Chapter 5

Life Cycle Assessment across the Food Supply Chain

Lisbeth Mogensen, John E. Hermansen, Niels Halberg, Randi Dalgaard +++

Introduction

The environmental impact is one of the major pillars of concerns when addressing the sustainability of food production and sustainable food consumption strategies.

To assess to what extent food production affects the environment, one needs to choose a proper environmental assessment tool. Different types of assessment tools have been developed to establish environmental indicators, which can be used to determine the environmental impact of livestock production systems or agricultural products. The environmental assessment tools can be divided into the area based or product based (Halberg et al., 2005). Area-based indicators are, for example, *nitrate leached per hectare* from a pig farm, and product-based indicators are, for example, *global warming potential per kg pork* (Dalgaard, 2007).

The area-based indicators are useful for evaluating farm emissions of nutrients such as nitrate that has an effect on the local environment. On the other hand, when considering the greenhouse gas emissions from the agricultural production, the product-based indicators are useful for evaluating the impact of food productions on the global environment (e. g., climate change) and have the advantage that in addition to emissions from the farms, emissions related to the production of input s (e.g., soybean and artificial fertilizer) and outputs (e.g., slurry exported to other farms) are also included. In that way it is easier to avoid *pollution* *swapping*, which means that the solving of one pollution problem creates a new (Dalgaard, 2007).

Product-based evaluation is called, life cyc1e assessment (LCA). LCA is an approach that evaluates all stage s of a product's life. During this evaluation environmental impacts from each stage is considered from raw material products, processing, distribution, use, and disposal. This methodology considers not only the flow of materials, but the outputs and environmental impacts of these. LCA processes have been standardized (e.g., ISO 14044) and follow the main steps of goal definition and scoping to define the process and boundaries; inventory analysis to identify material and energy flows and environmental releases; impact assessment to assess the environmental effects of the inventory analysis; and interpretation to draw conc1usions from the assessment (SAIC, 2006). Conc1usions can inc1ude decisions on different materials or processes. The benefit of LCA is that it helps avoid shifting environmental problems from one place to another when considering such decisions (SAIC, 2006).

Ultimately, the life cyc1e approach for a product is adopted to reduce its cumulative environmental impacts (European Commission, 2003). LCA is done in terms of a functional unit FU) – for food that usually is a finished product like a pound of cheese or kg of meat. LCA has been used for environmental assessment of milk (Thomassen 2008; Weidema et al. 2007; Thomassen and de Boer 2005; Cederberg and Mattsson, 2000; Haas et al. 2000), pork (Weidema et al. 2007; Basset-Mens et al. 2006; Dalgaard et al. 2007; Cederberg and Flysjö, 2004; Eriksson et al. 2005), beef (Ogino et al. 2007; Weidema et al. 2007), grains (Weidema et al. 1996, Dalgaard on soybeans) and other agricultural/horticultural products (Halberg et al. 2006).

The open access database LCAFood (www.LCAFood.dk) is a comprehensive LCA database covering most food products produced under Danish/North European countries.

In LCA all relevant emissions and resources used through the life cyc1e of a product are aggregated and expressed FU. Commonly applied environmental impact categories within LCA of food products are global warming, eutrophication, acidification, photochemical smog, and land use (Dalgaard, 2007). For each of the environmental impact categories, the emitted substances throughout the product chain that contribute to the environmental impact category are quantified (Table 5.1).

Global warming potential (GWP), the cause of c1imate change, refers to the addition of greenhouse gases to the atmosphere through burning of fossil fuels, agricultural practices, and certain industrial practices

Table 5.1. Selected impact categories with related units, contributing elements and characterization factors

Impact category	Unit	Contributing elements	Characterization factor s
Acidification	kg S02 eq	S02	1
		NH3	1.8 8
		NO	0.7 0
Global warming (GWP)b	kg CO2 eq	CO2	1
		CH4	21
		N20	310
Eutrophication (nutrient enrichment)	kg N03 eq	NO_x	1.3 5
		P20S	14.09
		NH3	3.6 4
		N03	1
		P03- 4	10.45
		NHt	3.6
		COD[c]	0.2 2
Land use	m2	Land occupation	1

[a] *NO* and $N0_2$.
[b] Assuming a l OO-year time horizon.
[c] Chemical oxygen demand: the amount of oxygen required to oxidize organic compounds in a water sample to carbon dioxide and water.
[d] After Thomassen et al. (2008).

leading to major changes in the earth's c1imate system. Nitrous oxide, methane, and CO_2 are the most important contributors to global warming, and, for instance, the contribution from agriculture to the Danish greenhouse gas emissions inventory has been estimated at 18% (Olesen, 2005). Nitrous oxide is emitted from slurry handling and from fields. For example, 4-5 kg nitrogen (N) from nitrous oxide (N_20) per hectare per year is emitted from a typical Danish pig farm (Dalgaard et al., 2006), and although this is a small amount compared to ammonia and nitrate emissions, the contribution to global warming is significant, because nitrous oxide is a very strong greenhouse gas, 310 times stronger than CO_2. Methane is emitted from enteric fermentation, in particular from ruminant animals and from manure/slurry handling and storage. Fossil CO_2 is emitted from the combustion of fossil fuels (traction, transport, and heating). Finally, CO_2 can be emitted from the soil if more organic matter is degraded than build up in the soil.

Eutrophication is caused by the addition of excess nutrients to water. This results in al gal blooms that lower the concentration of dissolved oxygen, and thereby killing fish and other organisms. Eutrophication contribution originates from a number of sources re1ated to N and P emission on farm and handling of waste from processes after the farm. The N compounds inc1ude ammonia, which evaporate from the slurry in the stable, when the manure/slurry is stored, and after it is applied to the field. The ammonia can be deposited in vulnerable zones where it might decrease species richness because of eutrophication. Nitrate is another important N compound. Nitrate can be leached to the surface water or the groundwater; thus, it can cause both nutrient enrichment of the aquatic environment or pollution of drinking water.

