCM.

2.2.4 Life Cycle Assessment

For each dairy farm, a “cradle to farm-gate” life cycle assessment (LCA) of milk production was performed (Haas *et al.*, 2000; De Boer, 2003). Theoretically, LCA computation of a dairy farm is comparable with an ecological footprint analysis, in having the same system boundaries (see Figure 2.1).

Table 2.4 Global warming potential assessment at an organic dairy farm

Element	Computation[a]	References
Off-farm GWP		
Purchase of concentrates	Q × GWP/kg concentrates	Thomassen (2003)
Purchase of roughage	Q × GWP/kg roughage	Thomassen (2003)
Purchase of manure	Q × GWP/manure	Brand and Melman (1993)
Purchase of animals	Q × GWP/animal	Brand and Melman (1993)
External labour	Q × GWP/l diesel	Michaelis (1998)
On-farm GWP		
On-farm emission CH_4 & N_2O	Fixed values for animals, manure, and soil	Cederberg (1998), Oenema *et al.* (2000), Mosier *et al.*(1998)
Use of diesel	Q × GWP/l diesel	Michaelis (1998)
Use of oil	Q × GWP/kg oil	Michaelis (1998)
Use of electricity[b]	Q × GWP/kWh electricity	Michaelis (1998), EIA (2001)
Use of gas	Q × GWP/m^3 gas	Michaelis (1998)
Allocation[c]		
Sale of milk (kg FPCM[d])	Q × milk price	LEI (2003), Snoek *et al.* (2000)
Sale of animals	Q × animal price	Snoek *et a*l.(2000)
Sale of roughage	Q × price of roughage	Van Delen (2003)
Sale of manure	Q × price of manure	Wagenaar (2003)

[a] Q is actual amount of product obtained from technical farm data.

[b] The composition in which different energy carriers (like oil, coal, natural gas, nuclear and renewable sources) are used to produce electricity, is based on a Power Mix of 1999 with related emissions based on a study done on continental European energy systems.

[c] The average distribution of final economic allocation of the eight farms is 88.8% milk; 10.7% animals; 0.4% roughage; 0.1% manure.

[d] FPCM is Fat and Protein Corrected Milk; 0.337 + 0.116 × %fat + 0.06 × %protein × kg milk produced (CVB, 2000).

Unlike ecological footprint analysis, however, LCA computes the environmental impact of various environmental issues separately. Impact categories that were assessed included land use, fossil energy use, global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP). The LCA computation of GWP, for example, is described in detail below. Other impact categories were computed similarly (for details see Thomassen, 2003).

To assess GWP at a dairy farm, three main greenhouse gasses were determined: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (De Boer, 2003). The GWP was expressed in kg CO_2 equivalents: 1 for CO_2, 21 for CH_4 and 310 for N_2O (Audsley *et al.*, 1997, assuming a 100-years time horizon).

To compute GWP of a dairy farm, the procedure as listed in Table 2.4 was followed. Off-farm GWP was computed by the amount of purchased concentrates, roughage, manure, animals and external labour (Q; see Table 2.4) and the related emissions of these resources.

The GWP of one kg of concentrates, for example, was computed from information about feed composition and from GWP of at least 75% of its main feed ingredients, depending on information made available by feed suppliers. GWP of one kg feed ingredient was computed from information on emission of CO_2, CH_4 and N_2O during its cultivation and transport. To determine GWP of a feed ingredient being a co-product, economic allocation was used (De Boer, 2003).

On-farm GWP was the result of combustion of fossil fuels; emission of CH_4 from cattle and manure; emission of N_2O from manure in the barn, in storage facilities, from grazing; and from fertilized agricultural land. Combustion of fossil fuels was computed by multiplying the amount of each fossil fuel used by its inherent GWP (Table 2.4). Methane, however, is produced in herbivores as a by-product of enteric fermentation, and from decomposition of manure under anaerobic conditions (Monteny *et al.*, 2001). The CH_4 emission due to enteric fermentation of milking cows and young stock was based on Cederberg (1998), whereas CH_4 emission from decomposition of manure was based on Spakman *et al.* (1997).

According to the Intergovernmental Panel on Climate Change guidelines, national reference values should be used if available, so N_2O emission from animal manure was based on Oenema et al. (2000), whereas N_2O emission from fertilized agricultural land was computed according to IPCC guidelines (IPCC, 1996; Mosier *et al.*, 1998).

Finally, GWP of a dairy farm was economically allocated to the main farm output, i.e., kg FPCM (Table 2.4) because it had a global impact (Haas *et al.*, 2000). The above-described analysis, therefore, yielded one environmental indicator: GWP expressed as kg CO_2-eq/kg FPCM.

Similarly, eutrophication potential (EP) at a dairy farm was computed based on the four main eutrophying components: nitrate (NO_3^-), nitrogen oxide (NO_x), ammonia (NH_3) and phosphate (PO_4^-). The EP was expressed in NO_3^- equivalents: 1 for NO_3^-, 1.35 for NO_x, 3.64 for NH_3, and 10.45 for PO_4^- (Weidema *et al.*, 1996). Unlike GWP, which has a global impact, EP has a local impact, and, therefore, was expressed per kg FPCM and per ha (Haas *et al.*, 2000). The EP indicator expressed per ha was computed in two ways: total EP divided by total area used and on-farm EP divided by ha farm area.

Acidification potential (AP) has a regional and local impact, and, therefore, was expressed per kg FPCM and per ha (Haas *et al.*, 2000). The AP indicator expressed per ha was computed in two ways: total AP divided by total area used and on farm AP divided by ha farm area. The SO_2 equivalents used were: 1 for SO_2, 0.7 for NO_x, and 1.88 for NH_3 (Audsley *et al.*, 1997).

The LCA, therefore, yielded the following environmental indicators: ha land use per kg FPCM, MJ fossil energy use per kg FPCM, GWP as kg CO_2-eq per kg FPCM, EP as on-farm kg NO_3^--eq per ha farm area and kg NO_3^--eq per ha total area or as g NO_3^--eq per kg FPCM, and AP as on-farm kg SO_2-eq per ha farm area and kg SO_2-eq per ha total area or as g SO_2-eq per kg FPCM.

2.2.5 Evaluation of environmental indicators: assessment of effectiveness

For each organic commercial dairy farm, the effectiveness of each environmental indicator was evaluated by assessing its relevance, quality and availability of data (Mitchell *et al.*, 1995; Bell and Morse, 1999; Cornelissen, 2003).

An indicator is relevant when it provides relevant information about the system in question (i.e., has large degree of relevance to the issue concerned) and if it is understandable to all stakeholders involved. To assess the relevance of an indicator, first we determined which environmental impact was assessed by that indicator, and second we assessed the extent to which that indicator determined that particular impact. The latter was obtained by assessing correlations among environmental indicators, using the Pearson correlation test. Finally, we evaluated, by means of a literature analysis, the degree to which the indicator was understandable to the main stakeholders: farmer, advisor, government and scientist.

An indicator is of good quality when it is reliable, sensitive and when a trend or target value can be determined. An indicator is reliable when similar results are obtained by repeated computations over time or persons. An indicator is sensitive when it senses relevant changes over time or space (Spangenberg *et al.*, 2002). To improve the performance of an environmental indicator, a trend or target value is necessary. To assess the quality of an indicator, therefore, we evaluated its reliability over time and persons, and its sensitivity over space, and we determined a possible trend or target value. Sensitivity over space was assessed by computing the coefficient of variation of several environmental indicators ((SD/mean) × 100%).

An indicator should be based on available data, i.e., information, that is available currently or that can be gathered, so that data collection is technically and financially feasible. Actors should have access to data collected periodically furthermore, to anticipate upon undesirable conditions, to be able to initiate effective action (Halberg *et al.*, 2005).

2.3 Results

2.3.1 Input-Output accounting

Average results of input-output accounting of N and P are shown in Table 2.5.

Nitrogen fixation caused the largest N-input (61.4 kg N ha^{-1} yr^{-1}), followed by N-deposition (42.9 kg N ha^{-1} yr^{-1}), concentrates (30.1 kg N ha^{-1} yr^{-1}), and roughage (27.4 kg N ha^{-1} yr^{-1}), whereas the largest N-output was due to the selling of milk (44.9 kg N ha^{-1} yr^{-1}). Annual NH_3 emission per ha farm area was 33.8 kg N, whereas annual losses due to NO_x, N_2O and NO_3^-, i.e., N surplus per ha farm area, was 82.5 kg N. Variation in N surplus was due mainly to variation in N-fixation by clover and variation in the amount of purchased roughage (Table 2.5). For P, import of feed, i.e. roughage (5.7 kg P ha^{-1} yr^{-1}) and concentrates (4.3 kg P ha^{-1} yr^{-1}) were the main inputs, whereas milk was the main output (7.6 kg P ha^{-1} yr^{-1}).

Table 2.5 Average nitrogen (N) and phosphorus (P) surplus in kg/ha for organic farms studied

	Mean (Standard deviation)	
	kg N/ha/yr	kg P/ha/yr
Input		
Fixation	61.4 (32.7)	-
Deposition	42.9 (13.6)	1 (0)
Animals	0.3 (1.0)	0.09 (0.3)
Concentrates	30.1 (22.0)	4.3 (3.3)
Roughage	27.4 (31.6)	5.7 (6.5)
Manure	9.6 (14.2)	1.9 (3.3)
Total	171.7 (69.5)	13 (7.9)
Output		
Animals	7.1 (2.4)	2.0 (0.7)
Milk	44.9 (12.1)	7.6 (2.1)
Roughages	1.1 (2.1)	0.1 (0.2)
Manure	2.1 (4.0)	0.9 (1.4)
Total	55.3 (11.1)	10.6 (2.7)
NH_3 volatilization	33.8 (8.3)	-
Surplus/ha	82.5 (61.6)	2.4 (7.0)
Coefficient of variation (%)	75	292

2.3.2 Ecological footprint analysis

The BPA of an organic dairy farm on average was 1.85 m^2/ kg FPCM (Table 2.6), due mainly to on-farm land use (1.10 m^2/ kg FPCM) and the cultivation and transport of purchased concentrates (0.37 m^2/ kg FPCM) and roughage (0.25 m^2/ kg FPCM).

Ecological footprint analysis is comprised of land and fossil energy use in one final unit, i.e. BPA expressed as m^2/kg FPCM. For each kg FPCM, summation of average actual land use (1.6 m^2) and average energy use (2.48 MJ = 0.248 BPA in m^2, using 1 MJ = 0.1m^2) resulted in the biologically productive area of 1.85 m^2 (see Table 2.6). Therefore, 86% of this BPA of 1.85 m^2/kg FPCM was due to actual land use and only 14% was due to energy combustion.

Table 2.6 Average results from ecological footprint analysis (i.e., biologically productive area (BPA) per kg FPCM) and from life cycle analysis (i.e., land use and fossil energy use per kg FPCM) for organic farms studied

	BPA m^2/kg FPCM Mean (S.D.)	Land use m^2/kg FPCM Mean (S.D.)	Energy use MJ/kg FPCM Mean (S.D.)
Off-farm			
Purchased concentrates	0.37 (0.18)	0.26 (0.15)	1.11 (0.74)
Purchased roughage	0.25 (0.35)	0.23 (0.33)	0.15 (0.23)
Purchased manure	0.00 (0.00)	0.00 (0.00)	0.04 (0.05)
Purchased animals	0.00 (0.03)	0.00 (0.02)	0.02 (0.05)
External labour	0.02 (0.01)	0.00 (0.00)	0.19 (0.07)
On-farm			
Land use	1.10 (0.34)	1.10 (0.34)	-
Fossil fuel use[a]	0.10 (0.03)	0.00 (0.00)	0.98 (0.27)
Total	1.85 (0.34)	1.60 (0.30)	2.48 (0.91)
Coefficient of variation (%)	18	19	37

[a] Fossil fuel use included direct energy use: gas, diesel and electricity use.

2.3.3 Life cycle assessment

An organic dairy farm used on average 1.6 m^2 of land per kg FPCM. From this land use, 69% was on-farm (1.10 m^2/kg FPCM), such as grassland and arable land, whereas 31% was off-farm (0.49 m^2/kg FPCM), mainly required for the cultivation of concentrates and roughage (see Table 2.6). Land use due to production and use of fossil fuels was negligible.

An organic dairy farm used on average 2.48 MJ per kg FPCM. From this energy use, 40% was required for the production and transportation of fossil fuels used on-farm (0.98 MJ/kg FPCM), whereas 60% was required for the production of farm inputs, mainly concentrates (1.11 MJ/kg FPCM; Table 2.6).

GWP of an average farm was 1.81 kg CO_2-eq per kg FPCM (Table 2.7) with 78% due to on-farm emissions of CH_4 (0.67 kg CO_2-eq/kg FPCM) and N_2O (0.75 kg CO_2-eq/kg FPCM), each accounting for about 50% of the 78%. The contribution of CO_2 to on-farm GWP was only 3%. Off-farm emission of greenhouse gasses was due mainly to cultivation and transport of concentrates and roughage (i.e., N_2O and CO_2).

Expressed per kg FPCM, EP of an average farm was 82.14 g NO_3^--eq, whereas expressed per total amount of ha used, EP was 1127.04 kg NO_3^--eq. For both values, 47% of EP is due to on-farm leaching of NO_3^- and PO_4^- to the soil (36%) and emission of NH_3 (11%). Off-farm EP was explained mainly by cultivation and transportation of concentrates and roughage. On-farm EP expressed per ha farm area, equalled 341.69 kg NO_3^--eq, which is for 74% due to leaching of NO_3^- and PO_4^- to the soil.

Table 2.7 Average global warming potential (GWP), eutrophication potential (EP) and acidification potential (AP) expressed per kg FPCM or per ha total area and EP and AP on farm expressed per ha farm area for organic dairy farms studied

	GWP	**EP**			**AP**		
	kg CO_2 eq/kg FPCM	g NO_3^- eq/kg FPCM	kg NO_3^- eq/ha total area	On farm kg NO_3^- eq/ ha farm area	g SO_2 eq/ kg FPCM	kg SO_2 eq/ ha total area	On farm kg SO_2 eq/ ha farm area
Off-farm							
Purchased concentrates	0.19 (0.09)	21.26 (12.93)	302.21 (218.87)		1.51 (0.80)	21.19 (13.96)	
Purchased roughage	0.13 (0.14)	19.15 (18.89)	286.84 (330.37)		1.37 (1.45)	25.19 (40.58)	
Purchased manure	0.00 (0.00)	0.06 (0.09)	0.65 (0.94)		0.04 (0.05)	0.39 (0.55)	
Purchased animals	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)		0.00 (0.00)	0.00 (0.00)	
External labour	0.01 (0.00)	0.38 (0.14)	5.41 (3.88)		0.22 (0.08)	3.16 (2.27)	
On-farm							
Emissions animals	0.67 (0.09)	9.67 (1.41)	121.98 (65.82)	81.94 (14.75)	5.00 (0.73)	63.02 (34.0)	42.34 (7.63)
Emissions soil	0.75 (0.79)	30.83 (34.92)	400.19 (527.1)	253.19 (276.33)	3.05 (1.00)	40.61 (27.44)	26.64 (10.54)
Fossil fuel use	0.05 (0.02)	0.79 (0.34)	9.76 (5.98)	6.56 (2.85)	0.62 (0.20)	7.56 (3.88)	5.18 (1.60)
Total	1.81 (0.86)	82.14 (38.58)	1127.04 (854.28)	341.69 (277.92)	11.81 (2.14)	161.12 (114.05)	74.15 (18.74)
Coefficient of variation (%)	48	47	76	81	18	71	25

Expressed per kg FPCM, AP of an average farm was 11.81 g SO_2-eq, whereas expressed per total amount of ha used, AP was 161.12 kg SO_2-eq. For both values, 69% of AP was due to on-farm emissions of mainly animal-based NH_3 (43%) and area-based NH_3 (26%). Off-farm AP was explained mainly by cultivation and transportation of concentrates and roughage. On-farm AP expressed per ha farm area was 74.15 kg SO_2-eq, which was for 57% due to animal-based emissions and for 36% due to area-based emissions

2.3.4 Evaluation of environmental indicators: effectiveness assessment

To evaluate the effectiveness of each indicator, its relevance, quality and availability of data were assessed.

2.3.4.1 Relevance

Three indicators can be derived from the input-output accounting approach (see Table 2.8). In theory, the indicator on-farm NH_3 emission per ha contributes to the environmental impacts AP and EP. Correlations were found between the environmental indicators NH_3 emission per farm area and on-farm AP per farm area ($r=0.99$, $p \leq 0.01$), and between NH_3 emission per farm area and AP per total area ($r=0.75$, $p \leq 0.05$) as expected, because for AP 69% was due to on-farm emission of mainly NH_3. No correlation, however, was found between NH_3 emission per ha area and on-farm EP per ha farm area. On-farm NH_3 emission appears to contribute only slightly (11%) to EP. Furthermore, the indicator NH_3 emission per ha is to a large extent understandable to the main stakeholders (Wever *et al.*, 1998; Kuipers *et al.*, 2001).

The indicators N- and P-surplus per ha farm area contribute to the environmental impact EP. Correlations were found between the input-output accounting indicator N surplus per ha and the LCA indicator EP on-farm (in kg NO_3^- eq per ha farm area: $r=0.80$, $p \leq 0.01$) and EP (in kg NO_3^- eq per ha total area: $r=0.91$, $p \leq 0.01$). A correlation was found also between the input-output accounting indicator P surplus per ha and EP on-farm (in kg NO_3^- eq per ha farm area: $r=0.78$, $p \leq 0.05$). On-farm leaching of NO_3^- and PO_4^- accounted for 36% of EP per total ha area and for 74% of on-farm EP per ha farm area, and therefore, the indicators N- and P-surplus/ha assess EP to a moderate extent. Furthermore, these indicators are to a moderate extent understandable to the main stakeholders. In countries, such as the Netherlands, where input-output accounting of nutrients already is applied, farmers had to become accustomed to this method (Ondersteijn *et al.*, 2002a,b).

One indicator can be derived from the ecological footprint analysis. Total BPA (in m^2) per kg FPCM includes BPA from actual land use and from fossil energy use. No correlation, however, was found between BPA from land use and BPA from energy use, which means that summation of BPA from land use and from fossil fuel combustion into one final value reduces the relevance of this indicator. Furthermore, inclusion of the BPA from fossil energy use (i.e., hypothetical land required to absorb CO_2 emission from fossil fuel combustion) into the ecological footprint indicator appears understandable to the main stakeholders only to a small extent (McDonald and Patterson, 2004).

Table 2.8 Evaluation of different environmental indicators: effectiveness assessment

Effectiveness[a]	Input-output accounting			Ecological footprint analysis	Life cycle assessment								
Indicator	NH_3 emission per farm area (kg NH_3/ha)	N-surplus (kg N/ha farm area)	P-surplus (kg P/ha farm area)	BPA (m^2/kg FPCM)	Land use (m^2/kg FPCM)	Energy use (MJ/kg FPCM)	GWP (kg CO_2 eq/ kg FPCM)	EP (gNO_3^- eq/kg FPCM)	EP on farm (kg NO_3^- eq/ha farm area)	EP (kg NO_3^- eq ha total area)	AP (g SO_2 eq/kg FPCM)	AP on farm (kg SO_2 eq/ha farm area)	AP (kg SO_2 eq/ha total area)
Relevance													
Which environmental impact (s)?	AP	EP	EP	Land use Energy use	Land use	Energy use	GWP	EP	EP	EP	AP	AP	AP
Relevant to the issue of concern	++	+	+	+/-	++	++	++	++	++	++	++	++	++
Comprehensibility													
Farmer	++	+	+	+/-	++	++	+/-	+/-	+/-	+/-	+/-	+/-	+/-
Advisor	++	+	+	+/-	++	++	+/-	+/-	+/-	+/-	+/-	+/-	+/-
Government	++	+	+	+/-	++	++	+/-	+/-	+/-	+/-	+/-	+/-	+/-
Scientist	++	++	++	+	++	++	+	+	+	+	+	+	+
Quality													
Reliability	+	+	+	+	+	+	+	+	+	+	+	+	+
Sensitivity	+/-	++	++	+/-	+/-	+	+	+	++	++	+/-	+	++
Trend/target value	+	++	++	+	+	+	+	+	+	+	+	+	+
Availability of data													
Measurement technically and financially feasible	+	+	+	+	+	+	+/-	+/-	+/-	+/-	+/-	+/-	+/-
Consistent data support	+	+	+	+	+	+	+/-	+/-	+/-	+/-	+/-	+/-	+/-

[a] Scale (--;-;+;++) varies from "not at all applicable" to "completely applicable".

Nine indicators can be derived from life cycle assessment (see Table 2.8), and these indicators to a large degree estimate the specific environmental impacts. The indicators land use and energy use are to a large degree understandable to the main stakeholders. However, due to their complexity the other indicators are to a small degree understandable to the main stakeholders, meaning they are difficult to understand and not transparent (Rebitzer *et al*., 2004; Robèrt, 2000).

2.3.4.2 Quality

All indicators derived from the three methods discussed above, were relatively reliable, because these indicators are means-based and do not depend on direct measurements (Van der Werf and Petit, 2002). In general, for means-based indicators, similar results are obtained after repeated computations across time and persons.

The indicators N- and P-surplus per farm area appear sensitive over space changes (De Boer *et al*., 2002; Monteny *et al*., 2002; Ondersteijn *et al*., 2002b). Coefficients of variation (CV) were relatively high: 75% for N-surplus and 292% for P-surplus (Table 2.5). The indicator NH_3 emission per ha appeared to be little sensitive over space, with a coefficient of variation of 25%.

Indicators BPA (in m^2) per kg FPCM and land use (in m^2 per kg FPCM) appeared little sensitive over space, with a coefficient of variation of about 18% (Table 2.6). Indicator energy use (in MJ per kg FPCM), however, seemed more sensitive over space, but is still relatively insensible, with a coefficient of variation of 37%.

Indicators GWP and EP expressed per kg FPCM appeared relatively sensitive over space, with a coefficient of variation of about 48% (Table 2.7). Indicator AP expressed per kg FPCM, however, appeared less sensitive over space, with a coefficient of variation of 18%.

The indicators on-farm EP expressed per ha farm area (CV=81%), total EP per ha total area (CV=76%), and AP per ha total area (CV=71%) to a large degree appeared sensitive over space. The indicator AP on farm per ha farm area appears less sensitive over space, with a coefficient of variation of 25%.

It seems possible to determine trends for all indicators. All indicators should approach, but not fall below zero; an equilibrium situation is the most desirable. For the indicators N-and P-surplus, a target value of zero can be set. If the surplus is negative, the soil is depleted due to a shortage of nutrients.

2.3.4.3 Availability of data

The availability of data to calculate an environmental indicator and the consistency of this data was assessed by evaluating the technical and financial feasibility of data collection.

Data required for the indicators NH_3 emission per ha, N- and P-surplus per ha are technically and financially feasible and can be collected on a regular basis. Nutrient contents of inputs are very transparent. On-farm data are quite easily obtainable in the Netherlands, because much research is directed towards the development of models to compute ammonia emissions, for example, from the barn, from manure storage facilities, from grazing and from manure application (Oenema *et al*., 2000; Van der Hoek, 2002).

On-farm data for the indicators BPA (in m^2) per kg FPCM, land use (in m^2 per kg FPCM) and energy use (in MJ per kg FPCM) are also technically and financially available and can be collected on a regular basis. On-farm data are quite easily obtainable. Outcomes of these three indicators depend to a large degree on on-farm processes; BPA for 65%, land use for 70%, and energy use for 40%. Data on off-farm processes, such as feed data, are difficult to collect.

In addition, data for the other LCA indicators are not easily available, and are difficult to collect on a regular basis. On-farm data collection is difficult. A distinction, however, should be made concerning on-farm data. Data on use of fossil resources, for example, are easily obtainable, whereas data on, for example, emission of N_2O from grassland or CH_4 from animals, are difficult to obtain.

Data collection for off-farm processes of LCA is increasingly difficult and time-consuming, especially data collection related to production processes of feed ingredients. The three main difficulties are logistics, lack of information, and lack of money to invest in collecting this information. Especially the quality of data for off-farm processes, such as cultivation and transport of concentrates, therefore, is lower generally than data quality for on-farm processes. More assumptions are made for off-farm data which, therefore, show less variation. The reliability of LCA indicators highly depends on data quality (Ardente *et al.*, 2004).

2.4 Discussion

The aim of this study was to evaluate the effectiveness of environmental indicators obtained from input-output accounting, ecological footprint analysis and LCA. Effectiveness of environmental indicators was evaluated by assessing their relevance, quality and availability of data. To evaluate the effectiveness of various indicators, data from eight organic commercial farms were used. These eight farms participated in a demonstration project of Dutch organic farmers (BIOVEEM). Data of these farms are used, because in the Netherlands, it is difficult to gather data from commercial organic farms. Although we realize that the sample size is limited, these eight farms participating in BIOVEEM show a high variation in farm management, which favours evaluation of indicators. In addition, the evaluation was conducted for the year 2000 only. To determine the exact environmental impact of, for example, milk production, data of various years should be used. The aim of this paper, however, was to evaluate different indicators, so that data of only one year are sufficient.

Input-output accounting of nutrients results in environmental indicators that monitor on-farm losses, mainly of nitrogen and phosphorus (i.e., N and P surplus per ha farm area), and emission of ammonia (i.e., NH_3 per ha farm area). These indicators are relevant to the issue concerned; are to a large degree understandable to the main stakeholders; are of good quality; and have data that are relatively easily feasible. The indicator NH_3 per ha farm area has a low sensitivity, probably because of calculations based on reference values. The sensitivity over space of the indicators N and P surplus per ha farm area implies that these indicators are valuable to show differences among production systems and to improve environmental performance within systems. Environmental indicators derived from input-output accounting, however, do not include all environmental impact categories (e.g., global warming), and merely focus on on-farm environmental losses.

Ecological footprint analysis is life cycle based and describes one final unit, the BPA per kg FPCM, which basically is a summation of on-farm and off-farm land and fossil energy use. This indicator has limited relevance to the issues concerned; land and fossil energy use, and is barely understandable to the main stakeholders. Furthermore, this indicator is of low quality because of its limited sensitivity over space. On-farm data, however, are relatively easy to access.

LCA indicators have a high relevance to the issues concerned. However, with the exception of land use and energy use, stakeholders have difficulty understanding these LCA indicators. Nevertheless, these indicators are of good quality, due to their reliability and sensitivity. The AP indicator per kg FPCM only, seems low sensitive over space. This low sensitivity is because calculations for the ammonia emission per animal have been based on reference values. Furthermore, it is possible to define specific indicator trends. In future, merely acceptable norms for the indicators can be set, because zero will never be approached; only realizable target values can be determined.

Nevertheless, data for LCA indicators are difficult to collect. In general, computation of LCA indicators could be facilitated by the introduction of a global tracking-and-tracing system of concentrates components across countries and organizations.

2.5 Conclusion

The environmental indicators derived from input-output accounting are effective in making accurate comparisons between current dairy production systems in the Netherlands, because of their high relevance, good quality and easy availability of data. These indicators, however, do not include all environmental impact categories, such as land use, energy use and global warming potential, and focus on on-farm emissions.

The environmental indicator derived from ecological footprint analysis is not effective for land and fossil energy use, because of its limited relevance and low quality, whereas LCA resource-based indicators are effective because of their high relevance, good quality and availability of data. LCA indicators for global warming, acidification and eutrophication potential are effective also, because of their good relevance and good quality. Data of these LCA indicators, however, are difficult to collect. To give a good insight into the environmental impact of a dairy production system, besides input-output accounting indicators, LCA indicators are required.

References

Ardente, F., Beccali, M., Cellura, M., 2004. F.A.L.C.A.D.E.: A fuzzy software for the energy and environmental balances of products. Ecological Modelling. 176, 359-379.

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, Brussels, Belgium.

Basset-Mens, C., Van der Werf, H.M.G., 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. Agriculture, Ecosystems and Environment 105 (1-2): 127-144.

Bell, S., Morse, S., 1999. Sustainability indicators. Measuring the immeasurable. Earthscan publications Ltd, London.

Bentrup, F., Küsters, J., Lammel, J., Kuhlmann, H., 2000. Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. Int. J. LCA 5(6), 349-357.

Bieleman, J., 1998. Landbouw en milieu. Een eeuwig spanningsveld? In: Castryck, G., Decaluwe, M. (Eds.), De relatie tussen economie en ecologie: gisteren, vandaag en morgen. Academia Press, Gent, Belgium.

Brand, R.A., Melman, A.G., 1993. Energie-inhoudsnormen voor de veehouderij. Instituut voor milieu- en energietechnologie TNO, Apeldoorn, The Netherlands.

Bureau Heffingen, 2001. MINAS Tabellenbrochure 2001. Ministerie van Landbouw, Natuurbeheer en Visserij, Assen, The Netherlands.

Cederberg, C., 1998. Life Cycle Assessment of Milk Production - A Comparison of Conventional and Organic Farming. SIK-report, no. 643, SIK, The Swedish Institute for Food and Biotechnology, Göteborg, Sweden.

Cederberg, C., Dalerius, K., 2000. Life Cycle Assessment of Cattle Meat - a Study of Different Production Systems. Naturresursforum Landstinget Halland, Sweden.

Cederberg, C., Mattson, B., 2000. Life Cycle Assessment of milk production- a comparison of conventional and organic farming. Journal of Cleaner Production. 8, 49-60.

Cederberg, C., Dalerius, K., 2001. Life Cycle Assessment of Pig Meat. Naturresursforum Landstinget Halland, Sweden.

Cornelissen, A.M.G., 2003. Common ground for sustainable development, and ground covered by selected sustainability indicators. In: The Two Faces of Sustainability, PhD thesis, Animal Production Systems Group. Wageningen University, the Netherlands.

CVB, 2000. Tabellenboek veevoeding 2000; voedernormen landbouwhuisdieren en voerderwaarde veevoeders. Centraal Veevoeder Bureau, Lelystad, The Netherlands.

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

De Boer, I.J.M., Smits, M.C.J., Mollenhorst, H., van Duinkerken, G., Monteny, G.J., 2002. Prediction of Ammonia Emission from Dairy Barns using Feed Characteristics. Part I: Relation between Feed Characteristics and Urinary Urea Concentration. J. Dairy Sci. 85, 3382-3388.

De Koeijer, T.J., Wossink, G.A.A., 1990. Emissies van meststoffen en bestrijdingsmiddelen in de akkerbouw. Leerstoelgroep agrarische bedrijfseconomie, Wageningen Universiteit, Wageningen, The Netherlands.

Energy Information Administration (EIA), 2001. International Energy Outlook 2001, www.eia.doe.gov/oiaf/ieo/electricity.html.

Goodlass, G. Halberg, N., Verschuur, G., 2003. Input-output accounting systems in the European community – an appraisal of their usefulness in raising awareness of environmental problems. European Journal of Agronomy 20, 17-24.

Haas, G., Wetterich, F., Geier, U., 2000. Life Cycle Assessment Framework in Agriculture on the Farm level. Int. J. LCA 5, 345-348.

Haas G., Wetterich, F., Köpke, U., 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agriculture, Ecosystems, and Environment. 83, 43-53.

Halberg, N., van der Werf, H.M.G., Basset-Mens, C., Dalgaard, R., de Boer, I.J.M., 2005. Environmental assessment tools for the evaluation and improvement of European livestock production systems. Livestock Production Science. 96, 33-50.

IPCC, 1996. Intergovernmental Panel on Climate Change. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (2-4). Available at: http://www.ipcc-nggip.iges.or.jp/public/gl/invs6.htm.

Kuipers, A., Zaalmink, W., Kuiper, D., 2001. Gebruik en acceptatie van bemestingsadviesprogramma’s door veehouders van praktijkcijfers. Project KLIMOP, Agro Management Tools, Wageningen, The Netherlands.

LEI, 2003. Statistieken Landbouw economisch onderzoeksinstituut. www.lei.dlo.nl/statistieken.

McDonald, G.W., Patterson, M.G., 2004. Ecological Footprints and interdependencies of New Zealand regions. Ecological Economics 50, 49-67.

Meijs, J., Bleumink, J., Van Eekeren, N., Baars, T., Kraak, T., Plomp, M., Smolders, G., Snijders, P., Zaalmink, W., Van der Wel, C., Gerretsen, J., 2000. Biologische veehouderij en management. PR-rapport 144, Praktijkonderzoek Rundvee, Schapen en Paarden, Lelystad, the Netherlands.

Michaelis, P., 1998. Life cycle assessment of energy systems. Centre for environmental strategy. University of Surrey, Great Britain.

Mitchell, G., May, A., McDonald, A., 1995. PICABUE: a methodological framework for the development of indicators of sustainable development. Int. J. Sustain. Dev. World Ecol. 2, 104-123.

Monteny, G.J., Groenestein, C.M., Hilhorst, M.A., 2001. Interactions and coupling between emissions of methane and nitrous oxide from animal husbandry. Nutrient Cycling in Agroecosystems. 60, 123-132.

