Including CO_2-emission in the formulation of animal feed: methodology and critical issues for translating theory into practice

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Abstract: *Feed production has a major contribution in the total energy use and related CO_2-emissions of intensive animal production systems. Hence, CO_2-emission from intensive animal production could be substantially decreased if compound feeds would be used that result in less CO_2-emission during manufacturing, compared to the feeds that are currently used in farming practice. To achieve this, we propose a methodology to formulate CO_2-low pig feeds that can readily be used in farming practice. A life cycle assessment will be performed for different feed components, starting with soybean meal. In this research, we pay specific attention to the transfer of the theoretical knowledge and methodology into a practical tool to be implemented by compound feed producers to decrease the CO_2-emission of their products. While performing this research, some major bottlenecks, related to the choice of boundaries, the availability of data and the development of a shared vision, became apparent that may prevent implementation of the proposed methodology in practice. These involve mainly statements and choices that have to be made by the intended end-users of the tool. Therefore, this study is performed in collaboration with experts and stakeholders from the animal feed industry.*

Keywords: *CO_2-emission, Life Cycle Assessment, pig feed, soybean production, stakeholder participation*

Introduction

Agriculture has a significant effect on climate and climate change and plays a major role in the global fluxes of greenhouse gases (GHG) (Robertson et al., 2000; Seguin et al., 2007). It affects the environment in two different ways: through the direct emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which contribute to global warming, and through land use change that disturbs the surface energy balance (Seguin et al., 2007). Worldwide, 18% of the total human-induced GHG emissions can be appointed to the animal agricultural sector (Steinfeld et al., 2006). In this paper, as an illustration of the methodology and to show the difficulties of transferring the methodology into practice, we only consider the emissions of CO_2 related to the use of fossil energy. Emissions of methane and nitrous oxide are not taken into account, although they are important (Flessa et al., 2002). Also indirect CO_2-emissions from land use change are very important (de Campos et al., 2005; Fearnside et al., 2009), but not considered here.

On farms, fossil energy is consumed in a ‘direct’ and an ‘indirect’ way (Hülsbergen et al., 2001; Pervanchon et al., 2002; Corré et al., 2003). Direct energy use comprises mainly diesel fuel, electricity and natural gas, and can be easily measured. The energy that is used to produce farm inputs such as mineral fertilizers, seeds, pesticides, feeds and machines is indirect energy. Purchased animal feedstuffs, comprising feed materials and compound feeds, seem to be the main energy input into livestock production. On pig fattening and dairy farms in Flanders, nearly 70% and 36% of the total energy input can be attributed to the used concentrates (Meul et al., 2007). Similarly, Ogino et al. (2004) found that feed production and feed transport accounts for almost all of the energy consumption through the life cycle of beef fattening and is the primary contributor to energy consumption, eutrophication and acidification. These studies show that the energy consumption and related CO_2-emission from intensive animal production systems could be significantly reduced by decreasing the CO_2-emissions from the manufacturing of animal feed.

Within the feed production however, until today very little effort has been put on assessing the emissions of GHG. While several studies investigated the carbon emissions from farm operations during primary production of feed components and raw materials (Adler et al., 2007; Dalgaard et al., 2008; Hillier et al., 2009; Lal, 2004a; Lal, 2004b; St. Clair et al., 2008), only a few studies investigated the environmental impact associated with the assimilation of feed components into compound feed. Lehuger et al. (2009) assessed the environmental impact of the substitution of imported soybean meal with locally produced rapeseed meal in French dairy production systems, and Van der Werf et al. (2005) performed a Life Cycle Assessment (LCA) to evaluate the environmental impact associated with the production of concentrated pig feed. However, depending on the applied methodology, system boundaries and assumptions made, different conclusions were drawn from these studies. While Lehuger et al. (2009) found that soybean meal was more environmentally-efficient because it involved less intensive management practices, Van der Werf et al. (2005) suggested that the environmental burdens associated with the production and delivery of pig feed can be decreased by using more locally produced feed ingredients so that transport is decreased. Other studies (Casey & Holden, 2005; Thomassen et al., 2008b) performed LCA's of the whole animal production chain which made it difficult to single out the specific contribution of the feed production chain.