Acidification is caused by re1ease of acid gases, mostly from the burning of fossil fuels. Acid gas, for example, ammonia, has an acidifying effect and can affect natural habitats, some of which may be transboundary (e.g., lakes in Sweden). The major element that contributes to acidification from livestock production is NH3 emitted from manure handling.

Production of food and animal feeds occupy some land that might have been used for other purposes eq maintaining biodiversity. The quality of the ecosystem is re1ated to the biodiversity in the agricultural landscape. For example, soybean production for pig feed contributes with approximately half of the total land use for pig meat. Increased soybean production results in agricultural expansion and causes a reduction in local biodiversity. However, land use is not only a negative concept, since part of the beef and milk production contributes to maintain valuable seminatural areas in the form of meadows (Weidema et al., 2005).

It is interesting to note that food production and consumption represent a large proportion of the total environmental impact that is re1ated to human activities. In Table 5.2 the proportion of the impact categories is given (acidification, eutrophication, global warming, and nature occupation), which is re1ated to the consumption of meat and dairy within the European Union (Weidema et al., 2007). While the total European consumption of meat and dairy products only constitutes 6.1% of the economic value of the total final consumption in Europe, meat and dairy products contribute from 14 to 35% to the impact categories like acidification, eutrophication, global warming, and nature occupation (Table 5.2).

Table 5.2. Environmental impact of annual consumption of meat and dairy products in EU-27 (the functional unit of the study) expressed relative to the impact ofEU-27 total consumption

Impact category	Unit	Impact of meat and dairy products relative to the total consumption
Acidification	m2 UES	24.9%
Eutrophication, aquatic	kg N03 eq kg	29.4%
Global warming Nature	CO2 eq m2	14.2%
occupation	arable land	35.8%

After Weidema et al. (2007).

These results highlight the importance of addressing the environmental impact re1ated to food production.

Comparison of Environmental Impact of the Agricultural Production of Food Products

Food is thus an important component of the environmental impact of a family, but earlier assessments have demonstrated large differences in the environmental impact per kg product of different foods (Halberg et al., 2006). This is both because different products, such as milk and potatoes, obviously require different production processes, and because a particular product can be produced and processed in several different ways.

The potential environmental impacts associated with the on-farm production of various types of foods are shown in Tables 5.3 and 5.4. Producing 1 kg of animal products, like meat and eggs produce much more greenhouse gas emissions than producing 1 kg plant-based product like potatoes. This is because the average amount of energy used per kg meat produced is more than 10 times that of plant-based products (Pimentel and Pimentel, 2003). For example, the energy from feed needed to produce 1 kg lamb meat requires 21 kg grain and 30 kg forage in feed input (Table 5.5), and the energy needed to produce 1 kg sheep meat is thus 23 MI from animal feed, compared with 12 MI for 1 kg of chicken meat and only 1.3 MI for production of 1 kg of potatoes (Foster et al., 2006). Sheep and beef meat have the highest climate impact of all types of meat, with a GWP of 17 and 20.4 kg CO_2 eq/kg of meat, while pig and poultry have less than one- fifth of that (Table 5.3). Furthermore,

Table 5.3. The main burden and resources used arising from animal products from Denmark[a] or England/Wales[b]

Impact per kg carcass, per 20 eggs, or per kg milk at farm gate	Sheep[b]	Beef *meat*[a]	Pork *meat*[a]	Chicken *meat*[a]	*Milk*[a]	Eggs[b]
GWPIOO (kg C02 eq)	17	20.4	2.9	2.6	1.0	5.5
Acidification potential (g S02)	380	205	52	47	10.4	306
Nutrient enrichment (g N03 eq)	2,090	1,729	280	204	51	805
Photochemica1 smog (g ethane eq)		4.2	0.89	0.5	0.3	
Land use (m2 year)	14	31.5	8.9	4.9	1.5	6.7

[a] LCA Food (2008).

[b] Williams et al. (2006).

methane (CH4) from enteric fermentation from cattle constitutes 32% of total greenhouse gas emissions from agriculture (Bellarby et al., 2008). So for ruminants, like sheep, beef, and dairy, methane production further increases greenhouse gas emissions per unit of food produced. Chicken meat production appears the most environmentally efficient due to several factors, inc1uding the very low overheads of poultry breeding stock (cf. 250 progeny per hen each year vs 1 calf per cow); very high feed

Table 5.4. The main burden and resources used arising from plant produets grown in *Denmark*[a]

Impact per kg at farm gate	Bread wheat	Oi1seed rape	Potatoes	Tomatoes (greenhouse)
GWPIOO (kg C02 eq)	0.7	1.5	0.16	3.5
Acidification potential (g S02 eq)	5.3	11.8	1.2	7.2
Nutrient enrichment (g N03 eq)	65	149	14	24.7
Photochemica1 smog (g ethane eq)	0.17	0.37	0.004	0.84
Land use (m^2 year)	1.5	3.5	0.31	0.02

[a] LCA Food (2008).

Table 5.5. Average consumption of grain/soy and forage (kg) for production of 1 kg of animal product (live weight)

	Beef meat (milk)	Pork meat	Chicken meat	Dairy
Grain/ soy	3.5	2.6	2.0	0.4
Forage	38	O	O	1.8

LCA Food (2008).

conversion; and high daily gain of poultry (made possible by genetic selection and improved dietary understanding) (Williams et al., 2006).

The production of field crops produces much less greenhouse gas emissions than producing animal products (Table 5.4). The GWP from field crops (exc1uding protected cropping like tomatoes) is dominated by N_20. N_20 contributes about 80% to GWP in wheat production (Williams et al., 2006). The N20 contribution falls to about 50% for potatoes as much fossil energy goes into cold storage. In contrast, in green house tomato production CO^2 from the use of natural gas and electricity for heating and lighting to extend the growing season is the dominant contribution to GWP (Table 5.4).

