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Carbon-footprints for food of animal origin, reduction potentials and research need

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The environmental assessment of human activities is presently a hot topic. It is not only important from an ecological perspective, but also from the view of efficient utilisation of limited natural resources such as fuel, land area, water und phosphorus. The environmental impact of food of animal origin is currently quantified by so-called CO_{2eq}-footprints (Carbon Footprints: CF).

To define CF, emissions arising along the food chain will be calculated according to their greenhouse potentials (carbon dioxide = 1 eq; methane ≈23 eq, laughing gas ≈300 eq). For the primary production of milk, meat and eggs, emissions during crop production, transportation, the storing and processing of feeds, animal keeping, enteric losses and excrement management can be mentioned as examples.

Data for CF of food of animal origin and edible protein are deduced in the paper. Furthermore reduction potentials and research need are summarised.

Keywords: carbon-footprints; food chain; milk; meat; eggs; edible protein; reduction potentials; research need

1. Introduction

The present situation all over the world is characterised by various growing processes such as:

- Growing population and growing need for feed and food (Steinfeld et al. 2006; FAO 2009; Godfray et al. 2010)
- Growing need for limited resources such as fuel, land area, water, phosphorus and further resources
- Growing emissions such as greenhouse gases (e.g. CO_2, CH_4, N_2O, etc.; IPCC 2006; Steinfeld et al. 2006; FAO 2010) and other substances (e.g. N, P, some trace elements)

For example, the atmospheric CO_2 concentration increased from ≈280 (nineteenth century) to 380 ppm (presently) and will probably increase to 550 ppm in 2050 (IPCC 2006) because of carbon burning from fuel and other activities. This increase is discussed in connection with global warming and climate change (IPCC 2006). Presently the global greenhouse gas (GHG) emission is estimated to be more than 40 billion tonnes (t) CO_2-equivalents (CO_{2eq}) per year, about one-third should come from agriculture (Isermeyer et al. 2008). The global growing rate is presently given with ≈1 billion tonnes CO_{2eq} per year. This increase provoked considerations to assess the emissions by so-called Life Cycle Assessment (LCA), also called eco-balances or CO_2-/carbon-footprints (CF) for manufacturing various products including food. The CF means the sum of all climate relevant emissions under consideration of their greenhouse potential such as '1' for CO_2, $23 \times CO_2$ for CH_4 and $\approx 300 \times CO_2$ for N_2O (IPCC 2006). The footprints are given as CO_2-equivalents (CO_{2eq}) in gram or kilogram per product. The aim of the footprints is to sensitise producers and consumers for an efficient use of fossil carbon sources and to reduce greenhouse gas emissions per product. Presently some companies already label their products with such footprints.

The objective of the present paper is to introduce footprints, to deduce CF for the primary agricultural production of selected food of animal origin, to come to reduction potentials, to open questions, and to further research needs. Food processing, trade and kitchen work are not considered in the present paper.

2. Materials and methods

The fundamentals to deduce and to decrease CF are described briefly in this chapter (see also Cederberg and Stadig 2003; Basset-Mens and van der Werf 2005; Williams et al. 2006; FAO 2010; IDF 2010; JRC 2010; Peters et al. 2010; Rotz et al. 2010). Knowledge about the emissions of greenhouse gases along the food chain (value-added chain, Figure 1) is the most important prerequisite for calculation of CF. Figure 1 shows some important inputs into the food chain and outputs along the chain. In the case of food of animal origin, knowledge of emissions from manufacturing resources (plant production, harvesting, transportation, storage, conservation, processing in feed mills, animal keeping, etc.) and animal-caused emissions from the digestive tract and the excrement management are fundamentals for further calculations. On the other hand, animal yields or products such as milk, eggs or food from the animal body, such as empty body weight or meat are considered as outputs. Finally calculations are carried out to find CF for edible protein of animal origin to compare various protein sources.

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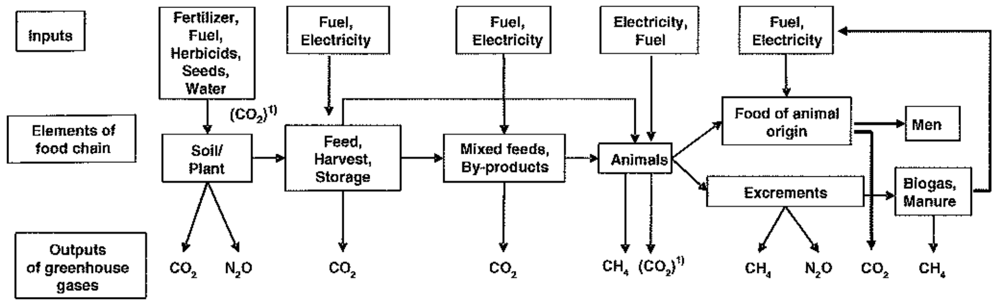

1) CO_2 will be fixed by photosynthesis and produced by animal metabolism, therefore it is considered as emissions-neutral

Figure 1. Substantial elements of the chain to produce food of animal origin as well as selected inputs of resources and outputs of greenhouse gases.

2.1. *Emissions from manufacturing resources*

The values of CO_2-emissions from fuel depend on the intensity of farm management especially from type and amount of fertiliser, but also from the plant yields and the expenditures for transportation, feed processing and animal keeping.

Table 1 summarises some values of CO_2-emissions from manufacturing resources under European conditions for various feeds by different authors. There is a considerable variation between feeds and authors. In most cases, organic farming shows lower CO_2-emissions per area and per product than conventional agriculture. The 0.12 kg CO_2 per kg dry matter (DM) of roughage and 0.22 kg CO_2 per kg DM of concentrate (average of some reviews, see Table 1) were used for further calculations of CF.

Less data are available for CO_2-emission for feed transportation and processing (see Bockisch et al. 2000; Feil 2005) and animal keeping (see HEA 1996; Bockisch et al. 2000; Brunsch et al. 2008; Hirschfeld et al. 2008). The LCAs have to include all energy and material inputs in the food chain (Peters et al. 2010). Further studies are required to quantify all processes.

2.2. *Animal caused emissions*

Methane (CH_4) is one of the most important greenhouse gas emissions from livestock production. Especially ruminants emit CH_4 as an unavoidable natural by-product of rumen fermentation because of their microbial settlement in the rumen (Figure 2). Mainly methane is produced from CO_2 and H_2 (see Baldwin 1995; Mills et al. 2001; Kebreab et al. 2006). On the other hand, and caused by the microbes, ruminants have very important potentials to convert cellulose and other low quality roughages as well as non-protein nitrogen-compounds in food of animal origin (e.g. milk and meat).

The methane amount varies between 4 and 10% (extreme values are given between 2 and 15%, see Flachowsky and Brade 2007) of the gross energy of the feed and depends on ration composition (Table 2) and added supplements with methane reduction potentials. The hindgut fermentation generally contributes to less than 10% to the total enteric CH_4-production (Kebreab et al. 2006). Apart from ruminants, non-ruminants also emit methane but to a much lower extent than ruminants (Table 3). About 40% of the global methane emission (≈240 Mio t) falls to animal husbandry. There are large differences between various regions (Table 4). Methane emissions arising from excrements may be reduced by utilisation of excrements for biogas-fermentation.