The present study aims at developing a methodology to formulate CO_2-low compound feeds. As a case-study, the production of pig feed will be considered. The presented methodology allows estimating the CO_2-emission of the different feed components for each processing step in the considered production chain and allows including the CO_2-emission of each feed component as a new variable in the formulation of pig feeds. To achieve this, an LCA is applied to describe the important steps in the production process and calculate the corresponding emissions. By evaluating the CO_2-emissions of several current and possible alternative feed commodities, a comparison can be made. In this research, we pay specific attention to the transfer of the theoretical knowledge and methodology into a practical tool to be implemented by compound feed producers to decrease the CO_2-emission of their products. Therefore, this study is performed in consultation with experts and stakeholders from the animal feed industry. Stakeholder participation and expert consulting has been found a successful approach for developing sustainability indicators of agricultural systems (van Calker et al., 2005; Meul et al., 2008). Moreover, discussions among stakeholders – based on scientific information – may themselves contribute to the development of sustainable systems (Rossing et al., 1997; Oels, 2003).

In the present article, we focus on the initial phases of the research and we describe the major bottlenecks that may prevent implementation of the proposed methodology in practice.

Methodology

Life Cycle Assessment

In order to achieve a 'sustainable development', methods and tools that help to quantify and compare the environmental impacts of products, are required (Rebitzer et al., 2004). Life cycle assessment is generally acknowledged as a useful tool employed by all sectors to help identify and reduce the integral environmental impact of different products and production systems (Consoli, 1995; Munkung & Gheewala, 2007). LCA is based on an inventory of the resources consumed and the emissions to the environment at each stage of the life cycle of a product. LCA involves four steps: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006).

Goal and scope definition

In the first phase of LCA, one needs to provide a description of the product system in terms of the system boundaries and a functional unit, i.e. a quantitative description of the service performance of the investigated product. This can be a quantity of material, but may also be the service that the product provides (e.g. the weight gain of animals when comparing different food types) (Rebitzer et al., 2004; Roy et al., 2009). The choice of goal and boundaries is mainly determined by the choice of LCA (Rebitzer et al., 2004). Two LCA modeling frameworks exist: attributional and consequential LCA (Tillman, 2000; Rebitzer et al., 2004; Ekvall et al., 2005). Attributional LCA (ALCA) reflects the environmental impact accounted for by the system and gives an overview of all the flows associated with the delivery of the functional unit. In ALCA the product system is hence modeled as it is. A consequential LCA (CLCA), in contrast, reflects the possible future environmental impact from a change in demand of the product under study. CLCA estimates the change of the system emissions due to a change in the level of the functional units produced (Rebitzer, 2004; Thomassen et al., 2008a).

During the goal definition, some major aspects need to be addressed or identified (ISO, 2006): intended application of the results, method and impact limitations of the usability of the LCA results, reasons for carrying out the LCA study and target audience of the results. Besides, the decision context needs to be identified: is the LCA used for small scale product decision support, in the short term or mid- and long term (beyond 5 years from present) future? Is the decision resulting in consequences that have the potential to influence one or more sectors of society at a large scale? Is the study intended for decision support or exclusively for monitoring?

During the scope phase, the object of the LCA study (i.e. the exact product system(s) to be analyzed) is defined in detail. The next and main part of the scope definition is to derive the requirements on methodology, quality, review and reporting in accordance with the goal of the LCA study, i.e. based on the reasons for the LCA study, the decision context, the intended applications, and the addressees of the results.

Inventory analysis

The second phase of an LCA is the inventory analysis, in which the production system is defined. Once the boundaries are set, the flow diagrams of the studied system with unit processes must be designed and data must be collected for each process of the product system. This data set compiles the inputs and outputs to the environment associated with the functional unit (Herrchen & Klein, 2000; Guinée, 2002; Rebitzer et al., 2004). The collected data does not have to be expressed in amount of emissions to the environment, but can exist of different units (e.g. liter diesel, amount of fertilizer used). When a process results in one or more functions for the product and/or for other products, allocation rules are in order (Ekvall & Finnveden, 2001). Allocation can be defined as the partitioning of environmental burdens and other material and energy flows to and from a technological activity between the products for which the activity is used (Russel et al., 2005). The difficulty is to decide how to divide the environmental burdens of the activity to the different products.

Allocation should be avoided, wherever possible, through division of the multifunction process into sub-processes, each producing different products from the same type of raw material. But the allocation problem can only be solved when environmental data can be obtained for each of these sub-processes. That way, each sub-process can be assessed separately. For many multifunctional processes, e.g. food production, oil refineries, pulp mills, the allocation problem cannot be eliminated since each of the separate material components is a product from the separation sub-process (Ekvall and Finnveden, 2001).