Monteny, G.J., Smits, M.C.J., Van Duinkerken, G., Mollenhorst, H., De Boer, I.J.M., 2002. Prediction of Ammonia Emission from Dairy Barns using Feed Characteristics Part II: Relation between Urinary Urea Concentration and Ammonia Emission. J. Dairy Sci. 85, 3389-3394.

Mooij, M., 1996. Samenstelling dierlijke mest. Expertisecentrum LNV, Ede.

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., Cleemput, O.,1998. Closing the global N2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutrient Cycling in Agroecosystems. 52, 225-248.

Oenema, O., Verdoes, N., Groot Koerkamp, P.W.G., Bannink, A., van der Meer, H.G., van der Hoek, K.W., 2000. Forfaitaire waarden voor gasvormige stikstofverliezen uit stallen en mestopslagen. Alterrra, Research Instituut voor de Groene Ruimte, rapport 107, Wageningen, the Netherlands.

Ondersteijn, C.J.M., Beldman, A.C.G, Daatselaar, C.H.G., Giesen, G.W.J., Huirne, R.B.M., 2002a. The Dutch Mineral Accounting System and the European Nitrate Directive: Implications for N and P management and farm performance. Agriculture, Ecosystems and Environment. 92, 283-296.

Ondersteijn, C.J.M., Harsh, S.B., Giesen, G.W.J., Beldman, A.C.G., Huirne, R.B.M., 2002b.

Management strategies on Dutch dairy farms to meet environmental regulations: a multi-case study. Neth. J. Agr. Sci. 50, 47-65.

Rebitzer, G., Ekvall., T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Review Life Cycle Assessment; Part 1: Framework, goal and scope definition, inventory analysis, and application. Environment International. 30, 701-720.

RIVM, 2002. Rijksinstituut voor volksgezondheid en milieu en interprovinciaal overleg, www.ipo.rivm.nl/ming/page/mingtotaal.html#41.

Robèrt, K-H., 2000. Tools and concepts for sustainable development, how do they relate to a general framework for sustainable development, and to each other? Journal of Cleaner Production. 8, 243-254.

Snoek, H., Hemmer, H., Kuunders, L., Ellen, H., 2000. Kwantitatieve informatie veehouderij 2000-2001. Praktijkonderzoek Veehouderij, Lelystad, The Netherlands.

Spakman, J., van der Loon, M.M.J., van der Auweraert, R.J.K., Gielen, D.J., Olivier, J.G.J., Zonneveld, E.A., 1997. Methode voor de berekening van broeikasgasemissies. Ministerie van VROM, Publikatiereeks Emissieregistratie 37, The Netherlands.

Spangenberg, J.H., Pfahl, S., Deller, K., 2002. Towards indicators for institutional sustainability:lessons from an analysis of Agenda 21. Ecological indicators 2, 61-77.

Thomassen, M., 2003. Life Cycle Assessment at commercial organic dairy farms. Comparison of three methodologies: LCA, Ecological Footprint-analysis and an adjusted nutrient balance. MSc thesis Animal Production Systems group, Wageningen University, Wageningen, The Netherlands.

Van der Werf, H.M.G., Petit, J., 2002. Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. Agriculture, Ecosystems and Environment. 93, 131-145.

Van Delen, J., 2003. Personal communication. Research Institute for Animal Husbandry. Lelystad, The Netherlands.

Van Dijk, A., 2001. Life Cycle Assessment of conventional and organic pig production in the Netherlands. MSc thesis Animal Production Systems group, Wageningen University, Wageningen, The Netherlands.

Van der Hoek, K.W., 2002. Uitgangspunten voor de mest- en ammoniakberekeningen 1997 tot en met 1999 zoals gebruikt in de Milieubalans 1999 en 2000. RIVM rapport 773004012, RIVM, Bilthoven, The Netherlands.

Wackernagel, M., Rees, W., 1996. Our ecological Footprint. Reducing Human Impact on the Earth. New Society Publishers, Canada.

Wagenaar, J.P., 2003. Personal communication. Louis Bolk Institute, Driebergen, The Netherlands.

Weidema, B.P., Morteson, B., Nielsen, P., Hauschild, M., 1996. Elements of an impact assessment of wheat production. Institute for Product development, Technical University of Denmark, Denmark.

Wever, C., Van Leeuwen, F., Geutink, T., 1998. Monitoring Mineralen- en ammoniakbeleid; Monitoringsorganisatie en beleidsinformatievragen. Informatie- en KennisCentrum Landbouw, Ede, The Netherlands.

Chapter 3

Attributional and consequential Life Cycle Assessment of milk production

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Abstract

Different ways of performing an LCA are used to assess the environmental burden of milk production. A strong connection exists between the choice between ALCA and CLCA and the choice of how to handle co-products. Insight is needed in the effect of choice on results of environmental analyses of agricultural products, such as milk. The main goal of this study was to demonstrate and compare attributional and consequential LCA of an average conventional milk production system in The Netherlands. Attributional LCA (ALCA) describes the pollution and resource flows within a chosen system attributed to the delivery of a specified amount of the functional unit. Consequential LCA (CLCA) estimates how pollution and resource flows within a system change in response to a change in output of the functional unit. For an average Dutch conventional milk production system, an ALCA (mass and economic allocation) and a CLCA (system expansion) were performed. Impact categories included in the analyses were: land use, energy use, climate change, acidification and eutrophication. The comparison was based on four criteria: hotspot identification; comprehensibility; quality and availability of data. Total environmental burdens were lower when using CLCA compared with ALCA. Major hotspots for the different impact categories when using CLCA and ALCA were similar, but other hotspots differed in contributions, order and type. As experienced by the authors, ALCA and use of co-product allocation are difficult to comprehend for a consequential practitioner while CLCA and system expansion are difficult to comprehend for an attributional practitioner.

Literature shows concentrates used within ALCA will be more understandable for a feeding expert than the feed used within CLCA. Outcomes of CLCA are more sensitive to uncertainties compared with ALCA, due to the inclusion of market prospects. The amount of data required within CLCA is similar compared with ALCA. The main cause of these differences between ALCA and CLCA is the fact that different systems are modelled. The goal of the study, or the research question to be answered, defines the system under study. In general, the goal of CLCA is to assess environmental consequences of a change in demand, whereas the goal of ALCA is to assess the environmental burden of a product, assuming a status-quo situation. Nowadays, however, most LCA practitioners chose one methodology independent of their research question. This study showed it is possible to perform both ALCA (mass and economic allocation) and CLCA (system expansion) of milk. Choices of methodology, however, resulted in differences in: total quantitative outcomes, hotspots, degree of understanding and quality.

We recommend LCA practitioners to better distinguish between ALCA and CLCA in applied studies to reach a higher degree of transparency. Furthermore, we recommend LCA practitioners of different research areas to perform similar case studies to address differences between ALCA and CLCA of the specific products as the outcomes might differ from our study.

3.1 Introduction

In The Netherlands over the period from 2001-2005, on average 10.7 million tons of milk per year was produced (BINternet, 2003). This milk was produced on mostly specialised dairy farms (24,400 in 2001 and 20,810 farms in 2005) that made use of many inputs, such as concentrates (BINternet, 2003). The production of milk causes environmental side-effects, such as emission of greenhouse gases and nutrient enrichment in surface water. The Dutch society pays much attention to ecological sustainability of milk production (Van Calker *et al.*, 2005). Life Cycle Assessment (LCA) was identified to be a useful tool to assess the integral environmental impact of different milk production systems (Thomassen and De Boer, 2005). Although guidelines are given on how to perform an LCA, differences among studies still exist due to different methodological choices.

Two different LCA approaches, attributional and consequential LCA, were identified and described (Heijungs, 1997; Frischknecht, 1998; Ekvall, 1999; Tillman, 2000; Weidema, 2003). Attributional LCA (ALCA) describes the pollution and resource flows within a chosen system attributed to the delivery of a specified amount of the functional unit (Rebitzer *et al.*, 2004). Consequential LCA (CLCA) estimates how pollution and resource flows within a system change in response to a change in output of the functional unit (Ekvall and Weidema, 2004; Rebitzer *et al.*, 2004).

When performing an LCA, in most cases multifunctional processes are included in the analysed system. Choices of how to handle co-products, therefore, are inevitably connected with performing an LCA. The distinction between ALCA and CLCA was developed in the process of resolving the methodological debates over allocation problems and the choice of data (Ekvall and Weidema, 2004). A strong connection, therefore, exists between the choice of ALCA and CLCA, and the choice of how to handle co-products. Within ALCA, avoiding allocation by using system expansion to handle co-products is optional, while co-product allocation is most frequently used. Avoiding allocation by system expansion, however, is the only way to deal with co-products within CLCA, as it reflects the consequences of a change in production (Weidema, 2003).

In previous Life Cycle Assessment studies of milk production performed in different European countries, mostly ALCA was used and some kind of allocation (mass, energy-based or economic) (Høgaas Eide, 2002; Hospido *et al.*, 2003; Casey and Holden, 2005; Thomassen *et al.*, 2008). Cederberg and Stadig (2003) applied system expansion within ALCA when dividing the environmental burden of the organic milk production system between milk and the co-products of meat and surplus calves. Only Nielsen *et al.* (2005) applied CLCA including system expansion for the Danish conventional milk production system. Obviously, LCA practitioners choose between ALCA and CLCA, and different ways of how to handle co-products. However, it is not clear what the effect of these choices are on outcomes. Insight is needed in the effect of this choice on results of environmental analyses of agricultural products, such as milk. The goal of this study is to demonstrate and compare ALCA (using mass and economic allocation) and CLCA (using system expansion) of an average conventional milk production system in The Netherlands. The comparison was based on four criteria: hotspot identification; comprehensibility; quality and availability of data.

3.2 Goal and scope definition

The chosen functional unit was ‘1 kg of Fat and Protein Corrected Milk (FPCM) leaving the farm gate’. This study was a cradle-to farm-gate LCA. The included impact categories were: land use, energy use, climate change, acidification and eutrophication. The following life cycle impact assessment methods were used: 1) the EDIP 97 method (updated version 2.3) (Wenzel *et al.*, 1997) and 2) the Cumulative Energy Demand (CED) (VDI, 1997). Both methodologies were implemented in the PC-tool SimaPro 7.
The comparison between both methodologies was based on four criteria. These criteria were derived from effectiveness assessments to evaluate environmental indicators (Thomassen and De Boer 2005; Cornelissen, 2003). Furthermore, hotspot identification was included, as this is an important aspect of an LCA. All four criteria were related to this specific study of milk production. Hotspot identification implies identification of elements within the system that contribute most to a certain impact category. Differences in hotspots were assessed. Comprehensibility was assessed by looking at the degree of difficulty in understanding by LCA practitioners, based on discussions among the authors, and by feeding experts, based on literature. To assess quality, the reliability of the results was evaluated by looking at uncertainties. The availability of data was assessed by looking at the amount of data required.

3.3 Inventory

Table 3.1 shows the set-up of the average conventional milk production system based on data of 286 conventional farms in The Netherlands from the year 2003 (BINternet, 2003). The system was simplified by assuming that farms were partly self-sufficient. This means no animals, roughage and organic fertiliser were purchased. In addition, it was assumed that no roughage and organic fertiliser were conveyed, so the only two outputs were milk and animals (mostly bull calves and milking cows).

Table 3.1 Description of the main characteristics of the average conventional milk production system in The Netherlands for the year 2003 (BINternet, 2003; Ter Veer, 2005)

Characteristic	Unit	Value
Grassland	ha	29.9
Arable land	ha	8.6
Milking cows	amount	63
Heifers >1 year	amount	25
Breeding calves <1 year	amount	21
Electricity use	kWh	25690
Diesel use	l	4780
Natural gas use	m^3	1430
Milk production	kg/cow	7630
Fat content	%	4.42
Protein content	%	3.49
Pesticides	kg[a]/ha	0.25
Concentrates	kg/cow	2160
Attributional		
- 90 DVE[b]	tonnes	85
- 120 DVE	tonnes	43
- 180 DVE	tonnes	7
Consequential		
- Soybean meal	tonnes DM[c]	71
- Spring barley	tonnes DM[c]	64
Purchased artificial fertiliser	kg N/farm	5750
Exported animals	kg N/farm	650

[a] Active substance matter.

[b] DVE = The intestine digestible protein content of the concentrates based on the Dutch DVE system (Tamminga *et al.*, 1994; Van Straalen, 1995).

[c] Dry matter.

3.3.1 Attributional LCI

Figure 3.1 shows the ALCA flowchart of the system based on average historical data. ALCA reflects the environmental impact accounted for by the system. An electricity mix for The Netherlands was used (EcoinventCentre, 2004). Purchased concentrates were related to three groups of concentrates with different protein and energy contents (Ter Veer, 2005). Each group of concentrates had a different composition based on national data from the feed industry (Doppenberg and De Groot, 2005). The Life Cycle Inventory of each ingredient was assessed including cultivation, processing and transport. Capital goods, seeds and medicines were excluded.

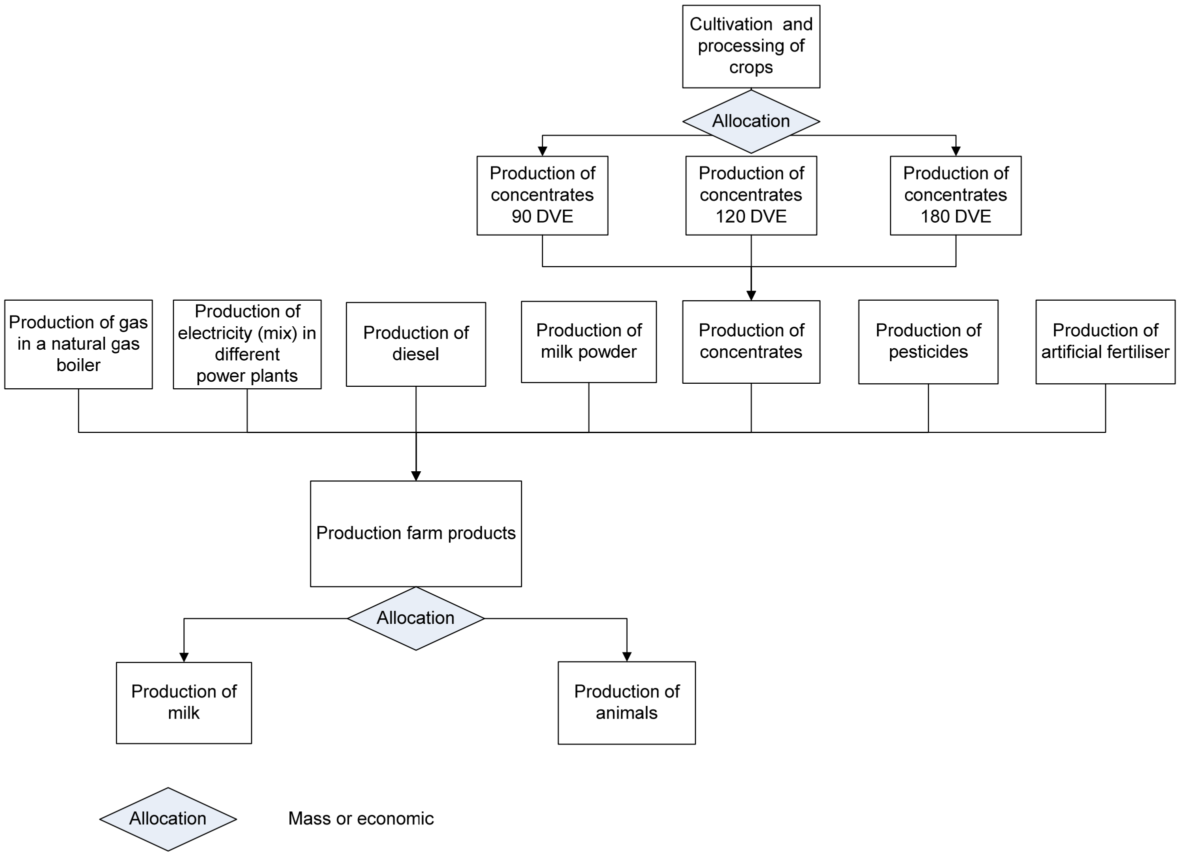

Figure 3.1 Flowchart for the attributional LCA of conventional milk production with allocation

3.3.1.1 Mass and economic allocation

Figure 3.1 also indicates where allocation of co-products is encountered. Allocation problems occur when concentrate ingredients are part of a multifunctional process and when dividing the environmental burden between milk and animals. Mass allocation was applied by computing the share in quantity of a product. Economic allocation was applied by computing the share in proceeds of a product by taking into account quantity and economic value of the products. Table 3.2 shows the mass and economic allocation factors used.

Table 3.2 shows some products, such as maize gluten meal and soy hulls, had a low allocation, which means a small amount of the environmental burden related to the main and co-product is ascribed to the co-product.

Table 3.2 Overview of allocation factors within attributional LCA

Product	Mass allocation (%)	Economic allocation (%)
Milk	96	92
Beet pulp	20	15
Molasses	10	5
Maize gluten meal	2.5	8
Maize gluten meal Prairy Gold	2.5	10
Palm kernel meal	11	3
Rape seed meal	56	28
Soy hulls	3	1
Tapioca	22	27
Triticale grain	60	71
Wheat grain	61	85
Wheat hulls	17	9

3.3.2 Consequential LCI

Figure 3.2 shows the CLCA flowchart of the system based on marginal data. CLCA reflects the possible future environmental impact from a change in demand of the product under study. The size of change in demand was an increase in milk production, which needed at least one more dairy farm. Marginal data were used, which means data representing technologies that are expected to be affected most by this increase (Schmidt and Weidema, In press). The most sensitive process is the most competitive in a situation with an increasing or constant market trend, while it is the least competitive in a situation with a decreasing market trend.

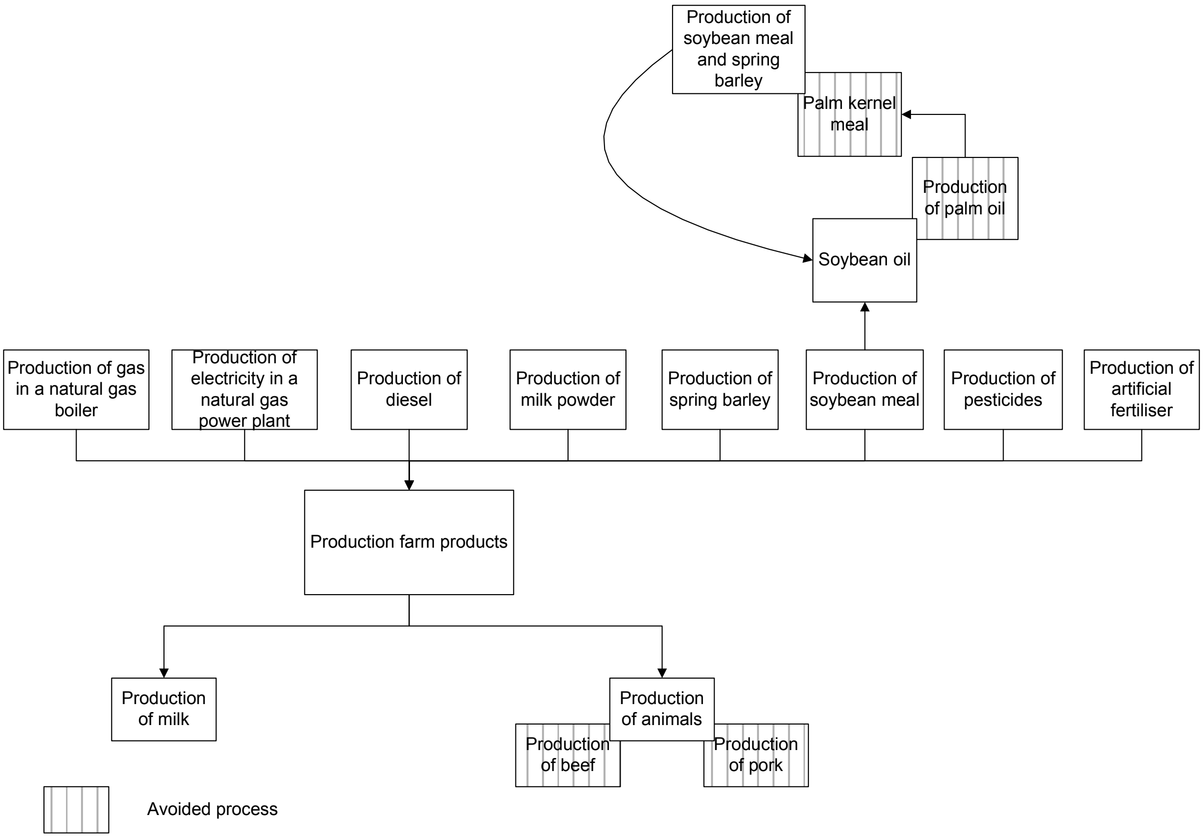

Figure 3.2 Flowchart for the consequential LCA of conventional milk production with system expansion

In the case of electricity (marginal input), the question to be asked is; what kind of electricity plant will be installed as a result of the current increase in demand for electricity in The Netherlands? After contacting the sector and taking into account production costs, the next power plant in The Netherlands was identified to be a natural gas power plant. In the case of feed, the question to be asked is; which feed ingredient will meet the increased protein demand as a result of the increased milk production? In addition, which feed ingredient will meet the increased energy demand as a result of the increased milk production? Taking into account market trend, production volume and price, the marginal fodder protein was identified as soybean meal (Dalgaard *et al.*, In press; Schmidt and Weidema, In press). The LCI of soybeans was based on production in Argentina, as the area covered with soybeans expanded from 6 million hectares in 1996 to 14.2 million in 2004. Furthermore, Argentina is projected to have the highest increase in export until 2014 (Pengue, 2006; FAPRI, 2007).

According to Weidema (Weidema, 2003), barley has the lowest gross margin and will be the marginal fodder energy on the European market, whereas wheat will be the marginal fodder energy on the global market. Nielsen et al. (2005) identified the marginal spring barley producer using an economic equilibrium model. We used this LCI as marginal fodder energy input, supplemented with transport to The Netherlands (Dalgaard *et al.*, In press).

The following formulas were used to compute the purchased amounts.

$$\mathrm{VEM}_{\text{requirement}} - \mathrm{VEM}_{\text{on-farm produced}} = \mathrm{VEM}_{\text{spring barley}} + \mathrm{VEM}_{\text{soybean meal}} \qquad (1)$$

whereby,

VEM= Dutch system that represents feed energy value (in VEM/kg DM where one VEM is 6.9 kJ of Net Energy) (Van Es, 1978)

$$\mathrm{VEM}_{\text{requirement}} = \sum_i \text{animals}_i \times \mathrm{VEM}\,(\text{maintenance} + \text{milk production} + \text{growth})_i$$

$$\mathrm{VEM}_{\text{on-farm produced}} = \sum_j \text{yield}_j \times \text{area}_j \times \mathrm{VEM}\,(\text{crop production})_j$$

i= different animals; calves, heifers, dairy cows

j= yield different feed crops; grass; maize, grain given in kg dry matter/hectare, area in hectare, and VEM crop production given in VEM/kg dry matter. Concerning fresh grass intake, amount of pasture days (185 for dairy cows), and grazing system (restricted for dairy cows) were taken into account.

$$\mathrm{DVE}_{\text{requirement}} - \mathrm{DVE}_{\text{on-farm produced}} = \mathrm{DVE}_{\text{spring barley}} + \mathrm{DVE}_{\text{soybean meal}} \qquad (2)$$

whereby,

DVE= Dutch system that represents intestine digestible protein content, unit kg (Tamminga *et al.*, 1994; Van Straalen, 1995)

$$\mathrm{DVE}_{\text{requirement}} = \sum_i \text{animals}_i \times \mathrm{DVE}\,(\text{maintenance} + \text{milk production} + \text{growth})_i$$

$$\mathrm{DVE}_{\text{on-farm produced}} = \sum_j \text{yield}_j \times \text{area}_j \times \mathrm{DVE}\ \text{crop production}_j$$

i= different animals; calves, heifers and dairy cows

j= yield different feed crops; grass; maize, grain given in kg dry matter/hectare, area in hectare, and DVE crop production given in DVE/kg dry matter. Concerning fresh grass intake, amount of pasture days (185 for dairy cows), and grazing system (restricted for dairy cows) were taken into account.

3.3.2.1 System expansion

The procedure known as system expansion, means that the boundaries of the system investigated are expanded to include the alternative production of exported functions. To include the alternative way of production, a competing product with a similar function must be identified to represent indirect effects of the exported functions (Ekvall and Finnveden, 2001; Weidema and Norris, 2002). This procedure reflects as closely as possible the consequences of a specific change in demand for a co-product (Ekvall and Finnveden, 2001; Weidema and Norris, 2002). Guinée *et al.* (2002) added to this definition, based on Tillman et al. (1994), not to add functions, but to subtract them from those alternatives providing additional functions, the so-called substitution or avoided burden method. When system expansion is performed, the environmental load of the avoided burden in most studies is subtracted. In this study, when using the system expansion method, we implement it as an avoided burdens method.

System expansion was applied whenever a multifunctional process had more than one functional flow. Figure 3.2 shows the avoided products when the chosen increase in milk production (at least one more dairy farm is needed) occurs.

For example, soybean meal has the co-product soybean oil. Therefore, increased demand for soybean meal leads to increased production of soybean oil, which substitutes palm oil, as Figure 3.2 shows. However, when less palm oil is produced also less palm kernel meal is produced. In order to compensate for this ‘missing’ palm kernel meal, more soybean meal should be produced. Both soybean meal and palm kernel meal are used as feed for livestock. According to Figure 2, the avoided production of palm kernel meal is compensated by both soybean meal and spring barley production. This is because the substitution ratio is based on both energy and protein content of the meal, and as the protein and energy content differs between palm kernel meal and soybean meal, part of the palm kernel meal is substituted by spring barley. For more details see Dalgaard *et al.* (In press).

The milk system was also expanded because milk is associated with the co-product of beef. When identifying the avoided burden of meat from dairy cows, the question to be asked was: what will not be purchased by retailers/supermarkets when more meat from dairy cows is provided? After contacting the sector, it was identified that this increased availability of beef will replace that from foreign dairy cows and pork, as meat from dairy cows is mainly used for minced meat and easy-to-prepare meat meals (Rang and Westra, 2006). Meat from foreign and domestic dairy cows, however, is constrained by quotas, and therefore, the marginal meat must come from beef cattle and pigs. However, calves, mostly bulls, are an output of the milk system as well, and will result in beef production after a growth period at a meat cattle farm. It was assumed, therefore, that beef (both from calves and dairy cows) substituted beef and pork. These data on beef and pork production were based on Danish CLCAs (Nielsen *et al.*, 2005).

3.4 General overview of ALCA and CLCA outcomes

Table 3.3 shows the characterised results of the average conventional milk production system using ALCA, and mass and economic allocation, besides CLCA and system expansion.

Table 3.3 shows that when using mass or economic allocation within ALCA total environmental burdens were influenced slightly. Furthermore, energy use computed by CLCA was only 35%-45% of energy use found by ALCA. Acidification computed by CLCA was around 40% of acidification by ALCA, climate change 55%-60%, eutrophication 65%-70% and land use 75%-80%. These lower values of CLCA are mainly caused by the subtraction of avoided burdens of identified alternative products. Avoided beef production was the main cause of the lower land use, while difference in feed type within ALCA (three concentrates with different compositions) and CLCA (spring barley and soybean meal) was the main cause of the lower energy use. Both avoided beef production and difference in feed type within ALCA and CLCA caused the lower acidification, eutrophication and climate change.

Table 3.3 Characterised results of the average conventional milk production system using attributional LCA and mass, economic allocation, besides consequential LCA and system expansion

Methodology Handling co-products Impact category	Unit/kg FPCM	Attributional Mass allocation	Attributional Economic allocation	Consequential System expansion
Land use[a]	m^2	1.18	1.16	0.90
Fossil energy use[b]	MJ	5.77	6.91	2.55
Eutrophication[a]	g NO_3-eq	163	170	113
Acidification[a]	g SO_2-eq	10.9	11.2	4.78
Climate change[a]	g CO_2-eq	1560	1610	901

[a] EDIP97 updated version 2.3.

[b] Cumulative Energy Demand; non-renewable fossil energy.

3.5 Comparison

The comparison of ALCA and CLCA in milk production was based on four criteria: hotspot identification, comprehensibility, quality and availability of data. Table 3.4 provides an overview of the main characteristics of ALCA and CLCA (Guinée *et al.*, 2002; Weidema, 2003) complemented with the comparison outcomes. Below, the outcomes of the comparison are discussed.

Table 3.4 Overview of main characteristics of attributional and consequential LCA (Guinée *et al.*, 2002; Weidema, 2003) complemented with the comparison outcomes

	Attributional LCA	Consequential LCA
Synonym	Status quo	Change-oriented
Type of questions answered	Accounting	Assessing consequences of changes
Data	Average historical	Marginal future
Knowledge required	Physical mechanisms	Physical and market mechanisms
Functional unit	Represents static situation	Represents change in volume
System boundaries	Static processes	Affected processes by change in demand
System expansion	Optional	Obligatory
Co-product allocation	Frequently used	Never used
Hotspot identification	System-dependent	System-dependent
Comprehensibility		
- LCA practitioner	Difficult use of arbitrary allocation factors	Difficult inclusion of future processes
- Feeding expert	Good; concentrates represent reality	Difficult to understand usage of two ingredients
Quality	Sensitive to uncertainties	Higher sensitivity to uncertainties
Data availability	Similar	Similar

3.5.1 Hotspot identification

Hotspot identification implies identifying elements within the system that contribute most to a certain impact category. Environmental hotspots of conventional milk production, for the different impact categories, were identified with a contribution analysis. The impact category climate change is highlighted by means of an illustration. The hotspots of the other impact categories are presented in Sections 3.5.1.2-3.5.1.5.

3.5.1.1 Climate change

Figure 3.3a shows the contribution of different processes in the conventional milk production system to climate change expressed in Global Warming Potential (GWP) of ALCA using both mass and economic allocation. Figure 3.3b shows the contribution of different processes in the conventional milk production system to climate change of CLCA using system expansion. Both figures show that emissions related to keeping animals and feed production at the dairy farm (mainly methane and nitrous oxide) contributed most to climate change when using ALCA and CLCA.

Within CLCA only the concentrates ingredients spring barley and soybean meal were used, while within ALCA many ingredients were used, of which maize gluten meal and soy hulls were the main contributing ingredients to GWP. Maize gluten meal and soy hulls contributed for 30% (economic allocation) and 18% (mass allocation) to GWP (Fig. 3.3a), while soybean meal and spring barley contributed for 27% to GWP (Fig. 3.3b). Within CLCA, the avoided beef production was higher than the avoided pork production, mainly due to methane emissions from beef cows.

3.5.1.2 Land use

The area covered by the dairy farm had the highest contribution to total land use both within CLCA and ALCA. Within CLCA the other hotspots were spring barley and soybeans, while within ALCA the other hotspots were related to feed as well; soybeans, maize grain, sugar beets and fresh fruit bunches. Within CLCA, the avoided beef production was higher than avoided pork, soy and palm production.

3.5.1.3 Energy use

Within both CLCA and ALCA the identified hotspots were diesel, transport by truck, electricity and natural gas. The only difference was that, within CLCA, electricity was based on generation in a natural gas power plant and, within ALCA, it was based on a mixture of generators.

3.5.1.4 Acidification

Emissions from the dairy farm contributed most to acidification potential both within CLCA and ALCA. Within CLCA, the other hotspots were spring barley, transport by ship, energy and N-fertiliser. Within ALCA, they were transport (both truck and freighter oceanic), diesel use, maize grain and N-fertiliser. Within CLCA, the avoided beef production was higher than avoided pork and palm production.