Comparison of Environmental Impact of Different Foods

For the consumers and the food industry, it is important to know the environmental impact of the produced food. The potential environmental impacts associated with various types of foods ex retail are shown in Tables 5.6-5.10. (All the foods are produced on farms in Denmark and processed in Denmark-http://www.LCAfood.dk)

Meat

The environmental impact of meat inc1udes both the impact from the production of, for example, the living pig on the farm (Table 5.3), all the processes after the pig leaves the farm and until the meat arrives at the refrigerated counter in the supermarket. This inc1udes the transport to the abattoir for slaughter, slaughtering, the cutting into primals, the packing, and the transport to the supermarket. However, the impacts associated with feed productionand raising the livestock and manure handling arethe greatest contributor to the impacts noted.

Table 5.6. The potential environmental impacts of pork and cattle meat (functional unit is 1 kg food ex retai1)

Impact per kg	Pork tenderloin	Pork mine ed ham meat	Pork	Cattle tenderloin	Cattle steak	Cattle mince d meat
GWPIOO (kg C02 eg)	4.6	3.0	2.3	68.0	42.4	4.4
Acidification potential (g S02 eq)	75	49	38	680	427	103
Nutrient enrichment (g N03 eq)	414	266	207	6,410	4,000	790
Photoehemiea1 smog (g ethane eq)	1.4	0.9	0.73	14	8.9	1.4
Land use (m^2 year)	12	8	6.0	90	56	11
2003 price in Danish supermarket (euro/kg)	18.8	12.1	9.4	40.2	25.5	9.4

http://www.lcafood.dk

The environmental impacts associated with each c1ass of pork/cattle meat have been determined by price allocation (Weidema, 2003) since it is anticipated that the most expensive cuts are major determinants of the *drive* in producing beef. This means, the total impact from producing one beef calf is divided among the output products, the different cuts according to the different prices. The resulting GWP for 1 kg cattle meat fluctuate from 68.0 kg CO_2 eq for tenderloin (the most expensive meat) to 4.4 kg CO_2 eq for minced meat (the cheapest meat). For pork, GWP fluctuate from 4.6 for tenderloin to 2.3 kg CO_2 eq for minced meat.

Meat is the food with the highest GWP (Table 5.6). The environmental impact from 1 kg meat from pig or poultry is of similar level (Table 5.7). For chicken the data shown are for uncut chicken and the processing inc1uding slaughtering etc. increased the GWP by 20%. However, if a frozen chicken instead of a fresh chicken is bought, the GWP is increased by additional 16%.

Fish

The fishing stage is the most important life cyc1e stage in terms of environmental burden for fish, and fishing activity is characterized by a significant fuel consumption and re1ease of problematic biocides from antifouling paint on the boats (Thrane, 2003). The GWP and acidification

Table 5.7. The potential environmental impacts of chicken and fish (functional unit is 1 kg food ex retail)

lmpact per kg	Chicken fresh	Chicken frozen	Cod fresh	Cod fresh, fillet	Cod frozen, fillet	Shrimp fresh	Shrimp peeled, frozen	MusseIs fresh
GWPlOO (kg CO_2 eg)	3.2	3.7	1.2	2.8	3.2	3.0	10.5	0.09
Acidification potential (g $S0_2$ eg)	47.9	48.3	15	32	32	38	120	0.82
Nutrient enrichment (g $N0_3$ eq)	207	208	25	55	56	65	198	1.4
Photochemical smog (g ethane eq)	0.62	0.67	1.8	3.9	4.0	4.6	14	0.15
Land use (m^2 year)	5	5						

http://www.1cafood.dk

potential of 1 kg wild cod fish is lower compared with 1 kg chicken, but dry matter content is not equal. The GWP of 1 kg fresh shrimp is similar to that of 1 kg fresh chicken, but three times higher for 1 kg peeled and frozen shrimps. Fresh mussels have a very low environmental impact for all impact categories. This is because mussels can filter plankton from the water and need no extra feed, and they can be raised on ropes hung on structures placed in coastal waters.

When looking at aquaculture, it resembles animal production more than fishing. As a result, the greatest impacts are typically seen in feed production (Ziegler, 2003). The relative environmental and resource use sustainability of aqua culture vs. fishing vs. livestock production needs further research (Ellingsen & Aanondsen, 2006)

Milk and Dairy

The environmental impact of different milk products is shown in Table 5.8. Manufacturing milk to drinking milk increases GWP by 19%. Further processing to shelf-stable milk (URT treated) increases the processing impact due to higher heating requirements and energy to

Table 5.8. The potential environmental impacts of milk product (functional unit is 1 kg food ex retail)

Impact per kg	Skimmed milk	Low-fat milk	Full milk	Mini milk	Yellow cheese
GWP100 (kg CO_2 eq)	1.2	1.2	1.1	1.2	11.3
Acidification potential (g SO_2 eq)	12	12	11	12	101
Nutrient enrichment (g NO_3 eq)	58	56	53	58	467
Photochemical smog (g ethane eq)	0.42	0.42	0.40	0.43	3.3
Land use (m^2 year)	1.7	1.6	1.5	1.6	13
Fat content (%)	0.1	1.5	3.5	0.5	
Raw milk consumption (4.29% fat)	1.12	1.08	1.02	1.11	
Cream production (38% fat)	0.12	0.08	0.02	0.11	

http://www.lcafood.dk

Table 5.9. The potential environmental impacts of flour and bread (functional unit is 1 kg food ex retail)

Impact per kg	Wheat flour	Rye flour	Oat flakes	Rolls (fresh)	Rolls (frozen)	Wheat bread (fresh)	Wheat (frozen) (frozen)	Rye bread (fresh)
GWP100 (kg CO_2 eq)	1.1	1.0	0.8	0.9	1.3	0.8	1.2	0.8
Acidification potential (g SO_2 eq)	6.9	6.8	7.0	5.1	5.4	5.0	5.3	4.9
Nutrient enrichment (g NO_3 eq)	84	73	17	59	60	59	60	54
Photochemical smog (g ethane eq)	0.34	0.39	0.40	0.29	0.32	0.27	0.30	0.29
Land use (m^2 year)	1.4	2.0	2.5	1.0	1.0	1.0	1.0	1.3

http://www.lcafood.dk

Table 5.10. The potential environmental impacts of vegetables, sugar, and oil (functional unit is 1 kg food ex retail)