Another possibility to deal with allocation is ‘system expansion’ and ‘substitution’, also called ‘system enlargement’. This means that the boundaries of the system investigated are expanded so that the alternative production of exported functions is included. A functional equivalence of compared systems can be achieved by either adding functions (system expansion) or subtracting them (substitution). Thus, the multifunctional process that results in co-production of product A and product B minus the alternative production of product B is equivalent with the production of product A and vice versa. System expansion requires that there is an alternative way of producing the co-product not under investigation and that data is available (ISO, 2006).

When none of the above is an option, allocation based on physical, causal or other relationships is possible. The allocation is in proportion to e.g. the economic value of the products or in proportion to a physical property (mass, volume, energy content) of the products (Ekvall & Finnveden, 2001). Allocation based on the economic value of the co-products or mass allocation is a common used method (Guinée et al., 2004; Werner & Richter, 2000).

Impact assessment

The outcome of the inventory analysis is the input for the impact assessment. First, the results of the inventory analysis are processed and interpreted in terms of environmental impact. Then, several impact categories of interest are chosen including global effects (global warming, ozone depletion, etc.), regional effects (acidification, eutrophication, etc.) and local effects (nuisance, effects of hazardous waste, effects of solid waste, etc.). During this classification step, the inventoried data are sorted and assigned to these impact categories based on the expected types of impacts on the environment (Pennington et al., 2004; Roy et al., 2009). The data are then characterized by multiplying them with characterization factors, which represent the potential of a single emission or resource consumption to contribute to the respective impact category. This gives an impact category indicator which is a value per functional unit for that impact category (Brentrup, 2004; Pennington et al., 2004).

Interpretation phase

A final interpretation needs to be made in the fourth phase. The results can be used for example to support a decision, to give a general idea about the production chain or to identify elements within the system that contribute most to a certain impact category. The results are linked to the goal at the start of the study. The findings of all previous phases are examined to find opportunities for reducing the environmental impact (Roy et al., 2009).

Case study

The production chain of pig feed is considered as a case study. The focus on pig feed is relevant, since pork production is an important sector of the total European animal production, and relies heavily on imported feedstuffs. The outcome of this case study may later be easily used for the poultry production chain, because of large similarities in the use of feed and in the production systems.

Pig feed production chain

Figure 1.A. shows the feed production chain as part of the animal production chain. For each step in the chain, the most important processes concerning energy use and CO_2-emission are indicated. Although the research puts most emphasis on the carbon emission of processes for the production of compound feed, it is important to also take into account the last step in the chain, i.e. the use of the compound feed on the livestock farm. This is necessary to avoid that a 'CO_2-low feed' is based on alternative feed materials that results in suboptimal animal performances and consequently increased CO_2-emission in this last step of the chain.

Obviously, processing of the feed will also have to be taken into account. In Western Europe, about 80% of the produced industrial compound feed is pelleted (step 4 in the production chain, Fig. 1.A.), which leads to a significantly increased energy consumption of ca. 60% compared to a feedstuff which is only ground and mixed (FEFAC, 2010). Extrusion is a reasonable alternative to pelleting, especially for feeds for young animals (whose digestion system is less developed) or for animals requiring high energy content diets. Extrusion also allows to include less common and problematic (e.g. high antinutritive) raw materials and/or agri-by-products (Pokorny et al., 2000). Hence, both pelleting and extrusion are widely applied.

The crop production and transformation processes of the raw materials and feed components (steps 1 to 3 in the production chain, Fig. 1.A.) depend on the type of feed component. Hence, for each feed component that is used in a compound feed, the specific production chain needs to be considered. As one of the most important components of pig feed, we selected soybean meal as the first feed component to be studied.