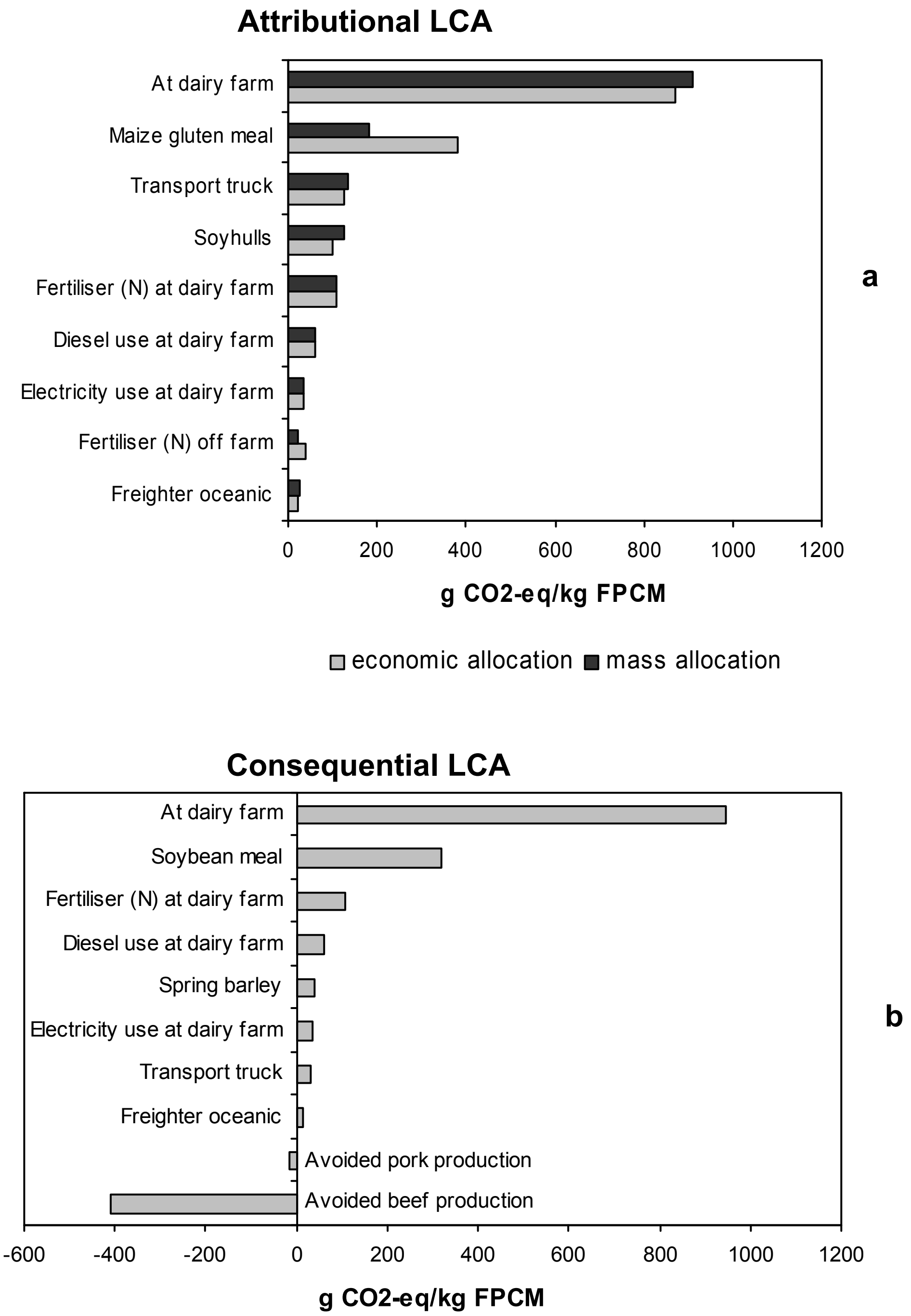

Figure 3.3 Contribution of different processes to climate change expressed in Global Warming Potential (GWP) of conventional milk production by attributional LCA (ALCA) using both mass and economic allocation (3.3a), and by consequential LCA (CLCA) using system expansion (3.3b) **Legend:**

The category 'at dairy farm' implies emissions related to keeping animals and on-farm feed production. The category fertiliser (N) at dairy farm implies related emissions to production and transport of fertiliser (N) purchased by the dairy farm. The category fertiliser (N) off-farm implies related emissions to production and transport of fertiliser (N) used for production of crops that were used as concentrates ingredients. The categories 'transport truck' and 'freighter oceanic' imply transport of feed**.** The categories 'maize gluten meal' and 'soy hulls' and 'spring barley' imply cultivation and production process. The category 'soybean meal' implies cultivation and production of soybean meal including avoided production of palm oil.

3.5.1.5 Eutrophication

Emissions and leaching at the dairy farm contributed the most to eutrophication potential both within CLCA and ALCA. Within CLCA the other hotspot was spring barley. Within ALCA they were maize grain, sugar beets, rape seed and soybeans. Within CLCA, the avoided beef production was higher than the avoided pork and palm production.

3.5.2 Comprehensibility

Degree of comprehensibility was assessed by looking at the degree of difficulty in understanding by LCA practitioners, based on discussions among the authors, and by feeding experts, based on literature.

The goal of ALCA is to assess the environmental burden of a product, assuming a status-quo situation, whereas the goal of CLCA is to assess the environmental consequences of a change in demand. ALCA requires a physical-accounting way of thinking, whereas CLCA requires a physical-accounting and economic-causal way of thinking. A consequential practitioner asks him/herself which processes are affected when a change in demand of the product under study occurs. The authors experienced that it was difficult for an attributional practitioner to understand how it is possible to include future processes in the analyses. For example, it is difficult to understand that the required electricity to produce the increased amount of the product under study is based on one power plant (the marginal one), instead of on an electricity mix. Furthermore, when performing system expansion within CLCA, it is difficult for an attributional practitioner to understand why and how to include avoided processes in the analyses (Heijungs and Guinée, 2007). On the other hand, the authors experienced that it was difficult for a consequential practitioner to understand that, within ALCA, market mechanisms and size of change in demand are ignored; the processes included within ALCA are not the processes affected by a change. Furthermore, using arbitrary allocation factors for dividing the environmental burden of a product, as a practical solution to overcome a technical obstacle, is difficult to understand for a consequential practitioner. Using a factor based on monetary values or physical amounts to divide the environmental burden over different products, while the environmental burdens of by-products are excluded, is not in line with their economic-causal way of thinking. Conclusively, as experienced by the authors, ALCA and use of co-product allocation are difficult to comprehend for a consequential practitioner, while CLCA and system expansion are difficult to comprehend for an attributional practitioner.

Feeding experts usually try to optimise growth and milk production by meeting the needs of the dairy cow. Nutritional and health aspects are important aspects that the feeding industry takes into consideration when composing concentrates (Eastridge, 2006; Goff, 2006). Within ALCA, real-life data of concentrates composition are used, which represents the requirements of the animals to produce milk. Within CLCA, energy and protein requirements are used to calculate the necessary amounts of spring barley and soybean meal to meet these needs (see Section 3.3.2). Although energy and protein requirements are the most important aspects to consider, a feed ratio based on a diet composed of only two ingredients, besides grass and maize silage intake produced on farm, might imply a loss of production, due to an un-balanced diet, especially when used over the long-term, and is not recommended by feeding experts (Morrison and

Patterson, 2007). Using soybean meal as the only protein ingredient, however, is supported by the strong connection between the world's expanding livestock sector and the expanding soybean area in South America (Steinfeld *et al.*, 2006). At this moment, it seems as if soybean will become increasingly important in the future as it is the most competitive protein source on the world market (Dalgaard *et al.*, In press) and because a still larger part of the livestock feed is soybean meal (Steinfeld *et al.*, 2006). Despite this increasing use of soybean meal as protein source, concentrates used within ALCA will be more understandable for a feeding expert compared with the feed used within CLCA, as it represents a realistic situation.

3.5.3 Quality

When analysing the reliability over time and individuals, we want to assess uncertainties. Every time an LCA is performed, uncertainties are included. Within ALCA, average data are used, and in most cases uncertainties can be quantified. For example, variations around ammonia emissions and nitrate leaching. When identifying marginal technologies within CLCA, with a market prospect of, at the highest, fifteen years, another uncertainty is brought into the analyses. Uncertain knowledge is used to predict future consequences. Within CLCA, this uncertainty can be quantified by performing sensitivity analysis with several alternative market situations. For instance, if we look at the marginal electricity supplier in The Netherlands, we identify the natural gas power plant. If the marginal electricity supplier was identified to be a wind power plant, outcomes would have been different, so sensitivity analyses are needed. In general, it can be concluded that outcomes of CLCA are more sensitive to uncertainties compared with ALCA, due to the inclusion of market prospects.

3.5.4 Availability of data

At first sight CLCA seemed to decrease the amount of data required. In the case of concentrates, data on only two ingredients were needed (protein-rich and energy-rich) while, within ALCA, data on all ingredients of different concentrates were needed. However, when applying system expansion the system is expanded and new data are needed each time. For instance, in case of milk production, the marginal pork production was included. So, data on pork production were suddenly needed when analysing milk production systems. The underlying theory is that data collection is lower within CLCA, because some constrained processes are not linked since these cannot change their output in response to a change in demand. Market data, however, are an additional data requirement for CLCA. Lack of marginal data is a problem when performing CLCA, which is probably due to the current small number of consequential practitioners. More research is needed to identify marginal processes.

In this study it can be concluded that the amount of data required within CLCA is similar compared with ALCA. On the one hand, less data are required within CLCA compared with ALCA while, on the other hand, marginal data are not always available and performing system expansion often implies the use of data on new processes within CLCA. In LCAs of products other than milk, however, differences in data requirement might exist.

3.6 Discussion and Conclusions

This article demonstrates how to perform ALCA (mass and economic allocation) and CLCA (system expansion) of an average conventional milk production in The Netherlands. Furthermore, this study presents an overview of the main differences between the two methodologies ALCA and CLCA when analysing a conventional milk production system.

Usage of allocation factors within ALCA and usage of system expansion within CLCA correspond with the ISO standards (ISO, 2006). According to these standards the first option is to avoid allocation by making use of subdivision or to expand the systems investigated. The second option is to allocate based on physical causal relationships between the environmental burdens and functions. The third and last option is to allocate according to relationships other than the physical causal. Applying system expansion within CLCA agrees with the first option given in the ISO standards. Applying some kind of allocation is not the first option given in the ISO standards. Applying system expansion within ALCA requires an economic-causal way of thinking. The authors experienced it was hard to perform system expansion within ALCA, as no change in demand is assumed and, therefore, it is hard to assess avoided burdens in a correct way. Both mass and economic allocation were applied within ALCA, which resulted in a small difference in total environmental burden. Although applying mass allocation is given preference over applying economic allocation according to the ISO standards, in most studies, economic allocation is used within ALCA. One argument for using economic allocation is that the value of co-products represents the causal factor for the production process.

Differences were found between ALCA and CLCA in total quantitative outcomes, hotspots, degree of understanding by various stakeholders and quality. Total outcomes computed by CLCA were only 35%-75% of outcomes computed by ALCA, different per impact category. Major hotspots were the same for all impact categories, computed by ALCA and CLCA, whereas the other hotspots differed in contribution, order and type. As experienced by the authors, ALCA and use of co-product allocation are difficult to comprehend for a consequential practitioner while CLCA and system expansion are difficult to comprehend for an attributional practitioner. Furthermore, literature shows concentrates used within ALCA will be more understandable for a feeding expert than the feed used within CLCA. Outcomes of CLCA are more sensitive to uncertainties as compared with ALCA, due to the inclusion of market prospects.

The main cause of these differences between ALCA and CLCA is the fact that different systems are modelled. The goal of the study, or the research question to be answered, defines the system under study. In general, the goal of CLCA is to assess consequences of a change in demand, whereas the goal of ALCA is to assess the environmental burden of a product, assuming a status-quo situation. Nowadays, however, most LCA practitioners choose one methodology independent of their research question. Only Ekvall and Andræ (2006) used both ALCA and CLCA to assess climate change when shifting from a tin-lead wave solder paste to a lead-free reflow solder paste. Due to lack of marginal data, average data were used besides the marginal data in the consequential LCI. Both methods showed the shift in solder paste resulted in reduced lead emissions and an increased GWP. Differences, however, were found in total quantitative outcomes and contribution of hotspots, which agree with the findings in our study.

3.7 Recommendations

We recommend that LCA practitioners better distinguish between ALCA and CLCA in applied studies in order to reach a higher degree of transparency. Furthermore, we recommend that LCA practitioners of different research areas perform similar case studies to address differences between ALCA and CLCA of the specific products, as the outcomes might differ from those in our study.

References

BINternet, 2003. Bedrijven-InformatieNet, Vol. 2006. Landbouwkundig Economisch Instituut, Wageningen, The Netherlands, www.lei.wur.nl/NL/statistieken/Binternet.

Casey, J.W., Holden, N.M., 2005. Analysis of greenhouse gas emissions from the average Irish milk production system. Agricultural Systems 86, 97-114.

Cederberg, C., Stadig, M., 2003. System Expansion and Allocation in Life Cycle Assessment of Milk and Beef Production. International Journal of Life Cycle Assessment 8, 350-356.

Cornelissen, A.M.G., 2003. The two faces of sustainability. Fuzzy evaluation of sustainable development, PhD thesis, Wageningen University, Wageningen, The Netherlands.

Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., Thrane, M., Pengue, W.A., In press. LCA of soybean meal. International Journal of Life Cycle Assessment.

Doppenberg, J., de Groot, J.P., 2005. Lineaire programmering rundvee-, varkens- en pluimveevoeders. VVM Bedrijfsbureau; Vereniging Voorlichting Mengvoerindustrie, Deventer, The Netherlands.

Eastridge, M.L., 2006. Major advances in applied dairy cattle nutrition. Journal of Dairy Science 89, 1311-1323.

EcoinventCentre, 2004. Ecoinvent data v1.1 Final reports ecoinvent 2000 (1-15). Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Ekvall, T. 1999. System expansion and allocation in Life Cycle Assessment; with implications for wastepaper management, PhD thesis, Chalmers University of Technology, Göteborg, Sweden.

Ekvall, T., Finnveden, G., 2001. Allocation in ISO 14041- a critical review. Journal of Cleaner Production 9, 197-208.

Ekvall, T., Weidema, B.P., 2004. System boundaries and input data in consequential life cycle inventory analysis. International Journal of Life Cycle Assessment 9, 161-171.

Ekvall, T., Andræ, A.S.G., 2006. Attributional and consequential environmental assessment of the shift to lead-free solders. International Journal of Life Cycle Assessment 11, 344-353.

FAPRI, 2007. Food and agricultural policy research institute, Vol. 2007, www.fapri.org.

Frischknecht, R. 1998. Life Cycle Inventory Analysis for decision-making, Zürich, Switzerland.

Goff, J.P., 2006. Major advances in our understanding of nutritional influences on bovine health. Journal of Dairy Science 89, 1292-1301.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H., van der Ven, B.L., Weidema, B.P. (Eds.), 2002. Handbook on Life Cycle Assessment; Operational Guide to the ISO Standards. Centrum voor Milieukunde- Universiteit Leiden (CML); Kluwer Academic Publishers., Leiden, The Netherlands.

Heijungs, R., 1997. Economic Drama and the Environmental Stage. Formal Derivation of Algorithmic Tools for Environmental Analysis and Decision-Support from a Unified Epistemological Principle, Leiden University, Leiden, The Netherlands.

Heijungs, R., Guinée, J.B., 2007. Allocation and 'what-if' scenarios in life cycle assessment of waste management systems. Waste Management 27, 997-1005.

Høgaas Eide, M., 2002. Life Cycle Assessment (LCA) of Industrial Milk Production. International Journal of Life Cycle Assessment 7, 115-126.

Hospido, A., Moreira, M.T., Feijoo, G., 2003. Simplified life cycle assessment of Galician milk production. International Dairy Journal 13, 783-796.

ISO, 2006. Environmental Management. The ISO 14000 family of international standards, ISO standards Collection on CD-ROM, Genève, Switzerland.

Morrison, S.J., Patterson, D.C., 2007. The effects of offering a range of forage and concentrate supplements on milk production and dry matter intake of grazing dairy cows. Grass and Forage Science 62, 332-345.

Nielsen, P.H., Nielsen, A.M., Weidema, B.P., Dalgaard, R., Halberg, N., 2005. LCA food database, Tjele, Denmark, www.lcafood.dk. The database is available in the LCA pc-software SimaPro 7.0.

Pengue, W.A., 2006. Increasing roundup ready soybean export from Argentina. In: Halberg N., A.H., Knudsen M.T., Kristensen, E.S. (Ed.), Global development of organic agriculture, Vol. Box 1.1 in chapter 1. CABI Publishing, pp. 20.

Rang, H., Westra, P.P., 2006. Prijsopbouw rundvlees. PVE; Productschappen Vee, Vlees en Eieren, Zoetermeer, The Netherlands.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environment International 30, 701-720.

Schmidt, J.H., Weidema, B.P., In press. Shift in the marginal supply of vegetable oil. International Journal of Life Cycle Assessment, 1-5.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C., 2006. Livestock's long shadow; environmental issues and options. Food and Agricultural Organization of the United Nations, Rome, Italy.

Tamminga, S., Van Straalen, W.M., Subnel, A.P.J., Meijer, R.G.M., Steg, A., Wever, C.J.G., Blok, M.C., 1994. The Dutch protein evaluation system: the DVE/OEB-system. Livestock Production Science 40, 139-155.

Ter Veer, D.F., 2005. Scenariostudie 100% biologisch voeren melkvee. Animal Sciences Group/Praktijkonderzoek, Lelystad, The Netherlands.

Thomassen, M.A., de Boer, I.J.M., 2005. Evaluation of indicators to assess the environmental impact of dairy production systems. Agriculture, Ecosystems & Environment 111, 185-199.

Thomassen, M.A., Van Calker, K.J., Smits, M.C.J., Iepema, G.L., De Boer, I.J.M., 2008. Life Cycle Assessment of conventional and organic milk production in The Netherlands. Agricultural Systems 96, 95-107.

Tillman, A.-M., Ekvall, T., Baumann, H., Rydberg, T., 1994. Choice of system boundaries in life cycle assessment. Journal of Cleaner Production 2, 21-29.

Tillman, A.-M., 2000. Significance of decision-making for LCA methodology. Environmental Impact Assessment Review 20, 113-123.

Van Calker, K.J., Berentsen, P.B.M., Giesen, G.W.J., Huirne, R.B.M., 2005. Identifying and ranking attributes that determine sustainability in Dutch dairy farming. Agriculture and Human Values 22, 53-63.

Van Es, A.J.H., 1978. Feed evaluation for ruminants 1. The systems in use from May 1977 onwards in The Netherlands. Livestock Production Science 5, 331-345.

Van Straalen, W.M. 1995. Modelling of nitrogen flow and excretion in dairy cows, PhD thesis Wageningen University and Research Centre, Wageningen, The Netherlands.

VDI, 1997. Cumulative Energy Demand - Terms, Definitions, Methods of Calculation. In: Ingenieure, V.D. (Ed.), VDI-Richtlinien 4600, Düsseldorf, Germany.

Weidema, B.P., Norris, G.A., 2002. Avoiding co-product allocation in the metals sector ICMM International Workshop on Life Cycle Assessment and Metals. A Dubreuil, Montreal, Canada.

Weidema, B.P., 2003. Market information in life cycle assessment. Danish Environment Protection Agency, Hørsholm, Denmark.

Wenzel, H., Hauschild, M., Alting, L., 1997. Environmental assessments of products- Vol 1:Methodology, tools and case studies in product developments. In: Edition, F. (Ed.). Champan&Hall, London (UK); Weinheim (Germany); New York (USA); Tokyo (Japan); Melbourne (Australia); Madras (India).

Chapter 4

Life Cycle Assessment of conventional and organic milk production in The Netherlands

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Abstract

Production of milk causes environmental side effects, such as emission of greenhouse gases and nutrient enrichment in surface water. Scientific evidence that shows differences in integral environmental impact between milk production systems in The Netherlands was underexposed. In this paper, two Dutch milk production systems, i.e. a conventional and an organic, were compared on their integral environmental impact and hotspots were identified in the conventional and organic milk production chains. Identification of a hotspot provides insight into mitigation options for conventional and organic milk production. Data of commercial farms that participated in two pilot-studies were used and refer to the year 2003. For each farm, a detailed cradle-to-farm-gate Life Cycle Assessment, including on and off farm pollution was performed. Results showed better environmental performance concerning energy use and eutrophication potential per kilogram of milk for organic farms than for conventional farms. Furthermore, higher on-farm acidification potential and global warming potential per kilogram organic milk implies that higher ammonia, methane, and nitrous oxide emissions occur on farm per kilogram organic milk than for conventional milk. Total acidification potential and global warming potential per kilogram milk did not differ between the selected conventional and organic farms. In addition, results showed lower land use per kilogram conventional milk compared with organic milk. In the selected conventional farms, purchased concentrates was found to be the hotspot in off farm and total impact for all impact categories, whereas in the selected organic farms, both purchased concentrates and roughage were found to be the hotspots in off farm impact.

We recommend to improve integral environmental performance of milk production by: (1) reducing the use of concentrates ingredients with a high environmental impact, (2) decreasing the use of concentrates per kilogram of milk, and (3) reducing nutrient surpluses by improving farm nutrient flows.

4.1 Introduction

An agricultural activity is considered to be ecologically sustainable if its polluting emissions and its use of natural resources can be supported in the long term by the natural environment. The first step in the assessment of ecological sustainability is assessment of its environmental impact (Payraudeau and Van der Werf, 2005). Assessing the environmental impact is a well-investigated issue in The Netherlands (Oenema *et al.*, 1998). Most research, however, has focused on eutrophication and acidification at farm level, whereas there has been little research on the integral assessment of the environmental impact (Van den Brandt and Smit, 1998; Erisman *et al.*, 2001; Schröder *et al.*, 2003; Van Calker *et al.*, 2004). An integral assessment means that several environmental burdens (e.g. use of natural resources or climate change) and the environmental burden of purchased inputs can be addressed together. Life Cycle Assessment (LCA) is a method for integral assessment of the environmental impact of products, processes or services by including all phases of the life cycle. In recent years, LCA has proven to be an internationally accepted method, used widely in the agricultural sector for integral assessment of the environmental impact and for identification of a hotspot[1] (Cederberg and Mattson, 2000; Haas *et al.*, 2001; Berlin, 2002; Basset-Mens and Van der Werf, 2005; Halberg *et al.*, 2005; Thomassen and De Boer, 2005).

Production of milk is an example of an agricultural activity that causes environmental side effects, such as emission of greenhouse gases and nutrient enrichment in surface water (Van Calker, 2005). In The Netherlands, milk production at farm level contributes nationally around 50% to the NH_3 emission, 15% to the CO_2 emission, 48% to the CH_4 emission, around 37% to the N_2O emission and around 45% to the nutrient enrichment in surface and groundwater (Velthof and Oenema, 1997; Van Egmond, 2004; Van der Schans *et al.*, 2005). To improve the environmental impact of agricultural activities, such as milk production, the Dutch Government and European Union introduced several environmental policies (Oenema, 2004). Dairy farmers are forced to look for different ways to address these environmental policies that focuses mostly on eutrophication and acidification at farm level (Oenema *et al.*, 2001; Baars *et al.*, 2002). One way to comply with future environmental policies may be to convert from a conventional milk production system to an organic one. In 2003, about 1.4% of the total milk sector consisted of organic dairy farms (Binternet, 2003). A comparison between the integral assessment of the environmental impact of conventional and organic systems is needed to address advantages or disadvantages of each system. In addition, identification of a hotspot provides insight into mitigation options for conventional and organic systems.

The objective of this study was to compare the integral assessment of the environmental impact of conventional and organic milk production systems and to identify hotspots in the conventional and organic milk production chains. The LCA of conventional and organic milk production systems was based on data of 21 commercial dairy farms in The Netherlands.

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[1] A hotspot is an element that has a high contribution to the environmental burden of a product (Guinée et al., 2002)

4.2 Material and methods

4.2.1 Data

Data from 10 conventional commercial dairy farms were collected in 2003, when these farms were considered to be conventional, complying with current environmental legislation. In 2004, the farms started to participate in a sustainability project 'Caring Dairy', which is an initiative of ice cream company Ben & Jerry's to develop guidelines for sustainable dairy farming practices (Van Calker *et al.*, 2005).

Data were also collected from 11 organic commercial dairy farms in 2003 that participated in a demonstration project of Dutch organic dairy farmers, the so-called BIOVEEM project (Baars, 2002; Baars *et al.*, 2002). This BIOVEEM project was started to broaden and strengthen organic dairy farming. Farmers worked together with researchers on themes, such as soil and fertilisation, animal health, economics, and production of fodder crops. The farms differed in management styles, scale, and soils. Every farmer had the intention, furthermore, to search for solutions or new developments. The ecological principle of organic farming is that farming should fit the cycles and ecological balances in nature to improve environmental quality and conserve resources (IFOAM, 2006).

Table 4.1 General characteristics of the participating farms in the two pilot studies in 2003

Parameters	Units[a]	Conventional	NL[b]	Organic	NL[b]
Farms	n	10		11[c]	
Grassland	ha	35.5 (10.9)	29.9	40.7 (19.4)	36.1
Arable land	ha	11.2 (6.8)	8.6	11.5 (11.4)	10.8
Milking cows	n	81 (24.9)	63	71 (32.4)	56
Milk production[d]	kg/cow	7991 (800)	7630	6138 (980)	6390
Milk fat	%	4.41 (0.11)	4.42	4.45 (0.66)	4.40
Milk protein	%	3.44 (0.08)	3.49	3.44 (0.30)	3.45
Density	LU/ha[e]	2.13 (0.3)	2.31	1.70 (0.4)	1.76
Intensity	kg FPCM/ha	14713 (2342)		8937 (2655)	
Soil type		100% sand		45% sand 36% clay	
Diesel use	L	4868 (2741)		5026 (3681)	
Electricity use	kWh	27113[f] (12733)		28738[f] (18984)	
Purchased pesticides	kg active matter /ha	0.25 (0.10)			

[a] Units of parameters are given. Numbers for participating farms are means with standard deviation.

[b] Average values of a typical conventional and organic dairy farm in The Netherlands (Binternet, 2003; CBS, 2003).

[c] Four farms were bio-dynamic.

[d] Milk with an economic value (e.g. delivered milk to the factory), due to lack of data of private milk use of some farms.

[e] LU = Dutch Livestock Units.

[f] Five farms used renewable electricity.

Some important aspects of organic dairy farming include: promoting natural behaviour of cows by having them spend most of the grazing period outdoors, forbidding use of synthetic fertilizer and pesticides during production of crops, and requiring at least 60% of cows' daily ration consist of roughage, produced organically preferably on farm (EEG, 1992). In 2003, at least 90% of concentrates must consist of organic ingredients (Ter Veer, 2005).

General characteristics of the farms in addition to average characteristics of typical Dutch conventional and organic farms are in Table 4.1 (Binternet, 2003; CBS, 2003).

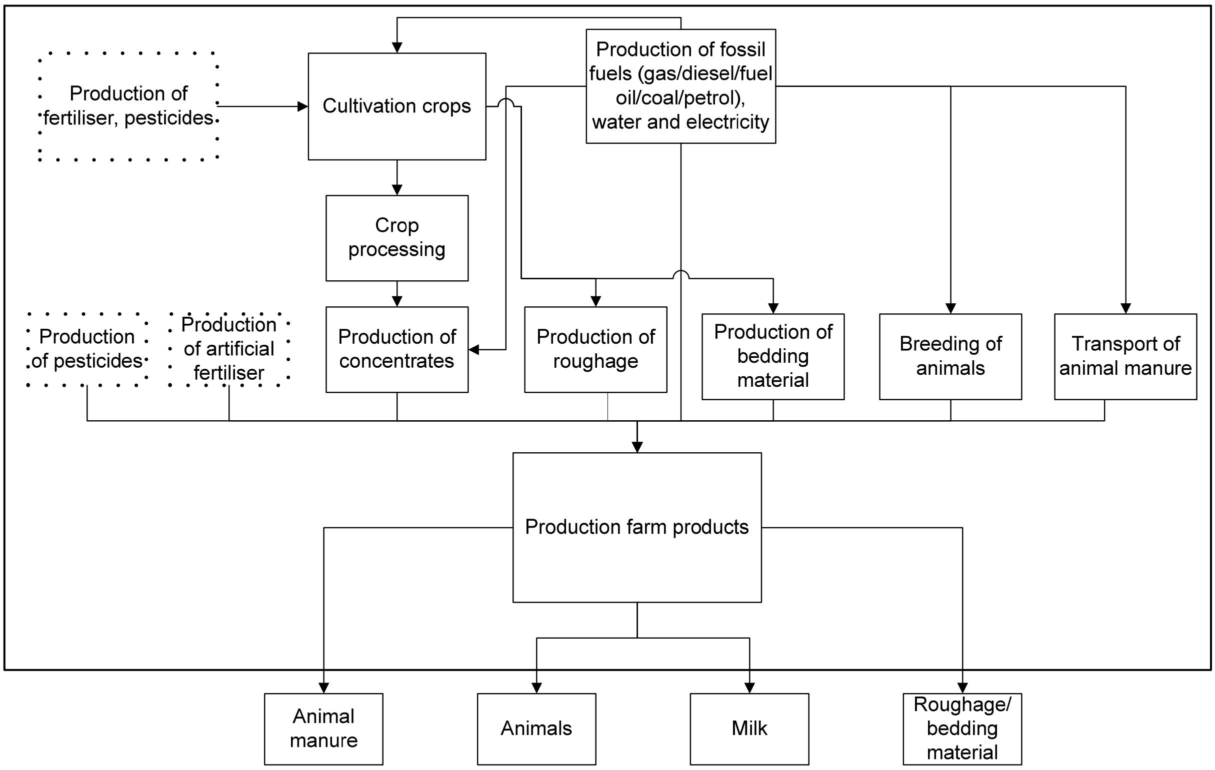
Compared with a typical conventional farm, participating conventional farms had more land, more milking cows, and higher milk production per cow. Furthermore, participating farms were less intensive (in Dutch Livestock Units per ha) and had a similar milk fat and lower milk protein percentage. Conventional farms were situated in the Northern region of The Netherlands. Compared with a typical organic farm, participating organic farms had more land, more milking cows and lower milk production per cow. The organic farms had similar intensity (in Dutch Livestock Units per ha) and similar milk fat and protein percentages. Organic farms were situated throughout The Netherlands.

4.2.2 Life Cycle Assessment (LCA)

LCA is a collection and evaluation of the inputs and outputs and the potential environmental impacts of a production system throughout its life cycle (Guinée *et al.*, 2002). Stages of LCA methodology include: goal and scope definition, inventory analysis (LCI), impact assessment (LCIA) and interpretation of results (ISO, 2006). For each dairy farm, a detailed "cradle-to-farm-gate" LCA was performed.

4.2.2.1 Goal and scope definition

The goal and scope definition is the stage in which initial choices are made that determine the working plan of the entire LCA. One aim of this study was to compare the integral assessment of the environmental impact of conventional and organic milk production systems. In order to compare systems, you need a Functional Unit (FU). The FU describes the primary function fulfilled by a production system and enables different systems to be treated as functionally equivalent (Guinée *et al.*, 2002). The primary function of dairy systems is milk production. The functional unit (FU) chosen was "1 kg of Fat and Protein Corrected Milk leaving the farm-gate" (CVB, 2000). In accordance with Guinée *et al.* (2002), we chose the baseline impact categories: land use, energy use, climate change, acidification, and eutrophication. Other baseline impact categories, such as terrestrial or aquatic eco-toxicity, human toxicity, or stratospheric ozone depletion (ODP) were not chosen. Necessary detailed data on pesticides and heavy metals were not available in order to include the impact categories eco-toxicity and human toxicity quantitatively, whereas in case of ODP, other studies showed milk production did not contribute significantly to this impact category (Berlin, 2002; Hospido *et al.*, 2003).



—— System boundary ‘cradle to farm-gate’ LCA

• • • Indicates these aspects are only applicable when conventional crops are produced

Figure 4.1 System boundaries ‘cradle to farm-gate’ LCA

The system under study included the whole life cycle required for the production of raw milk, from the production of inputs to products leaving the farm-gate, i.e. excluding transport or processing of raw milk (see Figure 4.1). Related transport associated with the production of purchased inputs was included. Medicines, seeds, and machinery were excluded because of their small impact (Cederberg, 1998). Buildings were excluded because we assumed similarity in buildings of the different farm types (Erzinger *et al.*, 2003)

4.2.2.2 Inventory analysis

The inventory analysis consists of the collection of data concerning resource use, energy consumption, emissions, and products resulting from each activity in the production system. In this stage, each process was further analysed, and factors to be included were defined (Table 4.2). Subsequently, data of each process were collected, allocation steps for multifunctional processes were performed, and final calculations were completed.

Table 4.2 Overview inventory data used in inventory analysis

	Element	Computation method[a]	Included factors	References[b]
Off farm[c]	Purchased pesticides	Q * LCI/kg active matter	Production/transport	Brand and Melman (1993)
	Purchased art. fertilizer	Q * LCI/kg art. fertilizer	Production/transport	Davis and Haglund (1999)
	Purchased concentrates	Q * LCI/kg concentrates	Crop cultivation[d]	FAO (2002/2003), Cederberg (1998), CVB (2000)
			Crop processing	Brand and Melman (1993), Cederberg (1998)
			Transport	Cederberg (1998), Michaelis (1998), WPD (2003)
	Purchased roughage and bedding material	Q * LCI/kg roughage	Crop cultivation	Dekkers (2001), LEI (2004), Koroneos *et al.* (2005)
			Transport	Cederberg (1998), Michaelis (1998)
	Purchased animals	Q * LCI/animal	Breeding[e]	Tamminga *et al.* (2000), Oenema *et al.* (2000)
			Transport	Cederberg (1998), Michaelis (1998)
	Purchased animal manure	Q * LCI/kg manure	Transport	Brand and Melman (1993)
	Contract work	Q * LCI/litre diesel	Diesel use	Brand and Melman (1993), Hanegraaf *et al.* (1996)
On farm	Use of diesel	Q * LCI/litre diesel	Supply and use	Michaelis (1998)
	Use of electricity	Q * LCI/kWh electricity	Supply and use	Michaelis (1998), EnergieNed (2002), CertiQ (2003)
	Use of gas	Q * LCI/m^3 gas	Supply and use	Michaelis (1998)
	Use of water	Q * LCI/m^3 water	Electricity supply	Michaelis (1998), EnergieNed (2002)
On/off	Emissions of CH_4	Fixed values animals	Enteric+ manure	Schils *et al.* (2006)
	Emissions of NH_3 and NO_x	Fixed values animals[f] and spreading of fertilizer	Stable/pasture/ deposit/spreading	Oenema *et al.* (2000),Van Geel (2004) Van der Hoek (2002), Mosier *et al.* (1998)
	Emissions of N_2O	Fixed values animals/soil	Direct and indirect	Mosier *et al.* (1998), Oenema *et al.* (2000)
	Leaching of NO_3 and PO_4	Farm-gate balance and	Net N-leaching factors	Schröder *et al.* (2005)
		Soil surface balance	Inputs and outputs	Van Eerdt and Fong (1998)

[a] Q is actual amount of product obtained from technical farm data. LCI is Life Cycle Inventory, which is in most cases end values of a computation procedure.