Recently many papers were published about the origin of methane, methane emission, influencing factors on methane fermentation and models to calculate methane emission (e.g. Kebreab et al. 2004; Flachowsky and Brade 2007; Tamminga et al. 2007; Bannink et al. 2008; Beauchemin et al. 2008; Ellis et al. 2008; Jouany 2008; Kreuzer and Soliva 2008; Mills 2008; Place and Mitloehner 2010). Therefore no further details should be discussed here.

Food producing animals do not excrete laughing gas (N_2O). They excrete various N-sources with

Table 1. Examples for CO_2-emissions from manufacturing resources of various feeds (by various authors).

Feed	CO_2-emission (kg/kg DM)	Authors
Roughages	0.07[a]	Bockisch et al. (2000)
Pasture/grass	0.22[a]	Bockisch et al. (2000)
	0.10	Brunsch et al. (2008)
	0.12–0.15	Kim and Dale (2004)
	0.10	Kraatz et al. (2006)
Grass silage	0.24[a]	Bockisch et al. (2000)
	0.09[a]	Bockisch et al. (2000)
	0.12	Brunsch et al. (2008)
	0.17	Kraatz et al. (2006)
Corn silage	0.09[a]	Bockisch et al. (2000)
	0.15[a]	Bockisch et al. (2000)
	0.12	Brunsch et al. (2008)
	0.15	Kraatz et al. (2006)
Hay	0.09[a]	Bockisch et al. (2000)
	0.25[a]	Bockisch et al. (2000)
	0.12	Brunsch et al. (2008)
	0.19	Kraatz et al. (2006)
Concentrates	0.27	Abel (1996)
Triticale	0.19[a]	Bockisch et al. (2000)
Corn	0.21[a]	Bockisch et al. (2000)
Barley	0.31[a]	Bockisch et al. (2000)
Wheat	0.26	Brunsch et al. (2008)
	0.32[a]	Brunsch et al. (2008)
	0.25–0.29	Kim and Dale (2004)
	0.20	Krataz et al. (2006)
	0.50[a]	Küstermann et al. (2007)
	0.36[a]	Küstermann et al. (2007)

[a]CO_{2eq} in organic farming.

different propensity to ammonia (NH_3)-formation (Figure 2). For example ammonia develops much faster from urea than from uric acid. Ammonia is considered as an important precursor for N_2O-formation (Figure 3), which depends mainly on microbial activities in the soil. Furthermore N_2O-formation is influenced by a source of N, soil quality, moisture, temperature and management of soil as summarised by Flachowsky and Lebzien (2007).

Normally the N_2O-emission depends on an amount of N-fertilisation (Table 5), but there also exist studies where the N_2O-emission is independent of the level of N-fertilisation (Oenema et al. 2005; Roelandt et al. 2005; Jungkunst et al. 2006). The N_2O-emission may vary between 0 and about 10% of N-amount given to the land (see Bockisch et al. 2000; Hirschfeld et al. 2008). Normally the IPCC (2006)-value of 1.25% of N transferred to N_2O-N in the soil is used for calculation of N-emissions from the soil. In some cases this average value may be wrong (Bockisch et al. 2000; Crutzen et al. 2007). Reduction of N-excretion via urine of animals would be an important contribution to lower N_2O-emissions (Flachowsky and Lebzien 2006; Arriaga et al. 2010; Calsamiglia et al. 2010).

2.3. Animal yields

Animal performance in terms of milk, meat or eggs is also considered as output and is the base for the CF per product. The edible fraction is in the case of milk and eggs clear, but there are some differences in the case of products from the animal body. Normally the hot standard carcass or the empty body is weighed in the slaughtering houses and in some studies (e.g. Fritsche and Eberle 2007; Hirschfeld et al. 2008) considered as meat. But the empty body also contains non-edible fractions such as bones, etc. Therefore it is really difficult to find out an adequate CF for meat or edible products from the animal body (Peters et al. 2010).

Edible protein of animal origin is one of the most important objectives of animal keeping in many countries. Based on feeding and slaughtering studies at our institute, edible protein was measured (see Flachowsky 2002) for various animal species and categories under consideration of animal performance, the edible fraction and the protein concentration of samples (see Table 6). There are large differences in edible protein per animal and day or per kg body weight and day depending on animal species and category as well as their performances and the fractions considered as edible.

2.4. Calculation of carbon footprints

The level of CF for food of animal origin depends primarily on the system limits (Figure 1); that means which emission sources will be considered for calculations and which animal yields are the basis for calculations. The principles to calculate CF are shown in Figure 4.

Table 7 demonstrates the calculations of CF for milk under consideration of fertiliser production, feeds, transport, processing, rumen fermentation and excrement management. Reproduction of cows, emissions from the previous achievements (e.g. machinery, cowshed, etc.), further processing, trade of milk and kitchen work have been not considered in the calculation of Table 7. About one-half up to two-thirds of total CF of milk and other ruminant products come from the enteric methane emission. Similar or higher values can be calculated for beef (see Tables 9 and 10) as well as sheep and goat meat (JRC 2010). Therefore studies to reduce the methane emissions from the rumen and to use methane from the excrement fermentation (see Table 4) have a high priority. Presently, many in vitro studies to lower methane emissions have been done (see Flachowsky and Brade 2007), but long-term in vivo studies are necessary to measure the sustainability of treatments

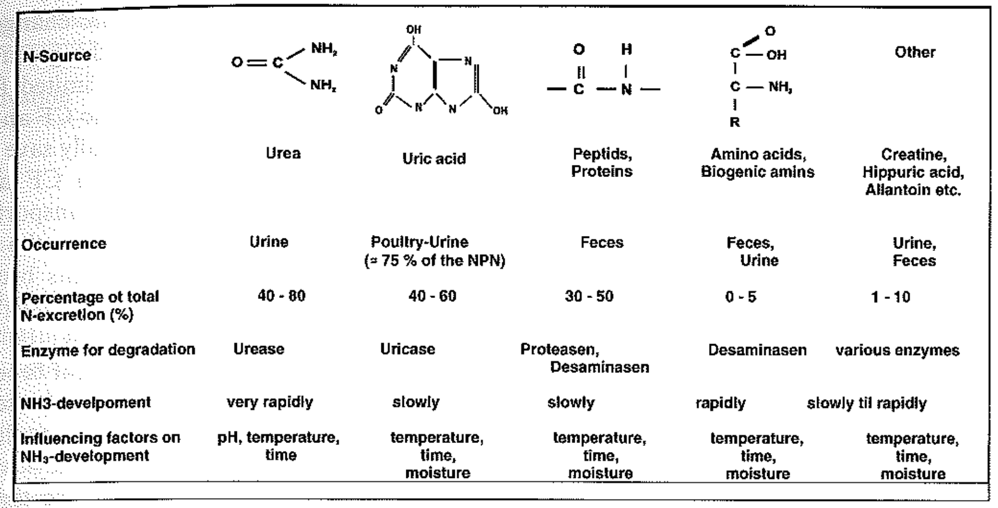

Figure 2. Important N-sources in excrements and their propensity to NH_3 – formation.

on methane reduction in animals (Flachowsky and Lebzien 2009).