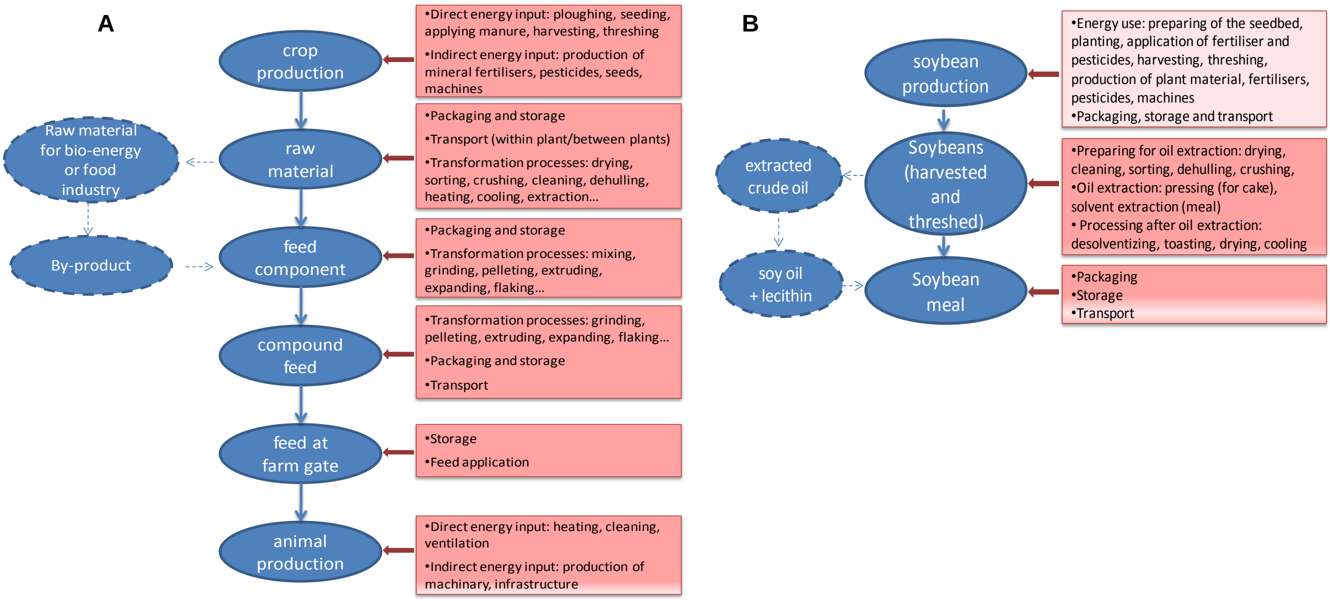

Figure 1. A. General scheme of the feed production chain as part of the animal production chain, with indication of the most relevant processes concerning CO_2-emission for each step **B.** Production and processing chain of soybean meal as a feed component

Soybean meal production chain

Soybean meal is the predominant protein source in pig diets in many countries around the world. The global area cultivated with soybeans has expanded from 38 million hectares in 1975 to 91 million hectares in 2005 (FAO, 2006), with the major land increases taking place in Argentina and Brazil. More than 40% of the increased soybean area in Argentina has come from virgin lands, including forests and savannahs, causing losses in biodiversity (Pengue, 2006). Likewise, in Brazil, woodland had to make place for the production of soy leading to a major deforestation. This causes an increasing risk for erosion, degradation of the soil and pollution of water from pesticides use for weed control. Besides, the transportation of the soybean or soybean meal to other countries also causes emissions to the environment. There is an expected duplication of the consumption of foodstuff of animal origin by 2050 and hence also of the global demand for soy and its derivatives (vegetable oil, animal feed) (FAO, 2006). The environmental burden is expected to increase with an increasing production and the need for a more sustainable soy production and consumption rises. One possibility to make the feed industry, specifically the protein flows, more sustainable is the use of alternative protein sources in the European feed. This could be achieved by reducing the import of proteins by replacing them with locally produced components (e.g. lupine or DDGS).

Figure 1.B. shows the production and processing chain of the feed components soybean meal. For each step in the chain, the transformation processes are mentioned. The oil that is extracted from the soybeans is used in the food industry, while the soybean meal is further processed as a component of animal feed. This implies that the processing of soybeans is a multifunctional process and hence allocation of CO_2-emission to the different end-products (oil and meal) will be required.

Results and discussion

In this section, we apply the LCA methodology to the case-study of estimating the CO_2-emission of pig feed production, with a focus on soybean meal as a feed component. We discuss the several choices that need to be made and the major bottlenecks.

Life cycle assessment

Goal and scope definition

The major goal of this study is to formulate CO_2-low compound feed for pigs, compared to the feeds that are currently used in farming practice. Therefore, an LCA is performed of the animal feed production chain, from the crop production up to the compound feed ready to be transported to the farms. Hence, the system boundaries include the steps 1 to 4 as indicated in Fig. 1.A.: crop production, raw material, feed component and compound feed and all production processes involved. The scope of this article lies on the estimation of the CO_2-emission of the production chain of soybean meal (Fig. 1.B.). As a functional unit, we use kilogram of soybean meal and kilogram of compound feed.