[b] Most important sources used for the assessment of the Life Cycle Inventory are given.

[c] Off farm includes upstream processes given in Figure 4.2 until production farm products.

[d] For estimating related emissions and resource use for cultivation and processing of concentrates ingredients, more references were used than given in this table. For a detailed description we refer to Jansen (2005) and ‘s Gravendijk (2006).

[e] Breeding includes all aspects of growing-up: feed intake, emissions during stable period and pasturing.

[f] For milking cows ammonia emission and nitrogen excretion were related to milk urea content (Van Duinkerken *et al.*, 2005; Schröder *et al.*, 2006).

Choice of allocation implies partitioning the environmental impact of a multifunctional process. Several multifunctional processes were present: the production of ingredients for concentrates, of roughage, and bedding material; and the joint production of milk, meat, roughage, and manure leaving the farm-gate. Economic allocation based on shares in proceeds of the products was performed for multifunctional processes (Guinée *et al.*, 2004). For joint production of conventional milk, on average 91% was ascribed to milk, 8.2 % to animals, and 0.8% to exported crops. For joint production of organic milk, on average 90% was ascribed to milk, 6.6% to animals, and 3.4% to exported crops and manure.

The computation method used and the most important references for data used in the inventory analysis are in Table 4.2, in addition to included factors for each element. Collected farm data augmented with feed supplier data were used to assess actual amount (Q), whereas data from literature and use of expert knowledge were used to assess and compute Life Cycle Inventories (LCIs).

To determine the LCI of purchased concentrates, three types of concentrates were distinguished: DVE≤95, 95<DVE≤110, and DVE>110, based on their intestine digestible protein content, using the Dutch DVE-system (Van Straalen, 1995), because DVE-content of the different purchased concentrates related to feeding strategy and milk urea content, and it could be detected relatively easy. After dividing concentrates, general ingredient composition, based on annual data (>95% of its main feed ingredients), of the three types of concentrates were recovered (Doppenberg and De Groot, 2003; Heuven, 2005). Table 4.3 shows the concentrate ingredients by system, their average share within the three types of concentrates, economic allocation, and their origins.

Table 4.3 Concentrates ingredients by system

Ingredient	Average share in concentrates[a]	Economic allocation (%)	Origin
Conventional system			
Maize gluten meal	28	8	France
Beet pulp	15	11	Netherlands
Palm kernel meal	17	3	Malaysia
Triticale	9	71	Netherlands
Wheat hulls	8	9	France/Germany
Soybeans	6	100	Brazil
Soymeal	4	72	Brazil
Organic system			
Palm kernel meal	17	3	Malaysia
Wheat grain[b]	13	83	Netherlands
Triticale[b]	12	77	Netherlands
Lucerne[b]	12	100	Netherlands
Lupines[b]	11	100	Australia
Maize gluten meal	8	8	France
Rape seed meal	8	33	Germany
Soy hulls[b]	5	1	Brazil

[a] Average of the three types of concentrates according to their DVE-content.

[b] Produced organically.

The most common concentrate ingredients used in the conventional system, which account for 60%, were maize gluten meal, beet pulp, and palm kernel meal. The most common concentrate ingredients used in the organic system, which account for 65%, were palm kernel meal, organic wheat grain, organic triticale grain, organic lucerne, and organic lupines. For each ingredient, a Life Cycle Inventory (LCI) was computed. The potential leaching of nitrate and phosphate were calculated by means of a soil surface balance (Van Eerdt and Fong, 1998).

The amount of diesel used for contract work (Q) was computed based on expenses of contract work (Table 4.2). Conversion factors were used to convert expenses into energy content and subsequently into diesel use (Brand and Melman, 1993; Hageman and Mandersloot, 1994; Hanegraaf *et al.*, 1996).

With respect to LCI of electricity, a mixture for conventional and renewable electricity was used (EnergieNed, 2002; CertiQ, 2003).

Emission of methane occurs in two ways: during enteric fermentation of a cow and from manure management. For the organic system, an emission during fermentation of 128 kg CH_4/dairy cow per year was assumed, whereas for the conventional system 113 kg CH_4/dairy cow per year was assumed (Schils *et al.*, 2006). This higher enteric emission in an organic production system compared to the conventional system, was due to the larger intake of roughage per cow and the lower content of starch in the roughage, which theoretically gives lower fermentation rapidity in the rumen (Jongbloed *et al.*, 2004). Emission from manure management was 0.0018 kg CH_4/kg manure per year for liquid manure and 0.00037 kg CH_4/kg manure per year for solid manure production in animal houses (Van der Hoek and Van Schijndel, 2006).

When a surplus of nitrogen or phosphorus exists, leaching of nitrate or phosphate may occur. Potential leaching of nitrate and phosphate on farm was calculated by means of a farm-gate balance approach. The farm-gate balance represents the amount of nutrients either lost to the environment or accumulated within the soil pools (Nielsen and Kristensen, 2005). Oenema *et al.* (2005) clarify that nutrient surpluses are an indicator for the potential nutrient loss, but not for the actual nutrient loss. To compute the leached fraction of the calculated farm-gate surpluses, we incorporated a soil specific net N-leaching factor, derived from a National Monitoring Program where soil N surpluses of farms were linked to corresponding nitrate N-concentrations in groundwater and surface water (Schröder *et al.*, 2005). Most agricultural soils in The Netherlands have a “high” to “very high” soil P status, and therefore it is assumed that the soils of the farms are saturated for P and that all surplus P is leached to groundwater and surface waters (Oenema *et al.*, 2005).

On farm, ammonia volatilizes mainly in four ways: from manure in the stable, from the inside and outside manure storage, during grazing, and during application of manure and of artificial fertilizer. For milking cows, estimated emission in stable (including inside manure storage) was related to milk urea (Van Duinkerken *et al.*, 2005). For non-producing cows, heifers and calves, fixed emissions were used based on the national regulation of animal husbandry (Van Geel, 2004). For milking cows, estimated nitrogen excretion was also related to milk urea (Schröder *et al.*, 2006). For non-producing cows, heifers and calves, fixed nitrogen excretions were used (Tamminga *et al.*, 2005). Subsequently, the nitrogen excretion of each animal was divided into nitrogen excretion during grazing and in stable, based on the grazing management and the number of days on pasture. Volatilization during grazing was computed as 8% of the amount of nitrogen excreted during grazing (Oenema *et al.*, 2000). When an outside storage was present, we assumed that 55% of total excreted nitrogen in stable was stored outside (Oenema *et al.*, 2000). Volatilization in the outside manure storage was computed as 4.8% for an open storage and 0.96% for a covered storage of the amount of nitrogen stored (Van der Hoek, 2002). Volatilization during application of manure was computed as a fixed fraction of total amount of nitrogen applied, dependent on: standard techniques to apply manure in The Netherlands according to manure type (solid/semi-liquid) and land type (grassland/arable land) (Van der Hoek, 2002). Volatilization during application of artificial fertilizer was computed as 2.6% of total amount of nitrogen applied (Van der Hoek, 2002).

Emission of nitrous oxide occurs directly from manure and from managed soils, and indirectly after nitrate leaching and after runoff of N and after redeposition of volatilised gases to soils and waters (IPCC, 2006). Emission of nitrous oxide in stable, from outside manure storage and during grazing, was computed in case of milking cows, as 0.1% for semi-liquid manure in stable and outside storage, 2% for solid manure in stable and outside storage, and 2% during grazing of total amount of excreted nitrogen (Velthof and Oenema, 1997; Oenema *et al.*, 2000). On farm, direct nitrous oxide emission from managed soils was calculated taking into account fertilizer application, nitrogen fixation, crop residues, and background emission (Mosier *et al.*, 1998; IPCC, 2006). Indirect nitrous oxide emission was calculated taking into account nitrate leaching and N-deposition (Mosier *et al.,* 1998; IPCC, 2006).

Off farm, ammonia volatilizes mainly in two ways: during application of manure and of artificial fertilizer for production of feed. Volatilization during application of manure was computed as a fixed fraction (domestic 4.8% for grassland and 13.8% for arable land; foreign 20%) of total amount of nitrogen applied (Mosier *et al.*, 1998; Van der Hoek, 2002). In foreign countries volatilization is higher due to applying more manure above-ground and to applying more manure combined with straw. Volatilization during application of artificial fertilizer was computed as a fixed fraction (domestic 2.6% and foreign 10%) of total amount of nitrogen applied (Mosier *et al.*, 1998; Van der Hoek, 2002). In foreign countries, volatilization during application of artificial fertilizer is assumed to be higher due to the lower bounding of ammonium in the artificial fertilizers used.

Off farm, direct and indirect nitrous oxide emissions of managed soils were calculated based on Mosier *et al.* (1998) and IPCC (2006).

4.2.2.3 Impact Assessment (LCIA)

The LCIA is the stage in which data collected during the inventory analysis are processed, and environmental impacts are computed. Furthermore, environmental effects were assigned qualitatively to the selected impact categories, and environmental effects were quantified in terms of a common unit for that category (characterization). Table 4.4 shows selected impact categories with related units, contributing elements and characterization factors. Characterization factors for land use, energy use and climate change were chosen according to the Dutch LCA handbook (Guinée *et al.*, 2002). According to the Dutch handbook, no site or regional dependent characterization factors for eutrophication and acidification were used (Huijbregts, 1999). Characterization factors for acidification were chosen from Heijungs *et al.* (1992).

Table 4.4 Selected impact categories with related units, contributing elements and characterization factors[a]

Impact category	Unit	Contributing elements	Characterization factors	References
Land use	m^2	Land occupation	1	Guinée *et al.* (2002)
Energy use	MJ	Energy	1	
Acidification	kg SO_2-eq	SO_2	1	Heijungs *et al.* (1992)
		NH_3	1.88	
		NO_x[b]	0.70	
Climate change	kg CO_2-eq	CO_2	1	Houghton *et al.* (1994)[c]
		CH_4	21	
		N_2O	310	
Eutrophication	kg NO_3^--eq	NO_x[a]	1.35	Heijungs *et al.* (1992)
		P_2O_5	14.09	
		NH_3	3.64	
		NO_3^-	1	
		PO_4^{3-}	10.45	
		NH_4^+	3.6	
		COD[d]	0.22	

[a] Based on the Dutch LCA handbook (Guinée *et al.*, 2002).

[b] NO and NO_2.

[c] Assuming a 100-year time horizon.

[d] Chemical Oxygen Demand; The amount of oxygen required to oxidize organic compounds in a water sample to carbon dioxide and water.

4.2.2.4 Interpretation

In this stage results are analysed and evaluated, and conclusions and recommendations of the study are formulated. A contribution check in the interpretation phase identified elements that contributed most to a certain impact category, the so-called hotspots.

4.2.2.5 Statistical analyses

For statistical analyses we used SAS (SAS, 2002). Shapiro-Wilk test showed that data had a normal distribution. Data were further analysed with an analysis of variance (GLM procedure). The following analysis of variance model was used for the milk production systems:

$$Y_i = \mu + F_i + \varepsilon_i \qquad (1)$$

where μ is the overall mean, F_i the overall effect of the farms and ε_i the error term.

4.3 Results

4.3.1 Land use

Table 4.5 shows results of this LCA study of the conventional and organic milk production system given by impact category. Total land use was less ($p<0.001$) for the conventional system (1.3 m^2/kg FPCM, 7% CV) than for the organic system (1.8 m^2/kg FPCM, 22% CV). On-farm land use of the organic system (1.1 m^2/kg FPCM) was higher ($p<0.01$) compared with the conventional system (0.64 m^2/kg FPCM), which was due mainly to lower yields (no use of artificial fertilizer and pesticides) and lower density (less animals per hectare) in the organic system. No differences were found in off-farm land use (about 0.7 m^2/kg FPCM) between the two systems. Off-farm land use of the conventional system consisted mainly (94%) of land required for production of purchased concentrates. Off-farm land use of the organic system consisted of land required for production of purchased concentrates (51%), and of purchased roughage (42%).

Table 4.5 Results given in mean (standard deviation) of this LCA study of the conventional and organic milk production system given by impact category

Impact category	Unit	Milk production system		Significance[a]	Hotspot[b]	
		Conventional	Organic		Conventional	Organic
Land use	m^2/					
On farm	kg FPCM	0.64	1.1	**	Farm area	Farm area
Off farm		0.64	0.7	-	C	C/R
Total		1.3 (0.1)	1.8 (0.4)	***	Farm area/C	Farm area
Energy use	MJ/					
Direct	kg FPCM	0.6	0.96	*	D/G	D/E
Indirect		4.4	2.17	***	C	C
Total		5.0 (0.6)	3.1 (0.88)	***	C	C
Eutrophication	kg NO$_3$-eq/					
On farm	kg FPCM	0.06	0.04	*	F	F/A
Off farm		0.05	0.03	***	C	C/R
Total		0.11 (0.01)	0.07 (0.03)	***	F/C	F/C/R
Acidification	g SO$_2$-eq/					
On farm	kg FPCM	5.6	7.37	**	A/FA	A/FA
Off farm		3.9	3.45	-	C	C/R
Total		9.5 (0.8)	10.8 (1.9)	-	A/C	A/FA
Climate change	kg CO$_2$-eq/					
On farm	kg FPCM	0.7	0.9	***	A/F	A
Off farm		0.7	0.55	-	C	C/R
Total		1.4 (0.1)	1.5 (0.3)	-	A/C	A/C/R

[a] * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

[b] A= animals; C= concentrates; D=diesel; E=electricity; F=field; FA= fertilizer application; G=gas; R=roughage.

4.3.2 Energy use

Table 4.5 shows that total energy use was higher ($p<0.001$) for the conventional system (5.0 MJ/kg FPCM, 13% CV) than for the organic system (3.1 MJ/kg FPCM, 28% CV). This higher use was due to a higher indirect energy use ($p<0.001$) of the conventional system compared with the organic system. Direct energy use was lower ($p<0.05$) for the conventional system (0.6 MJ/kg FPCM) than for the organic system (0.96 MJ/kg FPCM). Indirect energy use of both systems consisted mainly (83% conventional; 67% organic) of energy required for the production and transport of purchased concentrates.

4.3.3 Eutrophication

Table 4.5 shows that total eutrophication (in eutrophication potential) was higher ($p<0.001$) for the conventional system (0.11 kg NO_3-equivalents/kg FPCM, 11% CV) than for the organic system (0.07 kg NO_3-equivalents/kg FPCM, 44% CV). This higher total eutrophication was due to a higher off-farm eutrophication of the conventional system compared with the organic system ($p<0.001$) and a higher on-farm eutrophication of the conventional system compared with the organic system ($p<0.05$). The contributions of the elements to total eutrophication were different: nitrate accounted for 32% in the conventional and for 40% in the organic system, phosphate accounted for 53% in the conventional and for 31% in the organic system, and ammonia accounted for 12% in the conventional and for 25% in the organic system.

On-farm eutrophication consisted mainly of leaching of nitrate, and phosphate, and of volatilized ammonia during application of fertilizer during production of on-farm feed and of volatilized ammonia from excreted manure in the stable, manure storage(s), and during grazing. In the conventional system, on-farm feed production contributed 90% and animals contributed 9% to on-farm eutrophication, whereas in the organic system on-farm feed production contributed 75% and animals 23% to on-farm eutrophication. On-farm leaching of nitrate and phosphate explain a large part of the results. Therefore, we included outcomes of the nutrient balances to gain more insight in differences between conventional and organic farms. Total N and P_2O_5-surplus per hectare was higher for conventional farms (222.9 N and 36.1 P_2O_5) than for organic farms (103.8 N and 7.0 P_2O_5) (Table 4.6). These higher values for conventional farms were due mainly to the higher input of concentrates and the input of artificial fertilizer for conventional farms. In addition, the net N-leaching factor was higher for conventional farms (0.37) than for organic farms (0.25), because conventional farms were situated on sandy soils, which have a higher net N-leaching factor whereas organic farms were situated on clay or peat soils and have a lower net N-leaching factor.

Off-farm eutrophication consisted mainly of leaching of nitrate, and phosphate, and volatilized ammonia during application of fertilizer by production of purchased concentrates and purchased roughage. In the conventional system, purchased concentrates contributed 92%, whereas in the organic system purchased concentrates contributed 60% and purchased roughage 36%.

4.3.4 Acidification

Table 4.5 shows that total acidification (in acidification potential) for the conventional system was 9.5 g SO_2-equivalents/kg FPCM (8% CV), and for the organic system 10.8 g SO_2-equivalents/kg FPCM (17% CV). Total and off-farm acidification did not differ between the systems. On-farm acidification was higher ($p<0.01$) for the organic system (7.37 g SO_2-equivalents/kg FPCM) than for the conventional system (5.6 g SO_2-equivalents/kg FPCM). Ammonia was the element that accounted for most of total acidification (74% in the conventional and 81% in the organic system). On-farm acidification was caused mainly by: volatilization of ammonia from manure in the stable, from the inside and outside manure storage, during grazing, and during application of fertilizer. In the conventional system, manure in stable, storage, and during pasture contributed 52% and during application of fertilizer 41%, whereas in the organic system manure in stable, storage, and during pasture contributed 62% and during application of fertilizer 30%.

Table 4.6 Mean (standard deviation) nitrogen (N) and phosphate (P_2O_5) surplus in kg/ha per year by production system computed by means of a farm-gate balance

	Conventional		Organic	
	kg N/ha/yr	kg P_2O_5/ha/yr	kg N/ha/yr	kg P_2O_5/ha/yr
Input				
Fixation	15.7 (2.2)	-	64.5 (34.2)	-
Deposition	25.9 (0.9)	2.3 (-)	30.1 (7.6)	2.3 (-)
Animals	0.8 (1.7)	0.5 (1.1)	10.8 (28.9)	0.04 (0.1)
Concentrates	126.6 (31.6)	48.6 (10.7)	29.6 (18)	12.7 (8.5)
Artificial fertilizer	130.1 (42.8)	16.7 (11.7)	-	-
Roughage	8.4 (9.7)	2.6 (3.4)	41.2 (34.6)	12.7 (10)
Organic manure	6.4 (10.4)	3.6 (6.3)	9.9 (19.4)	4.5 (8.8)
Total	313.9 (38.9)	74.3 (15.2)	186 (56.8)	32.3 (13.7)
Output				
Animals	11.3 (3.9)	7.4 (2.6)	6.8 (3)	4.5 (2)
Milk	75.1 (12.3)	28.7 (4.6)	45.5 (13.6)	17.5 (5.5)
Roughage	3.5 (5.5)	1.4 (2.3)	10 (8.2)	3.8 (3.2)
Manure	1.2 (3.6)	0.7 (2.1)	19.8 (32.7)	9.1 (14.9)
Total	91 (13.8)	38.2 (6.3)	82.2 (38.6)	34.8 (17.7)
Surplus/ha	222.9 (38.9)	36.1 (11.2)	103.8 (59.6)	7.0 (9.5)
NH_3 volatilization				
Stable/pasture/storage	20.1 (4.5)		18.8 (4.3)	
Fertilizer application	19.6 (3.8)		9.4 (4.5)	
N_2O emission				
Stable/pasture/storage	1.3 (0.4)		1.9 (1)	
Field direct	3.6 (0.6)		1.8 (0.6)	
Indirect	1.9 (0.4)		1.1 (0.9)	
Net N-leaching factor	0.37 (0.06)		0.25 (0.2)	
Leaching/ha	64.2 (16.3)	36.1 (11.2)	21.1 (29.6)	7.0 (9.5)

Table 4.6 shows ammonia volatilisation of stable, and storage, and during pasture, and during application of fertilizer per hectare of the conventional and organic farms. We expressed the ammonia emissions given in Table 4.6 per kg FPCM as well, taking into account given intensities of the selected farms (14713 kg FPCM/ha for the conventional

and 8937 kg FPCM/ha for the organic farms) (Table 4.1). Ammonia volatilisation of stable, and storage, and during pasture was slightly higher for conventional farms per hectare but lower per kg of milk (20.1 kg N/ha; 1.36^x10^{-3} kg N/kg FPCM) compared with organic farms (18.8 kg N/ha; 2.1^x10^{-3} kg N/kg FPCM). Ammonia volatilisation during application of fertilizer was about twice as high for conventional farms per hectare but similar per kg of milk (19.6 kg N/ha; 1.33^x10^{-3} kg N/kg FPCM) compared with organic farms (9.4 kg N/ha; 1.05^x10^{-3} kg N/kg FPCM).

Off-farm acidification for the conventional system consisted of 83% of ammonia volatilization during production of purchased concentrates. Off-farm acidification for the organic system consisted of 43% of ammonia volatilization during production of purchased concentrates and of 37% during production of purchased roughage.

4.3.5 Climate change

Table 4.5 shows that total climate change (in global warming potential) for the conventional system was 1.4 kg CO_2-equivalents/kg FPCM (6% CV) and for the organic system 1.5 kg CO_2-equivalents/kg FPCM (17% CV). Total and off-farm climate change did not differ between the systems. On-farm climate change was higher ($p<0.001$) for the organic system (0.9 kg CO_2-equivalents/kg FPCM) than for the conventional system (0.7 kg CO_2-equivalents/kg FPCM). Contributions of the elements to total climate change were different: methane accounted for 34% in the conventional system and for 43% in the organic system, nitrous oxide accounted for 38% in the conventional and for 40% in the organic system, and carbon dioxide accounted for 29% in the conventional and for 17% in the organic system.

On-farm climate change consisted mainly of methane emission during enteric fermentation and manure management, direct nitrous oxide emission of manure and of managed soils, and indirect nitrous oxide emission after leaching and redeposition of volatilised gasses to soils and waters. In the conventional system, animals and manure contributed 68% and managed soils 24%, whereas in the organic system, animals and manure contributed 76% and managed soils 16%. It can be derived from Table 4.6 that direct and indirect nitrous oxide emissions per kg of milk were higher for the organic farms (5.4^x10^{-4} kg N/kg FPCM) than for the conventional farms (4.6^x10^{-4} kg N/kg FPCM).

Off-farm climate change consisted mainly of direct and indirect nitrous oxide emissions, carbon dioxide emissions of fossil fuels during production, and transport of purchased concentrates and roughage, in addition to nitrous oxide and carbon dioxide emission during production of artificial fertilizers. In the conventional system, purchased concentrates contributed 87%, whereas in the organic system purchased concentrates contributed 51% and purchased roughage 38%.

4.4 Discussion

In this study, we used LCA to gain insight into the integral assessment of the environmental impact of conventional and organic milk production systems in The Netherlands, as a case study. The potential environmental impact of a milk production system, as computed with an LCA, differs from the actual environmental impact for several reasons. First, it is difficult when performing an LCA of commercial farms to measure actual emissions or leaching on a farm. Instead, generally recognized standards or formulas based on experiments are used to assess emissions and leaching, using real farm data where possible.

Second, accurate environmental inventory data are not always available. In some cases, for example, data represented economic figures, because they were collected for purposes other than this LCA study. The effect of supply changes should in favour be addressed when assessing milk production. No data, however, were available for changes in supply of roughage, concentrates, and manure on the farms. Literature shows that the effect of change in supply is assumed to be small. Farms can have a negative or positive change in supply. The effect of change in supply on the differences between the systems is decreased by the large variation in integral environmental impact of the farms.

Comparing different systems producing similar products requires a high degree of accuracy for inventory data (Basset-Mens and Van der Werf, 2005). Furthermore, Basset-Mens and Van der Werf (2005) state that there needs to be available a large amount of data, representative of the systems to be evaluated. In total, 21 commercial dairy farms were analysed, at least 10 farms representing each production system, which is large compared with earlier LCA studies of milk production systems. Although this sample size is rather large, the farms were not chosen at random, and therefore, do not represent the total Dutch conventional and organic milk production.

In addition to inventory data and sample size, methodological choices affect final results. One choice of methodology, for example, is the question of how to handle co-products. Within attributional LCA of milk production, using economic allocation is justified, assuming a static situation (Guinée *et al.*, 2004). Within consequential LCA of milk production, however, system expansion is preferred assuming a change-oriented situation (Weidema, 2003; Dalgaard *et al.*, 2006). We used economic allocation, because this study was a descriptive attributional LCA. A second choice of methodology is the impact categories. No consensus has been reached yet on how to include land use effects such as soil quality and biodiversity (Milà i Canals *et al.*, 2006). We included only land use impacts in the LCA whereas several land quality issues might be better in organic production. In addition, we did not include the effects of pesticides, because of methodological issues, although another benefit from organic production is that no pesticides are used.

Taking into account the methodological constraints of this LCA-study mentioned above, we will first compare the integral assessment of the environmental impact of the conventional and organic systems, and then we will discuss identification of hotspots. The higher total land use per kg FPCM of the organic farms compared with the conventional farms implies that feeding less concentrates but more roughage, and producing a large part of the feed on farm with lower yields (no use of pesticides and artificial fertilizer), results in a higher use of on-farm land per kg milk produced. The similar off-farm land use for conventional and organic farms is because purchased organic concentrates contain a higher amount of main products compared with conventional concentrates, and main products carry the entire land use. In addition, production of organic concentrate ingredients requires in general more land due to lower yields, compared with conventional concentrate ingredients, because no fertilizer and pesticides are used. Lower indirect energy use and higher direct energy use per kg FPCM for organic farms compared with conventional farms implies that feeding more feed produced at farm level, feeding less concentrates, and using no pesticides and artificial fertilizers results in a lower total energy use per kg FPCM. The higher on-farm acidification potential per kg FPCM of the organic farms compared with conventional farms, can be because more animals were needed per kg milk produced for organic farms. No difference between the conventional and organic farms was found in off-farm acidification potential. Off-farm acidification potential for conventional farms consisted mainly of purchased concentrates, partly produced in foreign countries, whereas off-farm acidification potential for organic farms consisted of purchased roughage, mainly of national origin, in addition to purchased concentrates. On-farm acidification for organic farms, furthermore, was higher than for conventional farms. More ammonia emission occurs nationally on organic farms compared with conventional farms. On-farm global warming potential per kg FPCM for organic farms was higher than for conventional farms, because more animals were needed per kg organic milk produced, and enteric methane emission was assumed to be higher for each organic milking cow. The lower eutrophication potential per kg FPCM for organic farms than for conventional farms implies that feeding less concentrates but more roughage, producing a large part of the feed on farm, and using no artificial fertilizer results in a lower on and off-farm eutrophication potential.

Impact categories acidification and eutrophication also have a local and regional impact. These two impact categories, therefore, were also expressed in on-farm impact per ha farm area (Thomassen and De Boer, 2005). Although on-farm acidification potential per kg FPCM was higher for organic farms than for conventional farms, the on-farm acidification potentials per ha farm area were similar. An explanation for this result is that organic farms produced less milk per hectare than conventional farms. The on-farm eutrophication potential per ha farm area was lower for organic farms than for conventional farms. This result was the same for the product-related eutrophication (in kilogram milk).

A contribution analysis for the hotspot identification showed of all impact categories that purchased concentrates contributed most to the off-farm impact for conventional farms. Purchased concentrates contributed most to the indirect impact of energy use for organic farms, whereas for the other impact categories both purchased concentrates and purchased roughage contributed most to the off-farm impact for organic farms. Farmers, however, can only influence purchased amount of concentrates, but hardly composition, when purchased. Subsequently, farmers can hardly change the environmental impact of one kilogram of purchased concentrates. The environmental impact of concentrates consists mainly of transport and processing of certain ingredients in addition to cultivation of the crops.

We compared our hotspot identification with outcomes of a Dutch study in which 12 conventional farms that aim at efficient use of nitrogen and phosphorus were analysed using the LCA methodology with reference year 2002 (Werkman, 2005). Concentrates contributed around 70% to the off-farm impact of all impact categories in that study, which is similar to our hotspot identification for conventional farms.

We also compared our LCA outcomes with results of two Swedish studies and one German study (see Table 4.7). The Swedish ('96) study compared conventional and organic systems based on data of two specialised experimental farms (Cederberg and Mattson, 2000). Differences in environmental impact between the two systems could not be analysed statistically in this Swedish LCA case study because only two farms were analysed. The Swedish ('01/'02) study compared conventional high-production, conventional medium-production, and organic system based on data of 23 commercial farms (Cederberg and Flysjö, 2004). The German ('98) study compared conventional intensive, conventional extensive, and organic systems based on data of 18 commercial farms (Haas *et al.*, 2001). Only differences and not actual numbers between the different systems in the studies can be compared, because of differences in computational methods (De Boer, 2003).

Our results on land use (organic higher) and energy use (conventional higher) agree with all three studies (Table 4.7). The similar climate change of conventional and organic milk production agrees with the German ('98) study and the Swedish ('01/'02) study. Our result for product-related acidification (in tonnes milk) agrees with the German ('98) study and agrees with the Swedish ('01/'02) study. Our result for product-related eutrophication (in tonnes milk) was lower for organic production and agrees with the German ('98) study.

In the Swedish ('01/'02) study, organic production had the highest emission of ammonia and highest leaching of nitrate per kg milk, which resulted in a 25% higher product-related eutrophication, but this increase was not significant compared with conventional production. In the German ('98) study, the conventional production had a higher area-related acidification (136 and 119 kg SO_2-equivalents/farm ha) and eutrophication (566 and 326 kg NO_3-equivalents/farm ha) compared with organic production (107 kg SO_2-equivalents/farm ha; 141 kg NO_3-equivalents/farm ha), which agrees with our results.

Table 4.7 Results of two Swedish (Cederberg and Mattson, 2000; Cederberg and Flysjö, 2004) and one German (Haas *et al.*, 2001) LCA studies compared with results of this Dutch study (Dutch$^{’03}$) rounded to two digits

Case and year of data	No. of farms	Production system	Land use	Energy use	Climate change	Acidification		Eutrophication	
			m^2/t milk	GJ/t milk	kg CO_2-equivalents/ t milk	kg SO_2-equivalents/ t milk	farm ha	kg NO_3-equivalents/ t milk	farm ha
Swedish$^{’96}$	1	Conventional	1900	3.6	1080	18	130	61[a]	450
	1	Organic	3500	2.5	950	16	50	68	220
German$^{’98}$	6	Conventional intensive	-	2.7	1300	19	140	78[b]	570
	6	Conventional extensive	-	1.3	1000	17	120	47	330
	6	Organic	-	1.2	1300	22	110	29	140
Swedish$^{’01/’02}$	9	Conventional high	1500	2.6	900	10	-	39	-
	8	Conventional medium	1900	2.7	1040	10	-	43	-
	6	Organic	2900	2.1	940	12	-	52	-
Dutch$^{’03}$	10	Conventional	1300	5	1400	10	140	108	1600
	11	Organic	1800	3.1	1500	11	100	67	600

[a] Eutrophication Potential was given in O_2-equivalents and is transformed to NO_3-equivalents.

[b] Eutrophication Potential was given in PO_4-equivalents and is transformed to NO_3-equivalents.

4.5 Conclusion

This LCA case study, based on 10 conventional and 11 organic farms showed better environmental performance concerning energy use and eutrophication potential per kilogram of milk for organic farms than for conventional farms. Furthermore, higher on-farm acidification potential and global warming potential per kilogram organic milk implies that higher ammonia, methane, and nitrous oxide emissions occur on farm per kilogram organic milk than for conventional milk. Total acidification potential and global warming potential per kilogram milk did not differ between the selected conventional and organic farms. In addition, results showed lower land use per kilogram conventional milk compared with organic milk. Purchased concentrates was found to be the hotspot in the selected conventional farms in off farm and total impact for all impact categories. Whereas in the selected organic farms, concentrates was found to be the hotspot in off farm impact besides roughage.

Based on this LCA case study, we recommend to improve integral environmental performance of milk production by: (1) reducing the use of concentrates ingredients with a high environmental impact, (2) decreasing the use of concentrates per kilogram of milk, and (3) reducing nutrient surpluses by improving farm nutrient flows. In addition, we recommend further studies to focus on performing LCA's of concentrates ingredients in collaboration with Dutch feed suppliers. Environmental aspects should be taken into account together with cost price and nutritional aspects, for selecting concentrates components. We recommend also to enlarge integral assessment of the environmental impact of milk production systems by increasing the number of farms over several years.

