Animal Review
2015 Vol. 2, No. 2, pp. 19-57
ISSN(e): 2409-6490
ISSN(p): 2412-3382
DOI: 10.18488/journal.ar/2015.2.2/101.2.19.57

CLIMATE RELEVANT EMISSIONS FROM ANIMAL PRODUCTION AND REDUCTION POTENTIALS

Gerhard Flachowsky[1] --- Dirk von Soosten[2] --- Ulrich Meyer[3]*

[1,2,3]*Institute of Animal Nutrition Friedrich-Loeffler-Institut (FLI) Federal Research Institute for Animal Health Bundesallee, Braunschweig Germany*

ABSTRACT

Animal production contributes substantially to global greenhouse gas emissions (about 14.5%). The so-called Carbon Footprint (CF) considers the greenhouse gas potential of climate relevant gases (e.g., CO_2 *x 1;* CH_4 *x 23;* N_2O *x 296) and is given in* $CO_{2\text{-}eq}$ *per g or kg product or per unit edible protein. The CF may help to assess the greenhouse gas emissions associated with the production of foods of animal origin such as milk, meat, eggs or fish. The CF may contribute to sensitizing producers and consumers to a more resource-efficient and environmentally-friendly production, to the consumption of food of animal origin, and to avoiding food wastage. The highest CF per unit edible protein is calculated for products of growing ruminants (beef and lamb), followed by milk and pork and eggs and poultry meat with the lowest values. Discrepancies in the results of various studies are mainly explained by different system boundaries, allocation methods and computation of emissions, especially with regard to land use changes, enteric methane emissions and nitrous oxide emissions. A more standardized approach for data collection and CF-calculations would be a very useful tool to compare CF between production systems, regions and countries, and an indicator for food labelling, and is considered in the first part of this paper. The second part of the paper deals with the potential to reduce climate relevant gases from animal production. Some specific influencing factors, such as plant and animal breeding, feed production, animal feeding as well as animal keeping, animal health and excrement management are analysed more in detail. Most attention has been spent to the methane reduction potentials in the rumen. The reduction of CF in ruminant production per product should focus on a lowering of methane emissions from enteric fermentation and an increase of low production levels as well a reduction of ineffective animal numbers. In the future, results of plant and animal breeding may also substantially contribute to lower GHG emissions. Furthermore, new potentials to improve protein supply for human nutrition should be used. The production of food of animal origin is a very complex process and selective consideration, i.e., focussing on single factors, does not provide an assessment that reflects the complexity of the subject. Recommendations for further research activities are given.*

---

† Corresponding author

Keywords: Greenhouse gas emissions, Carbon footprints, Reduction potentials, Animals, Milk, Meat, Eggs, Aquaculture, Edible protein.

Received: 6 November 2014/ **Revised:** 24 March 2015/ **Accepted:** 28 March 2015/ **Published:** 2 April 2015

1. INTRODUCTION

More people and higher need for feed and food are associated with a growing demand for limited natural resources such as water, fuel, minerals, arable land, etc., and elevated emissions with greenhouse gas (GHG) potential such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (laughing gas; N_2O) and other substances (e.g., N, P, trace elements etc.). According to the [1, 2], the human population will increase globally from currently about 7 billion to more than 9 billion people in 2050, but the increase in the output of food of animal origin is estimated to be about 70% [3]; [4]. These changes characterize the situation all over the world (e.g., [5]; [6]; [7]; [1, 2]; [8]; [9]; [10]; [11]. Malnutrition in all its forms (under-nutrition, micronutrient deficiencies (e.g., iron, iodine, vitamin A, etc.), and over-nutrition – the so-called "triple burden" of malnutrition) is still recognized as a serious and intractable problem for humans [12]; [13]. Food of animal nutrition, also called animal source food (ASF; [14], may contribute to overcoming micronutrient deficiencies [15].

The energy and protein conversion efficiency from feed into food of animal origin is low and may vary between 3 % (energy - beef) and up to 40 % (energy - dairy; protein - chicken for fattening; [16]; [17]. In some countries (e.g., USA) between 67 % (energy) and 80% (protein) of the crops are used as animal feed [17].

These developments and complex connections present the following question: "Is there any need for food of animal origin?" As vegans demonstrate, there is no essential need for food of animal origin, if the human diets are supplemented with all essential nutrients. But on the other hand, the consumption of meat, fish, milk and eggs may contribute significantly to meeting the human requirements of amino acids (e.g., [18]; [19]; [20]; [21]; [22], [13, 15]; [23] and some important trace nutrients (such as Ca, P, Zn, Fe, I, Se, Vitamins A, D, E, B_{12}) especially for children and juveniles as well as for pregnant and lactating women [24]. Human nutritionists (e.g., [25]; [26] have recommended that about one third of the daily protein requirements (0.66 - 1g per kg body weight; e.g., [27]; [26]; [19] should originate from protein of animal origin. Consequently, about 20 g of the daily intake of about 60 g protein should be of animal origin, which is lower than the present average consumption throughout the world. Presently, there is an average consumption of protein of animal origin (without fish) of about 24 g per capita and day, ranging between 1.7 (Burundi) and 69.0 g (USA; Table 1). It is a challenge for the future to overcome this imbalance [23]. Meat, milk and eggs provide around 13% of the energy and 28% of protein consumed globally, with the higher share in the so-called developed countries (around 20 and 40 % resp., [1]. It is difficult to assess the protein intake from fish and other animal protein sources (e.g., insects). [28] estimate that half of the world´s population consumes at least 15% of their animal protein from aquaculture.

Table-1. Intake of milk, meat and eggs as well as protein of animal origin per capita and year and portion (%) of total protein intake (global minimum-values; maximum-values and averages as well as German values for comparison; kg per capita and year: data base 2005; [1]

Food	**Minimum**	**Average**	**Maximum**	**Germany**
Milk (kg per year)	1.3 (Kongo)	82.1	367.7 (Sweden)	248.7
Meat$^{1)}$ (kg per year)	3.1 (Bangladesh)	41.2	142.5 (Luxembourg)	83.3
Eggs (kg per year)	0.1 (Kongo)	9.0	20.2 (China)	11.8
Edible protein of animal origin (g per capita and day)	1.7 (Burundi)	23.9	69.0 (USA)	52.8
Portion of animal protein in % of total protein intake per capita	4.0 (Burundi)	27.9	59.5 (USA)	53.7

$^{1)}$ Probably empty body weight (meat plus bones)

Other reasons for consumption of food of animal origin are the high bioavailability of most nutrients and their considerable “enjoyment value”. Such food is presently also considered as an indicator for the standard of living in many regions of the world. Eating food of animal origin, esp. meat, is not only a reflection of nutritional needs, but it is also determined by taste, odour, and texture, as well as by geographical area, culture, ethics and wealth. Further reasons for the higher demand of food of animal origin in some countries are the increased income of the population [29] [30]; [31]; [12] and the imitation of the so-called “Western style of life” regarding the nutrition. Many developing countries continue to consume more animal products than they produce. Therefore, they will continue to drive the world demand for all agricultural products, including food of animal origin [32]. Higher food amounts of animal origin require higher plant yields and/or more area for feed production [33]; [34]; [35]; [36] and more animals and/or higher animal yields as well an increase in agricultural trade. Therefore, some authors propose a redefinition of agricultural yield and agriculture in general: “from tonnes to people nourished per hectare” [31]; [17] and ask for more sustainable animal agriculture (e.g., [37], [38]; [39].

On the other hand, changing the eating patterns [40] and eating less or no livestock products, esp. meat, are often seen as possible solutions to reduce the environmental impact of animal agriculture [41]; [42], [43] and to reduce the per capita land requirements (e.g., [44].

In the future there will be strong competition for arable land and further non-renewable resources such as fossil carbon-sources, water [45]; [46]; [47]; [48], some minerals (such as phosphorus; [49]; [50] as well as between feed, food, fuel, fibre, flower and fun; (6 F`s-concept; [51] and areas for settlements and natural protected areas.

In this connection, more attention should been paid to the need of limited natural resources per amount of animal product, expressed as footprints per product such as “Water Footprints” [52]; [53], “Mineral (esp. phosphorus; P) Footprints”, “Land (arable or total land) Footprints” (see [54]; [55]; [56], [36]. These Footprints are given in kilograms, litres or tonnes per unit product and characterize the efficiency of various production processes.

On the other side, special attention has also been paid to the outputs from agriculture e.g., [7]; [10] including livestock keeping esp. so-called GHG relevant emissions" such as CO_2, CH_4, N_2O and further gases. All the climate relevant emissions are summarized to so-called Carbon Footprints (CF). They have also been modified or called Ecological Footprint (EF), Eco-Balances (EB), Life Cycle Assessments (LCA) or Life Cycle Impact Assessment (LCIA). In all cases the term means a summarized parameter for all gaseous emissions with greenhouse gas potential to sensitize producers and consumers, e.g., [57]; [58]; [59], to an efficient use of fossil carbon sources and to reduce GHG emissions per product (see also [60]. CF or LCA are used as a tool for estimating environmental effects caused by products or processes. Furthermore, CF may also contribute to assessing the resource and feed efficiency between various regions and production systems. Recently, some authors have written about problems with LCAs, e.g., [61]; [62]; [63] and new developments such as more comprehensive Life Cycle Sustainability Analysis (LCSA; [64], but a unified solution to the subject is still lacking. Therefore, CF are calculated and interpreted in the present paper in a common way.

Agriculture, and especially animal husbandry, are considered as important GHG sources because of the high GHG potential of some emissions associated with animal production (e.g., methane (CH_4) and laughing gas (N_2O)), which are estimated at 7.1 Gt $CO_{2\text{-eq}}$ per annum, representing about 14.5% of human-induced GHG [65]. Table 2 summarized the present production of food of animal origin, expected growing rates and emissions for animal groups. Globally, ruminant supply chains are estimated to emit 5.7 Gt $CO_{2\text{-eq}}$ per year, of which 81%, 11% and 8% are associated with cattle, buffalo and small ruminant production [66].

Table-2. Present production, growth rates and emissions for some food producing animal groups (calculated from data by Gerber, et al. [65]; MacLeod, et al. [67], Opio, et al. [66]

Animal groups	Ruminants	Pigs	Poultry
Production (Mio. t)	Milk: 864 Meat: 81	CW[1]: 110	Eggs: 58 CW: 72
Growth rate (% per year; until 2030/50)	Milk: 1.1 Meat: 1.3	1.3	Eggs: 1.6 Meat: 2.4
Emissions (Gt; $CO_{2\text{-eq}}$ per year)	Milk: 2.0 Meat: 3.7	0.7	Eggs: 0.2 Meat: 0.4

[1] Carcass weight

Based on the developments mentioned above, philosophers and natural scientists of various disciplines studied and analysed more and more these global developments. The balance between Planet (global resources and emissions) – People (social aspects of population all over the world) and Profit (economic aspects, money-making) in the so-called 3P-concept, [68]; [69], is an important prerequisite for sustainable life and development on the earth. Some authors are afraid that the balance between the 3Ps is being more and more disturbed and that an ethical dimension should be introduced as the fourth dimension [68]. Profit should not and cannot be the single objective of production. We need to find a balance between a careful and sustainable use of limited resources (see above) on the one hand [70]; [71] and low emissions with local and global consequences for later generations [72] on the other hand.

More studies and analyses should be the base for consequences for a more efficient use of limited resources and lower emissions per product. Therefore, the objective of the present contribution is to analyse sources and amounts of greenhouse relevant gases associated with the production of food of animal origin and to deduce parameters to assess the level of emissions from animal production. Furthermore, possibilities to lower the GHG emission from animal production, esp. methane, are discussed in the second part of the paper. The Livestock Environmental Assessment and Performance (LEAP) initiative of the FAO [73] is an activity in many countries to include such environmental improvements in the livestock supply chain.

2. CALCULATIONS OF CARBON FOOTPRINTS (CF)

Carbon Footprints are defined as the total amount of GHG emissions (under consideration of their GHG potential) associated with a product along its supply (human food) chain. This chain includes "Plant production incl. harvesting, storing and treatment – Feed preparation – Feeding of food producing animals – Preparation of food (milk, meat, eggs etc.) – Distribution, market – Households". Sometimes CF includes also emissions from consumption, end-of-life recovery and disposal. Usually, CF`s are expressed in kg or t of carbon dioxide equivalents ($CO_{2\text{-eq}}$) per unit product [66]. Studies and publications about CF have increased dramatically during the last few years, demonstrating that the interest for more resource-efficient and cleaner production has been enhanced. Agriculture, and especially animal husbandry, are considered as important GHG sources because of the high greenhouse potential of their emissions (e.g., CO_2 x 1; CH_4 x 23 and N_2O x 296; [6]. Carbon Footprints consider the GHG potential of climate relevant gases and are given in $CO_{2\text{-eq}}$ per g or kg per product. Various authors calculated such CF for agriculture in general, but also for separate segments.

The public interest in CF is discussed in the context of global warming and possible climate changes [6]; [74]. The paper attempts to present the most important factors in agricultural primary production along the whole food chain, i.e., soil, plant production (harvesting, conservation), industrial feed production, livestock-keeping (incl. excrement management). It also addresses possible other influencing factors such as system boundaries, feed and food processing, transport and trade, resulting in climate-related emissions. Consequences of land-use change (LUC; e.g., change of forest into cropland or pasture) for CF-calculations should also be considered, but in some cases the values are not known or not considered in calculations (e.g., import of feeds).