Although in theory consequential modeling would be able to better depict the effect a product-related decision has beyond the analyzed production system, in practice the feasibility, reproducibility, and robustness as well as acceptance of the approach is limited (ISO, 2006). Therefore, in the present study, the attributional modeling framework will be applied. The product system and its environmental burden will be described as it is. For the interpretation of the LCA results, some impact limitations of the method applied in this study have to be considered: only the CO_2-emission related to fossil energy use will be calculated. No other GHG's, like methane and nitrous oxide or indirect emissions from land use change are taken into account.

Our main target audience is the feed industry, in our study represented by the Belgian Federation of Compound Feed Producers (BEMEFA). Concerning the decision context, , our study has the potential to support long term decisions on a large scale. We do not only want to monitor and describe the feed production system, but we want to inflict a change in the feed industry on a long term. Not only the feed sector but also the agricultural sector can be influenced when new CO_2-low feeds are produced based on the LCA results.

Inventory analysis and impact assessment

The production systems that are studied are shown in detail in Fig. 1.A. and Fig. 1.B. In scientific literature, many data are available concerning the energy use or CO_2-emission involved in the first step of the feed production chain, the primary production. However, as shown in Table 1, when for a specific item multiple data are available in the literature, they are often difficult to compare due to the large variety of units used. In addition, there is also a large range in the actual values reported in literature, caused by the specific assumptions and choices made within the different studies, such as the crop type or type of fertilizer involved. These obstacles make it very difficult to select a representative value for the processes involved in the primary production step.

For the processing of the feed components into compound feed (steps 2 to 4 in Fig. 1.A.), data on energy use or CO_2-emission are even much less available in literature (Table 1). We expect that these data are however available at the feed companies.

The processing of soybeans is a multi-functional process (production of oil and meal). Due to a lack of data of the two sub-processes and the difficulties to divide the soy cycle between the co-products (oil and meal), allocation needs to be applied. Mass or economic allocation can be used to distribute the environmental burden between the soybean meal and the soybean oil. According to which one is chosen, other results will be obtained. Because it is very difficult to scientifically justify the choice, both scenario's will be executed. Other authors also make the comparison between different types of allocation and observed different outcomes (Lehuger et al., 2009; Dalgaard et al., 2008; Thomassen et al., 2008b).

To estimate the environmental impact, CO_2-emissions will be calculated, based on the collected data and standard emission factors available from literature.

Interpretation phase

In the present study the LCA results will be used to identify feed components with high or low carbon emission and use these in an attempt to formulate compound feeds with a lower carbon emission compared to currently used feeds. The feed industry is permanently searching for feed ingredients that are available at the lowest cost while being safe and fulfilling the constraints of feed manufacturing and animal nutrient requirements. It is our aim to use the information on the carbon emission of the feedstuffs as an extra variable in the formulation of compound feeds, to produce CO_2-low feeds that also meet zootechnical and economic requirements.

Table 1. Non-limitative list of data on energy use and CO_2-emission of different processes within the feed production chain, found in scientific literature.

Production step	Units						References
Crop production							
Direct energy input	liter/ha	GJ/ha	kg C/ha*	l/ha/yr	kg CE/ha*	kg CE/hr	
plowing	20-25	0,78-0,99	17.01	32.7	4,5-31		a, b, c, d, e, f, g, h, i
planting/sowing	3-10,4	0,14-0,18	3,03-3,94	9,4-11,1	2,2-11,3		a, b, c, f, g, h, i
fertilizer application	1,5-9	0.06	1.34		0,5-1,3		a, c, d, e, f, g, i
harvest	8,9-100	0,60-1,28	26,59-28,15	27-47	8,5-18	33.3	a, b, c, d, e, f, g, h, i
spraying pesticides	1,1-2,63	0,068-0,1	2.23		1,4-5,95		d, e, h, i
Indirect energy input	kg CE/kg app	MJ/kg	kg CE/kg				
fertilizers	3.5		0,1-1,8				e, f, g, k, l
pesticides	10		1,2-12				e, g
seeds		1,3-98					d
machinery		108					d
Processing of raw material	no data found in literature						
Processing of feed components							
Emissions for milling plants	MJ/ton of soybeans		kWh/ton of soybeans				j
diesel for machinery	32						
electricity			12-68				
heat (oil)	145-340						
heat (gas)	282						
Compound feed production	no data found in literature						