References

Baars, T., 2002. Reconciling scientific approaches for organic farming research. Part I; Reflection on research methods in organic grassland and animal production at the Louis Bolk Institute, The Netherlands. PhD-thesis, Wageningen University and Research Centre, Wageningen, The Netherlands.

Baars, T., van Eekeren, N., Lutteken, F.F., Beldman, A., Bartels, C., Philipsen, A.P., Smolders, G., Pinxterhuis, J.B., 2002. Bioveem Projectplan 2001-2006 Biologische melkveehouderij versterken en verbreden. Rapport 1, Praktijkonderzoek Veehouderij, Louis Bolk Instituut, DLV-adviesgroep, Lelystad, The Netherlands.

Basset-Mens, C., Van der Werf, H.M.G., 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. Agriculture, Ecosystems & Environment 105, 127-144.

Berlin, J., 2002. Environmental life cycle assessment (LCA) of Swedish semi-hard cheese. International Dairy Journal 12, 939-953.

Binternet, 2003. Het Bedrijven-InformatieNet van het LEI, 2005, www.lei.wur.nl/NL/statistieken/Binternet/.

Brand, R.A., Melman, A.G., 1993. Energie-inhoudsnormen voor de veehouderij. TNO; Instituut voor milieu- en energietechnologie, Apeldoorn, The Netherlands.

CBS, 2003. Centraat Bureau voor de Statistiek; Statline databank, jaarstatistieken, Vol. 2005, statline.cbs.nl/nl/cijfers/statline/index.htm.

Cederberg, C., 1998. Life cycle assessment of milk production- a comparison of conventional and organic farming. SIK-Report No. 643. The Swedish Institute for Food and Biotechnology, Göteborg, Sweden.

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

Cederberg, C., Flysjö, A., 2004. Life Cycle Inventory of 23 dairy farms in South-Western Sweden. SIK-Report 728. The Swedish Institute for food and biotechnology, Göteborg, Sweden.

CertiQ, 2003. Groencertificatenbeheer duurzame electriciteit, 2005, www.certiq.nl.

CVB, 2000. Tabellenboek Veevoeding 2000: Voedernormen Landbouwhuisdieren en Voederwaarde Veevoeders. Centraal Veevoeder Bureau, Lelystad, The Netherlands.

Dalgaard, R., Halberg, N., Kristensen, I.S., Larsen, I., 2006. Modelling representative and coherent Danish farm types based on farm accountancy data for use in environmental assessments. Agriculture, Ecosystems and Environment 117, 223-237.

Davis, J., Haglund, C., 1999. Life cycle inventory (LCI) of fertiliser production; Fertiliser products used in Sweden and Western Europe. SIK-Report No. 654. The Swedish institute for food and biotechnology, Göteborg, Sweden.

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

Dekkers, W.A., 2001. Kwantitatieve informatie akkerbouw en vollegrondsgroenteteelt 2002. Praktijkonderzoek Plant en Omgeving B.V., Lelystad, The Netherlands.

Doppenberg, J., De Groot, J.P., 2003. Lineaire programmering rundvee-, varkens- en pluimveevoeders. VVM Bedrijfsbureau; Vereniging Voorlichting Mengvoerindustrie, Deventer, The Netherlands.

EEG, 1992. Verordening (EEG) Nr. 2092/91, www.skal.com.

EnergieNed, 2002. EnergieNed Federatie van Energiebedrijven in Nederland, Vol. 2005, Arnhem, The Netherlands, www.energiened.nl.

Erisman, J.W., De Vries, W., Kros, H., Oenema, O., Van der Eerden, L., Van Zeijts, H., Smeulders, S., 2001. An outlook for a national integrated nitrogen policy. Environmental Science & Policy 4, 87-95.

Erzinger, S., Dux, D., Zimmermann, A., Badertscher Fawaz, R., 2003. LCA of animal products from different housing systems in Switzerland: Relevance of feedstuffs, infrastructure and energy use. In: Halberg, N. (Ed.), Life cycle assessment in the agri-food sector. Danish Institute of Agricultural Science, Bygholm, Denmark.

FAO, 2002/2003. Food and Agricultural Organisation of the United Nations. FAO statistical databases, Vol. 2005, faostat.fao.org.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., De Koning, A., Van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., De Bruijn, H., Van Duin, R., Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H., Van der Ven, B.L., Weidema, B.P. (Eds.), 2002. Handbook on Life Cycle Assessment; Operational Guide to the ISO Standards. Centrum voor Milieukunde- Universiteit Leiden (CML); Kluwer Academic Publishers., Leiden, The Netherlands.

Guinée, J.B., Heijungs, R., Huppes, G., 2004. Economic allocation: Examples and derived decision tree. International Journal of Life Cycle Assessment 9, 23-33.

Haas, G., Wetterich, F., Kopke, U., 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agriculture, Ecosystems & Environment 83, 43-53.

Hageman, I., Mandersloot, F., 1994. Model energieverbruik melkveehouderijbedrijf Publicatienummer 86 Waiboerhoeve. Wageningen University and Research Centre, Wageningen, The Netherlands.

Halberg, N., Van der Werf, H.M.G., Basset-Mens, C., Dalgaard, R., De Boer, I.J.M., 2005. Environmental assessment tools for the evaluation and improvement of European livestock production systems. Livestock Production Science 96, 33-50.

Hanegraaf, M.C., Van Bergen, J.A.M., Biewinga, E.E., Van Miltenburg, J., 1996. Ervaringen met de energiemeetlat veehouderij. Cijfers en methodiek en rekenregels. Centrum voor landbouw en milieu, Utrecht, The Netherlands.

Heijungs, R., Guinée, J., Huppes, G., Lankreijer, R.M., Udo de Haes, H.A., Wagener Sleeswijk, A., Ansems, A.M.M., Eggels, P.G., van Duin, R., De Goede, H.P., 1992. Environmental Life Cycle Assessment of products. Guide and Backgrounds. CML, Leiden University, Leiden, The Netherlands.

Heuven, A., 2005. Reudink Biologische Voeders; Samenstelling biologisch rundveevoer In: 's Gravendijk, L., Wageningen, The Netherlands.

Hospido, A., Moreira, M.T., Feijoo, G., 2003. Simplified life cycle assessment of Galician milk production. International Dairy Journal 13, 783-796.

Houghton, J.T., Meira Filho, L.G., Bruce, J., Lee, H., Callander, B.A., Haites, E., Harris, N., Maskell, K., 1994. Climate change 1994. Radiative forcing of climate change and an evaluation of the IPCC IS92 Emission scenarios. Cambridge University, Cambridge, United Kingdom.

Huijbregts, M., 1999. Life Cycle Impact Assessment of acidifying and eutrophying air pollutants. Calculation of equivalency factors with RAINS-LCA. Interfaculty Department of Environmental Science, Faculty of Environmental Science, University of Amsterdam, Amsterdam, The Netherlands.

IFOAM, 2006. International Federation of Agriculture Movements, www.ifoam.org.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental panel on climate change Greenhouse gas inventory reference manual. Volume 4.

ISO, 2006. Environmental Management. The ISO 14000 family of international standards ISO standards Collection on CD-ROM, Genève, Switzerland.

Jansen, J., 2005. Life Cycle Assessment of Ben en Jerry's Ice Cream Production System. MSc thesis, Wageningen University and Research Centre, Wageningen, The Netherlands.

Jongbloed, A.W., Bannink, A., Cone, J.W., 2004. De invloed van voedingsmaatregelen op het optreden van gasvormige emissies binnen de veehouderij. Animal Sciences Group Wageningen University and Research Centre, Lelystad, The Netherlands.

Koroneos, C., Roumbas, G., Gabari, Z., Papagiannidou, E., Moussiopoulos, N., 2005. Life cycle assessment of beer production in Greece. Journal of Cleaner Production 13, 433-439.

LEI, 2004. Landbouw Economisch Instituut. Land- en tuinbouwcijfers 2000-2004. Jaarrapporten van het LEI en het CBS, Den Haag, The Netherlands.

Michaelis, P., 1998. Life cycle assessment of energy systems. Centre for environmental strategy. University of Surrey, Berkshire, United Kingdom.

Milà i Canals, L., Clift, R., Basson, L., Hansen, Y., Brandão, M., 2006. Expert workshop on land use impacts in Life Cycle Assessment (LCA). International Journal of Life Cycle Assessment 11, 363-368.

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., Van Cleemput, O., 1998. Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutrient Cycling in Agroecosystems 52, 225-248.

Nielsen, A.H., Kristensen, I.S., 2005. Nitrogen and phosphorus surpluses on Danish dairy and pig farms in relation to farm characteristics. Livestock Production Science 96, 97-107.

Oenema, J., Koskamp, K.J., Galama, P.J., 2001. Guiding commercial pilot farms to bridge the gap between experimental and commercial dairy farms: the project ‘Cows and Opportunities’. Netherlands Journal of Agricultural Science 49, 277-296.

Oenema, O., Boers, P.C.M., Van Eerdt, M.M., Fraters, B., Van der Meer, H.G., Roest, C.W.J., Schroder, J.J., Willems, W.J., 1998. Leaching of nitrate from agriculture to groundwater: the effect of policies and measures in The Netherlands. Environmental Pollution 102, 471-478.

Oenema, O., Velthof, G.L., Verdoes, N., Groot Koerkamp, P.W.G., Monteny, G.J., Bannink, A., Van der Meer, H.G., Van der Hoek, K.W., 2000. Forfaitaire waarden voor gasvormige stikstofverliezen uit stallen en mestopslagen. Rapport 107. Alterra, Onderzoeksinstituut voor de Groene Ruimte, Wageningen, The Netherlands.

Oenema, O., 2004. Governmental policies and measures regulating nitrogen and phosphorus from animal manure in European agriculture. Journal of Animal Science 82, E196-E206.

Oenema, O., Van Liere, L., Schoumans, O., 2005. Effects of lowering nitrogen and phosphorus surpluses in agriculture on the quality of groundwater and surface water in The Netherlands. Journal of Hydrology 304, 289-301.

Payraudeau, S., Van der Werf, H.M.G., 2005. Environmental impact assessment for a farming region: a review of methods. Agriculture, Ecosystems & Environment 107, 1-19.

SAS, 2002. Proprietary Software Release 9.1.3. SAS Institute Inc., SAS®,Cary, NC, USA.

Schils, R.L.M., Oudendag, D.A., Van der Hoek, K.W., De Boer, J.A., Evers, A.G., De Haan, M.H., 2006. Broeikasgasmodule BBPR. Praktijkrapport Rundvee 90. Animal Sciences Group, Alterra, RIVM, Wageningen, The Netherlands.

Schröder, J., Bannink, A., Kohn, R.A., 2006. Improving the efficiency of nutrient use on cattle operations. Nitrogen and phosphorus nutrition of cattle. Wallingford, United Kingdom.

Schröder, J.J., Aarts, H.F.M., Ten Berge, H.F.M., Van Keulen, H., Neeteson, J.J., 2003. An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. European Journal of Agronomy 20, 33-44.

Schröder, J.J., Aarts, H.F.M., Van Middelkoop, J.C., De Haan, M.H.A., Schils, R.L.M., Velthof, G.L., Fraters, B., Willems, W.J., 2005. Limits to the use of manure and mineral fertilizer in grass and silage maize production in The Netherlands, with special reference to the EU Nitrates Directive. Plant Research International B.V., Wageningen, The Netherlands.

's Gravendijk, L., 2006. Environmental impact assessment of Dutch commercial organic dairy farms. MSc thesis, Wageningen University and Research Centre, Wageningen, The Netherlands.

Tamminga, S., Jongbloed, A.W., Van Eerdt, M.M., Aarts, H.F.M., Mandersloot, F., Hoogervorst, N.J.P., Westhoek, H., 2000. De forfaitaire excretie van stikstof door landbouwhuisdieren. Rapport ID-Lelystad no. 00-2040. ID-Lelystad, Lelystad, The Netherlands.

Tamminga, S., Aarts, F., Bannink, A., Oenema, O., Monteny, G.-J., 2005. Actualiseren van geschatte N en P excreties voor rundvee. Wageningen University, Wageningen, The Netherlands.

Ter Veer, D.F., 2005. Scenariostudie 100% biologisch voeren melkvee. Animal Sciences Group Praktijkonderzoek, Lelystad, The Netherlands.

Thomassen, M.A., De Boer, I.J.M., 2005. Evaluation of indicators to assess the environmental impact of dairy production systems. Agriculture, Ecosystems & Environment 111, 185-199.

Van Calker, K.J., Berentsen, P.B.M., De Boer, I.J.M., Giesen, G.W.J., Huirne, R.B.M., 2004. An LP-model to analyse economic and ecological sustainability on Dutch dairy farms: model presentation and application for experimental farm "de Marke". Agricultural Systems 82, 139-160.

Van Calker, K.J., 2005. Sustainability of Dutch dairy farming; A modelling approach. PhD thesis, Wageningen University, Wageningen, The Netherlands.

Van Calker, K.J., Hooch Antink, R.H.J., Beldman, A.C.G., Mauser, A., 2005. Caring Dairy: A sustainable dairy farming initiative in Europe. International Farm Management Association; Developing entrepreneurship abilities to feed the world in a sustainable way, Brazil.

Van den Brandt, H.M.P., Smit, H.P., 1998. Mineral accounting: the way to combat eutrophication and to achieve the drinking water objective. Environmental Pollution 102, 705-709.

Van der Hoek, K.W., 2002. Uitgangspunten voor de mest- en ammoniakberekeningen 1999 tot en met 2001 zoals gebruikt in de Milieubalans 2001 en 2002, inclusief dataset landbouwemissies 1980-2001. RIVM Rapport 773004013. RIVM; Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven, The Netherlands.

Van der Hoek, K.W., Van Schijndel, M.W., 2006. Methane and nitrous oxide emissions from animal manure management, 1990-2003. Background document on the calculation method for the Dutch National Inventory Report. RIVM and MNP (Netherlands Environmental Assessment Agency), Bilthoven, The Netherlands.

Van der Schans, F., Remmers, J., Rougoor, C., Van Well, E., Kuneman, G., 2005. Naar een duurzame melkveehouderij; Verkenning van criteria voor duurzame(re) melkveebedrijven. Centrum voor Landbouw en Milieu, Stichting Natuur en Milieu, Culemborg, The Netherlands.

Van Duinkerken, G., André, G., Smits, M.C.J., Monteny, G.J., Šebek, L.B.J., 2005. Effect of rumen-degradable protein balance and forage type on bulk milk urea concentration and emission of ammonia from dairy cow houses. Journal of Dairy science 88, 1099-1112.

Van Eerdt, M.M., Fong, P.K.N., 1998. The monitoring of nitrogen surpluses from agriculture. Environmental Pollution 102, 227-233.

Van Egmond, N.D., 2004. Mineralen beter geregeld. Evaluatie van de werking van de Meststoffenwet 1998-2003. Milieu-en Natuurplanbureau RIVM, Bilthoven, The Netherlands.

Van Geel, P.L.B.A., 2004. Wijziging van de Regeling ammoniak en veehouderij (RAV). VROM Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, Den Haag, The Netherlands.

Van Straalen, W.M., 1995. Modelling of nitrogen flow and excretion in dairy cows, PhD thesis, Wageningen University and Research Centre, Wageningen, The Netherlands.

Velthof, G.L., Oenema, O., 1997. Nitrous oxide emission from dairy farming systems in The Netherlands. Netherlands Journal of Agricultural Science 45, 347-360.

Weidema, B.P., 2003. Market information in life cycle assessment. Danish Environment Protection Agency, Hørsholm, Denmark.

Werkman, S.R., 2005. Environmental Impact Assessment of Cows & Opportunities dairy farms. MSc thesis, Wageningen University and Research Centre, Wageningen, The Netherlands.

WPD, 2003. World-Ports Distances. 2005, www.distances.com; www.portworld.com.

Chapter 5

Relating Life Cycle Assessment indicators to net farm income for Dutch dairy farms

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Abstract

A need exists to place Life Cycle Assessment (LCA) studies of dairy cattle production systems into an economic context, to address the pillars planet and profit of sustainability. Such an analysis requires a relatively large number of dairy farms. This study investigates whether it is possible to perform an LCA of individual dairy farms by using the Dutch Farm Accountancy Data Network (FADN), besides analyzing the relationships between environmental and economic performance of dairy farms and underlying farm characteristics.

It was demonstrated using Dutch FADN to perform an LCA of individual dairy farms is possible, which enables to perform future LCAs of dairy farms based on FADN. Future LCAs could be strengthened by the inclusion of more suitable LCA-related data within FADN collection. Furthermore, it was demonstrated farms with a high net farm income had a low on farm land use, total land use, energy use at the dairy farm, on farm and total climate change, expressed per kg FPCM. On the other hand, farms with a high net farm income had a high total and on farm eutrophication and acidification, expressed per hectare. Farm characteristics of importance were: farm size, Dutch livestock units per hectare, milk production per cow, purchased concentrates per 100 kg FPCM, and milk urea content. Based on the relations found in this study between these characteristics, LCA indicators and net farm income, it is recommended to perform an 'optimum' analysis. Such an analysis can identify the optimum situation when net farm income is high while environmental burdens are low.

5.1 Introduction

The concept sustainability was introduced to address concerns about our future livelihood (WCED, 1987). Sustainability is a holistic concept, built upon the three pillars people, planet, profit, also known as the triple-bottom-line approach (Elkington, 1998). Most sustainability assessments of food production address one of the three pillars separately. Many studies focus on environmental sustainability of agricultural production only, because environmental pollution is a side-effect of agricultural food production. Production of milk by dairy cattle, for example, contributes to nutrient enrichment of the ecosystem, climate change and acid deposition. Life Cycle Assessment (LCA) is used to assess the environmental impact of products throughout its life cycle (Guinée *et al.*, 2002). As milk production by dairy cattle depends on many inputs, this life cycle approach is a justified tool to assess the environmental burden of milk (Thomassen and De Boer, 2005; Dalgaard *et al.*, 2006). By performing an LCA of dairy farms, insight is gained into environmental sustainability, the pillar "planet", of the dairy sector. Preferably, however, more than one pillar should be considered (Glavič and Lukman, 2007; Ness *et al.*, 2007; Van Passel *et al.*, 2007). No sector is sustainable without economic viable farms, the pillar "profit" (Van Passel *et al.*, 2004). An understanding of the relationship between profitability and environmental impact is a prerequisite for a better insight in sustainability to contribute to decision making (Norris, 2001; Mouron *et al.*, 2006). One way is to assess the relationship between farm income and environmental impact of milk production by dairy cattle. Such an analysis requires a relatively large number of dairy farms. Most LCA studies of dairy cattle production systems, however, are based on a limited number of farms, because data collection is time-consuming (Cederberg, 1998; Cederberg and Flysjö, 2004; Casey and Holden, 2005; Thomassen *et al.*, 2008). In addition, it is not always possible to use existing databases to perform an LCA, because these data are collected for other purposes and therefore do not include all the necessary information. Preferably, data of representative farms for the sector must be analyzed (Dalgaard *et al.*, 2006). In the Farm Accountancy Data Network (FADN), data of representative farms are collected. The FADN is a European Union (EU) initiative to gain insight in income of agricultural farms and to assess the impact of Common Agricultural Policy (FADN, 2007). The focus of collected data is mostly on technical and economic figures. Unlike FADN of other EU countries, the Dutch FADN consists of additional data, e.g. quantities of purchased inputs, and therefore, seems to enable an accurate LCA of individual farms. An LCA of individual Dutch dairy farms based on FADN has never been performed before. Performing an LCA of a large number of individual farms, enables to differentiate results among farms to study the relation between environmental and economic performance, and underlying characteristics.

The objectives of this study are:

- to identify if FADN can be used to perform an LCA of individual dairy farms;
- to study the relationship between environmental and economic performance of dairy farms;
- to identify which farm characteristics influence the relationship between environmental and economic performance.

5.2 Material and methods

5.2.1 Farm Accountancy Data Network (FADN)

The Agricultural Economics Research Institute in The Netherlands collects technical and economic figures from Dutch farms that subsequently are documented in the FADN. The objective of this documentation is to gain insight into the performance of a sector. From this dataset we used data of dairy farms of the year 2005. In 2005, data of 271 dairy farms were collected, corresponding with the rate of appearance of the dairy farms in The Netherlands. As this study focuses on specialised conventional dairy farms, organic farms were excluded, and conventional farms were selected only when at least 75% of the economic size (expressed in NGE[1]) originated from dairy activity and when no pigs and poultry were present. Due to a lack of indispensable data to perform an LCA (e.g., pasture system, milk urea content) or due to inconsistency of data (e.g., no specific data on purchased concentrates, while on the nutrient balance concentrates was given as an input), more farms were excluded from the analyses. In total, 119 dairy farms were analysed.

5.2.2 Life Cycle Assessment

Indicators used were derived from the Life Cycle Assessment methodology (Guinée *et al*., 2002). Figure 5.1 presents an overview of specifics during each LCA phase of this analysis of the 119 dairy farms. Figure 5.1 shows that during the goal and scope phase, attributional LCA was chosen, and economic allocation was used whenever a multifunctional process occurred (Thomassen *et al*., In press). Furthermore, the impact categories land use, energy use, acidification, eutrophication and climate change were assessed. These impact categories are important to consider when performing a cradle-to-farm gate LCA of dairy farms (Berlin, 2002; Høgaas Eide, 2002; Thomassen *et al*., 2008). The functional unit was one kg of Fat and Protein Corrected Milk (FPCM) for all impact categories, while acidification and eutrophication were expressed per hectare as well, as these have a local and regional impact. Figure 5.1 also shows the included on farm and off farm processes in the system. Characterisation factors used for eutrophication and acidification were based on Heijungs *et al.* (1992), while characterisation factors used for climate change were based on IPCC (2006). In general, the same approach as presented in Thomassen *et al.* (2008) was used, adjusted to new

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[1] NGE= Dutch scale unit; an economic parameter based on gross standard balance to represent the economic size of agricultural activities. NGE is, among others, used to assess rate of specialization of farms. In 2005, one NGE was 1.167 European size units, ESU (De Bont *et al*., 2003; LEI, 2007b).

insights, or adjusted to the way data were available within FADN, as described in the following paragraphs.

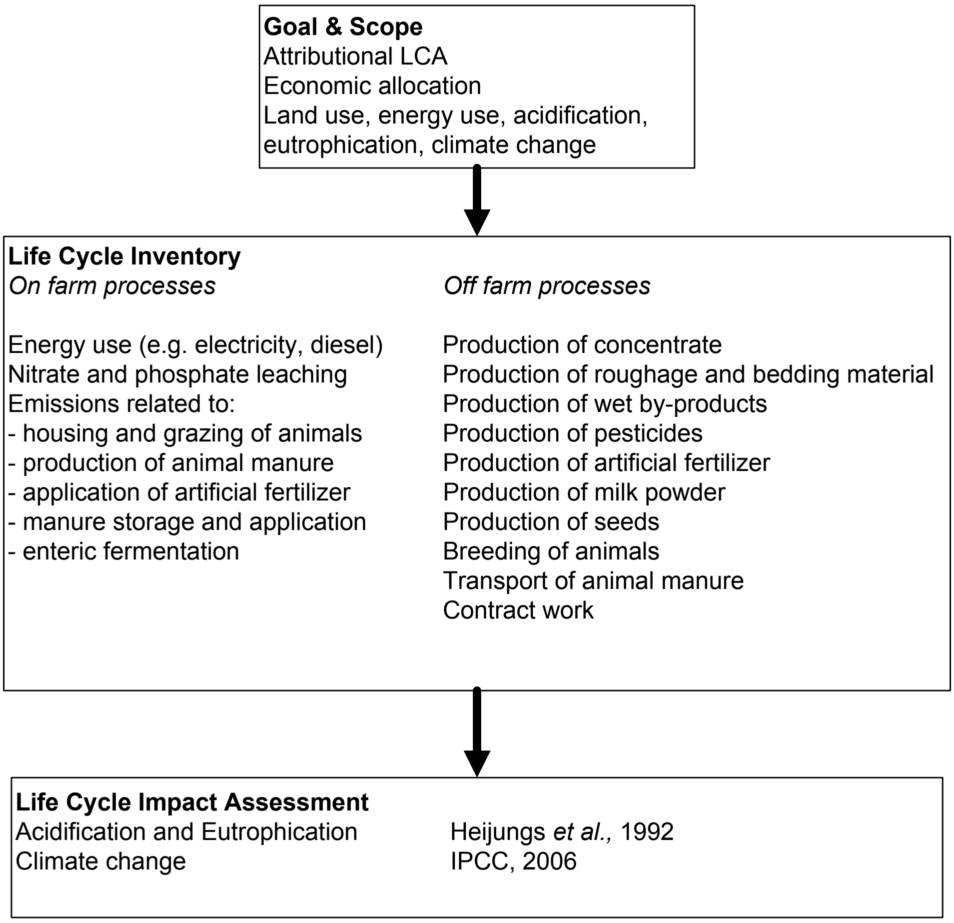

Figure 5.1 Overview of specifics during each LCA phase of the Life Cycle Assessment of dairy farms based on the Dutch Farm Accountancy Data Network

5.2.2.1 Feed

Purchased feed was divided into three categories: roughage, wet by-products and concentrates, based on the division made in the Dutch feeding value table (CVB, 2004). This division is based on dry matter content, besides practical insight of the feed industry. For each rough fodder, wet by-product and, singular concentrates, a Life Cycle Inventory (LCI) was computed, based on crop cultivation, crop processing and transport (Dolman, 2007). Crude protein content was used to distinguish among compound concentrates with different ingredients, and subsequently different environmental burdens (LCIs). Five types of concentrates were identified based on crude protein content, while in Thomassen *et al.* (2008) three types of concentrates were identified based on intestine digestible protein content. Compositions of the five concentrates were based on annual data (>95% of its main feed ingredients) (Doppenberg and De Groot, 2005). Palm kernel expeller contributed for 15-20% to all five concentrates. Citrus pulp contributed for around 10% and soy hulls or wheat hulls for around 15% to the two concentrates with a low crude protein content (crude protein content <160.1 g/kg). Maize gluten meal contributed for around 25-30% and rape seed meal for around 15%

to the three concentrates with a high crude protein content (160.2 g/kg< crude protein content <180.1 g/kg).

Purchased milk powder was included, based on an LCA of milk from conventional dairy farms supplemented with milk processing data of the dairy industry (Oldenhof, 2004; Thomassen *et al.*, 2008). Seeds (grass, rye, maize, potato, sugar beet and wheat) purchased by the dairy farm were included in the assessment, whereas seeds required for production of purchased feed were not included, because of lack of data (EcoinventCentre, 2004).

5.2.2.2 Emissions at the dairy farm

Thomassen *et al.* (2008) used a fixed value to estimate methane emission from enteric fermentation. Preferably, a farm-specific emission rate must be used to include variation among farms. In this study methane emission from enteric fermentation was estimated by taking into account consumed feed types (e.g., concentrates ingredients, roughage, wet by-products). Smink *et al.* (2003) estimated emission factors (expressed in g methane/kg dry matter) of different feed types based on the fermentation of carbohydrates into volatile fatty acids (VFAs). The quantity of consumed feed per dairy cow was estimated taking into account energy demand for maintenance and production, production of grass and other crops at the dairy farm, purchased concentrates, and purchased other feed (wet by-products and roughage). In this study methane emission from enteric fermentation was computed by combining the methane emission factor per feed type and the quantity of this feed type consumed by the dairy cow.

Furthermore, to include variation among farms, besides nitrogen excretion, also ammonia emission during housing was related to farm-specific milk urea content based on Smits *et al.* (2003; 2005).

In addition, the way manure was applied to the field was known for each farm, which enabled to relate ammonia emission to the technique of manure application. Soil type was taking into account when estimating the amount of nitrate leached, and when estimating the amount of direct nitrous oxide emitted from agricultural land (Schröder *et al.*, 2005; Schils *et al.*, 2006; Schils *et al.*, 2007).

5.2.2.3 Data assumptions

The following assumptions related to FADN were made to enable performing an LCA of the individual dairy farms (based on the LCA dairy farm model described in Thomassen *et al.*, 2008). No data on purchased quantities of sawdust were available, only costs. The cost price in 2005 of €0.16/kg sawdust was used to convert costs to quantities (Zevenbergen, 2006). The manure application technique was reported in frequencies, e.g., 40% injection and 40% narrow band spreading, without distinguishing between land types. Narrow band spreading is possible only on grassland (Van der Hoek, 2002), and therefore, this frequency was ascribed to grassland. Surface spreading and subsequently ploughing within two holes is possible only on arable land (Van der Hoek, 2002), and therefore, this frequency was ascribed to arable land. The division of manure injection was made based upon the ratio grassland/arable land. No data were available on the mineral nitrogen content of purchased and produced manure, and therefore, a fixed value of 48% for semi-liquid and a fixed value of 23% for solid manure were used (Mooij, 1996). Furthermore, it was assumed the Dutch soils were saturated with phosphorus and, therefore, it was assumed all phosphate surplus leached into the environment (Oenema *et al.*, 2005).

5.2.3 Economics

Profitability reflects the difference between the value of goods and services produced by the farm and the costs of resources used in their production (Barry *et al.*, 2000). The indicator Net Farm Income per Full Time Equivalent (NFI/FTE) was used to measure profitability (Van Calker *et al.*, 2004). NFI/FTE was computed using the following formulas (Handboek melkveehouderij, 2006).

NFI = Farmers' income + Labour family members (1)

where, Farmers' income is Net profit + Labour costs farmer + (Calculated - Paid interest), and Net profit is Agricultural revenues - Variable costs - Fixed costs

FTE = One healthy employee (>18 years) that works fulltime, (2)
expressed in labour hours, not exceeding 2000 hours per employee.

5.2.4 Selected farm characteristics

The third goal of this study was to identify which farm characteristics influence the relationship between environmental and economic performance of dairy farms. Selected farm characteristics represented technical figures or facts that could be obtained from the farm. These farm characteristics were: milk production per dairy cow, milk production per hectare, milk quota, farm size, Dutch livestock units per hectare, amount of purchased concentrates per 100 kg FPCM, amount of purchased roughage and wet by-products fed per 100 kg FPCM, diesel use per 100 kg FPCM, electricity use per 100 kg FPCM, gas use per 100 kg FPCM, milk urea content, purchased artificial fertiliser (kg N/ha and kg P_2O_5/ha), and purchased animal manure (kg N/ha and kg P_2O_5/ha). Furthermore, pasture system was selected as farm characteristic that possibly influences the relationship between environmental and economic performance. Pasture system is a major characteristic of Dutch dairy farming. Pasturing cows is of importance for the image of the Dutch dairy sector, in the way it is perceived by society. Furthermore, pasturing cows enables animals to perform natural behavior. Currently, pasturing dairy cows is under debate, as the amount of farmers that keep their cows indoors during the pasture season, increases. The main reasons for this increase are: enlargement of farms without expanding the farm area at the same level; a need to control the feed intake of high-producing cows; increase of automatic milking systems; ease of labor (De Haan *et al.*, 2005; Van den Pol-van Dasselaar, 2005). The 119 dairy farms were allocated to three groups; ad libitum grazing (n=20), limited grazing (n=81) and non-grazing (n=18). Dairy farms were allocated to the ad libitum group if ad libitum grazing days exceeded 75% of the total amount of grazing days, and total amount of grazing days exceeded 175 days. The other dairy farms that performed grazing were allocated to the limited grazing group. Dairy farms that did not pasture their cows and fed fresh cut grass besides dairy farms that performed summer feeding, were allocated to the non-grazing group.

5.2.5 Statistical procedures

To identify a possible relation between environmental and economic indicators, a correlation analysis was conducted. Data were tested for normality; the Pearson correlation test was used in case data were normally distributed, whereas the Spearman Rho's correlation test was used in case of non-normality. A trade-off was found, when net farm income was correlated positively with an LCA indicator, because a positive correlation indicates that a higher farm income resulted in a higher environmental burden. The data-reduction technique Principal Components Analysis (PCA) was conducted to identify relevant farm characteristics. Subsequently, a General Linear Model (GLM) was used to test if these farm characteristics and type of pasture system had an effect on the indicators. Not all indicators were distributed normally. In case of non-normality, indicator values were transformed using logarithm (LG10) or square root (SQRT).

$$Y = \mu + \alpha_i + b_j x_j + \varepsilon_{ij} \qquad (3)$$

where, Y= indicator, such as net farm income or total land use per kg FPCM

α_i= pasture system

x_j= farm characteristic

ε_{ij}= error term.

All statistical analyses were performed using the software SPSS (SPSS, 2007).