3. Carbon footprints for various food of animal origin

All the factors mentioned above and further variables influence the level of CF and their range as shown in Table 8 for milk by various authors (0.4–1.5 kg CO_{2eq}/kg milk). FAO (2010) calculated CF across different world regions and found a range from 1.3 (in Europe and North America) to 7.5 kg (in sub-Saharan Africa) per kg of milk. The average global emission in the process of milk production, processing and transport was estimated to be 2.4 kg per kg. In fact, the wide impact possibilities and the high variability the precisions of some data are unexpected. For the EU the average for cow milk is given with 1.4 kgCO_{2eq}/kg (JRC 2010).

Mostly the highest CF and high variations are described for beef (Tables 9 and 10). The values are influenced by body weight gain, feeding and the system limits (Table 9). The highest values were measured with beef cows (Table 10). The base for calculations such as body weight gain, hot standard carcass weight or empty body weight, edible fraction, meat or edible protein has an important influence on the CF (Peters et al. 2010). In a recent publication,

Table 2. Methane per kg dry matter in dependence on ration composition of ruminants (by various authors).

Concentrate (%)	% of gross energy intake	g/kg DM-intake
Nearly 0	8–10	25–40
50	6–8	20–25
90	4–6	15–20

Peters et al. (2010) summarised CF from 18 studies and found values between 5.9 (pasture; Africa) and 25.5 kg CO_2-equivalents per kg empty body weight. Similar values were calculated in our own studies (Table 9). Once again, the grade of accuracy of the data raises questions.

Adequate values as shown in Tables 9 and 10 have been measured for mutton sheep meat (10.1–17.5; Peters et al. 2010). Similar calculations were done for pork, poultry meat and eggs (e.g. Williams et al. 2006; Fritsche and Eberle 2007; Heissenhuber 2007; Hirschfeld et al. 2008). The authors compared conventional with organic farming (Figure 5). The results are characterised by a high variation between food sources and authors. There is no clear tendency concerning production system. Fritsche and Eberle (2007) calculated lower CF for organic farming, but there were no clear trends in the studies of all other authors (Figure 5). In a recent EU-calculation (JRC 2010), the averages for beef, sheep and goat meat, pork, poultry meat and eggs in the EU-27 are given with 22, 20, 7.5, 5, and 3 kgCO_{2eq}/kg product.

Table 3. Methane emission by various animal species (by various authors).

Animal group	Methane-emission	
	% of gross energy intake (average and range)	g/kg DM-intake (average and range)
Ruminants	6–8 (2–15)	20–25 (10–40)
Horses	2–3 (1–5)	6–8 (2–12)
Pigs[a]	0.5 (0–2)	2–3 (0–8)
Poultry[b]	(0–0.3)	(0–1)

[a]Highest values in sows, lowest values in piglets.
[b]Higher values with more fibre in diets (e.g. forage for laying hens, ducks, geese).

Table 4. Methane emissions from food producing animals in various regions (in Mio. t/year, Steinfeld et al. 2006).

	Methane-emissions	
Region	Digestion	Excrement-management
Africa and West Asia	15.2	0.9
India	11.8	1.0
China	8.8	3.8
Other Asia	8.0	1.1
North America	5.0	3.4
Middle and South America	21.2	1.4
Oceania and Japan	3.3	0.4
East Europe	5.7	1.4
Others	0.9	0.1
West Europe	5.7	4.1
Total	85.6	17.8

The main objective of animal husbandry in many regions of the world is the production of edible protein in milk, meat and eggs. Food of animal origin contains, apart from important amino acids, important essential trace nutrients and is characterised by a high enjoyment value. Therefore animal protein may be considered as a base for the calculation of CF. From the scientific view, edible protein seems to be a suitable parameter to compare various ways of animal production from the view of feed/resource efficiency and emissions. Table 11 summarises emissions per kg edible protein of various animal species and categories in dependence on their performances.

On the base of edible protein, the highest CFs were calculated for beef, followed by milk from low yielding cows because of the methane emissions from ruminants (see Table 7).

4. Assessment of carbon footprints

Carbon footprints should sensitise producer and consumer in the efficient use of limited natural resources especially fuel and to a low emission of greenhouse gases. But the CF should not be overestimated because of some weaknesses. Presently there is an urgent need to fill out the gaps for such CF-calculations. Sometimes there are contrary discussions about the global climate change, especially on the significance of CO_2 for the greenhouse effect (see Keil 2009). But CO_2 from limited fossil energy sources contributes significantly to CF and, therefore, a reduction of CF may substantially save such energy sources. The correlation between CF and primary energy demand (energy for feed, transport, processing and animal keeping, etc.) is higher in the case of non-ruminants and lower for ruminants because of the methane emissions (Williams et al. 2006; Verge et al. 2008; JRC 2010; Peters et al. 2010).

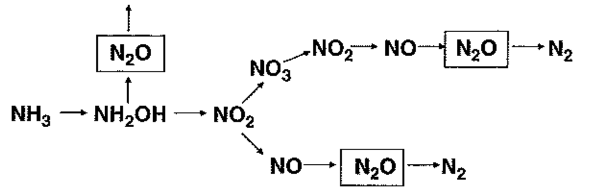

Figure 3. Laughing gas (N_2O) from ammonia (NH_3; by Wrage et al. 2001).

The assessments and rankings of foods of animal origin on the base of CF on the present stage of knowledge (Figure 5) may lead to preliminary and possible wrong conclusions for policy- and decision-makers. Furthermore there could be the impression that 'all things are clear' from the scientific point of view and there is no need for any further research. But the following research activities seem to be necessary to qualify and improve the CF:

- Further quantification of emissions along the food chain (see Figure 1) under consideration of influencing factors such as:
  - Better quantification of laughing gas emissions (see Figures 2 and 3)
  - Better quantification of manufacturing-caused emissions
  - Improvement on knowledge on enteric and management-caused methane emission
  - Standardisation of methods; clear definition of system borders (see Figure 1; Zehetmeier 2009; FAO 2010; JRC 2010)
- Improvement of knowledge to reduce emissions along the food chain (see Figure 1)
  - Lower CO_2-emissions
  - Reduction of N-excretion (especially urea-excretions by animals, see Figure 3)
  - Reduction of enteric methane emissions, use of excrements in biogas-fermentation
  - More in vivo studies to assess the emission reduction potential of various measurements (see Flachowsky and Lebzien 2009; Lopez et al. 2010)
- Assessment and consequences of 'modern' biotechnology on emissions (see Capper et al. 2008)

A cooperation of animal scientists (e.g. nutritionists, breeders, animal keepers, veterinarians, etc.) with scientists working in the fields of plant and feed science, ecology and economy seems to be necessary to solve the problems and to develop better and loadable CF.