* C=carbon; CE=carbon equivalent

References: (a) Adler et al., 2007; (b) Gerin et al., 2008; (c) Hallberg, 2008; (d) Hülsbergen et al., 2001; (e) Hillier et al., 2009; (f) Koga et al., 2003; (g) Lal, 2004b; (h) Tt Clair et al., 2008; (i) Dalgaard et al., 2001; (j) Dalgaard et al., 2008; (k) Meul et al., 2007; (l) Casey & Holden, 2005

Major bottlenecks and the role of stakeholders

During the first phase of the research, some meetings with representatives from the European feed industry were held. From these stakeholder discussions, three major bottlenecks became apparent that may stand in the way of a practical tool used by compound feed producers to decrease the CO_2 emission of their products.

Feed production has a close interaction with other industrial sectors, mainly the food and biofuel industry. For example, soybeans are used for production of oil (food) and meal (feed) while DDGS, a residual from biofuel production, is used as a feed component. Among these sectors, there seems to be a lack of consensus on the feed chain boundaries and the specific role each sector has in the environmental burden caused during the processing of the multifunctional raw materials. This induces a problem of allocating CO_2-emission to the different (co-)products and associated production chains. Depending on the type of allocation that is applied (for example economic vs. mass allocation), the contribution to CO_2-emission of the different co-products – and hence of the different industrial sectors – can be quite diverse. To solve this first bottleneck, consensus among the different industrial sectors that are involved in this multifunctional process is required.

Although the European feed industry participates in different initiatives that address sustainability issues (e.g. RTRS, 2010; RSPO, 2010), a shared vision on the contribution and solutions to sustainability and in particular to climate change is still missing among European feed producers. Meanwhile, several individual initiatives already exist to calculate the carbon footprint of animal feed, but underlying assumptions and methodologies are not standardized. Before a standard method can be applied, the European feed producers have to agree on the assumptions and choices that need to be made: which GHG's will be included in the LCA? Will the indirect emissions from land use change be taken into account? Which conversion factors will be applied? As researchers, we can provide scientifically based suggestions and calculate scenarios, but the final choices need to be made and agreed upon by the end-users.

The third bottleneck is the lack of appropriate data. Although a large amount of data is available from literature concerning CO_2-emission for the primary production (Table 1), values and units are very diverse. Data concerning the emission during the processing of the feed components are not readily available. Here, feed producers play a major role in measuring and collecting the data that are necessary to perform an accurate LCA.

In our study, we aim to solve some of these bottlenecks through a strong cooperation and participation with the stakeholders. This way, the methodology that we will propose could contribute to the development of a European standard for estimating the carbon emissions of animal feed.

Conclusion

The proposed methodology has the potential to translate scientific knowledge on CO_2-emission into a practical tool for compound feed producers. However, some critical issues may hamper the eventual use of the tool in practice. These relate to choices that have to be made and agreed upon by the intended end users of the tool and involve (i) achieving consensus on the feed chain boundaries among the different industrial sectors involved, (ii) the development of a shared vision on the contribution and solutions to climate change among European feed producers and (iii) measuring and collecting data that allow to perform an accurate LCA. Therefore, the study is performed in cooperation with representatives of the animal feed industry. This way, the proposed methodology could contribute to the stakeholder discussions to help them find consensus and to the development of a European standard methodology.

References

Adler, P.R., Del Grosso, S.J. and Parton, W.J. (2007) Life cycle assessment of net greenhouse-gas flux for bio-energy cropping systems. *Ecological Applications* 17(3): 675-691.

Brentrup, F., Küsters, J., Kuhlmann, H. and Lammel J. (2004) Environmental impact assessment of agricultural production systems using the life cycle assessment methodology. I. Theoretical concept of a LCA method tailored to crop production. *European Journal of Agronomy* 20(3): 247-264.

Casey, J.W. and Holden, N.M. (2005) Analysis of greenhouse gas emissions from the average Irish milk production system. *Agricultural Systems* 86(1): 97-114.

Consoli, F.J. (1995) Life cycle assessment: background and update. *Tapi Journal* 78(12): 41-43.

Corré, W., Schröder, J. and Verhagen, J. (2003) Energy use in conventional and organic farming systems. In: Proceedings No. 511, International Fertiliser Society, New York.Dalgaard, T., Halberg, N. and Porter, J.R. (2001) A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agriculture, Ecosystems and Environment* 87(1): 51-65.