Impact per kg	Sugar	Vegetable oil	Potatoes	Carrots	Onions	Tomatoes
GWPIOO (kg $C0_2$ eq)	0.96	3.6	0.22	0.12	0.38	3.5
Acidification potential (g $S0_2$ eq)	6.0	31	1.5	1.0	1.5	7.2
Nutrient enrichment (g N03 eq)	-12.1	439	14.4	3.6	15.0	24.7
Photochemical smog (g ethane eq)	0.83	2.1	0.14	0.15	0.15	0.84
Land use (m^2 year)	0.45	4.5	0.3	0.2	0.3	0.02

http://www.lcafood.dk

produce packaging (Hospido et al., 2007). The GWP of 1 kg cheese is 9 times higher than that of 1 kg drinking milk as it takes a lot of milk to make cheese (c1ose to a 9 x). It was assumed that milk is produced in a system without quotas and that milk fat in excess is converted into butter. Usage of milk from farm and contribution to butter production is specific for specific kinds of milk due to their different fat content (see Table 5.8).

Despite the need for refrigerated transport for most dairy products, agricultural production including feed remains the key contributor to the life cyc1e environmental impacts(Hospido et al. 2007; Erzinger 2003; Larsson, 2003). **In** particular, the feed has a significant contribution.

Dairy production may be more of less integrated with land use and feed production and vary from zero grazing to totally free ranged systems. Thus, any attempt to estimate the effects of changes in the level of intensity in crop and livestock compartments of a dairy system or changes in feed composition should take into account, all relevant sub systems including the use of and the emissions and impacts from manure.

Organic dairy systems have been found to have lower emissions of GHG pr ha and per kg milk compared with conventional in Germany, Sweden and Denmark, but not in the Netherland (Halberg et a., 2005, Thomassen et al., 2008). The nutrient losses were lower per ha and per kg milk in Denmark, Germany and the Netherlands.

Grain

The environmental impact of bread and flour is shown in Table 5.9. The processing cost of wheat into bread is an increase in GWP of 18%. However, if frozen bread is bought the GWP of the bread is increased by

43% compared with fresh bread. The bread is produced by baking dough made of flour and water and a number of other ingredients. The bread is baked in an industrial bakery using electricity for mechanical operations and light and natural gas for heating the oven etc. Compared with the animal products, the environmental impact of bread and flour is quite low; for example, the GWP of 1 kg bread is only 68% of that of 1 kg skimmed milk. It was demonstrated that organic wheat production could be more favourable than conventional production in relation to GWP (Braschkat et al. 2003, Nielsen et al., 2003).

Vegetables

Table 5.10 shows that field-grown vegetables and potatoes have a considerably lower GWP per kg product compared with other foods such as meat and bread. Both acidification and eutrophication for carrots, onions, and potatoes are less than 5% of the level of, for example, pork. Whereas tomatoes grown in a greenhouse have an environmental profile that is considerably different from field-grown vegetables, both because the heating needed in a greenhouse results in a relatively large emission of greenhouse gases and because the nutrient use is inefficient, leading to a significant loss of nitrogen and phosphorus (Halberg et al., 2006). A greenhouse production of vegetables is similar to a pork meat production in terms of greenhouse gas emissions, but causes slightly less acidification and nutrient loss. Compared with greenhouse vegetables, the field-grown vegetables have a low energy use and low emission of greenhouse gases per kg product, although it is somewhat higher for straw-covered carrots. The relative high importance of energy use in for example greenhouse tomatoes (heating) and carrots (soil preparation and straw coverage) and a large yield difference means that organic products have higher GHG emissions per kg compared with conventional. The nutrient losses per kg tomatoes is, however, lower in organic production, which uses a soil based system rather than hydroponics.

Sugar and Oils

Table 5.10 also shows the environmental impact from sugar and oil. Sugar is produced from sugar beets produced in agriculture and transported by truck to the sugar factory where it is processed into sugar. The global warming and acidification potential from 1 kg sugar is similar to that of 1 kg flour, whereas photochemical smog is higher. Land use is lower due to a high crop yield in sugar beats, and when nutrient enrichment is negative, it is due to that molasses, and feed pills are cogenerated during sugar production and returned to agriculture as animal feed and thereby substitute grain feed.

Rapeseed oil is produced by crushing rapeseed. Rapeseed cake is coproduced with rapeseed oil in rapeseed crushing process, and these rapeseed cakes are used in animal feed.

Environmental Impacts of Different Meals

When comparing foods on a weight for weight basis, one should, however, be cautious as the products are not substitutable (they cannot completely replace each other) but rather complementary (we need a little of each) (Halberg et al., 2006). There is more protein, for example, in meat and dairy products than in vegetables and a different mix of vitamins. The environmental impact of the individual pro duet must be seen in the light of how much it contributes to the total food consumption of a family. Table 5.11 shows a hypothetical evening meal for a Danish family, and Table 5.12 estimates the environmental impact of the meal. The meat has by far the largest impact. If you reduce the consumption of meat to approximately 100 g per person (the recommended level), you can reduce both the emission of greenhouse gases and the nutrient losses considerably (by respectively, 25 and 31%). The resulting environmental impact will, however, depend on whether you instead eat more field-grown vegetables or replace the meat with greenhouse vegetables. As Table 5.12 shows, half a kg of tomatoes will cancel out much of the saving in greenhouse gas emissions that results from a lower meat consumption (Halberg et al., 2006). It is also interesting to note that the environmental impact of the meal is considerably larger than the effect from, for example, driving a car for 3 km.