A number of factors (e.g., plant yield, animal species and performances, type of production) cannot be ignored when taking into account the greenhouse gas potential of the various gases (see above) to derive CF and for the comparison of values along the food chain. The origin of the most important GHG, such as carbon dioxide, methane and nitrous oxide, are discussed in the next paragraphs.

2.1. Carbon Dioxide (CO_2)

The direct carbon dioxide emission from the animals can be considered as emission-neutral. CO_2 will be fixed by photosynthesis of plants and excreted by the animals as a result of animal metabolism. But nevertheless, the CO_2 emission must be seen along the whole food chain and based on burning of fossil carbon during feed production and land-use changes (LUC; [75]; [76]; [59]; [67]. In general, non-carbon dioxide GHG such as methane (CH_4) and nitrous oxide (N_2O) come directly from animals or from animal manure practices.

2.2. Methane (CH_4)

Methane is emitted under anaerobic conditions from the enteric fermentation in the digestive tract of animals, mainly in the rumen, but also during the manure management. Excess of hydrogen during anaerobic fermentation in the rumen is catalysed by various reduction processes. The last step is catalysed with Methyl-Coenzyme M reductase of reduction of CO_2 to CH_4 by hydrogenotropic methanogenic archaea [77]. Details of the enteric methane production are described in many papers e.g., [78]; [79]; [80]; [81]; [82] and prediction equations are given, e.g., [6]; [83]; [84]; [85]; [86]; [87, 88]; [89]. Reduction potentials are analysed in Chapter 5 of this paper. Methane contributes not only to the greenhouse effect, between 2 and 12% of the ingested cross energy of ruminants can be lost to methane [90] depending on diet composition and other influencing factors. Apart from the environmental effect, this energy could potentially be used by the animals for growth and lactation as shown in a model calculation in Table 3.

Table-3. Model calculation to show the influence of methane reduction on the energy available for dairy cows and milk yields (Conditions for calculation: DMI: 20 kg per cow per day; body weight: 650 kg per cow, energy intake: 7 MJ NEL per kg DM with 20 g CH_4-emission; Niemann, et al. [91]

Methane reduction **(g per kg DMI)** **(g per cow per day)**	**30** **600**	**25** **500**	**20** **400**	**15** **300**
Energy intake (MJ NEL[1] per day)	130	135	140	145
Milk yield (kg per day)	28.0	29.5	31.0	32.5
Methane emission (g per kg milk)	21.4	17.0	12.9	9.2
Carbon footprint (g CO_{2eq} per kg milk)	735	585	440	315

[1] Net energy lactation

The methane emissions from the manure management are generally not directly associated with animals, but the losses can be considerably high [87, 88]; [92], esp. if the excreta are stored under anaerobic conditions.

2.3. Nitrous Oxide (Laughing Gas, N_2O)

Animals do not excrete nitrous oxide directly, but it can be formed in manure depending on the storage conditions and following land application, e.g., [93]; [88, 94]; [92]. N_2O is mainly produced in soils by microbial nitrification (the oxidation of ammonium NH_4^+ to nitrate NO_3^-) and denitrification (reduction of NO_3^- to N_2; [95]. These microbial processes depend on temperature, moisture content and oxidation status of the environment. High N-fertilization and soil compaction are important factors that increase N_2O emissions. Since 1750, the tropospheric concentration of N_2O increased from 270 to 320 ppb [96]. More details about N_2O production and emission from the soil are described by many authors and should not be considered in further details in the present paper, e.g., [97]; [98]; [99]; [100]; [101]; [102]; [103].

3. CF FOR FOOD OF ANIMAL ORIGIN

Beginning with one and two studies per year in 1998-2000, about 20 studies per year were published in the last years [28]. The studies dealt with calculations of CF for nearly all types of food of animal origin (see summaries by Williams, et al. [104]; Leip, et al. [105]; Gruenberg, et al. [106]; Flachowsky [107]; Flachowsky, et al. [108]; Lesschen, et al. [109]; Gerber, et al. [65]; MacLeod, et al. [67]; Opio, et al. [66].

Results of CF-calculation for foods of animal origin depend on many influencing factors such as animal species and categories, animal yields and endpoints of animal production. Advantages and weaknesses of endpoints (outputs) of various forms of animal production are summarized in Table 4. All endpoints are characterized by some advantages and disadvantages. From nutritional and scientific points of view edible protein seems to be the most favourable measurement (see Chapter 4), but in the case of meat production its measurement is not easy and requires some analytical work.

Table-4. Advantages and disadvantages of various outputs/endpoints of animal yields concerning the calculation of carbon footprints (by Flachowsky and Kamphues [110]

Animal yields	Advantages	Disadvantages
Milk, Eggs	Easily measurable, almost complete edible	Variation in protein, fat and energy yield, analyses may be useful
Body weight gain	Easily measurable	High portion of non edible fractions in the gains
Carcass weight	Easily measurable	Still contains fractions, which are not edible (e.g., bones)
Meat, edible fraction	Completely edible	Categorization and separation not easy
Edible protein	Most important objective of animal production; Comparison of various ways and sources to produce protein of animal origin	Categorization of various fractions as edible and difficulties to measure; additional analytical work; variation in N/protein content

For practical reasons carcass weight or weight gain (warm or cold) would be the most important endpoint to measure the yield of slaughtered animals because this weight is measurable in the slaughtering houses [111] and can be used for further calculations. Ways to calculate CF and examples for various food of animal origin are shown and discussed in the following sections (see Tables 6-11).

3.1. CF of Milk

Table 5 demonstrates some important emission sources and steps to calculate emissions per cow and year and per kg of milk. The values per cow or per kg milk depend mainly on the levels of emissions and on the milk yield. The calculation shows that in this case about 2/3 of emissions come from methane.

Table-5. Calculation of emissions per cow and year (Parameters: body weight: 650 kg per cow, milk yield: 8000 kg per year, 1 calf per year (by Dämmgen and Haenel [112]

	Emissions (kg per cow per year)		
Source of emissions	CO_2	CH_4	N_2O
Fertilizer	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$^{2)}$		- 1	1.8
Total	336	143	5
CO_2-Equivalents (kg/cow and year)	5200		
(g/kg milk)$^{1)}$	650		
CO_2- Equivalents of emission (kg/cow)	336	3290	1500
(% of total emissions)	6	65	29

$^{1)}$ without calf and heifer, $^{2)}$ no land-use change (LUC)

Table 6 shows exemplary the CF for milk under consideration of various boundaries. A clear definition of the system boundaries and the comprehensibility are important prerequisites for following the calculations and for making the results comparable [113, 114]; [115]. Furthermore, a clear definition of milk (e.g., energy, protein or fat corrected milk; see Table 6) is also necessary to compare calculations by various authors. Scientists working in this field should agree on the system boundaries and GHG factors of climate relevant gases.

Table-6. Model calculation to demonstrate the effects of various system boundaries of CF of milk (g $CO_{2\text{-eq}}$ per kg of milk; 30 kg milk per cow and day; diet on DM-base: 60% roughage, 40% concentrate; 4% milk fat, 3.4% milk protein; 305 days of lactation; 60 days dry period, 3 years lactation; 30 months calf and heifer period (by Flachowsky, et al. [108])

System	**System boundaries**	**CF (g $CO_{2\text{-eq}}$/kg milk)**
1	Animal caused emissions (incl. CH_4 during lactation period)	280
2	1 + Emissions of feed production (without LUC)	430
3	2 + Dry period of cows	500
4	3 + Heifer period	730
5	4 + Animal housing and milking	760
6	5 + Excrement management	820
7	6 + Processing, transportation and trade of milk	1 100

The large range in CF of milk comparing results of various authors depends on many influencing factors is shown in Table 7. The CF for milk by various authors varies between 0.4 and 1.5 kg $CO_{2\text{-eq}}$/kg in Europe, North America and Oceania, and under consideration of different world regions between 1.3 (Europe and North America) and >10 kg $CO_{2\text{-eq}}$/kg in sub-Saharan Africa or highlands in Peru [8]; [116]; see Table 7). Most authors considered only the emissions during production, but sometimes LUC as well as processing, transport and trade are also included in calculations. In their recent publication, [66] mentioned ranges from 1.6 to 9.0 kg $CO_{2\text{-eq}}$/kg fat and protein corrected milk (FPCM) for regional emission intensity. Generally, milk production in low productive systems has higher emissions per kg FPCM than in high production systems [117]. Methane and nitrous emissions per cow increase, but they decrease per kg milk with increasing productivity, while carbon dioxide increases because of a higher feeding of concentrates, but on a much lower scale.

Table-7. Examples for CF (kg $CO_{2\text{-eq}}$/kg milk) in dependence on type of production (conventional or organic) published by various authors

Country	**Type of production/farming**		**Authors**
	Conventional	**Organic**	
Germany	0.83	0.84	[118]
Germany	0.85	0.78	[119]
Sweden	0.90	0.94	[120]
Germany	0.94	0.88	[121]
The NL	0.97	1.13	[122]
Germany	0.98	0.92	[123]
Sweden	0.99	0.94	[124]
UK	1.06	1.23	[104]
Austria	1.20	1.00	[125]
UK	1.20	1.30	[126]
Germany	1.30	1.30	[127]
The NL	1.40	1.50	[128]
UK	1.6 (1.0-3.2)	1.3 (0.9-2.4)	[129]
Without differentiation conventional/organic			
Germany	0.40 (40 kg milk/day)		[130]
(Model	0.55 (20 kg milk/day)		“
calculation)	1.00 (10 kg milk/day)		“
Germany	0.65		[112]
New Zealand	0.65-0.75		[131]
Literature review	0.8 – 1.4 (on farm) 0.9 – 1.8 (on farm + post farm emissions)		[132]
New Zealand	0.86		[133]
Germany	0.98 (10 000) - 1.35 (6000kg milk per year; without allocation)		[134]
Sweden	1.00		[135]
Canada	1.00		[136]
UK	1.06		[104]
USA	1.09		[137]
EU	1.3 (1.0-2.3; EU-27)		[109]
Ireland	1.3-1.5		[138]
USA	1.35		[111]
Norway	1.5 – 1.6 (Combined milk/meat; expanded boundaries)		[139]
Global	2.4 (1.3-7.5; global)		[140]
Global, Cow	2.8		[66]
Buffalo	3.4		
Small ruminants	6.5		
Peru; Coast	3.2		[116]
Highlands	13.8		

3.2. CF of Food from Slaughtered Animals and Eggs

It is much more difficult to measure the yield from the animal body after slaughtering and processing of animals (see Table 4). Calculation of CF may base on various outputs. For practical reasons, carcass weight (warm or cold) or weight gain would be the most important endpoint to measure the yield of slaughtered animals. Based on the values derived from Table 8, CF is calculated for various endpoints under consideration of differences in feeding and GHG emissions and are shown in Table 9.

Table-8. Model-calculations of CF for beef (150-550 kg body weight[1)]) in dependence on feeding[2),3)], weight gain, methane- and N-emissions (by Flachowsky [118]

Weight gain (g/day)	Feed intake (kg DM/ animal and day	Portion concentrate (% of DM-intake))	Methane emissions (g/kg DM)	N-excretion (g/day)	N_2O-synthesis (% of N-excretion)	Carbon footprints (kg CO_{2-eq}/kg)			
						Weight gain	Empty carcass weight gain	Edible fraction gain	Edible Protein
500 (Pasture, no concentrate)	6.5	0	26	110	2	11.5	23.0	28.0	110
1000 (Indoor, grass silage, some concentrate)	7.0	15	24	130	1	5.5	11.0	13.8	55
1500 (Indoor, corn silage, concentrate)	7.5	30	22	150	0.5	3.5	7.0	9.0	35

[1)] Production of calf up to 150 kg BW is not considered; [2)] CO_2-Output: 120 g/kg roughage-DM; 220 g/kg concentrate-DM, [3)] Feed sources may have a strong influence on CF.

Co-products of feed and food industry (see [119] can reduce the CF of food of animal origin [120] because of their lower environmental costs [121]; see also Section 5.3.

Table-9. Model calculation for illustrating various endpoints for growing/fattening bulls (150-550 kg body weight; calculation based on data by Flachowsky [122]

Brutto weight gain (g/day)	**Weight gain without content of intestinal tract (g/day)**	**Carcass weight (warm; % of weight gain)**	**Carcass weight gain (warm; g/day)**	**Meat gain (% of weight gain)**	**Meat gain (g/day)**	**Edible fraction gain[1)] (g/day)**	**Edible protein (g/day; 19% protein in edible fraction)**
500	438	50	250	40	200	250	48
1 000	900	53	530	44	440	490	93
1 500	1 385	56	840	48	720	770	146

[1)] Meat plus other edible tissues

Under farm conditions, only the GHG-balance per kg body weight gain can be calculated. Normally, the GHG emissions for the whole beef system include also emissions of cows, calves and heifers needed to produce beef. They are much higher than in the system dairy cow – growing/fattening bulls for beef. The GHG-emissions to produce pork and poultry meat should also include the emissions of parent animals (sows and laying animals).