Dalgaard, T., Halberg, N. and Porter, J.R. (2001) A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agriculture, Ecosystems and Environment* 87(1): 51-65

Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., Thrane, M. and Pengue, W.A. (2008) LCA of soybean meal. *International Journal of life cycle assessment* 13(3): 240-254.

De Campos, C.P., Muylaert, M.S. and Rosa, L.P. (2005) Historical CO_2-emission and concentrations due to land use change of croplands and pastures by country. *Science of the Total Environment* 346(1-3): 149-155.

Ekvall, T. and Finnveden, G. (2001) Allocation in ISO 14041 - a critical review. *Journal of Cleaner Production* 9(3): 197-208.

Ekvall, T., Tillman, A.-M. and Molander, S. (2005) Normative ethics and methodology for life cycle assessment. *Journal of Cleaner Production* 13(13-14): 1225-1234.

Flessa, H., Ruser, R., Dörsch, P., Kamp, T., Jimenez, M.A., Munch, J.C. and Beese, F. (2002) Integrated evaluation of greenhouse gas emissions (CO_2, CH_4, N_2O) from two farming systems in southern Germany. *Agriculture, Ecosystems and Environment* 91(1-3): 175-189.

FAO (2006) World Agriculture: towards 2030/2050. Interim Report. Accessed on: http://www.fao.org/ES/esd/AT2050web.pdf.

Fearnside, P.M., Righi, C.A., Lima de Alencastro Graça, P.M., Keizer, E.W.H., Cerri, C.C., Nogueira, E.M. and Barbosa, R.I. (2009) Biomass and greenhouse-gas emissions from land-use change in Brazil's Amazonian "arc of deforestation": The states of Mato Grosso and Rondônia. *Forest Ecology and Management* 258(11): 1968-1978.

FEFAC (2010) European Feed Manufacturers' Federation. Accessed on: http://www.fefac.org.

Gerin, P.A., Vliegen, F. and Jossart, J.-M. (2008) Energy and CO_2 balance of maize and grass as energy crops for anaerobic digestion. *Bioresource Technology* 99(7): 2620-2627.

Guinée, J.B. (Ed.) (2002) Handbook on life cycle assessment. Operational guide to the ISO Standards. Centre of Environmental Science, Leiden University, Leiden.

Guinée, J.B., Heijungs, R. and Huppes, G. (2004) Economic allocation: examples and derived decision tree. International Journal of Life Cycle Assessment 9(1): 23-33.

Halberg, N. (2008) Energy use and greenhouse gas emission in organic agriculture. International conference organic agriculture and climate change, Enita of Clermont, France, 17-18 Apr. 2008.

Herrchen, M. and Klein, W. (2000) Use of the life cycle assessment (LCA) toolbox for an environmental evaluation of production processes. *Pure and Applied Chemistry* 72(7): 1247-1252.

Hillier, J., Hawes, C., Squire, G., Hilton, A., Wale, S. and Smith, P. (2009) The carbon footprints of food crop production. *International Journal of Agriculture Sustainability* 7(2): 107-118.

Hülsbergen, K.-J., Feil, B., Biermann, S., Rathke, G.-W., Kalk, W.-D. and Diepenbrock, W. (2001) A method of energy balancing in crop production and its application in a long-term fertilizer trial. *Agriculture, Ecosystems and Environment* 86(3): 303-321.

International Standard ISO 14040. Environmental management – life cycle assessment – principles and framework (2006).

Koga, N., Tsuruta, H., Tsuji, H. and Nakano, H. (2003) Fuel consumption-derived CO_2 emissions under conventional and reduced tillage cropping systems in northern Japan. *Agriculture, Ecosystems and Environment* 99(1-3): 213-219.

Lal, R. (2004a) Agricultural activities and the global carbon cycle. *Nutrient Cycling in Agroecosystems* 70(2): 103-116.

Lal, R. (2004b) Carbon emission from farm operations. *Environmental International* 30(7): 981-990.

Lehuger, S., Gabrielle, B. and Gagnaire, N. (2009) Environmental impact of the substitution of imported soybean meal with locally-produced rapeseed meal in dairy cow feed. *Journal of Cleaner Production* 17(6): 616-624.

Meul, M., Nevens, F., Reheul, D. and Hofman, G. (2007) Energy use efficiency of specialized dairy, arable and pig farms in Flanders. *Agriculture, Ecosystems and Environment* 119(1-2): 135-144.