If the foods were ranked according to their environmental profile in the same way as in the classical food pyramid, some goods would switch places in the pyramid. Greenhouse-grown tomatoes, for example, would

Table 5.11. Hypothetical meals for a family of four persons with different amounts of meat

	Typical	Less meat, more field-grown vegetables	Less meat, more greenhouse vegetables
Pork	0.75 kg	0.4 kg	0.4 kg
Potatoes	0.5 kg	0.75 kg	0.75 kg
Bread	0.5 kg	0.5 kg	0.5 kg
Milk	1.0 L	1.0 L	1.0 L
Carrots	0.5 kg	0.5 kg	0.4 kg
Onions	0.4 kg	0.2 kg	0.2 kg
Tomatoes	O kg	Okg	0.5 kg

Halberg et al. (2006).

Table 5.12. Environmental impact of different meals compared with that of transport, calculated using life cycle assessment method

Impact category	Typical	Less meat, more field-grown vegetables	Less meat, more greenhouse vegetables	Car (3 km)
Greenhouse effect (kg C02 eq)	4.4	3.2	4.0	1.1
Acidification (g S02 eq)	57	38	39	6
Eutrophication (g N03 eq)	315	218	223	8
Photochemical smog (g ethane eq)				5
Land use (m^2 year)	9.0	6.0	6.0	

Halberg et al. (2006).

be at the top immediately below animal products. Field-grown vegetables would, however, be part of the staple diet, both from a nutritional and environmental point of view, that is, at the bottom of the food pyramid (Halberg et al., 2006).

It is c1ear from the previous data that meat carries a huge environmental burden and that the on- farm part of the production chain is very important in this respect. Therefore, it is essential to consider the way the production takes place and to investigate if and where the environmental burdens can be alleviated.

Production Chain of Pork

When a pork chop reaches the refrigerated counter in the supermarket, it has accomplished a long journey as described by Dalgaard et al. (2007). First sows are raised to produce piglets; feed for the pigs is grown, harvested, and transported. Next the pigs are fed, slurry is excreted, and then applied to the fields. The pigs are transported to the slaughterhouse, slaughtered, carved up, and finally the pork chop is brought to the supermarket, from where it ends up in the shopping basket of a consumer and finally on a dinner plate as illustrated in Figure 5.1. In each of these steps energy is used and pollutants are emitted. For example, artificial fertilizer is applied to the field where pig feed is grown and energy is

Figure 5.1. Overview of the product chain of Danish pork delivered to the Port of Harwich in Great Britain. This represents a simplified view, where only the most important stages of the production chain are shown (Dalgaard et al., 2007).

used to produce this artificial fertilizer. In addition, different pollutants, for example, nitrate and nitrous oxide are emitted when the pig feed is grown or when slurry is excreted from the pig. Transport of fertilizer, pigs, and feed results in emission of CO_2 and other substances. All in all, many different kinds of pollutants in different amounts are emitted before the pork chop is ready for consumption. These pollutants contribute to c1imate change, eutrophication (nutrient enrichment), increasing acidity in the aquatic environment, changes in biodiversity, or other undesired impacts on the environment.

Results from Different LCAs of Pork

A number of LCA inventories on pork have been performed-mainly focusing on the part until the farm gate. These results are summarized in Table 5.13. It appears that the results are quit consistent regarding GWP, whereas some variations exist among the other results from different sources. This may reflect differences in the situation analyzed, but, no doubt, methodological differences also exist.

In organic pig production, sows need access to grazing in the summer time and growing pigs need access to an outdoor run. A longer lactation period in organic system decreases the number of weaned piglets per sow per year, and a poorer possibility to adjust feed composition in the organic system results in a higher feed consumption per kg gain. When comparing Danish conventional (Dalgaard et al., 2007) and Danish organic pig production (Halberg et al., 2008), GWP is 12% higher for

After Dalgaard et al. (2007).

pig meat from the organic production system. However, the differences were larger for the eutrophication, where organic production is 52% higher, mainly due to leaching from the grasslands. Furthermore, the organic system had 67% higher acidification per kg pig meat due to larger ammonia losses from outdoor runs.

Global Warming Potential

The greenhouse gas emission per kg pork, carcass weight is 3.6 kg CO_2 eq. This equals the amount of greenhouse gas emitted from a 10 km drive in passenger car (LCA Food, 2008). The most dominating

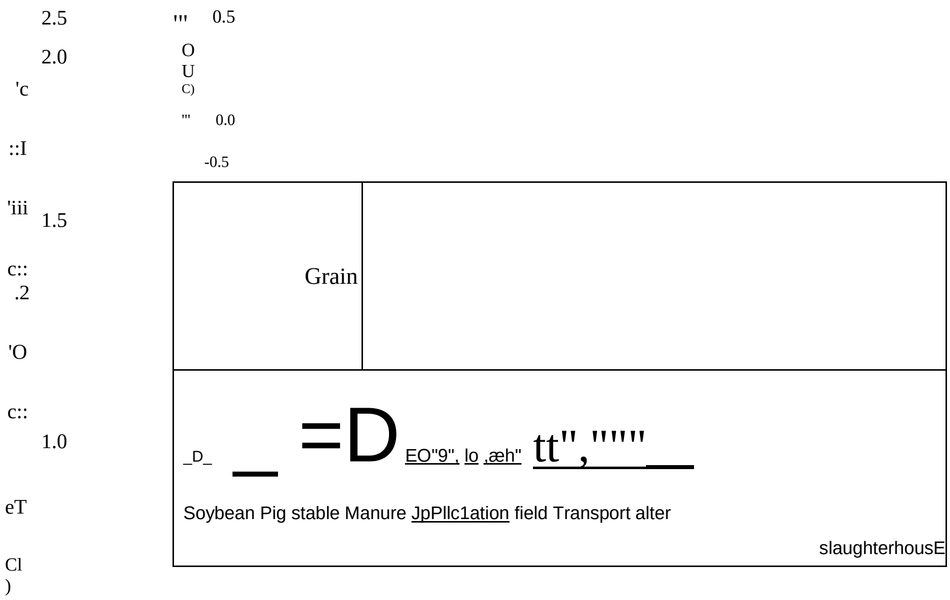

Figure 5.2. Contribution to GWP from the different stages of the product chain (Dalgaard et al., 2007),

contributors to GWP are nitrous oxide, methane, and CO_2, and they are responsible for 44, 32, and 20%, respectively, of the greenhouse gas emissions (Dalgaard et al., 2007).