The term "meat" is not clearly described and is used for both "real meat" and meat plus bones. [111] introduced the term "hot standard carcass weight" (HSCW) as the weight at the exit gate of the meat processing plant. It varies between 50-62% of the live weight of slaughtered cattle, but it may vary between 50% in the case of sheep and up to 80% for fattening turkeys [122]; [104]; [111] Therefore it is accompanied by substantial difficulties to find an adequate CF for meat or edible products from slaughtered animals (see Tables 4 and 9). Various authors used different bases to calculate CF for products from slaughtered animals. Williams, et al. [104] estimated the killing out percentages for beef and poultry with 55 and 70% and 72, 75 and 77% for pigs with final body weights by 76, 87 and 109 kg resp. Lesschen, et al. [109] used fixed values to calculate the carcass fraction from the final body weight of animals (e.g., 58% for beef; 75% for pork and 71% for poultry). Most authors used a fixed fraction of 0.9 for all animal species for conversion of carcass weight to edible meat.

Beef

The ruminant sector contributed to about 29% of the global meat production, but 5.7 Gt $CO_{2\text{-eq}}$ representing about 80% of the global livestock emissions per year come from all ruminants (see Table 2; [66]. The large range in CF comparing results of various authors, depending on many influencing factors, is shown in Table 10 for beef. The values are much higher than those for milk (compare Tables 7 with 10) and are influenced by body weight gain, feed production with or without LUC, feeding and keeping of animals as well as system boundaries. The calculation base for the output of growing animals is more difficult (see Tables 8 and 9) than calculating it for milk or eggs (see Table 4). In dependence on the calculation base, the authors found a high variation in CF of beef. The highest values are given for beef cows (Table 10). In general, all of the results, e.g., [111]; [123]; [108], [66], indicate that policies which are targeted at improvements in productivity and efficiency of resource use will result in a lower GHG-emission or lower CF per unit of product. In the case of beef production, about 15% of total emissions are associated with the expansion of grassland (LUC) from forests [66].

Pork

The pig sector contributes with 37% to global meat production, it will grow by 32% during the period 2005-2030 [67]. Only 0.7 Gt $CO_{2\text{-eq}}$ per annum representing about 9% of the livestock sector´s emissions comes from pigs (see Table 2; [67]. The main emission sources from global pig supply chains are feed production (60%) and excrement management (27%). The remaining 13% arises from post-farm processing, transport, enteric fermentation and indirect energy use in pig production [67]. 13% of the total emissions arise from LUC driven by increasing demand for feed crops (e.g., forest into arable land). MacLeod, et al. [67] compared the results of 14 studies with pigs from Europe, North America and Australia and found a range in emissions between 2.01 and 6.36 kg $CO_{2\text{-eq}}$/kg carcass weight. Later, the same authors adjusted all studies to the same scope according to FAO-rules and calculated values between 3.34 and 6.37 without LUC and values between 4.71 and 9.85 kg $CO_{2\text{-eq}}$/kg carcass weight with LUC. Tan, et al. [124] analysed three case studies from Australia and Canada and found similar results (4.5 kg $CO_{2\text{-eq}}$ per kg pork).

Table-10. Examples for CF (kg $CO_{2\text{-eq}}$/kg carcass weight gain) of beef cattle in dependence on type of production by various authors

Type of production/farming			**Authors**
Country	Conventional	Organic	
Germany	8.5	29.0 (beef cow)	[146]
Germany	8.7/10.1	10.2	[118]
Australia	9.9 (grain finished)	12.0 (grass finished)	[111]
Global	10 (intensive – dairy beef)	32 – 40 (organic – suckler beef)	[126]
Germany	13.3	11.4	[121]
Germany	15.2	17.5	[147]
UK	15.8	18.2	[104]
Ireland	23.6	20.2	[113]
Global	24.5	20.9	[148]
Without differentiation conventional/organic			
Germany	5.6 (6000) – 14.6 (10 000 kg milk per cow per year; without allocation)		[134]
Canada	5.9 – 10.4		[136]
Germany	7.0 – 23.0		[130]
Germany	8.4 (Fattening of calves from dairy cows) 16.8 (Fattening of calves from beef cows)		[119]
Sweden	10.1		[149]
Ireland	13.0 (11.3 – 15.6)		[113, 114]
EU	16.0-19.9 27.3 (suckler herd)		[55]
Norway	17.7 – 18.4 Combined milk/meat; expanded boundaries		[139]
Global	15.6 (Fattening of calves from dairy cows) 20.2 (Fattening of calves from beef cows)		[8]
Japan	19.6		[150]
Japan	36.4 (beef cows, fattening bulls; 40% meat yield)		[151]
5 studies, literature review	32		[152]
Global; beef buffalo small ruminants	46.2 53.4 23.8		[66]

All values mentioned above are much lower than data from beef (see Table 10). The main reasons for this are the enteric methane production in ruminants and the low growth intensity of beef cattle (mostly <0.5% weight gain per day of body weight) compared with pigs (mostly >1% weight gain per day of body weight; see also Table 10).

Poultry (Meat and Eggs)

Chickens meat accounts to about 24% to the global meat production. The global demand for chicken meat and chicken eggs are forecasted to grow by 61 and 39%, resp., during the period 2005-2030. Chickens are estimated to emit 0.6 Gt $CO_{2\text{-eq}}$ per year, representing about 8% of the livestock sector`s emissions (see also Table 2; [67]. In the case of chicken meat on the global scale, 78% of emissions come from feed production and only small amounts directly from farm energy use (8%), processing and transport of meat (7%) and excrement management (6%; [67]. Some authors did not consider emissions from LUC where it occurs. In such cases about 21% of poultry meat emissions and 13% of egg emissions came from LUC through the conversion of forest into arable land; [67]. These authors compared the emissions of 18 studies with broilers from Europe, North America, Brazil and Australia and found a range between 1.30 and 5.53 kg $CO_{2\text{-eq}}$/kg carcass weight. Later, the same authors adjusted all studies to the same scope according to FAO-rules and calculated values between 1.89 and 5.00 without LUC and values between 1.93 and 7.71 kg $CO_{2\text{-eq}}$/kg carcass weight with LUC. Tan, et al. [124] calculated 2.9 kg $CO_{2\text{-eq}}$/kg meat in three case studies on chicken from Brazil and Finland. The most important influencing factors of CF of broilers are the feed amounts needed per weight gain (feed conversion rate) and the feed transport [125]. The land-use change should not be neglected. In the case of eggs, feed production contributes to 69% and direct on farm energy use to 4%, post-farm processing and transport 6%, the rest of the emissions (about 20%) is manure storage and processing (excrement management; [67]. Pelletier, et al. [126] came to a similar assessment after analysis of egg production in the Midwestern United States. Composition of eggs is well defined, but it may vary between various sources and in dependence on animal breed, feeding of animals and other influencing factors (see Table 11). The yield can be measured as weight (kg, etc.) or on the basis of standardized products (e.g., standardized protein, fat, dry matter or energy). Therefore analysis of egg composition (protein; fat) may contribute to a more specific measuring of the animal yield incl. the energy yield. Eggs may be entirely used as food (except small amounts for egg shells; see Table 11).

In conclusion, growing intensity, laying performance, feed conversion rate (FCR), healthy animals and low animal losses are the key determinants of the emission intensity per kg food of animal origin from non-ruminants (pork, broiler meat and eggs).

3.3. CF of Aquaculture and Further Protein Sources

Aquaculture is a strongly upcoming way to produce food protein of animal origin. Recently some authors tried to determine CF for various forms of aquaculture. Mungkung, et al. [127] carried out a case study of combined aquaculture systems for carp and tilapia. The studied system included fingerling production in hatcheries, fish rearing in cages and transport of feed as well as that of harvested fish to markets.Avadi and Freon [28] reviewed 16 LCA-studies applied to fisheries and considered in the comparison the following aspects: scope and system boundaries, functional unit allocation strategies for co-products, conventional and fishery specific impact categories, fuel use, impact assessment methods, level of detail of inventories, normalisation of results and sensitive analysis. Fishery-specific impact categories and fuel use in fishing operation were identified as the main contributors to environmental impact. Nijdam, et al. [56] analysed 18 and 11 studies for seafood from fisheries and agriculture resp. The authors summarized CF between 1-86 for seafood from fisheries and 3-15 kg $CO_{2\text{-eq}}$ for seafood from agriculture resp. These authors also [28] define the need for a standardisation of fisheries LCA research for further studies on sustainability of seafood and fisheries-based agrifood. Apart from milk, meat, fish and eggs, other sources of protein of animal origin, such as wild animals and insects, are also consumed by humans. Nothing is known about CF of food from wild animals. Insects and their larvae are used in many countries. They are rich in protein (20 – 70%) and contain considerable amounts of fat (10 – 50% of dry matter; [8, 128]. More than two billion people include processed insects in their diets [8]; [129]. Experts assess [129] that about 1900 insect varieties are used as food and feed. The feed conversion of insects could be better than in "traditional" animals and lower CF are expected, but more research in these fields, and also concerning feeding and feed supplementation with insects is required [8]; [130]; [131]; [132].

4. CF FOR EDIBLE PROTEIN OF ANIMAL ORIGIN

The production of protein of animal origin is one of the most important goals of animal husbandry [54]; [109]; [110]; [56]. On the other hand, the efficiency and the emissions of food of animal origin can be also compared on the basis of edible protein. The N or protein (N x 6.25) content of various food of animal origin may vary from values used for calculations in Table 11. These data do not substantially disagree with values from human food tables [133]. Nijdam, et al. [56] used 160-200 g protein per kg food for seafood from fisheries and 170-200 g protein per kg food for seafood from agriculture for the calculation of CF.

Table-11. Protein content of some edible animal products by various authors (in g per kg edible product)

	References					
Product	[144]	[162-165]	[161]	[166]	[109] 1)	[56]
Cows' milk	34	34	33.3 (30.8-37.0)	34	34.4	35
Beef	190	170-200	220 2) (206-227)	206-212	206	200
Pork	150	157 (129-178)	220 2) (195-240)	183-216	156	200
Poultry meat	200	n.d.	199	182-242	206	200
Eggs	120	121 (110-124)	125	125	119	130

1) N-content x 6.25; 2) Muscle only; n.d.: no data

Under consideration of various influencing factors such as animal yields, feeding, edible fractions and protein content in the edible fractions, the yield of edible protein per day and per kg body weight of animals is given in Table 12. The feeding may influence the CF of food of animal origin. In the case of ruminants, higher amounts of concentrate are required with higher animal yields. The proportion of co-products, e.g., [121]; [119] used in animal nutrition not only has nutritional implications, but it also affects the results of calculations on land use [134]. There are large differences in animal protein yield per animal per day, or per kg body weight and day, depending on animal species and categories as well as their performances and the fractions considered as edible (see Table 12).

Table 12 shows the highest protein yields per kg body weight for growing broilers as well for laying and lactating animals, and the lowest values for growing/fattening ruminants. Based on those values, emissions per kg edible protein are given in Table 13. Higher portions of edible fractions or higher protein content may increase the protein yield and reduce the CF per product. At high levels of performance there are remarkable differences in CO_2 emissions due to a human consumption of 1 g protein from food of animal origin (eggs and meat from poultry < pork < milk < beef, see Table 13).

Table-12. Influence of animal species, categories and performances on yield of edible protein [122]

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 (650kg)	10kg milk	12	90/10	95	34	323	0.5
	20kg milk	16	75/25			646	1.0
	40kg milk	25	50/50			1292	2.0
Dairy goat (60kg)	2kg milk	2	80/20	95	36	68	1.1
	5kg milk	2.5	50/50			170	2.8
Beef cattle (350kg)	500g$^{1)}$	6.5	95/5	50	190	48	0.14
	1000g$^{1)}$	7.0	85/15			95	0.27
	1500g$^{1)}$	7.5	70/30			143	0.41
Growing/fattening pig (80kg)	500g$^{1)}$	1.8	20/80	60	150	45	0.56
	700g$^{1)}$	2	10/90			63	0.8
	1000g$^{1)}$	2.2	0/100			81	1.0
Broiler (1.5kg)	40g$^{1)}$	0.07	10/90	60	200	4.8	3.2
	60g$^{1)}$	0.08	0/100			7.2	4.8
Laying hen (1.8kg)	50%$^{2)}$	0.10	20/80	95	120	3.4	1.9
	70%$^{2)}$	0.11	10/90			4.8	2.7
	90%$^{2)}$	0.12	0/100			6.2	3.4

$^{1)}$Weight gain, $^{2)}$Laying performance

Table-13. Influence of animal species, categories and performances on emissions (per kg edible protein, own calculations on the base of data from Tables 11 and 12, see [110]

Protein source (Body weight)	**Performance per day**	**N-excretion (% of intake)**	**Methane emission (g per day)$^{3)}$**	**Emissions in kg per kg protein**			
				P	**N**	**CH$_4$$^{3)}$**	**CO$_{2\text{-eq}}$**
Dairy cow (650kg)	10kg milk	75	310	0.10	0.65	1.0	30
	20kg milk	70	380	0.06	0.44	0.6	16
	40kg milk	65	520	0.04	0.24	0.4	12
Dairy goat (60kg)	2kg milk	75	50	0.08	0.5	0.8	20
	5kg milk	65	60	0.04	0.2	0.4	10
Beef cattle (350kg)	500g$^{1)}$	90	170	0.30	2.3	3.5	110
	1000g$^{1)}$	84	175	0.18	1.3	1.7	55
	1500g$^{1)}$	80	180	0.14	1.0	1.2	35
Growing/fattening pig (80kg)	500g$^{1)}$	85	5	0.20	1.0	0.12	16
	700g$^{1)}$	80	5	0.12	0.7	0.08	12
	900g$^{1)}$	75	5	0.09	0.55	0.05	10
Broilers (1.5kg)	40g$^{1)}$	70	Traces	0.04	0.35	0.01	4
	60g$^{1)}$	60		0.03	0.25	0.01	3
Laying hen (1.8kg)	50%$^{2)}$	80	Traces	0.12	0.6	0.03	7
	70%$^{2)}$	65		0.07	0.4	0.02	5
	90%$^{2)}$	55		0.05	0.3	0.02	3

$^{1)}$Weight gain $^{2)}$Laying performance $^{3)}$CH$_4$-emission depending on composition of diet

Nijdam, et al. [56] analysed 52 LCA-studies (Table 14) and summarized CF per kg product and per kg edible protein of animal origin. The results indicate that large differences exist between the studies and the products. The outcomes for milk, pork, poultry meat and eggs show much more homogeneity than those for beef, mutton, lamb and seafood. This is largely because of the very wide variety in production systems of the last food groups. Meat from non-ruminants has a lower CF than those from ruminants because methane is the main contributor to CF in ruminants. Because of too low values for feed production and processing (see Tables 5 and 6), most values shown in Table 13 are considerably lower than data given in Table 14.