5.3 Results

5.3.1 Farm characteristics

General characteristics of the selected 119 dairy farms, and characteristics of these dairy farms divided in pasture system groups, are presented in Table 5.1. Average farm area of the 119 dairy farms was 53.4 hectare, of which 74% grassland and 26% arable land. The non-grazing group had a higher arable land use than the ad libitum and limited grazing group. Average milk quota of the 119 dairy farms was 684445 kg. The ad libitum grazing group had a lower milk quota than the non-grazing group. Average milk production of the 119 farms was 7613 kg per cow. The limited and non-grazing groups had a higher milk production per cow than the ad libitum grazing group. Average production intensity of the 119 farms was 12628 kg milk/ha. The non-grazing group had a higher production intensity than the ad libitum and limited grazing groups, while the limited grazing group had a higher production intensity than the ad libitum grazing group.

Average purchased roughage and wet by-products of the 119 farms was 7.2 kg dry matter per 100 kg FPCM, with a high variation of 9.7 kg dry matter per 100 kg FPCM. Average purchased animal manure of the 119 farms was 30 kg N/ha, with a high variation of 39 kg N/ha.

Table 5.1 General characteristics, given in mean (standard deviation) of the 119 dairy farms based on the Dutch Farm Accountancy Data Network in 2005, and divided in pasture system group

Parameters	Units	Total	Ad libitum grazing[a]	Limited grazing	Non-grazing
Farms	n	119	20	81	18
Grassland	ha	39.3 (22.4)	42.2 (31.2)	39.1 (20.3)	36.6 (21.3)
Arable land	ha	14.1 (16.2)	10.3[b] (14.9)	12.3[b] (12.4)	26.3[c] (25.6)
Milk quota	kg	684445 (437736)	534582[b] (399514)	655130 (322927)	982875[c] (732171)
Milking cows	n	85 (50)	77 (54)	82 (40)	112 (73)
Milk production	kg/cow	7613 (1269)	6608[e] (1334)	7692[f] (1128)	8376[f] (1170)
	kg/ha	12628 (4040)	9648[b] (3979)	12659[c] (2969)	15799[d] (5747)
Milk fat	%	4.41 (0.2)	4.38 (0.2)	4.43 (0.2)	4.33 (0.1)
Milk protein	%	3.51 (0.1)	3.51 (0.1)	3.51 (0.1)	3.48 (0.1)
Milk urea content	mg/100 gram	24.2 (3.5)	24.5 (4.6)	24.0 (3.3)	24.9 (3.3)
Animal intensity	GVE[g]/ha	2.0 (0.5)	1.8 (0.6)	2.0 (0.4)	2.2 (0.6)
Purchased concentrates	kg/100 kg FPCM[h]	24.1 (8.9)	25.2 (12.9)	24.9 (6.9)	19.4 (10.8)
Purchased other feed	kg DM[i]/100 kg FPCM	7.2 (9.7)	5.8 (10.4)	7.5 (9.7)	7.8 (9.7)
Diesel use	l/100 kg FPCM	1.0 (0.6)	1.3 (1.0)	0.9 (0.5)	1.1 (0.5)
Electricity use	kWh/100 kg FPCM	5.5 (2.7)	5.8 (2.1)	5.5 (2.9)	5.4 (2.6)
Gas use	m^3/100 kg FPCM	0.3 (0.3)	0.2 (0.3)	0.3 (0.3)	0.2 (0.2)
Artificial fertiliser	kg N/ha	148 (48)	134 (71)	148 (40)	160 (48)
Purchased animal manure	kg N/ha	30 (39)	47 (49)	26 (36)	29 (40)

[a] Ad libitum grazing days were >75% of the total amount of grazing days and total grazing days exceeded 175.

[bcd] Differences between or among groups indicated by a Mann-Whitney U test; $P<0.05$.

[ef] Differences between or among groups indicated by a Games-Howell t-test; $P<0.05$.

[g] Dutch Livestock Units.

[h] Fat and Protein Corrected Milk.

[i] Dry Matter roughage and wet by-products.

5.3.2 Environmental and economic performance

Table 5.2 shows results of both the LCA indicators given by impact category and of the economic indicator NFI/FTE. Total land use was 1.24 m^2/kg FPCM of which 60% was on farm land use, 24% consisted of land use related to purchased concentrates and 11% of land use related to purchased roughage and bedding material. Total energy use was 5.07 MJ/kg FPCM of which 58% consisted of purchased concentrates and 18% was related to on farm energy use. Total climate change was 1.32 kg CO_2-eq/kg FPCM, of which 43% consisted of emissions related to keeping animals (mostly methane and nitrous oxide) and 26% of emissions related to purchased concentrates.

Table 5.2 Environmental and economic performance of 119 dairy farms based on the Dutch Farm Accountancy Data Network in 2005

Indicator	Unit		Mean (standard deviation)
Land use	m^2/kg FPCM	On farm	0.75 (0.2)
		Off farm	0.49 (0.2)
		Total	1.24 (0.3)
Energy use	MJ/kg FPCM	On farm	0.92 (0.4)
		Off farm	4.15 (1.1)
		Total	5.07 (1.2)
Climate change	kg CO_2-eq/kg FPCM	On farm	0.77 (0.2)
		Off farm	0.55 (0.2)
		Total	1.32 (0.2)
Eutrophication	kg NO_3-eq/kg FPCM	On farm	0.10 (0.08)
		Off farm	0.05 (0.02)
		Total	0.15 (0.08)
	kg NO_3-eq/on farm ha	On farm	1401 (1326)
	kg NO_3-eq/off farm ha	Off farm	1214 (655)
	kg NO_3-eq/total farm ha	Total	1284 (935)
Acidification	g SO_2-eq/kg FPCM	On farm	7.3 (2.1)
		Off farm	3.9 (1.1)
		Total	11.2 (2.4)
	kg SO_2-eq/on farm ha	On farm	92.2 (26)
	kg SO_2-eq/off farm ha	Off farm	109 (43)
	kg SO_2-eq/total farm ha	Total	94 (22)
Net Farm Income/ Full Time Equivalent	euro		44900 (32030)

Total eutrophication was 0.15 kg NO_3-eq/kg FPCM of which 64% consisted of ammonia emission related to fertiliser application besides leaching of nitrate and phosphate at the dairy farm, whereas 17% was related to purchased concentrates and 10% to purchased roughage. Total eutrophication expressed per hectare, was 1284 kg NO_3-eq/total hectare. Total acidification was 11.2 g SO_2-eq/kg FPCM of which 37% consisted of emissions related to keeping animals and 24% of ammonia emission related to fertiliser application, whereas 26% consisted of emissions related to purchased concentrates. Total acidification expressed per hectare, was 94 kg SO_2-eq/total hectare. Net farm income per full time equivalent was 44900 euro.

5.3.3 Relating environmental and economic performance

The economic indicator net farm income per full time equivalent was analyzed in relation to the LCA indicators. A negative correlation between an LCA indicator and net farm income per full time equivalent indicates that an increased income could be achieved while the environmental impact was reduced. Table 5.3 shows farms with a high income had a low total land use per kg FPCM (r = -0.301; P<0.01) and a low on farm land use per kg FPCM (r = -0.365; P<0.001). In addition, farms with a high income had a low total energy use per kg FPCM (r = -0.208; P<0.05) and a low on farm energy use per kg FPCM (r = -0.209; P<0.05).

Table 5.3 Correlation of 'net farm income per full time equivalent' with Life Cycle Assessment (LCA) indicators of 119 dairy farms based on the Dutch Farm Accountancy Data Network in 2005

LCA indicators	Unit	r^a
Total Land use	m^2/kg FPCM	-0.301^{**}
On farm Land use		-0.365^{***}
Off farm Land use		ns
Total Energy use	MJ/kg FPCM	-0.208^{*}
On farm Energy use		-0.209^{*}
Off farm Energy use		ns
Total Climate change	kg CO_2-eq/kg FPCM	-0.214^{*}
On farm Climate change		-0.201^{*}
Off farm Climate change		ns
Total Eutrophication	kg NO_3-eq/kg FPCM	ns
On farm Eutrophication		ns
Off farm Eutrophication		ns
Total Eutrophication	kg NO_3-eq/total farm ha	0.205^{*}
On farm Eutrophication	kg NO_3-eq/on farm ha	0.219^{*}
Off farm Eutrophication	kg NO_3-eq/off farm ha	ns
Total Acidification	g SO_2-eq/kg FPCM	ns
On farm Acidification		ns
Off farm Acidification		ns
Total Acidification	kg SO_2-eq/total farm ha	0.245^{**}
On farm Acidification	kg SO_2-eq/on farm ha	0.317^{**}
Off farm Acidification	kg SO_2-eq/off farm ha	ns

[a] r = Spearman Rho's correlation. ns= not significant; *P<0.05; **P<0.01; ***P<0.001.

Furthermore, farms with a high income had a low total climate change (r = -0.214; P<0.05) and a low on farm climate change per kg FPCM (r = -0.201; P<0.05). Table 5.3 also shows that a trade-off was observed (positive correlation) between farm income and the area-related indicators (expressed per hectare) total and on farm eutrophication and acidification. Farms with a high income had a high eutrophication per hectare (mainly nitrate and phosphate leaching) at farm level (r = 0.219; P<0.05). In addition, farms with a high income had a high acidification per hectare (mainly ammonia emission) at farm level (*r* = 0.317; P<0.01).

5.3.4 Relating farm characteristics to indicators

The relevant farm characteristics after applying the data-reduction technique PCA were: farm size (ha), Dutch livestock units per hectare, milk production per cow, amount of purchased concentrates per 100 kg FPCM, and milk urea content. Table 5.4 shows the outcomes of the GLM procedure to identify if these farm characteristics and pasture system influenced net farm income and LCA indicators. Type of pasture system did not influence net farm income or the LCA indicators. Farm size, Dutch livestock units per hectare, and milk production per cow influenced net farm income, which indicates scale and intensity parameters influence net farm income. The combination of animal intensity and production intensity determine on farm land use per kg FPCM, because these characteristics determine the milk production per ha farm area, which is the reciprocal of on farm land use per kg FPCM. The relation found between net farm income and on farm land use per kg FPCM (see paragraph 5.3.3) therefore, can be partly explained by Dutch livestock units per hectare and milk production per cow. Table 5.4 also shows purchased amount of concentrates influenced all total LCA indicators, which resulted from the contribution of concentrates to the off farm impact. The relation found between net farm income and total land use per kg FPCM (see paragraph 5.3.3) can be partly explained by Dutch livestock units per hectare, milk production per cow, and amount of purchased concentrates per 100 kg FPCM. In addition, the relation found between net farm income and total climate change (see paragraph 5.3.3) can be partly explained by milk production per cow and amount of purchased concentrates per 100 kg FPCM. Purchased concentrates, however, also influenced on farm eutrophication expressed per hectare. Eutrophication at farm level consists for a large part of leaching of nitrate and phosphate. The contribution of purchased concentrates to the nutrient input on the nutrient balance, explains this significant effect. The relation found between net farm income and total and on farm eutrophication per hectare (see paragraph 5.3.3) can, therefore, be partly explained by farm size, Dutch livestock units per hectare, and amount of purchased concentrates per 100 kg FPCM. Table 5.4 shows Dutch livestock units per hectare and milk urea content influenced on farm acidification per hectare. The relation found between net farm income and on farm acidification per hectare (see paragraph 5.3.3) can, therefore, be partly explained by Dutch livestock units per hectare and milk urea content.

Table 5.4 Identification of farm characteristics that influence net farm income and/or LCA indicators

Indicator[a]	Pasture system	Farm size	Animal intensity	Production intensity	Concentrates	Milk urea
Unit		*ha*	*GVE[b]/ha*	*Mp[c]/cow*	*kg/100 kg FPCM[d]*	*mg/100 g*
Profitability *NFI/FTE*	ns[e]	***	**	**	ns	ns
Total LU *m^2/kg FPCM*	ns	ns	***	*	***	ns
On farm LU *m^2/kg FPCM*	ns	ns	***	***	ns	ns
On farm EU *MJ/kg FPCM*	ns	ns	**	**	ns	ns
Total EU *MJ/kg FPCM*	ns	ns	ns	ns	***	ns
Total GWP *kg CO_2-eq/kg FPCM*	ns	ns	ns	***	***	ns
On farm GWP *kg CO_2-eq/kg FPCM*	ns	ns	ns	***	ns	*
Total EP *kg NO_3-eq/total farm ha*	ns	*	***	ns	***	ns
On farm EP *kg NO_3-eq/total farm ha*	ns	**	***	ns	**	ns
Total AP *kg SO_2-eq/total farm ha*	ns	ns	***	ns	***	**
On farm AP *kg SO_2-eq/on farm ha*	ns	ns	***	ns	ns	***

[a] NFI/FTE= net farm income per full time equivalent; LU=Land Use; EU= Energy Use; GWP= Global Warming Potential; EP=Eutrophication Potential; AP= Acidification Potential.

[b] Dutch livestock units.

[c] Milk production.

[d] Fat and Protein Corrected Milk.

[e] ns = not significant; *$P<0.05$; **$P<0.01$; ***$P<0.001$.

5.4 Discussion

The first objective of this study was to identify if FADN could be used to perform an LCA of individual dairy farms. This study showed performing an LCA of individual dairy farms based on the Dutch FADN is possible. The LCA results are within the scope of former research (Cederberg and Flysjö, 2004; Thomassen *et al.*, 2008). Former LCA studies of dairy cattle production systems, however, analyzed a limited number of farms (20-30 at highest), whereas this study includes more variation among farms, as a large number of farms (119) was analyzed. Dalgaard *et al.* (2006) showed it was possible to use the Danish FADN to perform an LCA of the agricultural sector. Data used, were aggregated averages. Meul *et al.* (2007), used the Flemish FADN to compute the on and off farm energy use of individual specialised dairy, arable, and pig farms. This approach is similar to the one presented in this study, because individual farms are analyzed. Inclusion of variation among farms, is preferred to the use of aggregated averages, because the use of aggregated averages implies a loss of variation among farms.

This study focused on specialised conventional dairy farms. The analyzed 119 farms had a larger farm size (53.4) than an average Dutch dairy farm (40.9), and a higher number of milking cows (85) than an average Dutch dairy farm (65) (LEI, 2007a). In addition, the analyzed 119 farms had a slightly higher milk production per cow (7613) than an average Dutch dairy farm (7568) (LEI, 2007a). Furthermore, net farm income was higher (44900 euro) than an average Dutch dairy farm (40000 euro) (LEI, 2007a). These differences indicate the conclusions drawn in this study apply to the dairy farms under study that deviate from an average Dutch dairy farm.

Although it was possible to perform an LCA of the individual farms, data assumptions had to be made. To investigate the assumptions made a sensitivity analysis in the LCA dairy farm model was performed (Risk, 2007). Eutrophication and acidification at farm level were sensitive to changes of mineral nitrogen content of manure: acidification changes with 2.75% if mineral N changes with 10%, whereas eutrophication changes with 0.40% if mineral N changes with 10% (Dolman, 2007). This implies that using a fixed value for mineral nitrogen content of manure, as was done in this study due to lack of data, resulted in a loss of ammonia emission variation among the different farms. The sensitivity analyses also showed eutrophication at farm level was sensitive to changes of phosphate leaching: eutrophication changes with 5.5% if phosphate leaching changes with 10%. This implies the assumption made all phosphate surplus is leached due to phosphorus saturated soils, results in a loss of phosphate leaching variation among farms. A farm-specific soil phosphor saturation factor, however, was not available.

The second objective of this paper was to study the relationship between environmental and economic performance of dairy farms. Farms with a high net farm income had a low on farm land use, total land use, energy use at farm level, total climate change and on farm climate change. These indicators were product-related and expressed per kg FPCM. On the other hand, farms with a high net farm income had a high total eutrophication, total acidification, eutrophication at farm level, and acidification at farm level. These indicators were area-related and expressed per hectare.

The third objective of this paper was to identify which farm characteristics influence the relationship found between environmental and economic performance. Farm size (ha), Dutch livestock units per hectare, milk production per cow, purchased amount of concentrates per 100 kg FPCM, and milk urea content influenced the relation between environmental and economic performance. These farm characteristics affect the emissions or polluting elements that contribute to the chosen LCA impact category, they influence net farm income, or they influence the denominator in which the LCA indicator is expressed. Acidification and eutrophication have a local and regional impact and were therefore expressed both per kg FPCM and per hectare. Halberg *et al.* (2005) argue for acidification and eutrophication, and other environmental problems with a regional component, both a product-based and area-based indicator are needed. Different farm characteristics relate to the LCA indicators expressed per kg FPCM or per hectare. Milk production per cow influenced all LCA indicators expressed per kg FPCM, as amount of milk produced is the denominator of these indicators. Animal intensity influenced all LCA indicators expressed per hectare. Other studies also showed choice of functional unit influences LCA outcomes (Van der Werf *et al.*, 2007; Thomassen *et al.*, 2008).

The statistical analyses showed pasture system did not influence net farm income. Farms with a high net farm income also had a high "calculated – paid interest" (Binternet, 2007), which indicates if differences between "net profit" and "labour costs" among the different pasture system groups existed, these were leveled out. Table 1 shows the non-grazing group had a large farm area (62.9 ha), large milk quota (982875 kg), and a high milk production per cow (8376 kg). The non-grazing farms, therefore, can be considered as large dairy farms. Large dairy farms in general have a higher net farm income, which corresponds with other literature, as outlined below. Jager and Van Everdingen (2004) found a difference in net farm income between small farms that pastured their cows and farms that performed summer feeding. Net farm income between large farms that pastured their cows and farms that performed summer feeding, however, was similar, which corresponds with this study. Bossink (2007) found farms that pastured their cows made more profit per kg milk produced compared with farms that performed non-grazing when farms had a similar size. When non-grazing farms had a larger size, no differences in farm income were found between non-grazing farms and farms that pastured their cows which corresponds with this study.

Based on the relationships found in this study between net farm income and LCA indicators, besides the identification of farm characteristics that influence these relationships, an 'optimum' analysis can be carried out to gain insight into the optimum situation when net farm income is high while environmental burdens are low. In this study only structural on farm characteristics were taken into account. Agent (or managerial) characteristics, such as age of the farmer, education level, and succession, were not taken into account. Van Passel *et al.* (2007), however, recovered both structural and managerial characteristics influence economic and environmental sustainability. Farm characteristics in the proposed 'optimum' analysis, therefore, must preferably include more farm characteristics than the ones identified in this study.

5.5 Conclusion

This study showed Dutch FADN is suitable to perform an LCA of individual dairy farms, which enables to perform future LCAs of dairy farms based on FADN. Future LCAs can be strengthened by the inclusion of more suitable LCA-related data within FADN collection. This study also demonstrated farms with a high net farm income had a low on farm land use, total land use, energy use at the dairy farm, on farm and total climate change, expressed per kg FPCM. On the other hand, farms with a high net farm income had a high total and on farm eutrophication and acidification, expressed per hectare. Farm characteristics that influenced these relationships between environmental and economic performance were: farm size, Dutch livestock units per hectare, milk production per cow, purchased concentrates per 100 kg FPCM, and milk urea content.

In conclusion, negative and positive relations exist between LCA indicators and net farm income. Underlying farm characteristics influence these relations. It is, therefore, recommended to perform an 'optimum' analysis to gain insight into the optimum situation when net farm income is high while environmental burdens are low.

References

Barry, P.J., Ellinger, P.N., Hopkin, J.A., Baker, C.B., 2000. Financial Management in Agriculture. Interstate Publishers, Danville, Illinois, USA.

Berlin, J., 2002. Environmental life cycle assessment (LCA) of Swedish semi-hard cheese. International Dairy Journal 12, 939-953.

Binternet, 2007. Het Bedrijven-InformatieNet van het LEI, 2007 www.lei.wur.nl/NL/statistieken/Binternet/.

Bossink, G.J.N., 2007. Economische resultaten van weiden en opstallen Koe &Wij, Lelystad, The Netherlands

Casey, J.W., Holden, N.M., 2005. Analysis of greenhouse gas emissions from the average Irish milk production system. Agricultural Systems 86, 97-114.

Cederberg, C., 1998. Life cycle assessment of milk production- a comparison of conventional and organic farming. SIK-Report No. 643. The Swedish Institute for Food and Biotechnology, Göteborg, Sweden.

Cederberg, C., Flysjö, A., 2004. Life Cycle Inventory of 23 dairy farms in South-Western Sweden. SIK-Report No. 728. The Swedish Institute for food and biotechnology, Göteborg, Sweden.

CVB, 2004. Tabellenboek Veevoeding 2004: Voedernormen Landbouwhuisdieren en Voederwaarden Veevoeders. . Centraal Veevoeder Bureau, Lelystad, The Netherlands.

Dalgaard, R., Halberg, N., Kristensen, I.S., Larsen, I., 2006. Modelling representative and coherent Danish farm types based on farm accountancy data for use in environmental assessments. Agriculture, Ecosystems and Environment 117, 223-237.

De Bont, C.J.A.M., Van Everdingen, W.H., Koole, B., 2003. Standard Gross Margins in The Netherlands. Landbouw Economisch Instituut (LEI), Den Haag, The Netherlands.

De Haan, M.H.A., Evers, G.A., Van Everdingen, W.H., Van den Pol-van Dasselaar, A., 2005. Invloed mestbeleid met gebruiksnormen op weidegang. Praktijkrapport 69. Animal Sciences Group, Lelystad, The Netherlands.

Dolman, M.A. 2007. Trade-offs among economic and ecological sustainability indicators on dairy farms in The Netherlands. MSc thesis, Wageningen University and Research Centre, Wageningen, The Netherlands.

Doppenberg, J., De Groot, J.P., 2005. Lineaire programmering rundvee-, varkens- en pluimveevoeders. VVM Bedrijfsbureau; Vereniging Voorlichting Mengvoerindustrie, Deventer, The Netherlands.

EcoinventCentre, 2004. Ecoinvent data v1.1 Final reports ecoinvent 2000 (1-15). Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Elkington, J., 1998. Cannibals with forks: The triple bottom line of 21st century business. New Society Publishers, Gabriola Island, Canada.

FADN, 2007. Farm Accountancy Data Network, Vol. Available online (March 1st 2006), ec.europa.eu/agriculture/rica/index_en.cfm.

Glavič, P., Lukman, R., 2007. Review of sustainability terms and their definitions. Journal of Cleaner Production 15, 1875-1885.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., De Koning, A., Van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., De Bruijn, H., Van Duin, R., Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H., Van der Ven, B.L., Weidema, B.P., 2002. Handbook on Life Cycle Assessment; Operational Guide to the ISO Standards. Centrum voor Milieukunde- Universiteit Leiden (CML); Kluwer Academic Publishers., Leiden, The Netherlands.

Halberg, N., Van der Werf, H.M.G., Basset-Mens, C., Dalgaard, R., De Boer, I.J.M., 2005. Environmental assessment tools for the evaluation and improvement of European livestock production systems. Livestock Production Science 96, 33-50.

Handboek melkveehouderij, 2006. nieuwe editie 2006. Animal Sciences Group, Lelystad, The Netherlands.

Heijungs, R., Guinée, J., Huppes, G., Lankreijer, R.M., Udo de Haes, H.A., Wagener Sleeswijk, A., Ansems, A.M.M., Eggels, P.G., Van Duin, R., De Goede, H.P., 1992. Environmental Life Cycle Assessment of products. Guide and Backgrounds. CML, Leiden University, Leiden, The Netherlands.

Høgaas Eide, M., 2002. Life Cycle Assessment (LCA) of Industrial Milk Production. International Journal of Life Cycle Assessment 7, 115-126.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental panel on climate change pp. Greenhouse gas inventory reference manual. Volume 4.

Jager, J., Van Everdingen, W.H., 2004. Bedrijven met zomerstalvoedering zijn duurder uit LEI, Agri-Monitor, Vol. Augustus, 1-2.

LEI, 2007a. Landbouw Economisch Instituut. Land- en tuinbouwcijfers 2007. Jaarrapporten van het LEI en het CBS, Den Haag, The Netherlands.

LEI, 2007b. Landbouwkundig Economisch Instituut., Vol. 2007, Den Haag, The Netherlands, www.lei.wur.nl/NL/statistieken/BSS+en+NGE/.

Meul, M., Nevens, F., Reheul, D., Hofman, G., 2007. Energy use efficiency of specialised dairy, arable and pig farms in Flanders. Agriculture, Ecosystems & Environment 119, 135-144.

Mooij, M., 1996. Samenstelling dierlijke mest. Nederlands meststoffen instituut, Den Haag, The Netherlands.

Mouron, P., Scholz, R.W., Nemecek, T., Weber, O., 2006. Life cycle management on Swiss fruit farms: Relating environmental and income indicators for apple-growing. Ecological Economics 58, 561-578.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecological Economics 60, 498-508.

Norris, G.A., 2001. Integrating Life Cycle Cost Analysis and LCA. International Journal of Life Cycle Assessment 6, 118-120.

Oenema, O., Van Liere, L., Schoumans, O., 2005. Effects of lowering nitrogen and phosphorus surpluses in agriculture on the quality of groundwater and surface water in The Netherlands. Journal of Hydrology 304, 289-301.

Oldenhof, S., 2004. Uitgebreide energiestudie zuivelindustrie. SenterNovem B.V. KWA Bedrijfsadviseurs B.V., Amersfoort, The Netherlands.

Risk, 2007. Risk Analysis and Simulation for Microsoft Excel, @RISK 5.0, USA.

Schils, R.L.M., Oudendag, D.A., Van der Hoek, K.W., de Boer, J.A., Evers, A.G., de Haan, M.H., 2006. Broeikasgasmodule BBPR. Praktijkrapport Rundvee 90. Animal Sciences Group, Alterra, RIVM, Wageningen, The Netherlands.

Schils, R.L.M., De Haan, M.H.A., Hemmer, J.G.A., Van den Pol-van Dasselaar, A., De Boer, J.A., Evers, G.A., Holshof, G., Van Middelkoop, J.C., Zom, R.L.G., 2007. Dairywise, a whole-farm dairy model. Journal of Dairy Science 90, 5334-5346.

Schröder, J.J., Aarts, H.F.M., van Middelkoop, J.C., De Haan, M.H.A., Schils, R.L.M., Velthof, G.L., Fraters, B., Willems, W.J., 2005. Limits to the use of manure and mineral fertilizer in grass and silage maize production in The Netherlands, with special reference to the EU Nitrates Directive. Plant Research International B.V., Wageningen, The Netherlands.

Smink, W., Bos, K.D., Fitié, A.F., Van der Kolk, L.J., Rijm, W.K.J., Roelofs, G., Van den Broek, G.A.M., 2003. Methaanreductie melkvee: Een onderzoeksproject naar inschatting van de methaanproductie vanuit de voeding en naar de reductiemogelijkheden via de voeding van melkkoeien. In: NOVEM, Feed Innovation Services (FIS) B.V. Utrecht, The Netherlands.

Smits, M.C.J., Monteny, G.J., Van Duinkerken, G., 2003. Effect of nutrition and management factors on ammonia emission from dairy cow herds: models and field observations. Livestock Production Science 84, 113-123.

Smits, M.C.J., Van Jaarsveld, J.A., Mokveld, L.J., Vellinga, O., Stolk, A., Van der Hoek, K.W., van Pul, W.A.J., 2005. Het 'VELD'-project: een gedetailleerde inventarisatie van de ammoniak-emissies en -concentraties in een agrarisch gebied. Wageningen University and Research Centre; Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven, The Netherlands.

SPSS, 2007. Statistical Package for Social Sciences. SPSS Software Package 15.0 for Microsoft Windows, Chicago, Illinois, USA.

Thomassen, M.A., De Boer, I.J.M., 2005. Evaluation of indicators to assess the environmental impact of dairy production systems. Agriculture, Ecosystems & Environment 111, 185-199.

Thomassen, M.A., Van Calker, K.J., Smits, M.C.J., Iepema, G.L., De Boer, I.J.M., 2008. Life Cycle Assessment of conventional and organic milk production in The Netherlands. Agricultural Systems 96, 95-107.

Thomassen, M.A., Dalgaard, R., Heijungs, R., De Boer, I.J.M., In press. Attributional and consequential LCA of milk production. International Journal of Life Cycle Assessment.

Van Calker, K.J., Berentsen, P.B.M., De Boer, I.J.M., Giesen, G.W.J., Huirne, R.B.M., 2004. An LP-model to analyse economic and ecological sustainability on Dutch dairy farms: model presentation and application for experimental farm "de Marke". Agricultural Systems 82, 139-160.

Van den Pol-van Dasselaar, A., 2005. Weidegang in beweging - grazing on the move. Animal Sciences Group, Lelystad, The Netherlands.

Van der Hoek, K.W., 2002. Uitgangspunten voor de mest- en ammoniakberekeningen 1997 tot en met 1999 zoals gebruikt in de Milieubalans 1999 en 2002. RIVM Rapport 773004012. RIVM; Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven, The Netherlands.

Van der Werf, H.M.G., Tzilivakis, J., Lewis, K., Basset-Mens, C., 2007. Environmental impacts of farm scenarios according to five assessment methods. Agriculture, Ecosystems & Environment 118, 327-338.

Van Passel, S., Lepoutre, J., Nevens, F., Van Huylenbroeck, G., Mathijs, E., 2004. Economische duurzaamheid en toegevoegde waarde: Een eerste aanzet op basis van macro-economische gegevens. In: Stedula (Ed.), Publicatie 12. Steunpunt Duurzame Landbouw, België.

Van Passel, S., Nevens, F., Mathijs, E., Van Huylenbroeck, G., 2007. Measuring farm sustainability and explaining differences in sustainable efficiency. Ecological Economics 62, 149-161.

WCED, 1987. World Commission on Environment and Development: Our common future (The Brundtland report). Oxford University Press, Oxford, UK.

Zevenbergen, G.J., 2006. Ook de kleine strooiseltest bewijst: goedkoop zaagsel voldoet primaVeehouderij Techniek, Vol. mei, 2006, pp. 34-37.

Chapter 6

General discussion

6.1 Introduction

The aim of the research presented in this thesis was to quantify the integral environmental impact of dairy cattle production systems in The Netherlands. The following research questions were formulated:

1. What are effective indicators to assess the integral environmental impact of dairy cattle production systems?
2. What are the differences between attributional LCA and consequential LCA when assessing the integral environmental impact of dairy cattle production systems?
3. What are the differences in integral environmental impact and environmental hotspots between conventional and organic dairy cattle production systems?
4. Is the Farm Accountancy Data Network (FADN) suitable to perform an LCA of individual dairy farms?
5. What is the relationship between LCA indicators and net farm income of dairy cattle production systems, and what are the underlying farm characteristics that influence this relationship?

In this chapter research issues are discussed related to the answers to the research questions, and the main conclusions are drawn. First of all, however, choice of the dairy cattle production system will be discussed by placing the dairy cattle sector in perspective of the animal and total agricultural sector. In section 6.2 the contribution of the dairy cattle sector to the on farm and total environmental impact of the animal sector (pig, poultry, dairy cattle) and total agricultural sector is presented. In section 6.3 tools used to assess the integral environmental impact are discussed. In section 6.4 use of attributional LCA or consequential LCA within this thesis are discussed, besides choices made within each LCA phase. In section 6.5 implementation of the integral environmental impact assessment presented in this thesis is discussed. In section 6.6 the focus of this thesis on mainly the pillar planet of sustainability is discussed. Section 6.7 presents the main conclusions that are drawn from this research. Section 6.8 presents recommendations for further research.

6.2 Dairy cattle sector in perspective

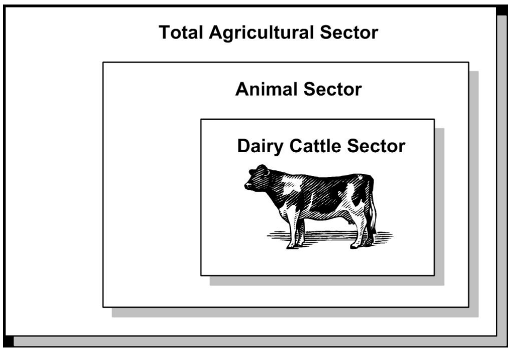

Figure 6.1 Dairy cattle sector in perspective of the animal and agricultural sector

This thesis focused on dairy cattle production systems. The dairy cattle sector must be placed in perspective to justify this focus. Therefore, the contribution of the dairy cattle sector to the on farm and total environmental impact of the animal sector (pig, poultry, dairy cattle) and total agricultural sector was assessed (see Figure 6.1).

A similar procedure as presented in Chapter 4 for dairy cattle production systems was used to assess the on farm and total environmental impact of the dairy cattle, pig, poultry, and total agricultural sector (Van Kernebeek, 2007). A cradle-to-farm gate LCA was performed, implying that all processes and transport until agricultural products leave the farm gate were included in the analyses (see Figure 4.1). Included off farm processes were transport and production of purchased compound concentrates and single concentrates, roughage and wet by-products, artificial fertiliser, animal manure, pesticides, contract work, and rock wool.

Figure 6.2 presents the contribution of the dairy cattle sector to the on farm and total environmental impact of the animal sector (pig, poultry, dairy cattle) and total agricultural sector.