But CF is only one way to assess and compare various foods of animal origin. Apart from low emissions, there is also a need for a more efficient use of limited natural resources such as arable land, water, fuel, phosphorus, etc. Furthermore many products such as grass, straw and other by-products from agriculture and food industry may be effectively used as feeds in animal nutrition especially in ruminant nutrition. Therefore, a more complex assessment of various ways to produce food of animal origin seems to be helpful and necessary. Figure 6 shows, on the base of a simple calculation, such an example for protein production by beef and pork. Six factors were considered in the spider web (fuel, area, water, phosphorus, CF and 'absolute' animal feed). Situation 1 is fixed as unfavourable, 0 would be the best situation. There is an urgent need for further development and improvement of such models (considering further factors, evaluation of factors, ways of calculation for total assessment, etc.). A total assessment would be possible by addition of individual values (0–1) or by calculation of the area in the spider web. Coming back to the examples in Figure 6, nearly the same total assessment value could be calculated for beef and pork under consideration of the values assumed in this simple model.

Table 5. N_2O-emissions in Germany from arable land and grassland in dependence of fertilising (Jungkunst et al. 2006).

Form of cultivation	Fertiliser	Number	Average (kg N_2O-N ha^{-1} a^{-1})	Minimum (kg N_2O-N ha^{-1} a^{-s1})	Maximum (kg N_2O-N ha^{-1} a^{-1})
Arable land	–	9	1.35	0.04	2.50
	+	50	4.85	0.07	17.10
Grassland	–	16	1.18	0.10	3.40
	+	28	2.15	0.30	10.00

5. Reduction potentials and research need

Carbon footprints and their influencing factors should be considered along the whole food chain (see Figure 1). For reduction of CF and research needs, one may distinguish into short (see chapter 4), medium and long-term programmes. The introduction of known and resource-efficient management factors in the present farming systems should be considered as short-term measures. Topics of present research and their introduction into farms are on the middle-term time scale. Research for the future and the application of those results to farms are on the long-term scale.

The following paragraphs will analyse the inputs of limited resources in plants for feed production and of feed to food-producing animals and their outputs from the view of animal nutrition. Furthermore it will find solutions for lower inputs and environmental

Table 6. Influence of animal species, categories and performances on yield of edible protein (by Flachowsky 2002).

Protein source (body weight)	Performance per day	Dry matter intake (kg per day)	Roughage to concentrate ratio (on DM base, %)	Edible fraction (% of product or body mass)	Protein in edible fraction (g per kg fresh matter)	Edible protein (g per day)	Edible protein (g per kg body weight)
Dairy cow (650 kg)	10 kg milk	12	90/10	95	34	323	0.7
	20 kg milk	16	75/25			646	1.0
	40 kg milk	25	50/50			1292	2.0
Dairy goat (60 kg)	2 kg milk	2	80/20	95	36	68	1.1
	5 kg milk	2.5	50/50			170	2.8
Beef cattle (350 kg)	500 g[a]	6.5	95/5	50	190	48	0.14
	1000 g[a]	7.0	85/15			95	0.27
	1500 g[a]	7.5	70/30			143	0.41
Growing/fattening pig (80 kg)	500 g[a]	1.8	20/80	60	150	45	0.56
	700 g[a]	2	10/90			63	0.8
	1000 g[a]	2.2	0/100			81	1.0
Broiler (1.5 kg)	40 g[a]	0.07	10/90	60	200	4.8	3.2
	60 g[a]	0.08	0/100			7.2	4.8
Laying hen (1.8 kg)	50%[b]	0.10	20/80	95	120	3.4	1.9
	70%[b]	0.11	10/90			4.8	2.7
	90%[b]	0.12	0/100			6.2	3.4

[a]Daily weight gain.
[b]Laying performance.

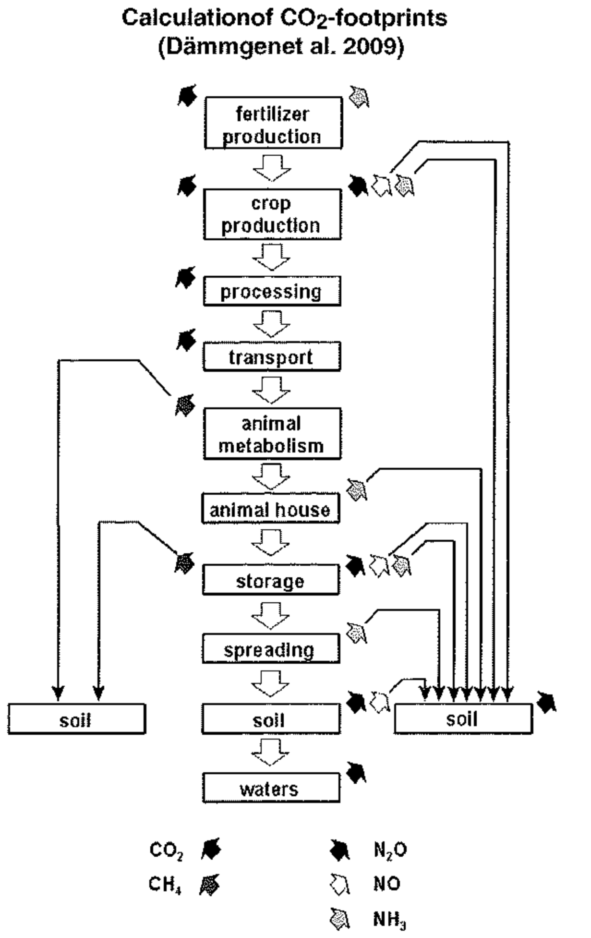

Figure 4. Calculation of CO_2-footprints (by Daemmgen et al. 2009).

Table 7. Calculation of emissions per cow and year (parameters: body weight: 650 kg per cow, milk yield: 8000 kg per year, 1 calf per year, Daemmgen and Haenel 2008).

	Emissions (kg per cow per year)		
Source of emissions	CO_2	CH_4	N_2O
Fertiliser	210	5.5	1.1
Feed	83		1.2
Transport treatment	43		
Rumen fermentation		119	
Fermentation of excrement management		19	0.9
Emissions from soil		1	1.8
Total	336	143	5
CO_2-equivalents (kg/cow and year)	5200		
(g/kg milk)[a]	650		
CO_2-Equivalents of emission (kg/cow)	336	3290	1500
(% of total emissions)	6	65	29

[a]Without calf and heifer.

Table 8. CF per kg milk in dependence on type of production (by various authors).

Type of production		
Conventional ($kg\ CO_{2eq}$/kg milk)	Organic	Authors
0.40 (40 kg milk/day)		Own data (2008)
0.55 (20 kg milk/day)		Own data (2008)
1.00 (10 kg milk/day)		Own data (2008)
0.65 (not given)		Daemmgen and Haenel (2008)
0.65–0.75		Basset-Mens et al. (2009)
1.00		Cederberg et al. (2009)
1.35		Capper et al. (2008)
2.4 (1.3–7.5)		FAO (2010)
1–2 (Europe, North America)		FAO (2010)
3.7 North Africa, Near East		FAO (2010)
4.6 (South Africa)		FAO (2010)
7.5 (sub-Saharian Africa)		FAO (2010)
0.83	0.84	Woitowicz (2007)
0.85	0.78	Hirschfeld et al. (2008)
0.89	1.13	Fritsche and Eberle (2007)
0.94	0.88	Fritsche and Eberle (2007)
0.97	1.13	van der Zijpp (2001)
0.99	0.94	Cederberg and Mattsson (2000)
1.06	1.23	Williams et al. (2006)
1.30	1.30	Haas et al. (2001)
1.40	1.50	Thomassen et al. (2008)

unfriendly outputs. The efficient use of limited natural resources, food security and environmental issues are strongly connected issues with long-term significance. Recently some international organisations or research teams (e.g. Steinfeld et al. 2006; Koning et al. 2008; SCAR 2008; Bruinsma 2009; FAO 2009; Fischer 2009; The Royal Society 2009; Godfray et al. 2010) have analysed and assessed the present and future global situation. These studies conclude for future research needs and priorities. Unfortunately, most attention has been paid to plant science and no, or less, attention has been given to the improvement of food-producing animals.