Table-14. Carbon footprints of protein of food of animal origin according to several LCA studies summarized by Nijdam, et al. [56]

Protein source (studies)	**kg CO_{2-eq} per kg product**	**kg CO_{2-eq} per kg protein**
Cow milk (n = 14)	1 - 2	28-43
Beef, Intensive system (n = 11)	9 – 42	45-210
Meadow, suckler herds (n = 8)	23 – 52	114-250
Extensive pastoral systems (n = 4)	12 - 129	58-643
Mutton and Lamb (n = 5)	10 - 150	51-750
Pork (n = 11)	4 - 11	20-55
Poultry meat (n = 5)	2 - 6	10-30
Eggs (n = 5)	2 - 6	15-42
Seafood from fisheries (n = 18)	1 - 86	4-540
Seafood from agriculture (n = 11)	3 - 15	4-75

Apart from protein, food of animal origin also contains other main nutrients (fat and lactose in the case of milk; fat in the case of meat and eggs), which contribute to human nutrition and which may replace energy of plant origin in human food. But at this point it has to be emphasized that this protein intake is accompanied - willingly or not - by an energy intake from the protein itself. Therefore, the exclusive attribution of the CO_2 burden to the protein fraction ("edible protein") should be avoided. To prevent this fact from being neglected, there are different alternatives. In a first simple method, the CO_2 emissions due to 1 kg edible protein could be used as CO_2 burden of consumed energy (for example: 1 kg edible protein of eggs corresponds to about 8 kg egg, corresponds to 51.6 MJ energy; this combined intake is related to a certain amount of CO_{2-eq}). "Nutritional allocation" and/or "economic allocation" [135]; [136]; [106]; [137]; [28]; [138] may distribute CO_2 emissions to different functions of the food, but should not be discussed in the present paper.

5 CHALLENGES FOR LOWER METHANE EMISSIONS AND REDUCTION POTENTIALS

Numerous factors contribute to the greenhouse gas emissions by animals. Developing strategies to reduce emissions offers the potential to increase production efficiency and to reduce the impact of animals on the environment. Most attention has been spent to reduce the methane production in ruminants as summarized recently by Hristov, et al. [88]. Methane reduction potentials will be considered in the following subchapters.

5.1. Plant Breeding

Plant breeding can be considered as the starting point of the food chain (see [139]; [140]. Traditional breeding, as well as "green" biotechnology or green chemistry [11], may result in changing of composition and nutritive value of feed plants. Lower fibre content and higher digestibility of plants may reduce methane emission from the rumen. Presently, special attention is given to the adaptation of plants to expected climate changes, e.g., [141]; [142]; [143]; [144] and to improving their yield and the nutritive value for global food security [145].

Genetically modified plants may contribute to achieving these objectives (see [146], but are presently under critical public discussion. Nutritionists distinguish genetically modified (GM) plants into plants of the first and second generation. This designation is purely pragmatic or historical; it does not reflect any particular scientific principle or technological development.

The first generation of GM plants is generally considered to be crops carrying simple input traits such as increased resistance to pests or tolerance against herbicides. Other inputs, such as more efficient use of water and/or nutrients, or an increased resistance against heat and drought, are not expected to cause any substantial change in composition and nutritive value. The newly expressed proteins that confer these effects occur in GM-plants in very low concentrations and do not change their composition or feeding value significantly when compared with isogenic lines.

GM-plants of the so-called second generation (or plants with output traits or substantial changes in composition) are being developed with specific benefits for the consumer or the animals. Such biofortified crops contain higher amounts of desirable nutrients/substances such as proteins/amino acids, specific fatty acids, minerals, vitamins, enzymes, antioxidative substances, etc., or lower contents of undesirable substances, such as fibre/lignin, phytates, glucosinolates, mycotoxins, etc., [147] give a review about new events of GM crops in the pipeline as feed for animal nutrition. Adequate feeding studies for the nutritional assessment of such feed of the second generation of GM crops are required.

Attention should be also devoted to changes in plant/feed composition in consequence of traditional plant breeding.

5.2. Feed Production, Harvesting, Storing and Processing

About 10 to 80% of GHG-emissions of animal husbandry come from feed production (see chapters above; lower values for ruminants, higher values for non-ruminants).

Feed production contributes to GHG-emissions by land uses changes (LUC; e.g., change of forest into cropland or pasture with the consequences of high CO_2-emissions; see [67], by N_2O-emission in consequence of fertilizing the soil and by CO_2 from burning of fuel by machinery on the field, during harvesting and further processing of feed before feeding.

Reduction of post-harvest losses and losses during feed storage can be considered as an important contribution to lower CF per feed unit [11]

More details and reduction potentials of GHG during feed production, harvesting, storing and processing incl. production of mixed feed for animals have been described by many authors, e.g., [121], [148] and his team; [108].

5.3. Feeds

The high portion of GHG-emission in non-ruminants comes from feed production (see Chapters 3.2 and 5.1). Therefore, an effective use of feeds and the partial replacement of feeds by co-products of agriculture, food and bio-fuel industry may contribute to reducing CF for food of animal origin. The reduction of feeds in animal nutrition, which can also be used in human nutrition (such as cereals, beans, oilseeds etc.), would also be a real challenge for animal feeding [149].

Apart from roughages and concentrates, co-products from agriculture, such as cereal straw, e.g., [150]; [151], but also from food production, e.g., [152]; [153] and the biofuel-industry [119] are commonly used in animal feeding.

Co-products are by-products of main processes such as grain production (e.g., straw, stalks, husks), processing of raw products in the food industry (e.g., extracted oil meals from the oil industry, bran from the cereal processing; beet pulp or bagasse from the sugar industry; animal co-products from milk, fish or meat processing) or from the biofuel industry (e.g., Distillers Dried Grains with Solubles (DDGS); rape seed cake/meal or rape seed extracted oil meal as well as cakes and meals from other oil seeds). According to the FAO [8], between 10 and 50% of the estimated concentrate feed comes from co-products in various global regions [117]. In some countries, up to 100% of concentrate may base on co-products.

Co-products are used in various amounts and proportions in animal diets. Cereal straws and other co-products rich in plant cell-walls are mostly characterized by a low digestibility and are thus poor in energy and protein delivery to the animal. They are fed to ruminants with low animal yields or to meet their maintenance requirements. For high yielding ruminants they can only be considered as a source of fibre. Normally, they are not used in the feeding of non-ruminants.

The importance of co-products of the food and biofuel industry as feed for animal nutrition will increase during the next few years [119]. Co-products from the food and fuel industry contain two to three times as many nutrients, which are not removed by processing (e.g., protein in the case of DDGS). They can be used as valuable sources of protein, minerals and other nutrients depending on the source material and the chemical or physical processing without any land-footprint. In the future more grains will be used for food and fuel and more co-products will be available for animal nutrition [131]. More details about the nutritive value and the utilisation of co-products from biofuel industry in animal nutrition were recently compiled by Makkar [119]. Co-products of agriculture and of industry are used to replace concentrates and roughage from grassland.

In the future, we may expect some new developments in the field of co-products as animal feed. More people all over the world need more food and more energy. Therefore cereals, legumes and oilseeds will be used directly in larger amounts for human nutrition and will be more extracted during processing. That means that less concentrate and more extracted co-products will be available for animal nutrition. More analytical data are required for such co-products. The detoxification of substances rich in protein and energy would be also a challenge to increase the potential of feeds and co-products [131].

Kitchen refusals are still used in many countries in animal nutrition. Presently, the feeding of such refusals is not permitted in the European Union because for hygienical reasons.

Because of the BSE-crisis (Bovine Spongiform Encephalopathy), the feeding of co-products from slaughterhouses (e.g., meat meal, blood meal, bone meal) has not been permitted in the European Union since 2001. Some research activities are underway for an efficient use of these valuable protein, energy and mineral sources in the future.

5.4. Animal Feeding and Animal Yields (Productivity)

One of the most important challenges to reduce the emissions per animal product is the increase of animal yields or an improved production efficiency [154]; [155]; [117] and in consequence, a reduction of animal numbers [156]. Investments in the productivity simultaneously result in reduced emission per unit of product as exemplarily shown in Table 15 and Figure 1 for the milk production.

The level of feed intake of animals is one of the most important prerequisites for animal yields. The higher the feed intake, the higher the portion of energy and nutrients available for animal performance, as shown in Table 15 for milk

Table-15. Model calculation to show the influence of dry matter intake (DMI; 7.0 MJ NEL/kg DM) of dairy cows (body weight: 650 kg; 4% milk fat; [157] on energy intake, percentage of energy for maintenance and milk yield, energy per kg of milk as well as emissions per kg of milk [91]

Dry Matter Intake (DMI, kg per day)	**10**	**15**	**20**	**25**	**30**
Energy intake (MJ NEL per day)	70	105	140	175	210
Energy requirement for maintenance (37.7 MJ NEL per cow per day; % of total NEL-Intake)	53.9	35.9	26.9	21.5	18.0
Energy requirement for milk production (3.3 MJ NEL per kg)	9.8	20.4	31.0	41.6	52.2
Net energy per kg milk (MJ NEL per kg milk)	7.1	5.1	4.5	4.2	4.0
Methane emission$^{1)}$					
(g per day)	240	360	480	600	720
(g per kg milk)	24.5	17.6	15.5	14.4	13.8
Carbon footprint (g CO_{2eq} per kg milk)$^{2)}$	825	605	530	495	475

$^{1)}$ according to Flachowsky and Brade [78]: 24g CH_4 per kg DMI for all diets

$^{2)}$ calculated on the basis of the greenhouse potential of CH_4 (x 23) and the calculations by Dämmgen and Haenel [112]

Similar trends can be seen in milk yield per year and emission per kg FPCM (Figure 1). The average of CF for the whole herd can be reduced after elimination of cows without milk or with very low milk yields.

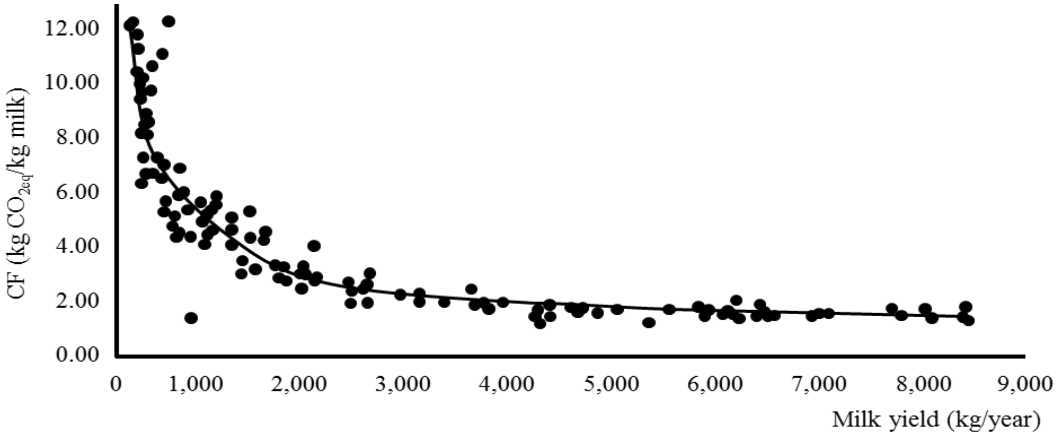

Figure-1. Emission intensity (CF kg$_{CO_{2eq}}$) in dependence of milk yield of cows (kg/year; by Gerber, et al. [117]; Opio [73]

5.5. Rumen Fermentation and Methane (CH_4) Emission

Some possibilities for the reduction of methane mitigation, such as increasing forage digestibility and digestible forage intake, dietary lipids or concentrate portions in the ruminant diets [158]; [159]; [160], as well as the application of various feed additives are shown by some authors, e.g., [161]; [162]; [108]; [163]; [164] (Table 16).