In Figure 5.2 the contributions to GWP from the different stage s of the product chain of Danish pork are presented. The feed consumed by the pigs *(soybean meal* and *grain)* contributes with more than 2.4 kg CO_2 eq and is therefore more important than any other parts of the product chain (Dalgaard et al., 2007). The greenhouse gas emission per kg barley is 0.694 kg CO_2 eq (LCA Food, 2008), so with a feed use of 2.3 kg barley per kg pig live weight and 79.2 kg carcass weight per 105 kg live weight, the greenhouse gas emission from grain amounts to approximately 2 kg CO_2 eq/functional unit.

From *pig stable and storage* 81% of the GWP is methane and 19% is nitrous oxide. 78% of the emitted methane in the stable is from the manure/slurry and only 22% is from the enteric fermentation of the pigs. The nitrous oxide comes exc1usively from the manure/slurry.

Contribution from *energy used in the stable* is both CO_2 emission from the production and distribution of electricity, and the CO_2 emitted from oil combusted for heat production at the farm. CO_2 is responsible for more than 98% of the greenhouse gases emitted. The contribution is 0.15 kg/functional unit and out of this 85% is from the use of electricity while the rest is re1ated to the heat production from oil.

The contribution from *manure application field* is negative because less artificial fertilizer is used when the manure/slurry is applied to the fields for fertilization of the crops. The production and transport of artificial fertilizer emit greenhouse gases, so when artificial fertilizer is substituted by manure/slurry, greenhouse gas emissions will be reduced. On the other hand, when manure/slurry is used for fertilization instead of artificial fertilizer, more nitrous oxide will be emitted and more diesel for tractor driving will be used. However, the saved artificial fertilizer counterbalances more than this.

The contribution from *slaughterhouse* is 0.17 kg CO_2 eq/functional unit and is thereby the second smallest contributor to the GWP (Dalgaard et al., 2007). The major contributor from slaughterhouse is use of electricity at the slaughterhouse and the transport of the pigs from the farm to the slaughterhouse (distance 80 km). However, some of the byproducts from the slaughterhouse cause saved emissions of greenhouse gases. Manure/slurry from the pigs is transported to a biogas plant where it is anaerobically digested, and the gas is used for heat and electricity production. The energy produced from manure/slurry substitutes fossil energy, and this results in a reduced emission of greenhouse gases. Also, the animal by-products (bone, blood, etc.) are used as bone and blood meal for animals or energy production. Nevertheless, the total avoided emissions of greenhouse gases due to manure/slurry and animal by-products are low, and in total they only sum up to -0.013 kg CO_2 eq/functional unit.

Transport from slaughterhouse in Denmark to Harwich harbor is the stage of the product chain, which emits the smallest amount of greenhouse gases (Dalgaard et al., 2007). From the transport by lorry 0.021 kg CO_2 eq/functional unit is emitted and 0.007 kg CO_2 eq is emitted from the transport by ship. So even though the transport by lorry is only 126 km whereas the transport by ship is 619 km, the emission by lorry is three times higher. Less than 1% of the greenhouse gas emitted during the production of Danish pork can be ascribed to the transport from the slaughterhouse to Harwich harbor in Great Britain.

Eutrophication Potential

The most important contributor to eutrophication potential is nitrate (62%), followed by ammonia (32%), nitrogen oxides (4%), and phosphate (2%) (Dalgaard et al., 2008). As Figure 5.3 shows, the contribution from soybean meal is very low because nitrate, in general, is not leached during the cultivation of soybeans in Argentina (Dalgaard et al., 2007).

Figure 5.3. Contribution to eutrophication potential from the different stages of the product chain (Dalgaard et al., 2007).

The highest contribution to eutrophication potential comes from grain (122 g $N0_3$ eq/functional unit), with nitrate and ammonia emitted during the cultivation of the grain, being the major contributors. The only contributing substance from *pig stable* is ammonia, which equals 47 g $N0_3$ eq/functional unit. The ammonia comes from the manure/slurry excreted in the stable and under storage. The contribution from *energy used in stable* is very low. The second highest contributor is manure application field, which contributes with 62 g $N0_3$ eq/functional unit. A major part of this is N in the manure that is leached, because it is not incorporated to the crops. Slaughterhouse contributes with -0.4 g $N0_3$ eq/functional unit, and is negative because animal by-products, to some extent, are used as animal feed and thereby substitute grain feed. From the *transport after slaughterhouse* small amounts of nitrogen oxides are emitted due to fossil fuel combustion, but the contribution per functional is very low. The key element regarding eutrophication potential is N in the form of nitrate leached from fields and ammonia, emitted from the manure/slurry. The contribution from P is less than 2% per functional unit.

Acidification Potential

Ammonia is responsible for 84% of the acidification potential (Dalgaard et al., 2007). Nitrogen oxides, sulfur oxides, and sulfur dioxides, which

Figure 5.4. Contribution to acidification potential from the different stages of the product chain (Dalgaard et al., 2007).

come from the use of energy, are responsible for 16% of the acidification potential. The contribution from soybean meal is low (see Figure 5.4) and almost exclusively related to the emissions of nitrogen oxides, sulfur oxides, and sulfur dioxides emitted during the transport of soybean meal from Argentina to Denmark. Pig stable is the largest contributor to acidification potential, with ammonia as the only acidifying substance. Contributions from energy used in stable and slaughterhouse are very small. Manure application field contributes because ammonia is emitted when the manure/slurry is applied to the field. However, a significant part of that ammonia is counterbalanced because the manure/slurry applied to the field substitutes artificial fertilizer, which again results in saved emission from the use of fossil fuel.

Possibility for Environmental Improvement in Pork Production

The environmental *hot spots* in the product chain of Danish pork are, seen in relation to global warming, the stages before the pigs' arrival to the slaughterhouse (Dalgaard et al., 2007). A key parameter in reducing the GWP is farm management. If the protein consumption per pig produced is decreased, less N in manure/slurry will be excreted and thereby less nitrous oxide will be emitted from the pig stable. In addition, less protein consumption will result in a decreased use of soybean meal and a small increase in grain use. But because the greenhouse gas emission is lower per kg grain compared to soybean meal, a net decrease in greenhouse gas emission from the feed production will appear.