5.1. Wishes to plant breeders

Phytogenic biomass by the photosynthesis of plants is the basis for animal and human beings. The better utilisation of sun energy and plant nutrients such as CO_2, N_2, P, etc., water, and various trace elements must be the most important objectives for plant breeding and biotechnology in the future (The Royal

Table 9. Calculations of CF for beef (150–550 kg body weight) in dependence on weight gain, feeding, methane- and N-emissions (Flachowsky 2008b).

						CO_{2eq} (kg/kg)		
Weight gain (g/day)	Feed intake (kg/DM/ animal and day	Portion concentrate (% of DM-intake)[a]	Methane emissions (g/kg DM)	N-excretion (g/day)	N_2O-synthesis (% of N-excretion)	Weight gain	Empty body gain	Edible fraction
500 (Pasture, no concentrate)	6.5	0	26	110	2	11.5	23.0	28.0
1000 (Indoor, grass silage, some concentrate)	7.0	15	24	130	1	5.5	11.0	13.8
1500 (Indoor, corn silage, concentrate)	7.5	30	22	150	0.5	3.5	7.0	9.0

[a]CO_2-output: 120 g/kg roughage-DM and 220 g/kg concentrate-DM.

Society 2009). So-called low input varieties should be the basis for the second green revolution (SCAR 2008; The Royal Society 2009; Fedoroff et al. 2010) for more efficient utilisation of limited resources and lower emissions along the food chain (see Figure 1). Fixation of nitrogen from the air (similar to legumes) should also be an aim of plant breeding (see Table 12). Furthermore, the plants must be resistant against biotic and abiotic stressors and the losses during harvesting and plant storage, and processing to feed and food must be decreased by new breeding technologies (Tester and Langridge 2010). The expectations for plant breeders from the global perspective and the view of animal nutritionists can be summarised as followed (by Flachowsky 2008a, see Table 12):

- Efficient use of limited natural resources such as water, fuel, land or crude mineral resources (low input varieties)

Table 10. CF per kg empty body gain of beef cattle in dependence on type of production (by various authors).

CF ($kg\ CO_{2eq}$/kg empty body weight gain)		
Type of production		
Conventional	Organic	Authors
8.5	29.0 (beef cows)	Reitmayr (1995)
8.7/10.1	10.2	Woitowicz (2007)
9.9 (grain finished)	12.0 (grass finished)	Peters et al. (2010)
13.3	11.4	Fritsche and Eberle (2007)
15.8	18.2	Williams et al. (2006)
15.2	17.5	Schlich and Fleissner (2005)
23.6	20.2	Casey and Holden (2006)
24.5	20.9	Subak (1999)
No distinction conventional/organic		
5.9–10.4		Verge et al. (2008)
7.0–23.0		Flachowsky (2008b)
10.1		Cederberg and Stadig (2003)
11.5		Wechselberger (2000)
15.6		Casey and Holden (2006)
15.6 (dairy cows, bulls)		FAO (2010)
20.2 (beef cows, calves)		FAO (2010)
36.4 (beef cows, fattening bulls; 40% meat yield)		Ogino et al. (2007)

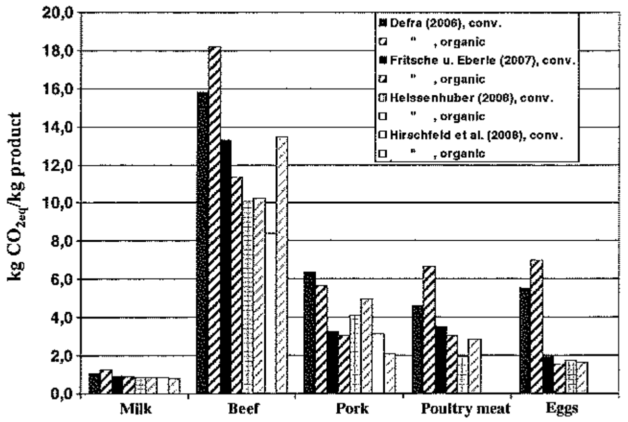

Figure 5. CF of food of animal origin from conventional and organic farming by various authors.

- Higher energy and nutrient yield per limited resource
- Intensive use of unlimited resources such as N_2, CO_2, sun energy and the genetic pool
- Higher resistance to plant and animal pests as well as abiotic factors (e.g. drought, salinity)
- Reduction in the content of undesired (antinutritive) components (e.g. substances that influence the availability of nutrients, toxic substances, mycotoxins, etc.)
- Increase in the content of value-determining components (e.g. nutrient precursors, nutrients, enzymes, probiotics, flavourings)

The plant breeders should react to the changed natural conditions (e.g. more CO_2) and to the limited natural resources as shown in Table 12.

5.2. *Wishes to animal breeders*

Animal breeders made some progress in genetic modification of domestic animals in recent years (Robi et al. 2007). Up to now much attention has been devoted to applications in biomedicine as recently summarised by Kues and Niemann (2004) and Niemann and Kues (2007), but a more efficient conversion of food into milk, meat and eggs and lower emission were not intensively considered by animal breeders (Reynolds 2009). Various possibilities exist to modify animals for a better utilisation of feed into food of animal origin and as a consequence to have lower emissions per product as summarised below:

- Higher feed intake of animals to improve the ratio between energy/nutrient requirements for maintenance and animal yields (see 'Energy and Nutrient Requirements' of various scientific societies)
- Higher digestibility of feed to make energy/nutrients more available from the feed (higher expression of enzymes or more efficient enzymes in the animals); higher absorption of digested nutrients
- Reduction of energy losses in the digestive tract (e.g. CH_4)

Table 11. Influence of animal species, categories and performances on emissions (per kg edible protein, own calculations).

Protein source (Body weight)	Performance per day	N-excretion (% of intake)	Methane emission (g per day)[c]	Emissions in kg per kg protein: *P*	*N*	CH_4[c]	CO_{2eq}
Dairy cow (650 kg)	10 kg milk	75	310	0.10	0.65	1.0	. 30
	20 kg milk	70	380	0.06	0.44	0.6	16
	40 kg milk	65	520	0.04	0.24	0.4	12
Dairy goat (60 kg)	2 kg milk	75	50	0.08	0.5	0.8	20
	5 kg milk	65	60	0.04	0.2	0.4	10
Beef cattle (350 kg)	500 g[a]	90	170	0.30	2.3	3.5	110
	1000 g[a]	84	175	0.18	1.3	1.7	55
	1500 g[a]	80	180	0.14	1.0	1.2	35
Growing/fattening pig (80 kg)	500 g[a]	85	5	0.20	1.0	0.12	16
	700 g[a]	80	5	0.12	0.7	0.08	12
	900 g[a]	75	5	0.09	0.55	0.05	10
Broilers (1.5 kg)	40 g[a]	70	Traces	0.04	0.35	0.01	4
	60 g[a]	60		0.03	0.25	0.01	3
Laying hen (1.8 kg)	50%[b]	80	Traces	0.12	0.6	0.03	7
	70%[b]	65		0.07	0.4	0.02	5
	90%[b]	55		0.05	0.3	0.02	3

[a]Daily weight gain.
[b]Laying performance.
[c]CH_4-emission depending on composition of diet.