Table-16. Feed measurements to reduce enteric methane emissions, importance on farm level and research need in ruminants

Measurements	Significance (esp. for Europe) on farm level	Research Need
More concentrate, less fibre in the diet	Limited, because of high amounts already in many diets	~
Forages with high digestibility, low fibre content	Consideration in plant breeding and practical feeding	⇑
Fats and fatty acids in the diets	Limited, because of some side effects in the rumen	⇑
Application of feed additives		
Halogen compounds (e.g., chloral hydrates)	Banned in the EU	~
Ionophores (e.g., monensin)	Banned in the EU	⇑
Addition of hydrogen acceptors, such as fumaric acid, acrylic acid etc.	Presently no significance	⇑
Addition of phytogenic substances (essential oils; plant extracts or plants containing such substances; e.g., garlic, tannines, saponines)	Presently no significance	⇑⇑
Addition of 3-nitrooxy-propanol and other nitrooxy-carboxylic acids	Presently no significance	⇑⇑
Further additives, such as yeasts, enzymes, etc.	Presently no significance	⇑

⇑⇑: High need; ⇑: Need; ~: less important

Enhanced animal productivity and feed efficiency with metabolic modifiers, such as growth hormones and ionophoric antibiotics [87], would reduce GHG emissions, but the applicability of these mitigation practices is limited to regions where the use of these substances is permitted. Appuhamy, et al. [165] analysed the methane reduction potential of the ionophoric substance monensin via meta-analysis. Data from 22 controlled feeding studies were used. The methane mitigation effects of monensin were small (12 or 14 g/d in dairy cows and beef cattle) when adjusted for the monensin dose.

Hydrogen acceptors, such as fumaric acid, acrylic acid and further substances may also contribute to H_2-binding in the rumen, but the in vivo effects are low and inconsistent, e.g. [166]; [167]. Many studies were done with phytogenic substances such as tannins, non-tannins, phenols, saponins, essential oils and whole plants or parts of plants, e.g., [168].

Despite of limitations of dietary fat in the range of 5% in ruminant rations [169], caused by lower fibre digestion and modification of the microbial population, experiments with single fatty acids and rapeseed oil showed potential to decrease methanogenesis. In vitro incubation of ruminal fluid added with ricinoleic acid resulted in a decline of 28 % in methane production. A reason for that observation could be differential toxic effects on not know methanogens [170] New metatranscriptomic approaches applied to ruminal fluid (sequencing of the rumen microbiome) give new insight into the abundance of rumen microorganisms and their gene expression. A novel group of methanogens (Thermoplasmata archaea) was recently described using this approach. Thermoplasmata uses methylamine as a substrate for methanogenesis and rapeseed oil supplementation reduced the occurrence of these thermoplasmata and methyl-coenzym M reductase. From these observations the authors concluded that thermoplasmata are a high potential target to reduce methane production in ruminants [171].

The development of new feed additives, mainly based on plant extracts to decrease methane production within the rumen, has attracted research activities over the last 20 years. The results remain variable and contradictory as summarized by Benchaar and Greathead [172]. The effectiveness of plants or plant extracts having a high content of saponins, flavonoids and tannins (see Table 16) varied depending upon the source, type and level of secondary metabolite present in the plant material. These may restrict the uptake and use of such phytogenic substances in the animal feeding market. The reasons for such restrictions may be related to several factors, including the lack of persistency of the effects when they are tested in vivo due to the adaptation of the microbial ecosystem, the variability of concentration of active compounds in plant extracts, the stability of the active substance within the rumen, and possible side effects that compromise overall rumen fermentation [173].

Most of the substances were tested in *in vitro* studies, they may have a potential to reduce methane emissions from ruminants although their long-term effect has not been well established and some are toxic, or may not be economically feasible. Impressive results of *in vitro* studies were mostly not repeated under *in vivo* conditions. Therefore, [174] proposed a five-stage programme to evaluate the effects of such additives under special consideration of phytogenic substances:

1. Botanical characterization of the plant(s) and their composition

2. Analytical characterization of the active phytogenic substance(s)
3. *in vitro* studies to test effects of substances on rumen fermentation and methanogenesis (i.e., screening)
4. *in vivo* studies (e.g., feed intake, rumen fermentation, CH_4 emissions)
5. Long-term feeding studies with target animal species/categories (e.g., animal health and performance, quality and safety of food of animal origin, environmental impact, adaptation of microbes).

Another reason for the restricted use of phytogenic substances as methane inhibitors may be their unclear transfer from feed into food of animal origin and possible residues in animal products and their effects in humans, e.g. [175]; [176]; [177].

The development of synthetic compounds with specific activities to influence metabolic pathways essential to ruminal archaea may overcome some restrictions of phytogenic compounds. Methyl-Coenzyme M reductase catalyses the last step of reduction of CO_2 to CH_4 by hydrogenotrophic methanogenic archaea [77].

In preliminary studies, e.g. [178]; [179]; [180, 181], some authors tested the effects of molecules, substituted at various positions with at least one nitrooxy group, as inhibitors of methyl-coenzyme M reductase, such as nitrooxy-propionate compounds on the ruminal fermentation and the methane emissions. These substances are able to reduce the final step of CO_2 to CH_4 by methanogenic archaea [182]. [183] studied the effect of ethyl-3-nitroxy propionate (E3NP) and 3-nitrooxypropanol (3NP) *in vitro* and *in vivo* in non-lactating sheep on ruminal methane production, fermentation pattern, the abundance of major microbial groups, and feed degradability. The *in vitro* batch culture trial tested 2 doses of E3NP and 3NP (40 and 80 µL/L) and found a substantial reduction of methane production (up to 95%) without affecting concentration of volatile fatty acids. In sheep methane production decreased by 29% in comparison with the unsupplemented control, without any effect on rumen dry matter degradation.

Reynolds, et al. [184] tested effects of feeding of 0.5 and 2.5 g 3-nitrooxypropanol per cow and day on methane emissions, digestion and energy and nitrogen balance of lactating cows. The substance was administered through the rumen fistula. Daily methane production was reduced by 3NP of 6.6 and 9.8% for 0.5 and 2.5 g/d, respectively. A homogenous mixing with feed or a sustained-release bolus may be more effective than application used in the present studies.

Haisan, et al. [185] applied the additive by hand-mixing 2.5 g 3NP per cow and day into the total mixed ration (TMR) once daily and measured a reduction of methane emission of about 60% (from 17.8 to 7.2 g/kg dry matter intake). Dry matter intake of cows, milk yield and milk composition were not significantly affected by the additive, but the additive increased body weight gain (1.06 vs. 0.39 kg/d), indicating that the reduction of methane emissions increased energy availability to animals. The inconsistency in methane reduction in studies with dairy cows requires further experimental studies to understand the mode of action of 3-nitrooxypropanol in the rumen (see [174].

5.6. Excrement Management

Anaerobic excrement storage may contribute to methane emission from the excreta. About 18% of the global methane emissions from animal husbandry come from excreta [7]. Therefore, the excreta should be used as substrate in biogas fermenters [186] or stored in airtight containers.

There are a number of animal and management practices that are feasible and can effectively reduce N_2O emissions from manure storage and/or land application [92].

Optimizing the animal diet to improve N use efficiency and balancing N input with production level are important steps in reducing N_2O emissions from the manure [187]; [188]. Due to the complex interaction between nutrition, production, animal health, and economic performance, diet modification to reduce N inputs should be done carefully to prevent reduced fibre digestibility and to maintain animal productivity [92].

5.7. Animal Keeping, Genetic and Animal Health

Animal health, low animal losses, long periods of productive life of reproductive animals such as dairy cows, sows etc., a reduction in the number of "unproductive" or low yielding animals and a feeding of animals according to species/categories as well as performances avoiding excess and deficiencies are general potentials for lower emissions with greenhouse potential. Some recent reviews analysed and summarized GHG-emissions during animal keeping,e.g., [189]; [190]; [191], animal feeding and management mitigation options [87, 88, 94]; [92]; [66]. In an excellent review [88] summarized non-CO_2 GHG mitigation opportunities by:

- Feed additives and feeding strategies
- Manure handling strategies
- Animal management strategies
- Reproductive management strategies
- Interactions among non-CO_2 GHG.

The authors assess the relative effectiveness, the input required to achieve desired effects and the applicability to regions. Improvement of Feed Conversion Rate (FCR) is one of the most efficient ways to reduce emission per kg animal product and to decrease CF. This statement is right for ruminants [66], non-ruminants [126] and aquaculture [127]; [192]. Special attention should be paid to the non-CO_2-emissions.Improved genetics and animal health care as well animal management in combination with better reproduction and feeding (higher digestibility and quality of forages) and reduction the breeding overhead (i.e., animals kept to maintain the herd and old animals without lactation) may contribute to reducing emissions (esp. CH_4) and CF [88]; [66]. [65] estimates that reducing the gap between livestock operations that generate high emissions vs. those that put out low emissions per unit of product could cut emissions by about 30 percent.

Higher feed intake is a key element for higher animal yields, improved feed efficiency and lower emissions per product [91], see Table 15. Another possibility to increase feed efficiency and to reduce emissions per unit edible protein is an increase in protein content in food of animal origin. It is not easy to increase the protein content of milk by cattle breeding, but it would be an efficient measurement to reduce the GHG-emissions per kg milk protein as shown in a model in Table 17. Control cows should produce 9 000 kg milk per year with 3.4% protein (306 kg protein per year; 1 000 cows produce 306 t protein per year). Table 17 shows the consequences of protein rich milk on animal numbers, methane emissions and GHG-amount per year in order to produce 306 t milk protein [193, 194].

Table-17. Required number of cows to produce 306 t milk protein in dependence on protein content of milk as well as methane emission from digestive tract, total GHG-emission and GHG-emission per kg milk protein [193, 194]

kg milk per cow and year	Milk fat (%)	Milk protein (%)	Required number of cows	CH_4 from enteric fermentation (t/year)	GHG-potential (t CO_{2eq}/year)	CO_{2eq} per kg edible milk protein
9 000	4.2	3.35	1 015	129	4 522	1.48
9 000 1)	4.1	3.40	1 000	126	4 421	1.44
9 000	3.7	3.60	945	116	4 046	1.32
9 000	3.6	3.65	932	114	3 959	1.29
9 000	3.4	3.75	907	110	3 790	1.24

1) Shown in bold type: basal variant for comparison (9 000 kg milk/year with 3.4% milk protein)

In summary, the reduction of CF in ruminant production per product should focus on a lowering of methane emissions from enteric fermentation and an increase of low production levels as well a reduction of ineffective animal numbers [78]; [65]; [88, 94]. In the future, results of plant (see [146] and animal breeding (e.g. [91]; [195] may also substantially contribute to lower GHG emissions.

6. CONCLUSIONS

Global emissions from livestock are estimated at 7.1 Gt CO_{2-eq} per year representing about 14.5% of human-induced GHG emissions [65]. Beef and milk cattle, pigs for meat production as well as poultry for meat and egg production contribute to 41, 20, 9 and 8% resp. of the total emissions. Feed production and processing and enteric fermentation from ruminants represent 45 and 39% of the total emissions.

Carbon Footprints may help to assess the GHG emissions associated with the production of food of animal origin. They may contribute to sensitizing producers and consumers to a more resource-efficient and environmentally-friendly production and consumption of food of animal origin and to avoiding food wastage [196].

Clear areas with high mitigation potential are the following:

- Improving the feed production, esp. fertilization (N, manure), management and reduced LUC.
- Reduction of post harvest feed losses, storing losses and losses and waste at food consumption [11].
- Improving feed supply, feeding practices and digestibility of diets.

- Improving animal yields through genetics, animal health, feeding practices, animal management (incl. excrement management) and, in consequence, reduction of the number of low yielding animals.

Differences in the calculated CF per kg product or per kg edible protein are obvious. Discrepancies in the results of various studies are explained by different system boundaries [197], allocation methods [137] and computation of emissions, especially with regard to land use changes, enteric methane and nitrous oxide emissions.

A more standardized approach for CF-calculations would be very useful tool to provide an indicator for food labelling, to compare CF between production systems, regions and countries as well to assess the resource efficiency, esp. in non-ruminants. The high portion of methane in the CF of food from ruminants does not allow use of the CF of food from ruminants and non-ruminants and conclude both food groups concerning feed efficiency.

Therefore, some authors (e.g. [62]; [197, 198]; [59]; [199] analysed limitations of CF as indicator of environmental sustainability and recommended significant efforts in more dynamic modelling to ameliorate the problems of spatial variation and local environmental uniqueness. Furthermore, methodological problems must be solved [12] and more diverse researchers should be involved in such studies in order to improve the data basis.

Reduction of methane emissions from ruminants and other emissions with greenhouse potential are a great challenge for all those involved in feed production and animal feeding. Some examples to do this are demonstrated in the paper.

In summary, the production of food of animal origin is a very complex process and selective consideration, i.e., focussing on single factors, does not provide an assessment that reflects the complexity of the subject.

Funding: This study received no specific financial support.

Competing Interests: The authors declare that they have no competing interests.

Contributors/Acknowledgement: All authors contributed equally to the conception and design of the study.

REFERENCES

[1] FAO, "The state of food and agriculture. Livestock in the balance," *State of Food and Agriculture*, p. 166, 2009.

[2] FAO, "How to feed the world in 2050. Rome," p. 35, 2009.

[3] N. Alexandratos and J. Bruinsma, *World agriculture towards 2030/2050: The 2012 revision*. Rome: FAO, 2012.

[4] HLPE, "Biofuels and food security (VO Draft). A zero-draft consultation paper," p. 72, 2013.