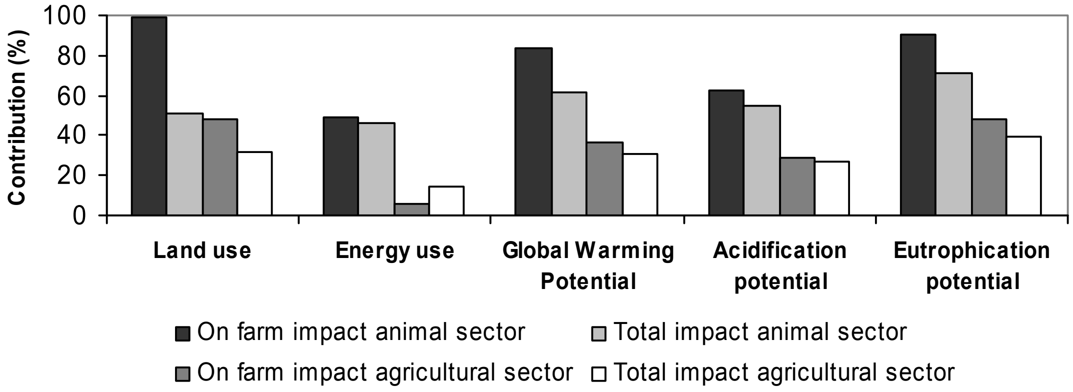

Figure 6.2 Contribution of the dairy cattle sector to the on farm and total environmental impact of the animal sector (pig, poultry, and dairy cattle) and total agricultural sector

Figure 6.2 shows the contribution of the dairy cattle sector to the animal sector was high for land use (99% on farm and 51% total), eutrophication (90% on farm and 71% total), climate change (Global Warming Potential: 84% on farm and 62% total), acidification (62% on farm and 55% total), and energy use (49% on farm and 46% total). In general, the contribution to the total impact was lower, due to the inclusion of off farm impacts. Purchased concentrates, for example, has a large contribution to the total environmental impact of the pig and poultry sector due to the landless character of these sectors in The Netherlands. The contribution of the dairy cattle sector to the total agricultural sector was mainly high for land use (48% on farm and 32% total), eutrophication (48% on farm and 40% total), climate change (36% on farm and 31% total), and acidification (28% on farm and 27% total). The contribution of the dairy cattle sector to the total agricultural sector was low for energy use (6% on farm and 14% total), mainly due to the high energy use of greenhouse horticulture.

In conclusion, results showed the focus of this thesis on dairy cattle production systems is justified due to the contribution of the dairy cattle sector to total eutrophication (71%), climate change (62%), acidification (55%), land use (51%), and energy use (46%) of the animal sector, and due to the contribution of the dairy cattle sector to total eutrophication (40%), land use (32%), climate change (31%), and acidification (27%) of the total agricultural sector. Results also showed that inclusion of environmental impacts of purchased inputs influence the contribution of the dairy cattle sector to the environmental impact of the animal and total agricultural sector.

6.3 Selection of methodology

Several methodologies exist to assess the environmental impact of an agricultural activity (Halberg *et al.*, 2005; Payraudeau and Van der Werf, 2005; Hermann *et al.*, 2007; Ness *et al.*, 2007). In general, the objectives of the user explain the environmental impact assessment method used. Most methodologies refer to the environmental impact assessment (EIA) procedure. EIA is a procedure that aims to ensure that a decision-making process on activities that influence the environment, takes into account the environmental aspects related to the decision (Tukker, 2000). One difference between EIA and LCA is that LCA helps in making decisions, while EIA is also concerned with the process of decision making itself (Tukker, 2000). Indicators are the basis of different methodologies for environmental impact assessment. In most EIAs related to food production, agro-environmental indicators are defined (Payraudeau and Van der Werf, 2005). Use of indicators avoids the difficulty of obtaining direct measurements due to methodological problems, practical reasons, or the cost or time needed to acquire them (Bockstaller and Girardin, 2003).

The first research question in this thesis was how the integral environmental impact of dairy cattle production systems could be assessed. The use of the term ‘integral’ implies: 1) a focus on more than one environmental aspect and 2) taking into account the production chain. This approach favors a systems analysis. Different degrees of integrality exist. Chapter 2 showed indicators derived from Input-Output Accounting (IOA) are integral at farm level, because these indicators focus on more than one environmental aspect, but do not take into account the production chain. Chapter 2 also showed indicators derived from Ecological FootPrint analysis (EFP) and Life Cycle Assessment (LCA) focus on the production chain. EFP, however, only focuses on depletion of resources (land and energy), whereas LCA focuses on more environmental aspects (e.g., eutrophication and climate change besides depletion of resources). LCA indicators are effective, although data are hard to retrieve, focus on more than one environmental aspect and take into account pollutants within the production chain. The computation of acidification and eutrophication potential requires a nutrient balance at farm level (see Chapter 4). Halberg *et al.* (2005) showed LCA covers more environmental aspects compared with indicators of resource use or input-output indicators, which corresponds with our conclusions in Chapter 2.

LCA indicators are effective to assess the integral environmental impact of dairy cattle production systems. In the next section, therefore, choices within LCA methodology are discussed.

6.4 Choices within LCA methodology

Chapter 2 showed LCA indicators are effective for an integral environmental impact assessment. Chapter 3, therefore, gained insight into choices within LCA methodology, and in Chapters 4 and 5 LCA indicators were applied when assessing the integral environmental impact of dairy cattle production systems. In Chapter 3 it was shown performing attributional LCA and economic or mass allocation results in different outcomes than performing consequential LCA and system expansion. Attributional LCA assumes a status-quo situation, while consequential LCA assumes a change in demand of the studied product. Most LCA practitioners choose one methodology independent of their research questions. In this thesis, however, attributional LCA was applied in Chapter 4 and 5 because of well-considered reasons described below.

In Chapter 4, the objective was to compare the integral assessment of the environmental impact of a conventional and an organic system. No change in demand occurred, and therefore, a status-quo situation was assumed. In addition, results were submitted to the sector, which favoured using attributional LCA, because Chapter 3 showed concentrates used within attributional LCA are more understandable for stakeholders within the sector than the feed used within consequential LCA.

In Chapter 5, one objective was to study the relationship between environmental and economic performance of dairy farms. Within economics, a status-quo situation or a changing situation can be chosen, similar to the choice between attributional LCA and consequential LCA. It is important to chose the right combination between LCA indicators and economic indicators. Attributional LCA was used, because the economic indicator net farm income assumes a status-quo situation. Furthermore, results presented in Chapter 5 needed to be comparable with results presented in Chapter 4, which also favoured the use of attributional LCA.

In the sections 6.4.1-6.4.4 choices within LCA methodology will be discussed, divided into the four LCA phases (Guinée *et al.*, 2002).

6.4.1 Choices within 'Goal and scope definition phase'

The LCA guidelines allow a large degree of freedom regarding system definition and structure of impact assessment. Choice of system boundaries and included impact assessment categories are decisive for the results and is therefore a crucial step.

A cradle-to-farm gate LCA was performed of the dairy cattle production system, implying that all processes and transport until milk leaves the farm gate were included in the analyses. The impact assessment categories included in this thesis were land use, energy use, climate change, acidification, and eutrophication (as outlined in Chapter 4).

The aim of this thesis was to quantify the integral environmental impact of dairy cattle production systems. Midpoint impact indicators were used, because a midpoint indicator is defined near the source of emissions (problem-oriented), which relates more to the goal of this thesis than an endpoint indicator that is defined near the final effect (damage-oriented) that often implies hidden assumptions (Guinée *et al.*, 2002; Jolliet *et al.*, 2004).

Berlin (2002) showed the dairy cattle production system, based on Cederberg (1998), contributed most to the impact categories climate change, acidification, and eutrophication compared with the cheese-making dairy. Høgaas Eide (2002) also showed the dairy cattle production system contributed most to total energy consumption, climate change, acidification, eutrophication, compared with the dairy processing, packaging, distribution, retailer, consumer and waste management phase. Chosen impact categories in this thesis, therefore, are justified concerning the selected system boundaries of the dairy cattle production system.

Transport of milk to the dairy, besides dairy processing, packaging, retailer, consumer phase, and waste management were not included in the LCA presented in this thesis. Høgaas Eide (2002), Berlin (2002), and Hospido *et al.* (2003) showed the impact categories stratospheric ozone depletion and photochemical-oxidant formation should be considered when system boundaries of the dairy cattle production system are expanded by including dairy processing, packaging, retailer, consumer phase, and waste management.

The impact categories human toxicity, terrestrial and aquatic eco-toxicity, biodiversity, soil quality, and water use were not addressed, although they are relevant for the chosen system boundaries. These impact categories will be discussed below. Some processes of the carbon cycle, such as photosynthesis and respiration were not included in the LCA and will be discussed below as well.

Human toxicity, terrestrial and aquatic eco-toxicity were not taken into account, because detailed data on pesticides and heavy metals of the inputs (e.g., cultivation of crops for purchased concentrates) were not available. To address toxicity, pesticide use (expressed in g active ingredient per kg FPCM) was assessed for the 119 dairy farms based on FADN (based on data presented in Chapter 5). Average total pesticide use of the 119 farms was 0.92 g active ingredient per kg FPCM, of which pesticide use at farm level contributed for 4%, and pesticide use for the production of purchased inputs (e.g., concentrates and roughage) contributed for 96%. This on farm pesticide use, 36.8 mg active ingredient per kg FPCM, was low compared with 75.9 mg active substance/kg Energy Corrected Milk found in Cederberg and Flysjö (2004). These Swedish conventional dairy farms, however, had a larger arable land area (80 hectare) than the Dutch dairy farms (14.1 hectare), which explains this difference.

Occupation of land (land use) was chosen as impact category. Occupation of land, however, does not cover the whole impact, because of several reasons. Firstly, land represents a scarce resource but can be re-used when treated properly. In addition, its functioning depends on how land is managed. Secondly, humans are not the sole users of land. It is recommended, therefore, by Milà i Canals *et al.* (2006), to include land use impacts in the LCA, such as biodiversity (diversity of flora and fauna), and soil quality. In this thesis, these impacts were not included, because no widely accepted assessment method is available for land use impacts (Milà i Canals *et al.*, 2007). Furthermore, detailed data on soil quality and number of species were not available of the analysed farms and of the land used in foreign countries for cultivation of crops. Subsequently, deforestation is not included, being part of loss of biodiversity. Especially for the comparison of conventional and organic production systems, as presented in Chapter 4, inclusion of impacts on biodiversity and soil quality will have a surplus value, because the way land is managed can be changeable.

Water use can be addressed by computing a WaterFootPrint (WFP) of a dairy farm (Chapagain and Hoekstra, 2004). Evapotranspiration (water used by a crop for growth and cooling purposes) both in foreign countries and in The Netherlands, has a large contribution to the WFP of a Dutch dairy farm (Gideonse, 2006). The difficulty is how to interpret the computed WFP of a dairy farm, because water flows within the water cycle are a continuous global process and drought is period- and region-dependent.

Photosynthesis, respiration, and soil processes (e.g., soil carbon sequestration), being part of the carbon cycle, were not included in this study. Methane released from enteric fermentation was taken into account, besides carbon stored on a large time-scale, such as in fossil fuels. Most LCA studies do not include photosynthesis and respiration (Cederberg, 2002; Casey and Holden, 2006; Dalgaard *et al.*, 2006). In this study, an equilibrium situation for photosynthesis and respiration on a short time-scale was assumed. Steinfeld *et al.* (2006) also mention livestock respiration is part of a rapidly cycling biological system, and emitted and absorbed quantities are considered to be equivalent. Steinfeld *et al.* (2006), however, also showed land use changes, and land degradation, such as Amazon deforestation, have a large contribution to the net release of carbon that can be attributed to the livestock sector, and should therefore be taken into account in future studies.

6.4.2 Choices within 'Life Cycle Inventory phase'

Pollutant emissions vary both in space and time. With respect to time, an annual basis was used in this thesis. This yearly basis is often used in LCA, considering all the emissions produced over the year. The duration of an effect, however, depends on the impact and may exceed 100 years, as for greenhouse gases. In addition, preferably, several years need to be taken into account when performing an LCA, to exclude weather effects (e.g., crop yields are affected by weather conditions).

Preferably, the spatial variability of pollutant emissions and the vulnerability of the affected environment need to be taken into account (Payraudeau and van der Werf, 2005). Soil type was taken into account in the LCI phase, e.g. by assessing the amount of nitrate leached, besides the location of the farm when estimating the amount of nitrogen deposited. Other regional aspects were not taken into account. No regional characterization factors, e.g. for acidification and eutrophication, for The Netherlands were available for the years under study (Guinée *et al.*, 2002). It was decided, therefore, to express both acidification and eutrophication per hectare, to address the local and regional aspect.

6.4.3 Choices within 'Life Cycle Impact Assessment phase'

Each impact category was addressed individually, by presenting individual outcomes of the LCA indicators. Indicators can also be used in the form of a composite index that combines individual indicator scores into a single number. A single aggregated number can be useful in communicating information to the public and decision-makers. Such an index, however, implies hidden assumptions, simplifications or implicit value judgments (Mollenhorst, 2005; Van Passel *et al.*, 2007). Daniel *et al.* (2004) showed the attribution of different weights to impact categories usually leads to different results.

6.4.4 Choices within 'Interpretation phase'

Information is preferably needed on the robustness of LCA results, because the interpretation phase requires knowledge of the uncertainty associated with these results.

Uncertainty depends on both the input data and the model that is used (Payraudeau and Van der Werf, 2005). Uncertainty can arise from a lack of knowledge of included processes or it can reflect a known variability of the processes included in the study (Basset-Mens *et al.*, 2005). An uncertainty analysis requires insight in variation factors of the included parameters. In this study, no uncertainties were quantified, because knowledge on variation factors were not available for all parameters. To assess the effect of a change of 10% of each parameter is not sufficient, because it is not known if this is an increase or decrease of the parameter. Based on the results of the contribution analysis (identification of environmental hotspots), as presented in Chapter 4, however, issues of concern can be selected. Both off farm processes (e.g., production of concentrates) and on farm processes (e.g., field emissions, leaching, and emissions related to keeping animals) were issues of concern. More knowledge is present on variability of on farm processes (De Vries *et al.*, 2003; Kroeze *et al.*, 2003; Monteny *et al.*, 2006). Insight is needed into the variability of off farm processes, to be able to perform a complete uncertainty analysis. In general, data of off farm processes, especially cultivation, processing and transport of concentrates ingredients, are hard to collect.

6.5 Implementation of integral environmental impact assessment

LCA indicators were used in Chapter 4 to compare a conventional and an organic dairy cattle production system. Bos *et al.* (2007) compared energy use and climate change of a conventional and organic dairy cattle production system, by defining Dutch dairy farm models. Energy use and climate change were both area- and product-related in that study. Differences between a conventional and organic production system were strengthened when area-related, because of the extensiveness of organic farms. In this thesis energy use and climate change were not expressed per hectare, because these were considered to be global effects, see Halberg *et al.* (2005). Choice of the denominator influences results in most studies. Chapter 4 showed differences between a conventional and organic production system were strengthened when expressed per hectare, when the organic system already had a lower impact, which corresponds with the findings in Bos *et al.* (2007). Chapter 5 also showed choice of functional unit, i.e., to express indicators per hectare or per amount of milk produced, resulted in different relations with net farm income, and different farm characteristics that influenced these relations. LCA indicators proved to be useful when comparing the integral environmental impact of different production systems (Chapter 4). LCA indicators are also useful to address if a management change at farm level does not imply a higher environmental burden elsewhere in the production chain. Chapter 5 indicated changes in farm characteristics influence the integral environmental impact. A higher milk production per cow, for example, implies lower greenhouse gas emissions at farm level per kg FPCM, but can imply a higher off farm climate change per kg FPCM, if more concentrates are fed. An integral assessment is also needed, when implementing different feeding strategies in order to reduce methane reduction from enteric fermentation (Tamminga *et al.*, 2007). The effect of different feeding strategies on other environmental aspects, such as ammonia volatilization at farm level, or greenhouse gas emissions elsewhere along the milk production chain, should be considered. LCA indicators, therefore, are useful to assess the integral environmental impact when evaluating innovations or mitigation options. The LCA dairy model constructed within the research presented in this thesis is a valid basis for further research.

6.6 The pillar planet of sustainability

Sustainability is based upon the three pillars people, planet, profit (Elkington, 1998), also referred to as societal, ecological, and economic sustainability. This thesis focused mainly on ecological sustainability, the pillar “planet”. Chapter 5, however, also addressed economic sustainability, the pillar “profit”, by assessing relationships between LCA indicators and net farm income. LCA is a chain approach, because upstream (e.g., purchased inputs) and downstream processes (e.g., dairy processing) can be included. In this thesis, only upstream processes were included, as discussed in paragraph 6.4.1. Net farm income also includes upstream processes, because cost price of purchased inputs is part of net farm income. This justifies using net farm income besides LCA indicators to identify relationships between economic and environmental performance.

Preferably, the three pillars of sustainability should be taken into account. Van Calker *et al.* (2005) showed a modelling approach how to assess all three pillars of sustainability of Dutch dairy farming at farm level. That approach can be expanded by including more processes along the milk production chain, such as presented for environmental sustainability in this thesis. The societal aspect animal welfare, for example, can be assessed not only at dairy farm level, but also during transport, and in the slaughter house. Weidema (2006) already showed that by using the chain-approach, different societal aspects along the production chain, such as working conditions and child labour, can be considered.

In conclusion, although two out of three pillars of sustainability were addressed in this thesis, the presented integral assessment is valuable and can be expanded by including other sustainability aspects along the milk production chain.

6.7 Main conclusions

The following conclusions can be drawn from this thesis within the boundaries of the presented research:

- The dairy sector contributed 71% to total eutrophication, 62% to total climate change, 55% to total acidification, 51% to total land use, and 46% to total energy use of the animal sector in The Netherlands.
- The dairy sector contributed 40% to total eutrophication, 32% to total land use, 31% to total climate change, 27% to total acidification, and 14% to total energy use of the total agricultural sector in The Netherlands.
- LCA indicators are effective for an integral environmental impact assessment of dairy cattle production systems, because they focus on more than one environmental aspect and take into account pollutants within the production chain.
- An LCA of dairy cattle production systems gives insight into pollution swapping between on and off farm processes.
- Choice of the functional unit, i.e., if indicators are product-related or area-related, influences results.
- The objective of the study determines the choice of attributional LCA or consequential LCA, which subsequently results in differences in: total quantitative outcomes, environmental hotspots, degree of understanding, and quality.
- The organic dairy cattle production system had a lower energy use and eutrophication potential than the conventional system, whereas the conventional system had a lower land use than the organic system.
- Acidification potential and global warming potential were similar for both the conventional and organic system, but higher emissions at farm level occured in the organic system.
- Purchased concentrates is an environmental hotspot for both the conventional and organic dairy cattle production system.
- The Dutch Farm Accountancy Data Network is suitable to perform an LCA of individual dairy farms, which allows to perform an LCA of a large number (several hundreds) of farms.
- Dairy cattle production systems with a high net farm income had a low on farm land use, total land use, energy use at the dairy farm, on farm and total climate change, but a high total and on farm eutrophication and acidification.
- The relation between net farm income and LCA indicators can be influenced by the farm characteristics: farm size, Dutch livestock units per hectare, milk production per cow, purchased concentrates per 100 kg FPCM, and milk urea content.

6.8 Recommendations

An outlook for further research can be given based on the research presented in this thesis.

The LCA dairy model constructed within the research presented in this thesis is a valid basis for further research to evaluate innovations and mitigation options. The integral environmental impact assessment of dairy cattle production systems can be strengthened by including more impact categories, site-specific characterization factors, downstream processes (inclusion of dairy processing and transport), uncertainty analyses, and validation of potential LCA impacts with measured data (such as nitrate concentrations in groundwater). Subsequently, more data are needed. Especially more insight is needed into variability and uncertainty of off farm impacts. The environmental performance of dairy cattle production systems can be improved by reducing the use of concentrates ingredients with a high environmental impact. Researchers and the feed industry should collaborate in order to reduce the environmental impact of concentrates ingredients. Research should be carried out to gather specific data of processing, cultivation, and transport of the different ingredients produced in foreign countries. Data collection systems should be introduced in order to realize a database of concentrates ingredients produced in different countries.

The objective of the study, or research question, determines choice of attributional LCA or consequential LCA. Both attributional LCA and consequential LCA should be harmonized and standardized. LCA practitioners should collaborate, in order to gain insight into which research question should be answered by attributional LCA or consequential LCA, and to secure the possibility of comparing LCA studies.

The Dutch FADN can be used to perform an LCA of individual dairy farms. Future LCAs of individual farms of various agricultural sectors should be performed to gain insight into the integral environmental impact of the agricultural sector. Money can be saved by expanding existing data collection. Organisations that collect farm data, e.g. accountancy firms that collect economic data, should therefore expand their data collection, in order to address environmental issues.

Research should also be initiated to address the three pillars of sustainability along the milk production chain. Initiatives of the agricultural sector, related industries, and research institutions to realize such a chain approach must be stimulated.

References

Basset-Mens, C., Van der Werf, H.M.G., Durand, P., Leterme, P., 2005. Implications of uncertainty and variability in the life cycle assessment of pig production systems. International Journal of Life Cycle Assessment 11, 298-304.

Berlin, J., 2002. Environmental life cycle assessment (LCA) of Swedish semi-hard cheese. International Dairy Journal 12, 939-953.

Bockstaller, C., Girardin, P., 2003. How to validate environmental indicators. Agricultural Systems 76, 639-653.

Bos, J., De Haan, J., Sukkel, W., 2007. Energieverbruik, broeikasgasemissies en koolstofopslag: de biologische en de gangbare landbouw vergeleken. Plant Research International B.V., Praktijkonderzoek Plant & Omgeving, Wageningen University, Wageningen, The Netherlands.

Casey, J.W., Holden, N.M., 2006. Quantification of GHG emissions from sucker-beef production in Ireland. Agricultural Systems 90, 79-98.

Cederberg, C., 1998. Life cycle assessment of milk production- a comparison of conventional and organic farming. SIK-Report No. 643. The Swedish Institute for Food and Biotechnology, Göteborg, Sweden.

Cederberg, C., 2002. Life Cycle Assessment (LCA) of animal production. PhD thesis, Göteborg University, Göteborg, Sweden.

Cederberg, C., Flysjö, A., 2004. Life Cycle Inventory of 23 dairy farms in South-Western Sweden. SIK-report No. 728. The Swedish Institute for food and biotechnology, Göteborg, Sweden.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of nations. Volume 1: Main report. Value of Water Research Report Series No. 16. UNESCO-IHE Delft, Delft, The Netherlands.

Dalgaard, R., Halberg, N., Kristensen, I.S., Larsen, I., 2006. Modelling representative and coherent Danish farm types based on farm accountancy data for use in environmental assessments. Agriculture, Ecosystems and Environment 117, 223-237.

Daniel, S.E., Tsoulfas, G.T., Pappis, C.P., Rachaniotis, N.P., 2004. Aggregating and evaluating the results of different Environmental Impact Assessment methods. Ecological Indicators 4, 125-138.

De Vries, W., Kros, J., Oenema, O., De Klein, J., 2003. Uncertainties in the fate of nitrogen II: A quantitative assessment of the uncertainties in major nitrogen fluxes in The Netherlands. Nutrient Cycling in Agroecosystems 66, 71-102.

Elkington, J., 1998. Cannibals with forks: The triple bottom line of 21st century business. New Society Publishers, Gabriola Island, Canada.

Gideonse, B., 2006. Water use and efficiency in the Dutch dairy sector. MSc thesis, Wageningen University, Wageningen, The Netherlands.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H., van der Ven, B.L., Weidema, B.P. (Eds.), 2002. Handbook on Life Cycle Assessment; Operational Guide to the ISO Standards. Centrum voor Milieukunde- Universiteit Leiden (CML); Kluwer Academic Publishers, Leiden, The Netherlands.

Halberg, N., van der Werf, H.M.G., Basset-Mens, C., Dalgaard, R., de Boer, I.J.M., 2005. Environmental assessment tools for the evaluation and improvement of European livestock production systems. Livestock Production Science 96, 33-50.

Hermann, B.G., Kroeze, C., Jawjit, W., 2007. Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. Journal of Cleaner Production 15, 1787-1796.

Høgaas Eide, M., 2002. Life Cycle Assessment (LCA) of Industrial Milk Production. International Journal of LCA 7, 115-126.

Hospido, A., Moreira, M.T., Feijoo, G., 2003. Simplified life cycle assessment of Galician milk production. International Dairy Journal 13, 783-796.

Jolliet, O., Müller-Wenk, R., Bare, J., Brent, A., Goedkoop, M., Heijungs, R., Itsubo, N., Peña, C., Pennington, D., Porring, J., Rebitzer, G., Stewart, M., Udo de Haes, H., Weidema, B., 2004. The LCIA Midpoint-damage Framework of the UNEP/SETAC Life Cycle Initiative. International Journal of Life Cycle Assessment 9, 394-404.

Kroeze, C., Aerts, R., Van Breemen, N., Van Dam, D., Van Der Hoek, K., Hofschreuder, P., Hoosbeek, M., De Klein, J., Kros, H., Van Oene, H., Oenema, O., Tietema, A., Van Der Veeren, R., De Vries, W., 2003. Uncertainties in the fate of nitrogen I: An overview of sources of uncertainty illustrated with a Dutch case study. Nutrient Cycling in Agroecosystems 66, 43-69.

Milà i Canals, L., Clift, R., Basson, L., Hansen, Y., Brandão, M., 2006. Expert workshop on land use impacts in Life Cycle Assessment (LCA). International Journal of Life Cycle Assessment 11, 363-368.

Milà i Canals, L., Bauer, C., Depestele, J., Dubreuil, A., Freiermuth Knuchel, R., Gaillard, G., Michelsen, O., Müller-Wenk, R., Rydgren, B., 2007. Key elements in a framework for land use impact assessment within LCA. International Journal of Life Cycle Assessment 12, 5-15.

Mollenhorst, H., 2005. How to house a hen: assessing sustainable development of egg production systems. PhD thesis, Wageningen University, Wageningen, The Netherlands.

Monteny, G.J., Bannink, A., Chadwick, D., 2006. Greenhouse gas abatement strategies for animal husbandry. Agriculture, Ecosystems & Environment 112, 163-170.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecological Economics 60, 498-508.

Payraudeau, S., van der Werf, H.M.G., 2005. Environmental impact assessment for a farming region: a review of methods. Agriculture, Ecosystems & Environment 107, 1-19.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C., 2006. Livestock's long shadow; environmental issues and options. Food and Agricultural Organization of the United Nations, Rome, Italy.

Tamminga, S., Bannink, A., Dijkstra, J., Zom, R., 2007. Feeding strategies to reduce the methane loss in cattle. Praktijkrapport 34. Animal Sciences Group, Wageningen University Wageningen, The Netherlands.

Tukker, A., 2000. Life cycle assessment as a tool in environmental impact assessment. Environmental Impact Assessment Review 20, 435-456.

Van Calker, K.J. 2005. Sustainability of Dutch dairy farming; A modelling approach. PhD thesis, Wageningen University, Wageningen, The Netherlands.

Van Kernebeek, H., 2007. Contribution of the animal production sector to the environmental impact of the total agricultural sector. MSc thesis, Wageningen University, Wageningen, The Netherlands.

Van Passel, S., Nevens, F., Mathijs, E., Van Huylenbroeck, G., 2007. Measuring farm sustainability and explaining differences in sustainable efficiency. Ecological Economics 62, 149-161.

Weidema, B., 2006. The integration of economic and social aspects in Life Cycle Impact Assessment. International Journal of Life Cycle Assessment 11, 89-96.

Summary

Milk production on dairy farms in the Netherlands contributed to food production for centuries. As a consequence of intensified agricultural production in the Netherlands, such as large-scale intensification of the dairy cattle production system, environmental side-effects became visible after World War II. Milk production on dairy farms causes ammonia emission, which contributes to acid deposition; leaching of nitrate and phosphate, which contribute to nutrient water enrichment; and carbon dioxide, methane, and nitrous oxide emissions, which contribute to climate change. To limit side-effects of intensified agricultural production, environmental policy measures were implemented. Environmental aspects were addressed individually in legislation, which stimulated research on individual environmental aspects. Most research related to milk production focused on analysis or improvement of the environmental impact at dairy farm level. Transfers between environmental pollutants, referred to as pollution swapping, can occur at farm level. Pollution swapping between on and off farm pollution can occur as well, because a good environmental performance at dairy farm level can imply a high environmental burden elsewhere in the production chain. More knowledge is present about environmental impact of dairy cattle production systems at farm level than about off farm and total environmental impact. An integral environmental impact assessment of the dairy cattle production system in the Netherlands is needed that takes into account the production chain, and that focuses on more than one environmental aspect. The objective of the research presented in this thesis was to quantify the integral environmental impact of dairy cattle production systems in the Netherlands.

The first goal was to inventory how the integral environmental impact of dairy cattle production systems can be assessed. Chapter 2 presents an evaluation of the effectiveness of indicators derived from Input-Output Accounting (IOA), Ecological FootPrint analysis (EFP), and Life Cycle Assessment (LCA). IOA is a process-oriented on-farm method frequently used to assess nutrient surpluses of agricultural production systems, whereas EFP and LCA are life-cycle-based methods that include impacts of the entire production chain. Evaluation of the effectiveness of indicators was based on an assessment of their relevance, quality, and availability of data. An indicator is relevant when it provides relevant information about the system in question and if it is understandable to all stakeholders involved. An indicator is of good quality when it is reliable, sensitive, and when a trend or target value can be determined. An indicator should be based on available data, i.e., information, that is available currently or that can be collected, so that data collection is technically and financially feasible. To evaluate the effectiveness of the various indicators, data from eight organic dairy farms were used.

The three indicators derived from IOA are effective, because of their high relevance, of good quality, and easy availability of data. These indicators, however, focus on only a few environmental aspects and focus on environmental performance at farm level only. The indicator derived from EFP is not effective, because of its limited relevance and low quality. The nine indicators derived from LCA are effective because of their high relevance and good quality. Data of these LCA indicators, however, are hard to retrieve. The computation of acidification and eutrophication potential requires a nutrient balance at farm level. IOA indicators are necessary to perform an LCA. To summarize, to give a good insight into the environmental impact of a dairy production system, LCA indicators are required.

The second goal was to assess differences between attributional LCA and consequential LCA when assessing the integral environmental impact of dairy cattle production systems. Attributional LCA (ALCA) describes the pollution and resource flows within a chosen system attributed to delivery of a specified amount of the functional unit. Consequential LCA (CLCA) estimates how pollution and resource flows within a system change in response to change in output of the functional unit. LCA practitioners choose between ALCA and CLCA, and different ways of handling co-products. It is not clear, however, what the effect of these choices are on outcomes. Chapter 3 demonstrates and compares attributional and consequential LCA of a conventional milk production system. The comparison was based on four criteria: hotspot identification; comprehensibility; quality and availability of data. Within ALCA, mass and economic allocation were applied, because avoiding allocation by using system expansion to handle co-products is optional, while co-product allocation is most frequently used. Within CLCA, system expansion was applied, because avoiding allocation by system expansion is the only way to deal with co-products within CLCA, as it reflects the consequences of a change in production. This study showed it is possible to perform both ALCA (mass and economic allocation) and CLCA (system expansion) of milk. Choices of methodology, however, resulted in differences in: total quantitative outcomes, hotspots, degree of understanding and quality, while data availability was similar. Total outcomes computed by CLCA were only 35%-75% of outcomes computed by ALCA, different per impact category. Major hotspots were the same for all impact categories, computed by ALCA and CLCA, whereas the other hotspots differed in contribution, order and type. As experienced by the authors, ALCA and use of co-product allocation are difficult to comprehend for a consequential practitioner while CLCA and system expansion are difficult to comprehend for an attributional practitioner. Furthermore, literature shows data on feed used within ALCA will be more understandable for a feeding expert than data on feed used within CLCA. Outcomes of CLCA are more sensitive to uncertainties as compared with ALCA, due to the inclusion of market prospects. To summarize, performing attributional LCA or consequential LCA results in different outcomes, because different systems are modelled. Most LCA practitioners choose one methodology independent of their research question. It is recommended, therefore, to relate the research question to the choice of ALCA or CLCA in applied studies.