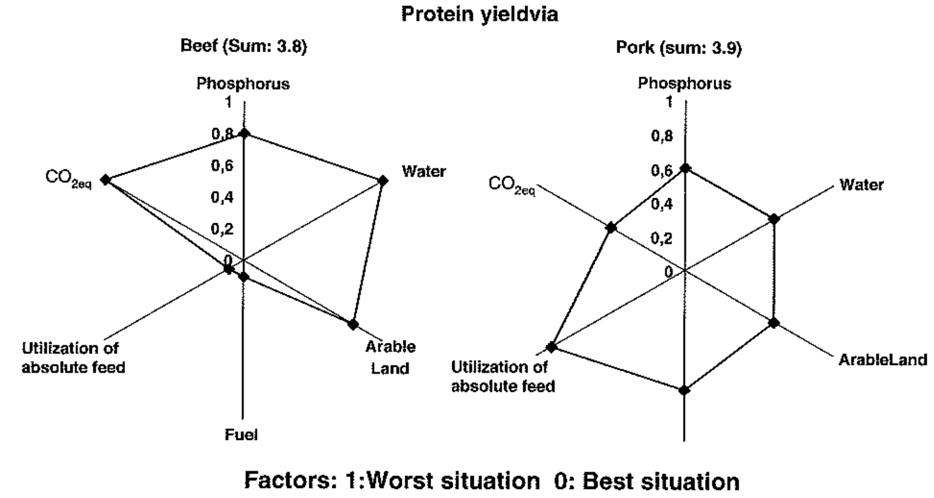

Figure 6. Proposal of complex assessment of production of protein of animal origin on the base of beef and pork under consideration of various parameters.

- Lower energy/nutrient requirements for maintenance of animals
- Lower energy need for protein synthesis in the body or increase of anabolic processes and lower catabolic processes in the animal
- Lower fat content in animal bodies, lower excretion of fat in milk and eggs, or lower excretion of lactose in milk (lower energy content in food of animal origin)

An improvement of animal health, more stability against biotic and/or abiotic stressors, and lower animal losses may also contribute to a more efficient conversion of feed into food and lower emissions per product. Special attention must be spent to the welfare and the nutrition of such modified animals (Maga and Murray 2010).

Research activities mentioned above could be considered as sustainable on the long-term scale. They are the basis for a more efficient conversion of limited resources into plant biomass and animal products and also for lower emissions per unit milk, meat and eggs or per kg edible protein of animal origin.

Table 12. Potentials to produce phytogenic biomass and their availability per inhabitant under consideration of increase of population (Flachowsky 2010).

Plant nutrients in the atmosphere (N_2, CO_2)	↑↔
Sun energy	↔
Agricultural area	↓
Water	↓
Fossil energy	↓
Mineral plant nutrients	↓
Variation of genetic pool	↑

↑ Increase, ↓ Decrease, ↔ no important influence.

6. Conclusion

At the present stage of knowledge, ranking of food of animal origin on the basis of CO_{2eq}-footprints may be indicative of product produce and CF, but may also lead to wrong conclusions in the absence of complete information on the chain of production and processing. The database for CF needs to be improved before it may contribute to the assessment of greenhouse gas emissions during the primary production of food of animal origin. Further factors such as limited natural resources or utilisation of grassland or agricultural/industrial by-products should be considered for a complex assessment of various production systems in future. More attention should be given on reduction potentials and research for a more efficient conversion of natural resources in feed and food and in consequence to lower emissions per product and more interdisciplinary cooperation.

References

Abel HJ. 1996. Energieaufwand und CO_2-Ausstoß bei verschiedenen Formen der Lebensmittelerzeugung [Energy expenditure and CO_2.emission for various forms of food production]. Schriftenreihe der Schaumann-Stiftung zur Förderung der Agrarwissenschaften. Hülsenberger Gespräche 16:153–161.
Arriaga H, Salcedo G, Martinez-Suller S, Calsamiglia S, Merino P. 2010. Effect of dietary crude protein modification on ammonia and nitrous oxide concentration on a tie-stall dairy barn floor. Journal of Dairy Science 93:3158–3165.
Baldwin RL. 1995. Modelling ruminant digestion and metabolism. London (UK): Chapman and Hall.
Bannink A, France J, Lopez S, Gerrits WJJ, Kebreab E, Tamminga S, Dijkstra J. 2008. Modelling the implication of feeding strategy on rumen fermentation and