[5] C. L. Delgado, "Rising consumption of meat and milk in developing countries has created a new food revolution," *J. Nutr.*, vol. 133, pp. 3907S-3910S, 2003.

[6] IPCC (Intergovernmental Panel on Climate Change), "Guidelines for national greenhouse gas inventories," *Agriculture, Forestry and other Land use*, vol. 4, 2006.

[7] FAO, "Livestock´s long shadow, environmental issues and options. Rome," p. 406, 2006.

[8] FAO, "Greenhouse gas emissions from the dairy sector. A life cycle assessment Rome," p. 94, 2010.

[9] H. C. Godfray, J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, and J. F. Muir, "Food security: The challenge of feeding 9 billion people," *Science*, vol. 327, pp. 812-818, 2010.

[10] S. J. Vermeulen, B. M. Campbell, and J. S. I. Ingram, "Climate change and food systems," *Annual Review of Environment and Resources*, vol. 37, pp. 195-222, 2012.

[11] M. Guillou and G. Matheron, *The world's challenge - feeding 9 billion people.* Springer Berlin: Springer Netherlands; Ed. QuE, 2014.

[12] HLPE, *Note on critical and emerging issues for food security and nutrition.* Rome, 06082014: FAO, 2014.

[13] B. Thompson and L. Amoroso, *Improving diets and nutrition: Food-based approaches.* Wallingford UK and Boston: Food and Agriculture Organisation of the United Nations (FAO), Rome and CAB International, 2014.

[14] C. G. Neumann, N. O. Bwibo, C. A. Gewa, and N. Drorbaugh, *Animal source foods as a food-based approach to improve diet and nutrition outcomes. In: Thompson B, Amoroso L, Eds. improving diets and nutrition: Food-based approaches.* Wallingford: Cabi, 2014.

[15] B. Thompson and L. Amoroso, *Combating micronutrient deficiencies: Food-based approaches: Food based approaches.* Wallingford UK: Food and Agriculture Organisation of the United Nations (FAO), Rome and CAB International, 2010.

[16] V. Smil, "Feeding the world: A challenge for the twenty-first century, feeding the world: A challenge for the twenty-first century," p. xxviii + 360, 2000.

[17] E. S. Cassidy, P. C. West, J. S. Gerber, and J. A. Foley, "Redefining agricultural yields: From tonnes to people nourished per hectare," *Environ. Res. Lett.*, vol. 8, 2013.

[18] V. R. Young, D. M. Bier, and P. L. Pellett, "A theoretical basis for increasing current estimates of the amino acid requirements in adult man, with experimental support," *Am. J. Clin. Nutr.*, vol. 50, pp. 80-92, 1989.

[19] F.A.U. WHO, "Protein and amino acid requirements in human nutrition," Report of a Joint WHO/FAO/UNU Expert Consultation World Health Organization Technical Report Series, 2007.

[20] C. G. Neumann, M. W. Demment, A. Maretzki, N. Drorbaugh, and K. A. Galvin, *The livestock revolution and animal source food consumption: Benefits, risks, and challenges in urban and rural settings of developing countries. In: Steinfeld H, Mooney HA, Schneider F, Neville LE, Eds. Livestock in a changing landscape,: Drivers, consequences and responses* vol. 1. Washington: Island Press, 2010.

[21] J. P. F. D'Mello, *Amino acids in human nutrition and health.* Wallingford (UK) and Cambridge (USA): International C, 2011.

[22] R. R. Pillai and A. V. Kurpad, *Amino acid requirements: Quantitative estimates. In: D'Mello JPF, Eds. Amino acids in human nutrition and health.* Wallingford: Cabi, 2011.

[23] J. Smith, K. Sones, D. Grace, S. MacMillan, S. Tarawali, and M. Herrero, "Beyond milk, meat, and eggs: Role of livestock in food and nutrition security," *Animal Frontiers*, vol. 3, pp. 6-13, 2013.

[24] H. Wennemer, G. Flachowsky, and V. Hoffmann, "Protein, population, politics - how protein can be supplied sustainable in the 21st century: Plexus Verlag, Mittenberg and Frankfurt/Main," p. 160, 2006.

[25] J. C. Waterlow, "The mysteries of nitrogen balance," *Nutrition Research Reviews*, vol. 12, pp. 25-54, 1999.

[26] A. A. Jackson, *Protein. In: Mann, J and S Truswell (Eds): Essentials of human nutrition*, 3rd ed.: Oxford Univ. Press, 2007.

[27] W. M. Rand, P. L. Pellett, and V. R. Young, "Meta-analysis of nitrogen balance studies for estimating protein requirements in healthy adults," *Am. J. Clin. Nutr.*, vol. 77, pp. 109-127, 2003.

[28] A. Avadi and P. Freon, "Life cycle assessment of fisheries: A review for fisheries scientists and managers," *Fish Res.*, vol. 143, pp. 21-38, 2013.

[29] M. A. Keyzer, M. D. Merbis, I. F. P. W. Pavel, and C. F. A. Van Wesenbeeck, "Diet shifts towards meat and the effects on cereal use: Can we feed the animals in 2030," *Ecol. Econ.*, vol. 55, pp. 187-202, 2005.

[30] D. Tilman, C. Balzer, J. Hill, and B. L. Befort, "Global food demand and the sustainable intensification of agriculture," *Proc. Natl. Acad. Sci. USA*, vol. 108, pp. 20260-20264, 2011.

[31] T. Kastner, M. J. Rivas, W. Koch, and S. Nonhebel, "Global changes in diets and the consequences for land requirements for food," *Proc. Natl. Acad. Sci. USA*, vol. 109, pp. 6868-6872, 2012.

[32] H. Guyomard, S. Manceron, and J. L. Peyraud, "Trade in feed grains, animals, and animal products: Current trends, future prospects, and main issues," *Animal Frontiers*, vol. 3, pp. 14-18, 2013.

[33] P. W. Gerbens-Leenes and S. Nonhebel, "Consumption patterns and their effects on land required for food," *Ecol. Econ.*, vol. 42, pp. 185-199, 2002.

[34] R. Naylor, H. Steinfeid, W. Falcon, J. Galloways, V. Smil, and E. Bradford, "Losing the links between livestock and land," *Science*, vol. 310, pp. 1621-1622, 2005.

[35] S. Wirsenius, C. Azar, and G. Berndes, "How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030," *Agricultural Systems*, vol. 103, pp. 621-638, 2010.

[36] G. Flachowsky, U. Meyer, and K. H. Südekum, "Land use for edible protein of animal origin - A review," *Food Security in Press*, vol. 6, 2014.

[37] E. Kebreab, "Sustainable animal agriculture," *CAB International*, p. xiii + 321, 2013.

[38] SAFA, *Sustainable assessment of food and agriculture systems indicators*. Rome: FAO. Available: http://wwwfaoorg/docrep/015/an913e/an913epdf, 2013.

[39] FAO, "Dairy Asia: Towards sustainability," in *Proceedings of an International Consultation, Held in Bangkok*, Thailand, 2014, pp. 65. [Accessed 21-23 May 2014].

[40] H. Guyomard, B. Darcy-Vrillon, C. Esnouf, M. Marin, M. Russel, and M. Guillou, "Eating patterns and food systems: Critical knowledge requirements for policy design and implementation," *Agriculture and Food Security*, vol. 1, p. 3. [Accessed 3 September 2012], 2012.

[41] D. Pimentel and M. Pimentel, "Sustainability of meat-based and plant-based diets and the environment," *Am. J. Clin. Nutr.*, vol. 78, pp. 660S-663S, 2003.

[42] L. Reijnders and S. Soret, "Quantification of the environmental impact of different dietary protein choices," *Am. J. Clin. Nutr.*, vol. 78, pp. 664S-668S, 2003.

[43] L. Baroni, L. Cenci, M. Tettamanti, and M. Berati, "Evaluating the environmental impact of various dietary patterns combined with different food production systems," *Eur. J. Clin. Nutr.*, vol. 61, pp. 279-286, 2007.

[44] C. J. Peters, J. L. Wilkins, and G. W. Fick, "Testing a complete-diet model for estimating the land resource requirements of food consumption and agricultural carrying capacity: The New York State example," *Renew Agr. Food Syst.*, vol. 22, pp. 145-153, 2007.

[45] A. Y. Hoekstra and A. K. Chapagain, "Water footprints of nations: Water use by people as a function of their consumption pattern," *Water Resour. Manag.*, vol. 21, pp. 35-48, 2007.

[46] D. Renault and W. W. Wallender, "Nutritional water productivity and diets," *Agr. Water Manage*, vol. 45, pp. 275-296, 2000.

[47] A. C. Schlink, M. L. Nguyen, and G. J. Viljoen, "Water requirements for livestock production: A global perspective," *Rev. Sci. Tech.*, vol. 29, pp. 603-619, 2010.

[48] J. Deikman, M. Petracek, and J. E. Heard, "Drought tolerance through biotechnology: Improving translation from the laboratory to farmers' fields," *Curr. Opin. Biotechnol.*, vol. 23, pp. 243-250, 2012.

[49] D. C. Hall and J. V. Hall, "Concepts and measures of natural-resource scarcity with a summary of recent trends," *J. Environ. Econ. Manag.*, vol. 11, pp. 363-379, 1984.

[50] R. W. Scholz and F. W. Wellmer, "Approaching a dynamic view on the availability of mineral resources: What we may learn from the case of phosphorus," *Global Environ. Chang*, vol. 23, pp. 11-27, 2013.

[51] S. Aerts, "Agriculture´s 6 F´s and the need for more intensive agriculture. In: Potthast T, Meisch, S., Eds. Climate change and sustainable development," *Wageningen Acad. Publ.*, pp. 192-195, 2012.

[52] M. M. Mekonnen and A. V. Hoestra, *The green, blue and grey water footprint of farm animals and animal products. Value of Water Res. Rep. Ser. No. 48*. Delft, The Neterlands: UNESCO-IHE, 2010.

[53] U. Amarsinghe, *Water footprint of the dairy sector*. Bangkok Thailand: Proc of an Intern Consultation. [Accessed 21-23 May 2014], 2014.

[54] M. De Vries and I. J. M. De Boer, "Comparing environmental impacts for livestock products: A review of life cycle assessments," *Livestock Science*, vol. 128, pp. 1-11, 2010.

[55] T. L. T. Nguyen, J. E. Hermansen, and L. Mogensen, "Environmental consequences of different beef production systems in the EU," *J. Clean Prod.*, vol. 18, pp. 756-766, 2010.

[56] D. Nijdam, T. Rood, and H. Westhoek, "The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes," *Food Policy*, vol. 37, pp. 760-770, 2012.

[57] P. Upham, L. Dendler, and M. Bleda, "Carbon labelling of grocery products: Public perceptions and potential emissions reductions," *J. Clean Prod.*, vol. 19, pp. 348-355, 2011.

[58] W. Young, S. xHwang, S. McDonald, and C. J. Oates, "Sustainable consumption: Green consumer behaviour when purchasing products," *Sustainable Development*, vol. 1, pp. 20-31, 2010.

[59] K. R. Caffrey and M. W. Veal, "Conducting an agricultural life cycle assessment: Challenges and perspectives," *Sci. World J.*, 2013.

[60] R. A. F. De Alvarenga, V. P. D. Silva Junior, S. R. Soares, R. A. F. De Alvarenga, and V. P. Da Silva Junior, "Comparison of the ecological footprint and a life cycle impact assessment method for a case study on Brazilian broiler feed production," *J. Clean Prod.*, vol. 28, pp. 25-32, 2012.

[61] A. Ciroth, G. Fleischer, and J. Steinbach, "Uncertainty calculation in life cycle assessments - a combined model of simulation and approximation," *Int. J. Life Cycle Ass.*, vol. 9, pp. 216-226, 2004.

[62] J. Reap, F. Roman, S. Duncan, and B. Bras, "A survey of unresolved problems in life cycle assessment," *Int. J. Life Cycle Ass.*, vol. 13, pp. 374-388, 2008.

[63] S. A. Morais and C. Delerue-Matos, "A perspective on LCA application in site remediation services: Critical review of challenges," *Journal of Hazard Mater*, vol. 175, pp. 12-22, 2010.

[64] J. B. Guinee, R. Heijungs, G. Huppes, A. Zamagni, P. Masoni, and R. Buonamici, "Life cycle assessment: Past, present, and future," *Environ. Sci. Technol.*, vol. 45, pp. 90-96, 2011.

[65] P. J. Gerber, H. Steinfeld, B. Henderson, A. Mollet, C. Opio, and F. Dijkman, *Tackling climate change through livestock - a global assessment of emissions and mitigation opportunities*. Rome: Food and Agriculture Organisation of the United Nations (FAO), 2013.

[66] C. Opio, P. Gerber, A. Mottet, A. Falcucci, G. Tempio, and M. MacLeod, *Greenhouse gas emissions from ruminant supply chains - A global life cycle assessment*. Rome: Food and Agriculture Organisation of the United Nations (FAO), 2013.

[67] M. MacLeod, P. Gerber, A. Mottet, G. Tempio, A. Falcucci, and C. Opio, *Greenhouse gas emissions from pig and chicken supply chains - a global life cycle assessment*. Rome: Food and Agriculture Organisation of the United Nations (FAO), 2013.

[68] IUNC, "The IUNC programm 2005-2008. Many voices, one earth. Bangkok, Thailand. Available: https://cmsdata.iunc.org/downloads/programme-english.pdf. [Accssed 17-25 Nov. 2004]," 2005.