The third goal was to assess differences in integral environmental impact between conventional and organic dairy cattle production systems, and to identify environmental hotspots[1] within these two systems. Dairy farmers are forced to look for different managerial ways to address environmental policy, e.g. in a conventional or organic way. It is prohibited for organic farmers to use artificial fertilizer and pesticides. Organic farms use fewer inputs and therefore it is expected that organic farms have a lower

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[1] An identified environmental hotspot is an element that has a high contribution to the environmental burden of a product (Guinée et al., 2002)

environmental burden than conventional farms. A comparison between conventional and organic systems is needed to address advantages and disadvantages of each system. Chapter 4 presents the comparison of the integral environmental impact of the conventional and organic systems, by using ALCA and economic allocation. Data of ten commercial conventional and eleven organic dairy farms that participated in two pilot-studies were used. This study showed a better energy use and eutrophication potential per kilogram of milk for organic farms than for conventional farms. Furthermore, higher on-farm acidification potential and global warming potential per kilogram organic milk implies that higher emissions of ammonia, methane, and nitrous oxide occur on farm per kilogram organic milk than for conventional milk. Total acidification potential and global warming potential per kilogram milk did not differ between the selected conventional and organic farms. In addition, results showed lower land use per kilogram conventional milk compared with organic milk. In the selected conventional farms, purchased concentrates was found to be the hotspot in off farm and total impact for all impact categories, whereas in the selected organic farms, both purchased concentrates and roughage were found to be the hotspots in off farm impact. To summarize, differences exist in environmental performance between conventional and organic dairy cattle production systems, while purchased concentrates was identified to be a hotspot in both systems. It is recommended, therefore, to improve the environmental performance of both systems by reducing the use of concentrates ingredients with a high environmental impact.

The fourth goal was to assess the relation of LCA indicators with net farm income of dairy cattle production systems. The concept sustainability is built upon the three pillars: people, planet, and profit. Preferably, more than one pillar of sustainability should be addressed. By performing an LCA of dairy cattle production systems, insight is gained into environmental sustainability, the “planet”, of the dairy sector. No sector is sustainable without economic viable farms, the “profit”. A need exists to place LCA studies of dairy cattle production systems into an economic context, to address the pillars “planet” and “profit” of sustainability. Such an analysis requires a relatively large number of dairy farms. Chapter 5 addresses the possibility to perform an LCA of 119 individual dairy farms by using the Dutch Farm Accountancy Data Network (FADN), besides analyzing the relationships between environmental and economic performance of dairy farms and underlying farm characteristics. It was demonstrated that using Dutch FADN to perform an LCA of individual dairy farms is feasible, which enables to perform future LCAs of dairy farms based on FADN. Future LCAs could be strengthened by the inclusion of more suitable LCA-related data within FADN collection. Furthermore, it was demonstrated farms with a high net farm income had a low on farm land use, total land use, energy use at the dairy farm, on farm and total climate change, expressed per kg FPCM. On the other hand, farms with a high net farm income had a high total and on farm eutrophication and acidification, expressed per hectare. Farm characteristics of importance were: farm size, Dutch livestock units per hectare, milk production per cow, purchased concentrates per 100 kg FPCM, and milk urea content. To summarize, negative and positive relations exist between LCA indicators and net farm income. Underlying farm characteristics influence these relations. It is recommended, therefore, to perform an ‘optimum’ analysis. Such an analysis can identify the optimum situation when net farm income is high while environmental burdens are low.

In the discussion, the dairy cattle sector was placed in perspective of the animal and total agricultural sector, to justify the focus of this thesis on dairy cattle production systems. A cradle-to-farm gate LCA of the dairy cattle, pig, poultry, and total agricultural sector was performed, implying that all processes and transport until agricultural products leave the farm gate were included in the analyses.

The final conclusions from the research presented in this thesis are:

- The dairy sector contributed 71% to total eutrophication, 62% to total climate change, 55% to total acidification, 51% to total land use, and 46% to total energy use of the animal sector in the Netherlands.
- The dairy sector contributed 40% to total eutrophication, 32% to total land use, 31% to total climate change, 27% to total acidification, and 14% to total energy use of the total agricultural sector in the Netherlands.
- LCA indicators are effective for an integral environmental impact assessment of dairy cattle production systems, because they focus on more than one environmental aspect and take into account pollutants within the production chain.
- An LCA of dairy cattle production systems gives insight into pollution swapping between on and off farm processes.
- Choice of the functional unit, i.e., if indicators are product-related or area-related, influences results.
- The objective of the study determines the choice of attributional LCA or consequential LCA, which subsequently results in differences in: total quantitative outcomes, environmental hotspots, degree of understanding, and sensitivity to uncertainties.
- The organic dairy cattle production system had a lower energy use and eutrophication potential than the conventional system, whereas the conventional system had a lower land use than the organic system.
- Acidification potential and global warming potential were similar for both the conventional and organic system, but higher emissions at farm level occurred in the organic system.
- Purchased concentrates is an environmental hotspot for both the conventional and organic dairy cattle production system.
- The Dutch Farm Accountancy Data Network is suitable to perform an LCA of individual dairy farms, which allows to perform an LCA of a large number (several hundreds) of farms.
- Dairy cattle production systems with a high net farm income had a low on farm land use, total land use, energy use at the dairy farm, on farm and total climate change, but a high total and on farm eutrophication and acidification.
- The relation between net farm income and LCA indicators can be influenced by the farm characteristics: farm size, Dutch livestock units per hectare, milk production per cow, purchased concentrates per 100 kg FPCM, and milk urea content.

An outlook for further research can be given based on the research presented in this thesis. The LCA dairy model constructed within the research presented in this thesis is a valid basis for further research to evaluate innovations and mitigation options. The integral assessment can be strengthened by including more impact categories, site-specific characterization factors, downstream processes (inclusion of dairy processing and transport), uncertainty analyses, and validation of potential LCA impacts with measured data (such as nitrate concentrations in groundwater).

Researchers and the feed industry should collaborate in order to reduce the environmental impact of concentrates ingredients. Research should be carried out to gather specific data of processing, cultivation, and transport of the different ingredients produced in foreign countries. Data collection systems should be introduced in order to realize a database of concentrates ingredients produced in different countries. LCA practitioners should collaborate, in order to gain insight into which research question should be answered by attributional LCA or consequential LCA, and to secure the possibility of comparing LCA studies. Future LCAs of individual farms of various agricultural sectors should be performed to gain insight into the integral environmental impact of the agricultural sector. Organisations that collect farm data, e.g. accountancy firms that collect economic data, should expand their data collection, in order to address environmental issues. Research should also be initiated to address the three pillars of sustainability along the milk production chain. Initiatives to realize such a chain approach of the agricultural sector, related industries, besides research institutions, must be stimulated.

Samenvatting

De melkveehouderij in Nederland draagt sinds eeuwen bij aan de humane voedselvoorziening. Na de Tweede Wereldoorlog veranderde de landbouw, als gevolg van schaalvergroting, mechanisatie en intensivering. Deze intensivering van de landbouw inclusief de melkveehouderij, had gevolgen voor het milieu. Een melkveebedrijf kan op verschillende manieren een effect hebben op het milieu: vervluchtigde ammoniak draagt bij aan stikstofdepositie, ook wel zure regen genoemd; uitgespoelde nitraat en fosfaat leidt tot nutriëntenverrijking van sloten en andere wateren; vervluchtigde koolstofdioxide, methaan, en lachgas dragen bij aan klimaatverandering. Milieuwet- en regelgeving werd ingevoerd vanaf 1980 om de milieueffecten als gevolg van intensivering van de landbouw te beperken. In deze wet- en regelgeving werden verschillende milieuaspecten opgenomen, zonder dat ze aan elkaar werden gerelateerd. Daarnaast lag het aandachtspunt van deze wet- en regelgeving op de milieuaspecten op bedrijfsniveau. Hierdoor werd gefragmenteerd onderzoek op bedrijfsniveau gestimuleerd. Het grootste deel van het onderzoek aangaande melkproductie was gericht op analyses en verbetering van de milieubelasting op het melkveebedrijf, en niet op andere schakels in de keten.
Uitwisseling tussen verschillende milieuelementen kan plaatsvinden op bedrijfsniveau, zoals een uitwisseling tussen ammoniakvervluchtiging en nitraatuitspoeling. Daarnaast kan uitwisseling tussen milieueffecten op bedrijfsniveau en buiten het bedrijf ook voorkomen. Een lage milieubelasting op het melkveebedrijf kan namelijk samengaan met een hoge milieubelasting elders in de melkketen. Tot op heden was er meer kennis van de milieubelasting op het melkveebedrijf dan van de milieubelasting elders in de melkketen. Een integrale bepaling van de milieubelasting van het Nederlandse melkproductiesysteem was daarom noodzakelijk. Een integrale bepaling betekent dat de keten wordt geanalyseerd, en dat tevens gekeken wordt naar verschillende milieuaspecten. De doelstelling van het onderzoek beschreven in dit proefschrift was om de integrale milieubelasting van het Nederlandse melkproductiesysteem te kwantificeren.

Voordat de integrale milieubelasting gekwantificeerd kan worden, is het noodzakelijk te inventariseren welke milieu-indicatoren gebruikt kunnen worden. De effectiviteit van indicatoren afgeleid van een nutriëntenbalans, een ecologische voetafdruk en een levenscyclusanalyse zijn beoordeeld in hoofdstuk 2. Indicatoren van een nutriëntenbalans worden gebruikt om nutriëntenoverschotten op bedrijfsniveau te schatten, terwijl de indicatoren van de ecologische voetafdruk en een levenscyclusanalyse de milieubelasting in de gehele keten analyseren. Data van acht commerciële biologische melkveebedrijven zijn gebruikt om de indicatoren afgeleid van de drie methodieken op hun effectiviteit te beoordelen. De evaluatie van de effectiviteit van de indicatoren was gebaseerd op de bepaling van de relevantie, kwaliteit, en beschikbaarheid van data. Een indicator is relevant wanneer het relevante informatie verschaft over het milieuthema dat geanalyseerd wordt en het begrijpelijk is voor betrokken partijen, de ‘stakeholders’. Een indicator is van goede kwaliteit wanneer die betrouwbaar is en gevoelig voor verandering, en wanneer een streefwaarde vastgesteld kan worden. Een indicator zou gebaseerd moeten zijn op informatie die beschikbaar is of die verzameld kan worden, zodat de dataverzameling technisch en financieel haalbaar is. De drie indicatoren van de nutriëntenbalans waren effectief, door hun hoge relevantie, goede kwaliteit en de informatie was makkelijk te verkrijgen. Echter, deze indicatoren richtten zich voornamelijk op verzuring en vermesting op bedrijfsniveau. De indicator van de ecologische voetafdruk was niet effectief, door een matige relevantie en een lage kwaliteit. De negen indicatoren van de levenscyclusanalyse waren effectief door een hoge relevantie en een hoge kwaliteit, alhoewel data relatief gezien moeilijk zijn te verkrijgen. Dit wordt veroorzaakt doordat specifieke data aangaande fabrieksprocessen nodig zijn naast buitenlandse data voor teelt van gewassen. Een nutriëntenbalans op bedrijfsniveau is nodig voor de berekening van verzuring en vermesting binnen de levenscyclusanalyse. Om inzicht te krijgen in de integrale milieubelasting van een melkproductiesysteem, zijn levenscyclusanalyseindicatoren vereist.

Binnen de levenscyclusanalyse worden twee benaderingen onderscheiden voor het schatten van de integrale milieubelasting van een productiesysteem: de “attributional“ benadering en de “consequential” benadering. De “attributional“ benadering bepaalt de vervuiling en het gebruik van natuurlijke hulpbronnen binnen een gedefinieerd systeem om een bepaalde hoeveelheid product te leveren. De “consequential” benadering bepaalt hoe de vervuiling en het gebruik van natuurlijke hulpbronnen binnen een gedefinieerd systeem veranderen als gevolg van een verandering in de hoeveelheid te leveren product. Onderzoekers kiezen meestal één van deze benaderingen om de integrale milieubelasting van een productiesysteem te bepalen, en gebruiken daarnaast verschillende manieren om de milieubelasting toe te wijzen aan co-producten, zoals allocatie of uitbreiding van systeemgrenzen. Het is echter onduidelijk wat het effect van deze keuzes is op eindresultaten. In hoofdstuk 3 zijn deze twee benaderingen daarom vergeleken door de integrale milieubelasting van een gemiddeld gangbaar Nederlands melkproductiesysteem via beide benaderingen te bepalen. De vergelijking van beide benaderingen is beoordeeld met behulp van vier criteria: identificatie van elementen die een grote bijdrage hebben aan de milieubelasting; mate van begrijpelijkheid; kwaliteit en beschikbaarheid van data. Binnen de “attributional“ benadering werd massa- of prijsallocatie toegepast om de milieubelasting toe te wijzen aan co-producten, omdat deze vormen van allocatie vaak worden toegepast door onderzoekers binnen de “attributional“ benadering. Binnen de “consequential” benadering werden de systeemgrenzen uitgebreid met productieprocessen die veranderen als gevolg van een verandering in het te leveren product. Het bleek mogelijk om met beide benaderingen de integrale milieubelasting van het melkproductiesysteem te kwantificeren. Echter, de verschillende benaderingen resulteerden in verschillen in: totale kwantitatieve uitkomsten; elementen die een grote bijdrage hadden aan de milieubelasting; mate van begrijpelijkheid, en kwaliteit, terwijl de beschikbaarheid van data gelijk bleef. De totale kwantitatieve uitkomsten berekend met de “consequential” benadering waren slechts 35-75% van de uitkomsten berekend met de “attributional“ benadering. De elementen die de grootste bijdrage hadden aan de milieubelasting waren gelijk binnen de twee benaderingen. Echter, de overige elementen die een grote bijdrage hadden aan de milieubelasting verschilden in bijdrage, volgorde en soort. De “attributional“ benadering en het gebruik van allocatie waren moeilijk te begrijpen voor de auteurs (die meewerkten aan dit onderzoek) die bekend waren met de “consequential” benadering, terwijl de “consequential” benadering en de uitbreiding van systeemgrenzen moeilijk te begrijpen waren voor de auteurs (die meewerkten aan dit onderzoek) die bekend waren met de “attributional“ benadering. Literatuur wees verder uit dat het gebruik van informatie over krachtvoer beter te begrijpen was voor veevoerexperts wanneer de “attributional“ benadering werd toegepast (gebaseerd op werkelijke krachtvoersamenstellingen), dan wanneer de “consequential” benadering werd toegepast (gebruik van één eiwitrijke component en gebruik van één energierijke component). De berekende resultaten binnen de “attributional“ benadering waren minder gevoelig voor onzekerheden dan de resultaten binnen de “consequential” benadering, omdat voorspellingen van de markt worden meegenomen binnen de “consequential” benadering. Geconcludeerd kan worden dat de “attributional“ en “consequential” benadering resulteren in verschillende resultaten, omdat verschillende systemen worden gemodelleerd. Onderzoekers kiezen meestal één levenscyclus benadering onafhankelijk van hun onderzoeksvraag. Het wordt daarom aanbevolen om de onderzoeksvraag te relateren aan de keuze tussen de “attributional“ en “consequential” levenscyclus benadering.

De integrale milieubelasting van het melkproductiesysteem kan gekwantificeerd worden, nadat meer inzicht is verkregen in de keuze van de methodiek. De levenscyclusanalyse benadering kan gebruikt worden om de integrale milieubelasting van verschillende melkproductiesystemen te vergelijken. Melkveehouders voldoen via verschillende bedrijfsvoeringen aan de milieuwet- en regelgeving. Er bestaat een gangbare en biologische bedrijfsvoering. Biologische melkveehouders mogen een aantal producten, zoals kunstmest en pesticiden, niet aanvoeren. Er wordt daarom verwacht dat de biologische bedrijfsvoering een lagere milieubelasting heeft. Om inzicht te krijgen in de voor- en nadelen van elk systeem is een vergelijking nodig tussen de milieubelasting van een gangbaar en een biologisch melkproductiesysteem. In hoofdstuk 4 is de integrale milieubelasting van beide melkproductiesystemen bepaald en vergeleken, door de “attributional” levenscyclusanalyse benadering en het gebruik van economische allocatie. Daarnaast zijn de elementen die een grote bijdrage hebben aan de totale milieubelasting van elk systeem vastgesteld. Data van tien commerciële gangbare en elf commerciële biologische melkveebedrijven, die meededen aan een pilotstudie, werden gebruikt. De biologische bedrijven hadden een lager energieverbruik en een lagere vermestingspotentieel per kg meetmelk (melk gecorrigeerd voor eiwit- en vetgehalte) dan de gangbare bedrijven. Op bedrijfsniveau hadden de biologische bedrijven een hogere verzurings- en broeikaspotentieel per kg meetmelk dan de gangbare bedrijven. Het totale verzurings- en broeikaspotentieel per kg meetmelk waren echter gelijk voor de gangbare en biologische bedrijven. De gangbare bedrijven hadden een lager landgebruik per kg meetmelk in vergelijking met de biologische bedrijven. Aangekocht krachtvoer had de grootste bijdrage aan de totale milieubelasting van de gangbare bedrijven, terwijl zowel aangekocht krachtvoer als aangekocht ruwvoer de grootste bijdrage hadden aan de totale milieubelasting van de biologische bedrijven.
Geconcludeerd kan worden dat het biologisch melkproductiesysteem beter scoort voor energieverbruik en vermesting, maar slechter voor landgebruik in vergelijking met de gangbare bedrijven. Aangekocht krachtvoer heeft in beide systemen een grote bijdrage aan de totale milieubelasting. Het wordt daarom aanbevolen om de milieubelasting van beide systemen te verlagen door het gebruik van krachtvoeringrediënten met een hoge milieubelasting te reduceren, en de voerefficiëntie op bedrijfsniveau te verbeteren.

De focus van het onderzoek tot nu toe beschreven in dit proefschrift ligt op de pijler milieu van duurzaamheid, door het uitvoeren van een levenscyclusanalyse van het melkproductiesysteem. Het concept duurzaamheid is gebaseerd op de drie pijlers, economie, milieu en sociaal-maatschappelijk. Door een integrale milieuanalyse te relateren aan de economische prestatie van het melkproductiesysteem wordt inzicht verkregen in de relatie tussen de twee pijlers milieu en economie van duurzaamheid. In hoofdstuk 5 zijn daarom de levenscyclus- indicatoren gerelateerd aan het netto bedrijfsinkomen van het melkproductiesysteem. Een tweede doel was het verklaren van eventuele correlaties tussen economie en milieu-indicatoren met behulp van bedrijfskarakteristieken. Het verklaren van eventuele correlaties met behulp van bedrijfskarakteristieken vereist informatie van een relatief grote groep bedrijven. In hoofdstuk 5 is daarom ook gekeken of het bestaande Nederlandse Bedrijven Informatie Netwerk (BINternet, eigendom van het Landbouwkundig Economisch Onderzoeks-instituut) geschikt is om een levenscyclusanalyse uit te voeren. Het BINternet bleek geschikt om een levenscyclusanalyse uit te voeren van gespecialiseerde melkveebedrijven. Dit betekent dat in de toekomst levenscyclusanalyses van verschillende landbouwsectoren op basis van BINternet uitgevoerd kunnen worden. Toekomstig onderzoek zou verbeterd kunnen worden door meer informatie in BINternet op te nemen dat nodig is voor het verfijnen van de levenscyclusanalyse. Een voorbeeld hiervan is nauwkeurigere informatie aangaande hoeveelheden van de aangekochte producten op landbouwbedrijven.

Daarnaast toonde het onderzoek aan dat per kg meetmelk melkveebedrijven met een hoog netto bedrijfsinkomen een laag landgebruik, energieverbruik, en uitstoot van broeikasgassen hadden op bedrijfsniveau, naast een laag totaal landgebruik en totaal broeikaspotentieel. Melkveebedrijven met een hoog bedrijfsinkomen hadden echter ook een hoog vermestings- en verzuringspotentieel op bedrijfsniveau, en een hoog totaal vermestings- en verzuringspotentieel per hectare. De bedrijfskarakteristieken die deze relaties tussen de levenscyclusanalyse indicatoren en het netto bedrijfsinkomen beïnvloedden waren: bedrijfsgrootte (uitgedrukt in hectare), veedichtheid (uitgedrukt in Nederlandse grootvee-eenheden per hectare), melk productie per koe (uitgedrukt in kg), aangekocht krachtvoer (uitgedrukt in kg per 100 kg meetmelk), en melkureumgehalte (uitgedrukt in mg per 100 gram meetmelk)

Geconcludeerd kan worden dat levenscyclus indicatoren zowel positief als negatief correleren met het netto bedrijfsinkomen van melkveebedrijven. Onderliggende bedrijfskarakteristieken beïnvloeden deze correlaties. Het wordt daarom aanbevolen om een optimalisatieanalyse uit te voeren om inzicht te krijgen in een situatie wanneer het netto bedrijfsinkomen zo hoog mogelijk is en de integrale milieubelasting zo laag mogelijk.

Om inzicht te krijgen in de bijdrage van de melkveehouderij aan de totale milieubelasting vanuit de Nederlandse landbouw, is in de discussie de milieubelasting van de melkveehouderijsector vergeleken met de milieubelasting van de dierlijke sector en van de totale landbouwsector. Hiervoor is van de Nederlandse melkveehouderij-, varkenshouderij-, en pluimveehouderijsector een levenscyclusanalyse tot aan het boerderijhek uitgevoerd. Dit houdt in dat alle processen en het transport zijn meegenomen totdat de producten worden opgehaald van de boerderij.

De volgende conclusies kunnen worden getrokken op basis van en binnen de grenzen van het onderzoek gepresenteerd in dit proefschrift:

- De melkveehouderij droeg voor 71% bij aan het totaal vermestingspotentieel, 62% aan het totaal broeikaspotentieel, 55% aan het totaal verzuringspotentieel, 51% aan totaal landgebruik, en 46% aan totaal energieverbruik van de dierlijke sector in Nederland.
- De melkveehouderij droeg voor 40% bij aan het totaal vermestingspotentieel, 32% aan totaal landgebruik, 31% aan het totaal broeikaspotentieel, 27% aan het totaal verzuringspotentieel, en 14% aan totaal energieverbruik van de gehele landbouwsector in Nederland.
- Levenscyclusanalyseindicatoren zijn effectief om de integrale milieubelasting van het melkproductiesysteem te bepalen, omdat ze zich richten op meerdere milieuaspecten en op de keten.
- Een levenscyclusanalyse van het melkproductiesysteem geeft inzicht in uitwisseling tussen milieueffecten op het bedrijf en buiten het bedrijf.
- Keuze van de eenheid waarin de indicatoren uitgedrukt worden, bijvoorbeeld per kg meetmelk of per hectare, beïnvloedt de onderzoeksresultaten.
- De onderzoeksvraag relateert aan de keuze tussen de “attributional” of “consequential” levenscyclus benadering, en deze keuze resulteert vervolgens in verschillen in: totale kwantitatieve uitkomsten; elementen die een grote bijdrage hebben aan de milieubelasting; mate van begrijpelijkheid, en gevoeligheid voor onzekerheden.
- Het biologisch melkproductiesysteem had een lager totaal energieverbruik en lager totaal vermestingspotentieel, en een hoger totaal landgebruik dan het gangbare systeem.
- Het totale verzurings- en het totaal broeikaspotentieel was gelijk tussen het gangbare en biologische melkproductiesysteem, maar in het biologische systeem vond meer uitstoot op bedrijfsniveau plaats.
- Aangekocht krachtvoer heeft een grote bijdrage aan de totale milieubelasting van zowel het gangbare als biologische melkproductiesysteem.
- Het Nederlandse Bedrijven Informatie Netwerk is geschikt om een levenscyclus-analyse uit te voeren, hetgeen het mogelijk maakt om in de toekomst een levenscyclusanalyse uit te voeren van verschillende landbouwsectoren op basis van een groot aantal landbouwbedrijven (enkele honderden).
- Melkproductiesystemen met een hoog netto bedrijfsinkomen hadden een laag landgebruik, energieverbruik, en uitstoot van broeikasgassen op bedrijfsniveau, en een laag totaal landgebruik en totaal broeikaspotentieel, maar een hoog vermestings- en verzuringspotentieel op bedrijfsniveau, en een hoog totaal vermestings- en verzuringspotentieel.
- De relaties tussen levenscyclusanalyseindicatoren en netto bedrijfsinkomen kunnen beïnvloed worden door: bedrijfsgrootte, veedichtheid, melkproductie per koe, aangekocht krachtvoer, en melkureumgehalte.

Uit dit proefschrift kunnen de volgende aanbevelingen voor vervolgonderzoek worden afgeleid. Het ontwikkelde model kan worden toegepast om innovaties en milieureductiemaatregelen te evalueren. De integrale milieubelastingbepaling van het melkproductiesysteem kan worden verbeterd door: te kijken naar meerdere milieuaspecten; gebruik te maken van regiospecifieke karakterisatiefactoren; de gehele keten mee te nemen (inclusief melkverwerking, retailer, consument); gevoeligheidsanalyses uit te voeren; berekende potentiële milieuvervuiling te relateren aan daadwerkelijk gemeten waarden (zoals nitraatconcentratie in grondwater).

Daarnaast wordt aanbevolen om de milieubelasting van krachtvoeringrediënten te verminderen, bijvoorbeeld door samenwerking tussen onderzoekers en de mengvoerindustrie. Data moeten worden verzameld aangaande teelt, transport en verwerkingsprocessen gerelateerd aan de productie van verschillende krachtvoeringrediënten uit verschillende landen. Het wordt aanbevolen om een collectief datasysteem aangaande krachtvoerproductie in verschillende landen op te zetten.

Onderzoekers die werken met de levenscyclusanalysemethodiek zouden samen moeten werken om inzicht te krijgen in welke onderzoeksvraag met welke benadering (“attributional” of “consequential”) beantwoord moet worden. Daarnaast moet de vergelijking tussen verschillende toegepaste levenscyclusanalyses gewaarborgd blijven. Het wordt ook aanbevolen om levenscyclusanalyses van commerciële landbouwbedrijven uit te voeren om inzicht te krijgen in de integrale milieubelasting van de landbouwsector. Organisaties die al een dataverzamelingsysteem hanteren, zoals boekhoudbureaus die economische kengetallen verzamelen, zouden hun dataverzameling moeten uitbreiden om milieuaspecten te incorporeren. Het wordt tevens aanbevolen om de drie pijlers van duurzaamheid in de melkproductieketen te analyseren. Initiatieven voor een duurzame ketenbenadering vanuit de landbouwsector moeten worden gestimuleerd.

Publications

Refereed scientific papers

Thomassen, M.A., de Boer, I.J.M., 2005. Evaluation of indicators to assess the environmental impact of dairy production systems. Agriculture, Ecosystems & Environment 111, 185-199. (Chapter 2)

Thomassen, M.A., Van Calker, K.J., Smits, M.C.J., Iepema, G.L., De Boer, I.J.M., 2008. Life Cycle Assessment of conventional and organic milk production in The Netherlands. Agricultural Systems 96, 95-107. (Chapter 4)

Thomassen, M.A., Dalgaard, R., Heijungs, R., De Boer, I.J.M., In press. Attributional and consequential LCA of milk production. International Journal of Life Cycle Assessment. (Chapter 3)

Thomassen, M.A., Dolman, M.A, Van Calker, K.J., De Boer, I.J.M., Submitted. Relating LCA indicators to net farm income for Dutch dairy farms. Ecological Economics. (Chapter 5)

Papers in conference proceedings

De Boer, I.J.M., Iepema, G.J., Thomassen, M.A., 2003. Environmental impact assessment at commercial dairy farms. In: N. Halberg (ed.) 4th International Conference LCA in the Agri-Food sector, Bygholm, Denmark, 214-217.

Thomassen, M.A., de Boer, I.J.M., 2007. Integral assessment of acidification of the animal sector as part of the total agricultural sector in The Netherlands. In: G-J. Monteny, E. Hartung (ed.). International ammonia conference. Ammonia emissions in agriculture, Wageningen Academic Publishers The Netherlands, 254-256.

Thomassen, M.A., Dalgaard, R., Heijungs, R., de Boer, I.J.M., 2007. Consequential and attributional LCA of conventional and organic milk production. In: U. Sonesson (ed.) The 5th International Conference LCA in Foods, Göteborg, Sweden, 13-16.

Abstracts in conference proceedings

Thomassen, M.A., de Boer, I.J.M., 2006. Life Cycle Assessment of milk production in The Netherlands. In: 2nd International Conference on Quantified Eco-Efficiency Analysis for Sustainability, Egmond aan Zee, The Netherlands, 51.

Thomassen, M.A., de Boer, I.J.M., 2007. Integral assessment of acidification of the animal sector as part of the total agricultural sector in The Netherlands. In: Ammonia conference abstract book. Wageningen Academic Publishers, The Netherlands, 119.

Other publications

Thomassen, M.A., de Boer, I.J.M., Smits, M.C.J., Iepema, G.J., 2006. Milieubelasting melkveebedrijf stopt niet bij de erfgrens. Koeien en kansen nieuwsbrief 24, 3.

Thomassen, M.A., de Boer, I.J.M., Smits, M.C.J., Iepema, G.J., van Calker, K.J., Werkman, R., Jansen, J., ‘s Gravendijk, L., 2007. Krachtvoer heeft grote invloed op milieubelasting melkveehouderij. V-focus 1 (4), 20-22.

Curriculum vitae

Marlies Antoinette Thomassen werd geboren op 15 oktober 1978 te Maarssen. In 1997 behaalde zij haar VWO diploma aan het Niftarlake College te Maarssen. In datzelfde jaar begon zij met de studie Zoötechniek aan de toenmalige Landbouwuniversiteit Wageningen. Tijdens deze studie deed ze twee afstudeervakken, in de richtingen Agrarische Geschiedenis en Dierlijke Productiesystemen. In 2003 studeerde zij af in de specialisatie Dierlijke Productiesystemen. Hierna werkte ze een korte tijd als financieel medewerkster voor het Ministerie LNV tijdens de afhandelingen van de vogelpest-uitbraak. In november 2003 kwam zij in dienst als toegevoegd docente bij de leerstoelgroep Dierlijke Productiesystemen van Wageningen Universiteit. In augustus 2005 begon ze binnen deze leerstoelgroep aan een promotietraject aangaande bepaling van de integrale milieubelasting van de melkveehouderij, mede mogelijk gemaakt door financiering van het Ministerie van LNV. Het onderzoek dat zij daar uitvoerde werd in januari 2008 afgerond en staat beschreven in dit proefschrift. Sinds 1 februari 2008 is zij werkzaam als onderzoeker op het gebied van duurzame energie uit biomassa bij de divisie Veehouderij van de Animal Sciences Group in Lelystad.

Training and Supervision Plan		**Graduate School WIAS**
Name	Marlies Thomassen	
Group	Animal Production Systems	
Daily supervisor(s)	Dr ir I.J.M. de Boer	
Supervisor(s)	Prof. dr ir A.J. van der Zijpp, Dr ir G-J. Monteny	
Period	August 2005 - January 2008	

	Year	ECTS
WIAS Introduction Course	2007	1.5
Course on philosophy of science and/or ethics	2007	1.5
SUBTOTAL		**3**
Scientific Exposure		
International conferences		
Intern. Conf. on Quantified Eco-Eff.for Sustainability. Egmond aan Zee, NL (oral presentation)	2006	1.8
First International Ammonia Conference Ede, NL (oral and poster presentation)	2007	2.9
LCA Food Conference Gothenburg, Sweden (oral presentation)	2007	1.6
International Conference Climate Changes Spatial Planning Den Haag, NL	2007	0.6
Seminars and workshops		
Biologisch: een markt zonder grenzen? Amersfoort	2004	0.3
Kunnen landbouw en milieu samen door de Europese deur? Ede	2004	0.3
Economie van diergezondheid en voedselveiligheid. Wageningen	2005	0.2
WIAS Science Day. Wageningen (2006 poster presentation)	2004-7	2.2
SUBTOTAL		**10**
In-Depth Studies		
Advanced Course on LCA, SENSE, CML, Leiden, NL	2005	3.0
Bridging environmental and economic assessments for decision support, Ålborg, Denmark	2006	10.0
SUBTOTAL		**13**
Professional Skills Support Courses		
Course Techniques for Scientific Writing	2006	1.2
OWU Course Supervising MSc thesis work	2004	1.0
OWU Course 'oral presentations'; how to give lectures	2004	2.0
OWU Course supervising student groups	2005	1.0
OWU Course Didactic basics	2006	3.0
SUBTOTAL		**8**
Didactic Skills Training		
Lecturing		
Lecturer BSc-course PPS-10806 'Organic Production Systems'	2004-5	2.9
Lecturer BSc-course BFS-20306 'Diagnosis of animal, plant, environment and human'	2004-5	1.0
Supervising practicals and excursions		
Supervising excursion APS-10303	2004-5	0.5
Supervising MSc theses		
Supervising minor MSc thesis 'LCA laying hens' C. van Woudenbergh	2004	1.5
Supervising major MSc thesis 'Analysis animal hobby sector' L. Schuit	2004	2.0
Supervising major MSc thesis 'LCA commercial organic dairy farms' L. 's Gravendijk	2005	2.0
Tutorship		
Supervising BSc-group farm project YLS-10806	2004-6	1.0
SUBTOTAL		**11**
Management Skills Training (optional)		
Co-ordinator colloquia MSc-students	2004-5	1.0
Co-ordinator BSc-course APS-30804 'Sustainable Food Security'	2004	2.0
Co-ordinator BSc-course YLS-30306 'Sector Integration Course'	2004-5	2.0
Member of organisation seminar 'Choices for the future'	2005	0.3
Subtotal Management Skills Training		**5**
TOTAL		**50**

One ECTS credit equals a study load of approximately 28 hours

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