In the debate on climate change the focus is predominantly on CO_2 emissions and the use of energy by the industry and the transport sector. However, when considering food products (and in particular livestock products), methane and nitrous oxide are more important than CO_2 for the total impact on global warming. This is in accordance with the results presented above where the transport and the slaughterhouse are less important, but the emissions from feed production, stable, etc., are much more significant. But what if the Danish pork is transported to Munich in the south of Germany or Tokyo in Japan? To answer these questions two additional transport scenario s were established. One where the pork was transported 1,075 km by lorry (size 32 tons), which equals the distance from Horsens slaughterhouse to Munich and one scenario where the pork was transported 21,153 km, which equals the distance from Esbjerg harbor to Tokyo harbor in Japan. These longer transport distances increased the emissions from 3.6 kg CO_2 eq/functional unit to 3.7 and 3.8 kg CO_2 eq for the Munich and the Tokyo scenario, respectively. So even though the transport is much longer, the increase in the pork's contribution to GWP is limited.

Conclusions

From the food product life cyc1e research conducted globally, agriculture production is generally the largest contributor to the life cyc1e impact compared with other compartments such as transport and processing. Further, animal products have greater impact than plant productsproducing 1 kg of animal products like meat produce much more greenhouse gas emissions than producing 1 kg of plant-based products like cereal or potatoes. This is due to the animal feed conversion rate and feed impacts themselves and to the emissions of nutrients and GHG from the livestock.

However, certain ways s of production can increase plant products impact, as was demonstrated with greenhouse growth of tomatoes being similar in impact to animal products. Organic production is most often more energy efficient and have lower GHG emissions compared with conventional while nutrient losses are lower per ha but not always per FU.

The supposed environmental benefits of non-use of pesticides in organic systems are usually not included in LCA's due to methodological difficulties. Thus, comparing the two systems using State-of-art LCA is not fully satisfactory. Besides this, there is large variation in environmental impact between farmers and farming systems producing the same livestock output. LCA methodology may be used to benchmark the better performing systems and product chains in and to demonstrate the relative importance of the feed production external to the livestock farm itself.

Downstream compartments have relatively lower impacts, but can range depending on the product. Even more important the relative high proportion of food wasted in households adds significantly to the environmental burden per kg of food actually consumed. Consumer transport to purchase food can be a significant impact. And finally, consumer use of the food, when inc1uding cooking, can be a major contributor to the life cyc1e impact.

In general, following to a high degree current health advise regarding diet composition, especially eating a high proportion of basic vegetables will also minimise the environmental impact per meal. Thus, changing diets are potentially one of the most powerful ways of reducing the environmental impact per capita.

References

Basset-Mens, C., and H.M.G. van der Werf. 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. *Agric. Ecosyst. Environ.105(1-2):127-144.*

Basset-Mens, C., H.M.G. van der Werf, P. Durand, and P. Leterme. 2006. Implications of uncertainty and variability in the life cycle assessment of pig production systems. *Int. J. Life Cyde Assess. 11(5):298-304.*

Bellarby, 1., B. Foereid, A. Hastings, and P. Smith. 2008. *Campaigning for Sustainable Agriculture.* Amsterdam, the Netherlands: Green Peace International.

Braschkat, 1., A. Patyk, A. Quirin, and G.A. Reinhardt. 2003. "Life cycle assessment of bread production-a comparison of eight different scenarios." In: *Life Cycle Assessment in the Agri-Food Sector: Proceedings from the 4th International Conference, October* 6-8, Bygholm, Denmark.

Cederberg, C. 2003. "Life cycle assessment of animal products." In: *Environmentally-Friendly Food Processing,* eds B. Mattsson and U. Sonesson. Cambridge, England: Woodhead Publishing Limited.

Cederberg, C., and A. Flysjo. 2004. Environmental assessment of future pig farming systems---quantifications of three scenarios from the FOOD 21 synthesis work. *SIK-rapport* 723: l-54.

Cederberg, C., and B. Mattsson. 2000. Life cycle assessment of milk production-a comparison of conventional and organic farming. *J. Clean. Prod. 8:49-60.*

Dalgaard, R. 2007. *The Environmental Impact of Pork Production from a Life Cyde Perspective,* p. 135. Ph.D. thesis, Aalborg University, Denmark.

Dalgaard, R., H. Halberg, I.S. Kristensen, and I. Larsen. 2006. Modelling representative and coherent Danish farm types based on farm accountancy data for use in environmental assessments. *Agric. Ecosyst. Environ. 117(4):223-237*.

Dalgaard, R, N. Halberg, and JE. Hermansen. 2007. Danish pork production. An environmental assessment. *DJF Anim. Sci. 82:1-34.*

Dalgaard, R, J. Schmidt, H. Halberg, P. Christensen, M. Thrane, and W.A. Pengue. 2008. LCA of soybean meal. *Int. J. LCA. 13(3):240-254.*

Ellingsen, H. & Aanondsen, S.A. 2006. Environmental impacts of wild caught cod and farmed salmon – a comparison with chicken. Int. J. LCA. 1, 60-65.

Eriksson, LS., H. Elmquist, S. Stem, and T. Nybrant. 2005. Environmental systems analysis of pig production-the impact of feed choice. *Int. J. LCA 10(2):143-154.*

Erzinger, S., D. Dux, A. Zimmermann, RB. Fawaz. 2003. "LCA of animal products from different housing system in Switzerland: Relevant of feed stuffs, infrastructure, and energy use." In: *Life Cycle Assessment in the Agri-Food Sector: Proceedings from the 4th International Conference, October* 6-8, *2003,* Bygholm, Denmark.