[69] R. Boonen, S. Aerts, and L. De Tavernier, *Which sustainability soits you? In: Climate change and sustainable development*. Wageningen Acad. Publ.: Potthast, T., Meisch, S, 2012.

[70] N. V. Fedoroff, D. S. Battisti, R. N. Beachy, P. J. Cooper, D. A. Fischhoff, and C. N. Hodges, "Radically rethinking agriculture for the 21st century," *Science*, vol. 327, pp. 833-834, 2010.

[71] D. Giovannucci, S. Scherr, D. Nierenberg, C. Hebebrand, J. Shapiro, and J. Milder, *Food and agriculture: The future of sustainability. A strategic input to the sustainable development in the 21st century (SD21) project*. New York: United Nations Department of Economic and Social Affairs, Division for Sustainable Development, 2012.

[72] J. A. Foley, N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, and M. Johnston, "Solutions for a cultivated planet," *Nature*, vol. 478, pp. 337-342, 2011.

[73] C. Opio, "Environmental performance of the dairy sector," in *Proc of An International Consultation, Bangkok, Thailand, 21-23052014*, 2014, pp. 12-13.

[74] IPCC, "IPCC. (Intergovernmental Panel on Climate Change). Mitigation of climate change," Contribution of Working III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA, Cambridge University Press2014.

[75] H. Kim, S. Kim, and B. E. Dale, "Biofuels, land use change, and greenhouse gas emissions: Some unexplored variables," *Environ. Sci. Technol.*, vol. 43, pp. 961-967, 2009.

[76] K. Hergoualch and L. V. Verchot, "Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: A review," *Global Biogeochemical Cycles; GB2001*, vol. 25, pp. 1-13, 2011.

[77] G. Attwood and C. McSweeney, "Methanogen genomics to discover targets for methane mitigation technologies and options for alternative H-2 utilisation in the rumen," *Aust. J. Exp. Agr.*, vol. 48, pp. 28-37, 2008.

[78] G. Flachowsky and W. Brade, "Reduction potentials for methane emissions from ruminants," *Züchtungskunde*, vol. 79, pp. 417-465, 2007.

[79] S. Tamminga, A. Bannink, Z. Dijkstra, and R. Zom, "Feeding strategies to reduce methane losses in cattle," *Animal Science Group, Wageningen UR, Rep.*, vol. 34, p. 44, 2007.

[80] A. Bannink, J. France, S. Lopez, W. J. J. Gerrits, E. Kebreab, and S. Tamminga, "Modelling the implications of feeding strategy on rumen fermentation and functioning of the rumen wall," *Anim. Feed Sci. Technol.*, vol. 143, pp. 3-26, 2008.

[81] J. P. Jouany, *Enteric methane production by ruminants and its control. In: Andrieu S, Wilde D, (Eds). Gut efficiency: The key ingredient in ruminant production elevating animal performance and health.* Wageningen: Wageningen Academic Publishers, 2008.

[82] K. A. Beauchemin, T. A. McAllister, and S. M. McGinn, "Dietary mitigation of enteric methane from cattle," *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, vol. 4, pp. 1-18, 2009.

[83] R. L. M. Schils, J. E. Olesen, A. Del Prado, and J. F. Soussana, "A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems," *Livestock Science*, vol. 112, pp. 240-251, 2007.

[84] T. Yan, M. G. Porter, and C. S. Mayne, "Prediction of methane emission from beef cattle using data measured in indirect open-circuit respiration calorimeters," *Animal Science Group, Wageningen UR, Rep.*, vol. 3, pp. 1455-1462, 2009.

[85] J. Dijkstra, J. France, S. Lopez, J. L. Ellis, E. Kebreab, and A. Bannink, "Modelling biochemical rumen functions with special emphasis on methanogenesis," *23 Hülsenberger Gespräche 2010, Lübeck, Germany, 02-04062010*, pp. 79-89, 2010.

[86] J. L. Ellis, A. Bannink, J. France, E. Kebreab, and J. Dijkstra, "Evaluation of enteric methane prediction equations for dairy cows used in whole farm models," *Global Change Biol.*, vol. 16, pp. 3246-3256, 2010.

[87] A. N. Hristov, J. Oh, J. L. Firkins, J. Dijkstra, E. Kebreab, and G. Waghorn, "Mitigation of methane and nitrous oxide emissions from animal operations: I A review of enteric methane mitigation options," *J. Anim. Sci.*, vol. 91, pp. 5045-5069, 2013.

[88] A. N. Hristov, J. Oh, C. Lee, R. Meinen, F. Montes, and T. Ott, *Mitigation of greenhouse gas emissions in livestock production - a review of technical options for non-CO2 emissions. In: Gerber PJH, B.; Makkar, H.P.S., (Eds).* Rome, Italy: FAO Animal Production and Health Paper No. 177, FAO, 2013.

[89] P. Ricci, J. A. Rooke, I. Nevison, and A. Waterhouse, "Methane emissions from beef and dairy cattle: Quantifying the effect of physiological stage and diet characteristics," *J. Anim. Sci.*, vol. 91, pp. 5379-5389, 2013.

[90] K. A. Johnson and D. E. Johnson, "Methane emissions from cattle," *J. Anim. Sci.*, vol. 73, pp. 2483-2492, 1995.

[91] H. Niemann, B. Kuhla, and G. Flachowsky, "Perspectives for feed-efficient animal production," *J. Anim. Sci.*, vol. 89, pp. 4344-4363, 2011.

[92] F. Montes, R. Meinen, C. Dell, A. Rotz, A. N. Hristov, and J. Oh, "Special topics—mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options," *J. Anim. Sci.*, vol. 91, pp. 5070-5094, 2013.

[93] G. Flachowsky and P. Lebzien, "Food producing animals and greenhouse gases - possibilities of animal nutrition for reduction of the emissions (In German)," *Übers z Tierern*, vol. 35, pp. 191-231, 2007.

[94] A. N. Hristov, T. Ott, J. Tricarico, A. Rotz, G. Waghorn, and A. Adesogan, "Mitigation of methane and nitrous oxide emissions from animal operations: III A review of animal management mitigation options," *J. Anim. Sci.*, vol. 91, pp. 5095-5113, 2013.

[95] R. J. Stevens, R. J. Laughlin, L. C. Burns, J. R. M. Arah, and R. C. Hood, "Measuring the contributions of nitrification and denitrification to the flux of nitrous oxide from soil," *Soil Biol. Biochem.*, vol. 29, pp. 139-151, 1997.

[96] IPCC (Intergovernmental Panel on Climate Change), "Synthesis report for policymakers," 2007.

[97] H. Flessa, W. Pfau, P. Dorsch, and F. Beese, "The influence of nitrate and ammonium fertilization on N2O release and CH4 uptake of a well-drained topsoil demonstrated by a soil microcosm experiment," *Z Pflanz Bodenkunde*, vol. 159, pp. 499-503, 1996.

[98] O. Oenema, G. L. Velthof, S. Yamulki, and S. C. Jarvis, "Nitrous oxide emissions from grazed grassland," *Soil Use Manage*, vol. 13, pp. 288-295, 1997.

[99] J. W. Van Groenigen, G. L. Velthof, F. J. E. V. D. Bolt, A. Vos, P. J. Kuikman, and F. J. E. V. Der Bolt, "Seasonal variation in N 2O emissions from urine patches: Effects of urine concentration, soil compaction and dung," *Plant and Soil*, vol. 273, pp. 15-27, 2005.

[100] C. Lampe, K. Dittert, B. Sattelmacher, M. Wachendorf, R. Loges, and F. Taube, "Sources and rates of nitrous oxide application of N-15-labelled emissions from grazed grassland after mineral fertilizer and slurry," *Soil Biol Biochem.*, vol. 38, pp. 2602-2613, 2006.

[101] C. Bessou, B. Mary, J. Leonard, M. Roussel, E. Grehan, and B. Gabrielle, "Modelling soil compaction impacts on nitrous oxide emissions in arable fields," *Eur. J. Soil Sci.*, vol. 61, pp. 348-363, 2010.

[102] P. Weisskopf, R. Reiser, J. Rek, and H. R. Oberholzer, "Effect of different compaction impacts and varying subsequent management practices on soil structure, air regime and microbiological parameters," *Soil Till Res.*, vol. 111, pp. 65-74, 2010.

[103] M. Schmeer, R. Loges, K. Dittert, M. Senbayram, R. Horn, and F. Taube, "Legume-based forage production systems reduce nitrous oxide emissions," *Soil and Tillage Research*, vol. 143, pp. 17-25, 2014.

[104] A. G. Williams, E. Audsley, and D. L. Sanders, "Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities," Main Report Defra

Research Project IS0205, Bedford: Cranfield University and Defra. Available: wwwsilsoecranfiedacuk, and wwwdefragovuk, 2006.

[105] A. Leip, F. Weiss, T. Wasenaar, I. Perez, T. Fellmann, and P. Loudjami, "Evaulation of the livestock sector´s cntribution to the EU greenhouse gas emissions (GGELS)," Final Report, JRC, EU2010.

[106] J. Gruenberg, H. Nieberg, and T. G. Schmidt, "Carbon footprints of food: A critical reflection," *Langbauforschung-Ger*, vol. 60, pp. 53-72, 2010.

[107] G. Flachowsky, "Carbon-footprints for food of animal origin, reduction potentials and research need," *J. Appl. Anim. Res.*, vol. 39, pp. 2-14, 2011.

[108] G. Flachowsky, W. Brade, A. Feil, J. Kamphues, U. Meyer, and M. Zehetmeier, "Carbon (CO 2)-footprints of producing food of animal origin - data base and reduction potentials (In German)," *Übers Z Tierern*, vol. 39, pp. 1-45, 2011.

[109] J. P. Lesschen, M. Van den Berg, H. J. Westhoek, H. P. Witzke, and O. Oenema, "Greenhouse gas emission profiles of European livestock sectors," *Anim. Feed Sci. Technol.*, vol. 166-67, pp. 16-28, 2011.

[110] G. Flachowsky and J. Kamphues, "Carbon footprints for food of animal origin: What are the most preferable criteria to measure animal yields," *Animals*, vol. 2, pp. 108-126, 2012.

[111] G. M. Peters, H. V. Rowley, S. Wiedemann, R. Tucker, M. D. Short, and M. Schulz, "Red meat production in australia: Life cycle assessment and comparison with overseas studies," *Environ. Sci. Technol.*, vol. 44, pp. 1327-1332, 2010.

[112] U. Dämmgen and H. D. Haenel, "Emissions of greenhouse gases and gaseous air pollutants - a challenge for animal nutrition," *Proceedings of the Society of Nutrition Physiology*, vol. 17, pp. 163-167, 2008.

[113] J. W. Casey and N. M. Holden, "Quantification of GHG emissions from sucker-beef production in Ireland," *Agricultural Systems*, vol. 90, pp. 79-98, 2006.

[114] J. W. Casey and N. M. Holden, "Greenhouse gas emissions from conventional, agri-environmental scheme, and organic Irish suckler-beef units," *J. Environ. Qual.*, vol. 35, pp. 231-239, 2006.

[115] H. S. Matthews, C. T. Hendrickson, and C. L. Weber, "The importance of carbon footprint estimation boundaries," *Environ. Sci. Technol.*, vol. 42, pp. 5839-5842, 2008.

[116] K. Bartl, C. A. Gomez, and T. Nemecek, "Life cycle assessment of milk produced in two smallholder dairy systems in the Highlands and the Coast of Peru," *J. Clean Prod.*, vol. 19, pp. 1494-1505, 2011.

[117] P. Gerber, T. Vellinga, C. Opio, and H. Steinfeld, "Productivity gains and greenhouse gas emissions intensity in dairy systems," *Livestock Science*, vol. 139, pp. 100-108, 2011.

[118] G. Flachowsky, "Greenhouse gases and resource efficiency. Aspects of production of food of animal origin (In German)," *Ernährungs-Umschau*, vol. 55, pp. 414-419, 2008.

[119] H. P. S. Makkar, "Biofuel co-products as livestock feed - opportunities and challenges. Biofuel co-products as livestock feed - opportunities and challenges," p. xviii + 533, 2012.

[120] E. V. Elferink, S. Nonhebel, and H. C. Moll, "Feeding livestock food residue and the consequences for the environmental impact of meat," *J. Clean Prod.*, vol. 16, pp. 1227-1233, 2008.

[121] F. J. Bockisch, H. J. Ahlgrimm, H. Böhme, A. Bramm, U. Dämmgen, and G. Flachowsky, "Evaluation of organic and conventional agriculture concerning energy input and greenhouse gas emission output (In German)," *Landbauforschung Völkenrode*, vol. SH 211, p. 206, 2000.

[122] G. Flachowsky, "Efficiency of energy and nutrient use in the production of edible protein of animal origin," *J. Appl. Anim. Res.*, vol. 22, pp. 1-24, 2002.

[123] F. P. O'Mara, "The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future," *Anim. Feed Sci. Technol.*, vol. 166-67, pp. 7-15, 2011.

[124] M. Q. B. Tan, R. B. H. Tan, and H. H. Khoo, "Prospects of carbon labelling – a life cycle point of view," *J. Clean Prod.*, vol. 72, pp. 76-88, 2014.