functioning of the rumen wall. Animal Feed Science and Technology 143:3–26.
Basset-Mens C, Ledgard S, Boyes M. 2009. Eco-efficiency of intensification scenarios for milk production in New Zealand. Ecological Economics 68:1615–1625.
Basset-Mens C, van der Werf HMG. 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. Agriculture, Ecosystems and Environment 105:127–144.
Beauchemin KA, Kreuzer M, O'Mara F, McAllister TA. 2008. Nutritional management for enteric methane abatement: a review. Australian Journal of Experimental Agriculture 48:21–27.
Bockisch FJ, Ahlgrimm HJ, Böhme H, Bramm A, Dämmgen U, Flachowsky G, Heinemeyer O, Höppner F, Murphy DPL, Rogasik J, et al. 2000. Bewertung von Verfahren der ökologischen und konventionellen landwirtschaftlichen Produktion im Hinblick auf Energieeinsatz und bestimmte Schadgasemissionen, Landbauf [Assessment of organic and conventional agriculture under consideration of energy use and gas emissions]. Völkenrode, SH 211, 206 p.
Bruinsma J. 2009. The resource outlook to 2050: by how much do land, water use and crop yields need to increase by 2050? Proceedings of FAO Expert Meeting on How to Feed the World in 2050; 2009 June 24–26; Rome, Italy. Available from: www.fao.org.
Brunsch R, Kraatz S, Berg W, Rus C. 2008. Ermittlung der Energieeffizienz in der Tierhaltung auf der Grundlage von Energiebilanzen [Calculation of energy efficiency in animal husbandry on the basis of energy balances]. KTBL-Schrift 463:115–125.
Calsamiglia S, Ferret A, Reynolds CK, Kristensen NB, van Vuuren AM. 2010. Strategies for optimizing nitrogen use by ruminants. Animal 4:1184–1196.
Capper JL, Castaneda-Gutierre E, Cady RA, Bauman DE. 2008. The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. Proceedings of the National Academy of Sciences USA 105:9668–9673.
Casey JW, Holden NM. 2006. Greenhouse gas emission from conventional, agri-environmental scheme and organic Irish suckler-beef units. Journal of Environmental Quality 35:231–239.
Cederberg C, Sonesson U, Henriksson M, Sund V, Davis J. 2009. Greenhouse gas emissions from Swedish production of meat, milk and eggs 1990 and 2005. Goeteborg (Sweden): SIK, The Swedish Institute for Food and Biotechnology.
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.
Cederberg C, Mattson B. 2000. Life cycle assessment of milk production – A comparison of conventional and organic farming. Journal of Cleaner Production, 8 (1), 350–356.
Crutzen PJ, Mosier AR, Smith KA, Winiwarter W. 2007. N_2O-release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics Discussion 7:1191–1205.
Daemmgen U, Brade W, Haenel HD, Rosemann C, Doehler H. 2009. Modelling CO_2-footprints and trace gas emissions for milk protein produced under varying performance and feeding conditions. Proceedings of the 60th Annual EAAP-Meeting; 2009 Aug 24–28; Barcelona, Spain.
Daemmgen U, Haenel HD. 2008. Emissions of greenhouse gases and gaseous air pollutants – a challenge for animal nutrition. Proceedings of the Society of Nutrition Physiology 17:163–167.
Ellis JL, Dijkstra J, Kebreab E, Bannink A, Odongo NE, McBride BW, France J. 2008. Aspects of rumen microbiology central to mechanistic modelling of methane production in cattle. Journal of Agricultural Science 146:213–233
FAO. 2009. The state of food and agriculture – livestock in the balance. Rome (Italy): Food and Agriculture Organization, 180 p.
FAO. 2010. Greenhouse gas emissions from the dairy sector. A life cycle assessment. Rome (Italy): Food and Agriculture Organization, 94 p.
Fedoroff NV, Battisti DS, Beachy RN, Cooper PJM, Fischhoff DA, Hodges PC, Knauf VC, Lobell D, Mazur BJ, Molden D, et al. 2010. Radically rethinking agriculture for the 21st century. Science 327:833–834.
Feil A. 2005. IFF-Kolloquium 2005 – Sind Maßnahmen zur Reduzierung der Energiekosten denkbar? [Do we have measurements to reduce energy costs?] Aufbereitungstechnik 46:11, 52–56.
Fischer G. 2009. World food and agriculture to 2030/50: how do climate change and bioenergy alter the long-term outlook for food, agriculture and resource availability? Proceedings of FAO Expert Meeting on How to Feed the World in 2050; 2009 June 24–26; Rome, Italy. Available from: www.fao.org.
Flachowsky G. 2002. Efficiency of energy and nutrient use in the production of edible protein of animal origin. Journal of Applied Animal Research 22:1–24.
Flachowsky G. 2008a. What do animal nutritionists expect from plant breeding? Outlook on Agriculture 37:95–103.
Flachowsky G. 2008b. Treibhausgase und Ressourceneffizienz. Aspekte der Erzeugung von Lebensmitteln tierischer Herkunft[Greenhouse gases and resource efficiency: Aspects of production of food of animal origin]. Ernährungsumschau 55:414–419.
Flachowsky G. 2010. Globale Ernährungssicherung: Land in Sicht? [Global food security: Is there any solution?] Novoargumente 105:64–68.
Flachowsky G, Brade W. 2007. Potenziale zur Reduzierung der Methan-Emmission bei Wiederkäuern [Potentials to reduce methane emissions in ruminants]. Züchtungskd 79:417–465.
Flachowsky G, Lebzien P. 2006. Possibilities for reduction of nitrogen (N) excretion from ruminants and the need for further research – a review. Landbauforschung Völkenrode 56:19–30.
Flachowsky G, Lebzien P. 2007. Lebensmittal liefernde Tiere and Triebhausgase – Mäglichkeiten der Tierernährung zur Emissionminderung [Food producing animals and greenhouse gases: possibilities of animal nutrition to reduce emissions]. Übersicht Tierern 35:191–231.
Flachowsky G, Lebzien P. 2009. Comments on in vitro studies with methane inhibitors. Animal Feed Science and Technology 151:337–339.
Fritsche R, Eberle U. 2007. Treibhausgasemissionen durch Erzeugung und Verarbeitung von Lebensmitteln. Arbeitspapier, Öko-Institut e.V. Darmstadt, 13 p.

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Wawrence D, Muir J, Pretty J, Robinson S, Thomas SM, Toulmin C. 2010. Food security: the challenge of feeding 9 billion people. Science 327:812–818.
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.
HEA (Hauptverwaltungsstelle für Elektrizitätsanwendung e.V.) [Electricity – Recommendations for farmers]. 1996. Strom – Tips für Landwirte. HEA (Hrsg.), Energieverlag GmbH, Heidelberg, S. 14 ff.
Heissenhuber A. 2007. Ökonomische Aspekte einer energieeffizienten Landwirtschaft [Economic aspects of energy efficiency in agriculture]. KTBL-Vortragstagung, 08./09.04.2008, Fulda, KTBL-Schrift 463:42–53.
Hirschfeld J, Weiß J, Precht M, Korbun T. 2008. Klimawirkungen der Landwirtschaft in Deutschland [Climatic effects of agriculture in Germany]. Schriftenreihe des IÖW 186/08, Berlin, 188 p.
IDF (International Dairy Federation). 2010. A common carbon footprint approach for dairy. The IDF guide to standard lifecycle assessment methodology for the dairy sector. Bulletin of the International Dairy Federation 445:41.
IPCC (Intergovernmental Panel on Climate Change). 2006. IPCC guidelines for national greenhouse gas inventories. Vol. 4. Agriculture, forestry and other land use. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006/gl/vol4.htm.
Isermeyer F, Otte A, Christen O, Frohberg K, Hartung J, Kirschke D, Schmitz M, Sundrum A. 2008. Nutzung von Biomasse zur Energiegewinnung – Empfehlungen an die Politik, Gutachten [Use of biomass for energy - Recommendations for policy]. Berichte über Landwirtschaft, SH 116, 198 p.
Jouany JP. 2008. Enteric methane production by ruminants and its control. In: Andrieu A, Wilde D, editors. Gut efficiency; the key ingredient in ruminant production. The Netherlands: Wageningen Academic Publishers. p. 35–59.
JRC (Joint Research Centre). 2010. Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS) – final report. Ispra (Italy), 32 p.
Jungkunst HF, Freibauer A, Neufeldt H, Bareth G. 2006. Nitrous oxide emissions from agricultural land use in Germany – a synthesis of available annual field data. Journal of Plant Nutrition and Soil Science 169:341–351.
Kebreab E, Clark K, Wagner-Riddle K, France J. 2006. Methane and nitrous oxide emissions from Canadian agriculture. A review. Canadian Journal of Animal Science 86:135–158.
Kebreab E, Mills JAN, Crompton LA, Bannink A, Dijkstra J, Gerrits WJJ, 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.
Keil G. 2009. Klimakonferenz Kopenhagan – Der Weltuntergang fällt aus! [Climate Conference Copenhagen: The end of the world will be cancelled]. NovoArgumente 103:48–53.
Kim S, Dale BE. 2004. Cumulative energy and global warming impact from the production of biomass for biobased products. Journal of Industrial Ecology 7:147–162.
Koning NBJ, van Ittersum MK, Becx GA, van Boekel MAJS, Brandenburg WA, van den Broek JA, Goudriaan J, van Hofwegen G, Jongeneel RA, Schiere JB, et al. 2008. Long-term global availability of food: continued abundance or new scarcity. NJAS 55:229–281.
Kraatz S, Berg W, Küstermann B, Hülsbergen KJ. 2006. Energy and carbon balancing in livestock keeping. Proceedings of the World Congress: Agricultural Engineering for a Better World Congress. Bonn, 2006 Sep 3–7; VDI-Berichte Nr. 1958. Düsseldorf (Germany): VDI-Verlag, p. 417–418.
Kreuzer M, Soliva CR. 2008. Nutrition: key to methane mitigation in ruminants. Proceedings of the Society of Nutrition Physiology 17:168–171.
Kues WA, Niemann H. 2004. The contribution of farm animals to human health. Trends in Biotechnology 22:286–294.
Küstermann B, Kainz M, Hülsbergen K.-J. 2007. Modelling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems. Renewable Agriculture and Food Systems 23:1–16.
Lopez S, Makkar HPS, Soliva CR. 2010. Screening plants and plant products for methane inhibitors. In: Vercoe PE, Makkar HPS, Schlink AC, editors. In vitro screening of plant resources for extra-nutritional attributes in ruminants: nuclear and related methodologies. New York: Springer, p. 191–231.
Maga EA, Murray J. 2010. Welfare applications of genetically engineered animals for use in agriculture. Journal of Animal Science 88:1588–1591.
Mills JAN. 2008. Modelling methane emission from farm animals. In: France J, Kebreab A, editors. Mathematical modelling in animal nutrition. Wallingford (UK): CABI Publishing, p. 189–203.
Mills JAN, Dijkstra J, Bannink A, Cammell SB, Kebreab E, France J. 2001. A mechanistic model of whole-tract digestion and methanogenesis in the lactating dairy cow: model development, evaluation and application. Journal of Animal Science 79:1584–1597.
Niemann H, Kues W. 2007. Transgenic farm animals: an update. Reproduction, Fertility, and Development 19:762–770.
Oenema O, Wrage N, Velthof GL, van Groeningen JW, Dolfing J, Kuikman PJ. 2005. Trends in global nitrous oxide emissions from animal production systems. Nutrient Cycling in Agroecosystems 72:51–65.
Ogino A, Orito H, Shimada K, Hirooka H. 2007. Evaluating environmental impacts of the Japanese beef cow-calf system by the life cycle assessment method. Animal Science Journal 78:424–432.
Peters GM, Rowley HS, Wiedemann S, Tucker R, Short MD, Schulz M. 2010. Red meat production in Australia: life cycle assessment and comparisons with overseas studies. Environmental Science & Technology 44:1327–1332.
Place SE, Mitloehner FM. 2010. Invited review: contemporary environmental issues: a review of the dairy industry's role in climate change and air quality and the potential of mitigation through improved production efficiency. Journal of Dairy Science 93:3407–3416.
Reitmayr T. 1995. Entwicklung eines rechnergeschtützten Kennzahlensystems zur ökonomischen und