European Commision. 2003. *Communication from the commission to the council and the European parliament. Integrated product policy.* Building on Environmental Life-Cycle Thinking. COM(2000) 302 final. Available from ht1p://www.aeanet.org/ forums/IPPfinalcommunicationI8June2003.pdf. Accessed June 2, 2008.

Foster, C., K. Green, M. Bleda, P. Dewick, B. Evans, A. Flynn, and l Mylan. 2006. *Environmental Impacts of Food Production and Consumption: A Report to the Department for Environment Food and Rural Affairs,* pp. 1-199. Defra, London: Manchester Business School.

Haas, G., F. Wetterich, and U. Geier. 2000. Life cycle assessment framework in agriculture on the farm level. *International Journal of LCA* 5:345-348. Available from ht1p:/ /www2.dmu.dkIl_ viden/2Yublikationer/3_fagrapporter/rapporter/ FR380_samlet.pdf (in Danish).

Halberg, N., R. Dalgaard, and M.D. Rasmussen. 2006. Miljøvurdering af konventionel og økologisk avl af grøntsager: Livscyklusvurdering af produktion i væksthuse og på friland: Tomater, agurker, løg, gulerødder. Arbejdsrapport fra Miljøstyrelsen 5.

Halberg, N., JE. Hermansen, LS. Kristensen, l Eriksen, and N. Tvedegaard. 2008. "Comparative environmental assessment of three systems for organic pig production in Denmark." In: *Proceedings of ISOFAR Conference: Organic Agriculture in Asia,* Korea, March 13-14, pp. 249-261.

Halberg, N., H.M.G. van der Werf, C. Basset-Mens, R Dalgaard, and LIM. de Boer. 2005. Environmental assessment tools for the evaluation and improvement of European livestock production systems. *Livest. Prod. Sci. 96:33-50.*

Hospido, A., M.T. Moreira, G. Feijoo. 2007. "Comparative LCA of liquid milk: Pasteurized versus sterilized milk." In: *Proceedings of the 5th International Conference on LCA in Foods, April* 25-26, *2007,* Gothenburg, Sweden.

Larsson, L 2003. "Possible benefits from using LCA in the agrofood chain, example from Arla foods." In: *Life Cycle Assessment in the Agri-Food Sector: Proceedings from the 4th International Conference, October* 6-8, *2003,* Bygholm, Denmark.

LCA Food. 2008. Available from ht1p://www.1cafood.dk. Accessed August 28,2008. Madsen, J.**,** and S. Effting. 2003. Using I/O data to find hot spots in LCA: Example of a hamburger meal. In: *Life Cycle Assessment in the Agri-food Sector: Proceedings from the 4th International Conference, October 608, 2003,* Bygholm, Denmark.

Nielsen P.H., Nielsen AM, Weidema BP, Dalgaard R and Halberg N. 2003. LCA food data base. www.lcafood.dk.

Ogino, A., H. Orito, K. Shimada, and H. Hirooka. 2007. Evaluating environmental impacts of the Japanese beef cow-calf system by the life cycle assessment method. *Anim. Sci. J. 78(4):424--432.*

Olesen, JE. 2005. Drivhusgasser fra jordbruget-reduktionsmuligheder. *DJF rapport Markbrug* 113:161 (in Danish).

Pimentel, D., and M. Pimentel. 2003. Sustainability of meat-based and plant-based diets and the environment. *Am. J. Clin. Nutr. 78:6608-6663.*
SAIC. 2006. *Life Cycle Assessment: Principles and Practice.* Available from ht1p:/ /www.epa.gov/ORDINRMRL/lcaccess/pdfs/600r06060.pdf. Accessed Au gust 16, 2008.

Thomassen, M.A 2008. *Environmental Impact of Dairy Cattle Production Systems An Integral Assessment*, pp.I-113. Ph.D. thesis, Wageningen University, the Netherlands.

Thomassen, M.A, and LIM. de Boer. 2005. Evaluation of indicators to assess the environmental impact of dairy production systems. *Agric. Ecosyst. Environ.* **111** (1--4): 185-199.1

Thomassen, M.A, K.I van Calker, M.C.J. Smits, G.L. Jepema, and I.J.M. de Boer. 2008. Life cycle assessment of milk production systems in the Netherlands. *Agric. Syst.96(1):95-107.*

Thrane, M. 2003. *Environmental Impacts from Danish Fish Products.* Ph.D. disserta tion, Ålborg University, Denmark, Department of Development and Planning.

Weidema, B. 2003. *Market Information in Life Cycle Assessments.* Technical report, Danish Environmental Protection Agency. Environmental Project No 863.

Weidema, B.P., B. Mortensen, P. Nielsen, and M. Hauschild. 1996. *Elements of an Impact Assessment of Wheat Production,* pp. 1-12. Institute for Product Development, Technical University of Denmark.

Weidema, B.P., A.M. Nielsen, H. Halberg, LS. Kristensen, C.M. Jespersen, and L. Thodberg. 2005. Sammenligning af miljøpåvirkningen af konkurrerende jordbrugsprodukter. Miljørapport nr. 1028. Miljøstyrrelsen, Miljøministreriet.

Weidema, B.P., M. Wesnæs, J. Hermansen, T. Kristensen, and N. Halberg, 2007. *Environmental Improvement Potentials of Meat and Dairy Products,* p. 190. Final Report. Sevilla: Institute for Prospective Technology Studies.

Williams, A, E. Audsley, and D. Sandars. 2006. *Environmental Burdens of Agricultural and Horticultural Commodity Production-Defra-funded Projects IS0205 and IS0222.* Available from ht1p:/ /www.silsoe.cranfield.ac.uk/iwe/expertise/lca.htm. Accessed August **14,** 2008.

Yakovleva, N. 2005. "Sustainability indicators for the UK food supply chain." In: *Measuring Sustainability of the Food Supply Chain Seminar, October* 27, *2005,* Cardiff University.

Ziegler, F. 2003. "Environmental impact assessment of seafood products" In: *Environmentally-Friendly Food Processing,* eds B. Mattsson, and U. Sonesson. Cambridge, England: Woodhead Publishing Limited.