Meul, M., Van Passel, S., Nevens, F., Dessein, J., Rogge, E., Mulier, A. and Van Hauwermeiren, A. (2008) MOTIFS: a monitoring tool for integrated farm sustainability. *Agronomy for sustainable development* 28(2): 321-332.

Mungkung, R. and Gheewala, S. (2007) Use of life cycle assessment (LCA) to compare the environmental impacts of aquaculture and agri-food products. In D.M. Bartley, C. Brugère, D. Soto, P. Gerber and B. Harvey (eds). Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons. FAO/WFT Expert Workshop. 24-28 April 2006, Vancouver, Canada. FAO Fisheries Proceedings. No. 10. Rome, FAO. 2007. pp. 87–96

Oels, A. (2003) Evaluating stakeholder participation in the transition to sustainable development. Methodology, case studies, policy implications, LIT Verslag, Münster.

Ogino, A., Kaku, K., Osada, T. and Shimada, K. (2004) Environmental impacts of the Japanese beef-fattening system with different feeding lengths as evaluated by a life cycle assessment method. *Journal of Animal Science* 82(7): 2115-2122.

Pengue, W. (2006) Increasing Roundup Ready soybean export from Argentina. In: N. Halberg, H. Alrøe, M.T. Knudsen, E.S. Kristensen (ed.) *Global Development of Organic Agriculture: Challenges and Prospects.* Cabi publishing, pp. 20.

Pennington, D.W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T. and Rebitzer, G. (2004) Life cycle assessment Part 2: Current impact assessment practice. *Environment International* 30(5): 721-739.

Pervanchon, F., Bockstaller, C. and Girardin, P. (2002) Assessment of energy use in arable farming systems by means of an agro-ecological indicator: the energy indicator. *Agricultural Systems* 72: 149-172.

Pokorny, J., Reblova, Z., Moscicki, L., Kozłowska, H. and van Zuilichem, D.J. (2000) Chemical changes during the extrusion cooking of rapeseed and faba bean mixtures. CHISA 2000, Prague, CD Proceedings.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P. and Pennington, D.W. (2004) Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International* 30(5): 701-720.

Robertson, G.P., Paul, E.A. and Harwood, R.R. (2000) Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. *Science* 289(5486): 1922-1925.

Rossing, W.A.H., Meynard, J.M. and van Ittersum, M.K. (1997) Modelbased explorations to support development of sustainable farming systems: case-studies from France and the Netherlands, *European Journal of Agronomy* 7: 271-283.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N. and Shiina, T. (2009) A review of life cycle assessment (LCA) on some food products. *Journal of Food Engineering* 90(1): 1-10.

RSPO (2010) Roundtable on Sustainable Palm Oil. Accessed on: http://www.rspo.org/

RTRS (2010) Round Table on Responsible Soy Association. Accessed on http://www.responsiblesoy.org/

Russel, A., Ekvall, T. and Baumann, H. (2005) Life cycle assessment – introduction and overview. *Journal of Cleaner Production* 13(13-14): 1207-1210.

Seguin, B., Arrouays, D., Balesdent, J., Soussana, J., Bondeau, A. and Smith, P. (2007) Moderating the impact of agriculture on climate. *Agricultural and Forest Meteorology* 142(2-4): 278-287.

St. Clair, S., Hillier, J. and Smith, P. (2008) Estimating the pre-harvest greenhouse gas costs of energy crop production. *Biomass and Bioenergy* 32(5): 442-452.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M. and de Haan, C. (2006) Livestock's long shadow. Food and Agriculture Organisation of the United Nations, Rome.

Tillman, A.-M. (2000) Significance of decision-making for LCA methodology. *Environmental Impact Assessment Review* 20(1): 113-123.

Thomassen, M.A., Dalgaard, R., Heijungs, R. and de Boer, I. (2008a) Attributional and consequential LCA of milk production. *International Journal of Life Cycle Assessment* 13(4): 339-349.

Thomassen, M.A., van Calker, K.J., Smits, M.C.J., Iepema, G.L. and de Boer, I.J.M. (2008b) Life cycle assessment of conventional and organic milk production in the Netherlands. *Agricultural Systems* 96(1-3): 95-107.

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

Van der Werf, H.M.G., Petit, J. and Sanders, J. (2005) The environmental impacts of the production of concentrated feed: the case of pig feed in Bretagne. *Agricultural Systems* 83(2): 153-177.

Werner, F. and Richter, K. (2000) Economic allocation in LCA: a case study about aluminium window frames. International Journal of Life Cycle Assessment 5(2): 79-83.