ökologischen Beurteilung von agrarischen Bewirtschaftungsformen – Dargestellt an einem Beispiel [Development of a computer based data system for economic and ecological assessment of agricultural systems – Demonstrated with an example]. Agrarwirtschaft, Frankfurt/Main, SH 147.

Reynolds LP. 2009. Perspectives: the decline of domestic animal research in agriculture and biomedicine. Journal of Animal Science [Internet]. [cited 2009 Aug 14]; doi:10.2577/jas.2009-2102.

Robi JM, Wang P, Kasinathan P, Kuroiwa P. 2007. Transgenic animal production and animal biotechnology. Theriogenology 67:127–133.

Roelandt C, van Wesemael B, Rounsevelli M. 2005. Estimation annual N_2O-emissions from agricultural soils in temperature climates. Global Change Biology 11:1701–1711.

Rotz CA, Montes F, Chianese DS. 2010. The carbon footprint of dairy production systems through partial life cycle assessment. Journal of Dairy Science 93:1266–1282.

SCAR EU Commission – Standing Committee on Agricultural Research. 2008. New challenges for agricultural research: climate change, food security, rural development, agricultural knowledge systems. The 2nd SCAR Foresight Exercise; 2008 Dec; Brussels, 112 p.

Schlich EH, Fleissner U. 2005. The ecology of scale: assessment of regional energy turnover and comparison with global food. International Journal of Life Cycle Assessment 10:219–223.

Steinfeld D, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C. 2006. Livestock's long shadow. Environmental issues and options. Rome (Italy): food and agriculture organization of the UN. Available from: http://www.virtualcentre.org/on/library/key.pub/longshad/AO701EOO.pdf.

Subak S. 1999. Global environmental cost of beef production. Ecological Economics 30:79–91.

Tamminga S, Bannink K, Dijkstra J, Zorn R. 2007. Feeding strategies to reduce methane loss in cattle. Report 34. The Netherlands: Animal Science Group, Wageningen University, 44 p.

Tester, M, Langridge P. 2010. Breeding technologies to increase crop production in a changing world. Science 327:818–822.

The Royal Society. 2009. Reaping the benefits: science and the sustainable intensification of global agriculture. RS Policy document 11/09, issued: Oct. 209 RS 1608, ISBN: 978-0-85403-784-1, 64 p.

Thomassen MA, van Calker KJ, Smits MCJ, Iepema GL, de Boer IJM. 2008. Life cycle assessment of conventional and organic milk production in the Netherlands. Agricultural Systems 96:95–107.

van der Zijpp IAJ. 2001. Animal production systems: on integration and diversity [Habil. thesis]. The Netherlands: Wageningen University.

Verge XPC, Dyer JA, Desjardins RI, Worth D. 2008. Greenhouse gas emissions from the Canadian beef industry. Agricultural Systems 98:126–134.

Wechselberger P, 2000. Ökonomische und ókologische Beurteilung unterschiedlicher landwirtschaftlicher Bewirtschaftungsmaβnahmen und – systeme anhand ausgewählter Kriterien [Economic and ecological assessment of different agricultural management measurements and systems on the base of various parameters]. FAM–Bericht, Shaker–Verlag, Aachen, 502p.

Williams AG, Audsley E, Sanders DL. 2006. Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Main Report. Defra Research Project IS0205, Bedford (UK): Cranfield University and Defra, 97 p. Available from: www.silsoe.cranfied.ac.uk and www.defra.gov.uk

Woitowicz A. 2007. Auswirkungen einer Einschränkung des Verzehrs von Lebensmitteln tierischer Herkunft auf ausgewählte Nachhaltigkeitsindikatoren – dargestellt am Beispiel konventioneller und ökologischer Wirtschaftsweise [Consequences of lower consumption of food of animal origin on selected indicators of sustainability – demonstrated with conventional and organic farming]. Diss., TU München, 237 p.

Wrage N, Velthof GL, van Beusichem ML, Oenema O. 2001. Role of nutrifier denitrification in the production of nitrous oxide. Soil Biology and Biochemistry 33:1723–1732.

Zehetmeier M. 2009. Einfluss einer Leistungssteigerung in der Milchviehhaltung uf ausgewählte Parameter. Schriftenreihe aus den Inst [Influence of higher milk yield on selected parameters]. Für Nutztierwissenschaften, ETH Zürich, Bd. 32:155–160.