[125] A. Thévenot, J. Aubin, E. Tillard, and J. Vayssières, "Accounting for farm diversity in life cycle assessment studies – the case of poultry production in a tropical Island," *J. Clean Prod.*, vol. 57, pp. 280-292, 2013.

[126] N. Pelletier, M. Ibarburu, and H. W. Xin, "A carbon footprint analysis of egg production and processing supply chains in the Midwestern United States," *J. Clean Prod.*, vol. 54, pp. 108-114, 2013.

[127] R. Mungkung, J. Aubin, T. H. Prihadi, J. Slernbrouck, H. M. G. Van Der Werf, and M. Legendre, "Life cycle assessment for environmentally sustainable aquaculture management: A case study of combined aquaculture systems for carp and tilapia," *J. Clean Prod.*, vol. 57, pp. 249-256, 2013.

[128] M. D. Finke, *Nutrient content of insects - organic value recovery solution studies. Encyclopedia of entomology*: Springer, 2004.

[129] A. Van Huis, "Potential of insects as food and feed in assuring food security," *Annu. Rev. Entomol.*, vol. 58, pp. 563-583, 2013.

[130] A. Van Huis, J. V. Itterbeeck, H. Klunder, E. Mertens, A. Halloran, and G. Muir, "Edible insects: Future prospects for food and feed security, FAO forestry paper," p. xvi + 187, 2013.

[131] W. Windisch, C. Fahn, D. Brugger, M. Deml, and M. Buffler, "Strategies for sustainable animal nutrition strategien fur eine nachhaltige tierernahrung," *Zuchtungskunde*, vol. 85, pp. 40-53, 2013.

[132] J. Mlcek, O. Rop, M. Borkovcova, and M. Bednarova, "A comprehensive look at the possibilities of edible insects as food in Europe - A review," *Polish Journal of Food and Nutrition Sciences*, vol. 64, pp. 147-157, 2014.

[133] S. W. Souci, W. Fachmann, and H. Kraut, *Food table for the practice. The little Souci-Fachmann-Kraut (in German)," Ed, Deutsche Forschungsanstalt für Lebensmittelchemie, Freising*, 7th ed. Stuttgart: Wiss Verlagsgesellschaft mbH, 2008.

[134] M. J. Vandehaar, "Efficiency of nutrient use and relationship to profitability on dairy farms," *J. Dairy Sci.*, vol. 81, pp. 272-282, 1998.

[135] C. Cederberg and M. Stadig, "System expansion and allocation in life cycle assessment of milk and beef production," *Int. J. Life Cycle Ass.*, vol. 8, pp. 350-356, 2003.

[136] M. A. Thomassen, K. J. Van Calker, M. C. J. Smits, G. L. Iepema, and I. J. M. De Boer, "Life cycle assessment of conventional and organic milk production in the Netherlands," *Agricultural Systems*, vol. 96, pp. 95-107, 2008.

[137] M. Zehetmeier, J. Baudracco, H. Hoffmann, and A. Heissenhuber, "Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach," *Animal*, vol. 6, pp. 154-166, 2012.

[138] A. G. Roer, A. Johansen, A. K. Bakken, K. Daugstad, G. Fystro, and A. H. Stromman, "Environmental impacts of combined milk and meat production in Norway according to a life cycle assessment with expanded system boundaries," *Livestock Science*, vol. 155, pp. 384-396, 2013.

[139] T. R. Society, "Reaping the benefits: Science and the sustainable intensification of global agriculture. RS policy document 11/09, issued Oct 2009, RS 1608," 2009.

[140] G. Flachowsky, U. Meyer, and M. Grün, "Plant and animal breeding as starting points for sustainable," *In: Sustainable Agriculture Reviews: E. Lichtfouse*, pp. 201-224, 2012.

[141] D. B. Lobell, M. B. Burke, C. Tebaldi, M. D. Mastrandrea, W. P. Falcon, and R. L. Naylor, "Prioritizing climate change adaptation needs for food security in 2030," *Science*, vol. 319, pp. 607-610, 2008.

[142] M. P. Reynolds, *Climate change and crop production.* Wallingford/Cambridge, USA: CAB International, 2010.

[143] J. A. Newman, M. Anand, H. A. L. Henry, S. Hunt, and Z. Gedalof, "Climate change biology," *Climate Change Biology*, p. xiii + 289, 2011.

[144] HLPE, *Food security and climate change. A report by the high level panel of experts on food security and nutrition, June 2012.* Rome: Committee on World Food Security; FAO, 2012.

[145] T. Fischer, D. Byerlee, and G. Edmeades, "Crop yields and global food security: Will yield increase continue to feed the world?, Crop yields and global food security: will yield increase continue to feed the world?," p. xxi + 634, 2014.

[146] G. Flachowsky, *Animal nutrition with transgenic plants. In: Flachowsky G, editor. Animal nutrition with transgenic plants.* CABI: Wallingford; UK, 2013.

[147] P. Tillie, K. Dillen, and E. Rodriguez-Cerezo, *The pipeline of GM crops for improved animal feed: Challenges for commercial use. In: Flachowsky G, Editor. Animal nutrition with transgenic plants.* Wallingford: Cabi, 2013.

[148] F. Taube, "Efficient utilization of resources - feed production for dairy cows (In German), 23 Hülsenberger Gespräche 2010, Lübeck, Germany, 02-04062010," pp. 176-183, 2010.

[149] W. Windisch, D. Brugger, M. Buffler, M. Deml, and C. Fahn, "Animal nutrition is looking for new feed sources (In German)," presented at the 12 BOKU-Symposium Tierernährung, Wien, 11042013, 2013.

[150] F. Sundstol and E. Owen, "Straw and other fibrous by products as feed," *Developm Animal VetSci, 14, Elsevier Amsterdam*, p. 610, 1984.

[151] G. Flachowsky, *Stroh als futtermittel : Ergebnisse und erfahrungen bei der strohaufbereitung und beim einsatz von unterschiedlich behandeltem stroh als futtermittel.* Berlin: VEB Deutscher Landwirtschaftsverlag, 1987.

[152] M. B. Kling and W. H. Wöhlbier, *Handelsfuttermittel, Bd. 1.* Stuttgart: Verlag Eugen Ulmer, 1977.

[153] H. Jeroch, G. Flachowsky, and F. Weissbach, *Futtermittelkunde.* Stuttgart: Gustav Fischer Verlag Jena, 1993.

[154] S. E. Place and F. M. Mitloehner, "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," *J. Dairy Sci.*, vol. 93, pp. 3407-3416, 2010.

[155] T. Yan, C. S. Mayne, F. G. Gordon, M. G. Porter, R. E. Agnew, and D. C. Patterson, "Mitigation of enteric methane emissions through improving efficiency of energy utilization and productivity in lactating dairy cows," *J. Dairy Sci.*, vol. 93, pp. 2630-2638, 2010.

[156] M. Herrero, P. Gerber, T. Vellinga, T. Garnett, A. Leip, and C. Opio, "Livestock and greenhouse gas emissions: The importance of getting the numbers right," *Anim. Feed Sci. Technol.*, vol. 166/167, pp. 779-782, 2011.

[157] GfE, *Recommendations for energy and nutrient requirements of dairy cattle and heifers (In German). No. 8. In: Energy and nutrient requirements of domestic animals.* Frankfurt: DLG-Verlags-GmbH, 2001.

[158] V. Fievez, G. Goel, C. Boeckaert, and B. Vlaeminck, *Potential of fatty acids mitigating ruminal methanogenisis. In: Doppenberg J, Van Der Aar, P., Editor. Dynamics in animal nutrition*: Wageningen Acad. Publ., 2010.

[159] C. Martin, D. P. Morgavi, and M. Doreau, "Methane mitigation in ruminants: From microbe to the farm scale," *Animal*, vol. 4, pp. 351-365, 2010.

[160] R. J. Eckard, C. Grainger, and C. A. M. De Klein, "Options for the abatement of methane and nitrous oxide from ruminant production: A review," *Livestock Science*, vol. 130, pp. 47-56, 2010.

[161] K. L. Blaxter and J. Czerkawski, "Modifications of the methane production of the sheep by supplementation of its diet," *J. Sci. Food Agric.*, vol. 17, pp. 417-421, 1966.

[162] J. A. Mills, J. Dijkstra, A. Bannink, S. B. Cammell, E. Kebreab, and J. France, "A mechanistic model of whole-tract digestion and methanogenesis in the lactating dairy cow: Model development, evaluation, and application," *J. Anim. Sci.*, vol. 79, pp. 1584-1597, 2001.

[163] K. A. Beauchemin, M. Kreuzer, F. O'Mara, and T. A. McAllister, "Nutritional management for enteric methane abatement: A review," *Aust. J. Exp. Agr.*, vol. 48, pp. 21-27, 2008.

[164] T. A. McAllister and C. J. Newbold, "Redirecting rumen fermentation to reduce methanogenesis," *Aust. J. Exp. Agr.*, vol. 48, pp. 7-13, 2008.

[165] J. A. D. R. N. Appuhamy, A. B. Strathe, S. Jayasundara, C. Wagner-Riddle, J. Dijkstra, and J. France, "Anti-methanogenic effects of monensin in dairy and beef cattle: A meta-analysis," *J. Dairy Sci.*, vol. 96, pp. 5161-5173, 2013.

[166] E. Bayaru, S. Kanda, T. Kamada, H. Itabashi, S. Andoh, and T. Nishida, "Effect of fumaric acid on methane production, rumen fermentation and digestibility of cattle fed roughage alone," *Animal Science Journal*, vol. 72, pp. 139-146, 2001.

[167] N. Remling, S. Riede, P. Lebzien, U. Meyer, M. Höltershinken, and S. Kersten, "Effects of fumaric acid on rumen fermentation, milk composition and metabolic parameters in lactating cows," *J. Anim. Physiol. Anim. Nutr.*, vol. 98, pp. 968-981, 2014.

[168] R. Bodas, S. Lopez, M. Fernandez, R. Garcia-Gonzalez, A. B. Rodriguez, and R. J. Wallace, "In vitro screening of the potential of numerous plant species as antimethanogenic feed additives for ruminants," *Anim. Feed Sci. Technol.*, vol. 145, pp. 245-258, 2008.

[169] D. L. Palmquist, *Use of fats in diets for lactating dairy cows. In Fats in animal nutrition. Ed. by J. Wiseman*: Butterworth, Boston, 1984.

[170] E. R. Morales, M. A. M. Espinosa, N. McKain, and R. J. Wallace, "Ricinoleic acid inhibits methanogenesis and fatty acid biohydrogenation in ruminal digesta from sheep and in bacterial cultures," *J. Anim. Sci.*, vol. 90, pp. 4943-4950, 2012.

[171] M. Poulsen, C. Schwab, B. B. Jensen, R. M. Engberg, A. Spang, and N. Canibe, "Methylotrophic methanogenic Thermoplasmata implicated in reduced methane emissions from bovine rumen," *Nat. Commun.*, vol. 4, p. 1428, 2013.

[172] C. Benchaar and H. Greathead, "Essential oils and opportunities to mitigate enteric methane emissions from ruminants," *Anim. Feed Sci. Technol.*, vol. 166-67, pp. 338-355, 2011.

[173] K. J. Hart, D. R. Yanez-Ruiz, S. M. Duval, N. R. McEwan, and C. J. Newbold, "Plant extracts to manipulate rumen fermentation," *Anim. Feed Sci. Technol.*, vol. 147, pp. 8-35, 2008.

[174] G. Flachowsky and P. Lebzien, "Effects of phytogenic substances on rumen fermentation and methane emissions: A proposal for a research process," *Anim. Feed Sci. Technol.*, vol. 176, pp. 70-77, 2012.

[175] EFSA, "Guidance on safety assessment of botanicals* and botanical preparations** intended for use as ingredients in food supplements," *EFSA Journal*, vol. 7, p. 1249, 2009.

[176] G. Speijers, B. Bottex, B. Dusemund, A. Lugasi, J. Toth, and J. Amberg-Muller, "Safety assessment of botanicals and botanical preparations used as ingredients in food supplements: Testing an European food safety authority-tiered approach," *Mol. Nutr. Food Res.*, vol. 54, pp. 175-185, 2010.

[177] S. J. Van Den Berg, L. Serra-Majem, P. Coppens, and I. M. Rietjens, "Safety assessment of plant food supplements (PFS)," *Food Funct*, vol. 2, pp. 760-768, 2011.

[178] G. Martinez-Fernandez, A. Acro, L. Abecia, G. Cantalapiedra-Hijar, A. Molina-Alcaide, and I. Martin-Garcia, "The addition of ethyl-3-nitrooxy propionate and 3-nitrooxypropanol in the diet of sheep substantially reduces methane emissions and the effect persists over a month," *Advances in Animal Biosciences*, vol. 4, 2013.

[179] C. K. Reynolds, D. J. Humphries, P. Kirton, M. Kindermann, S. Duval, and W. Steinberg, "Effects of incremental rumen doses of 3-nitrooxypropanol on methane production, digestion and rumen parameters in lactating dairy cows," *Advances in Animal Biosciences*, vol. 4, p. 261, 2013.

[180] Romero Perez, K. A. Beauchemin, S. M. McGinn, E. K. Okine, L. L. Guan, and M. Oba, "The potential of 3-nitrooxipropanol to lower enteric methane emissions from beef cattle," *Advances in Animal Biosciences*, vol. 4, p. 387, 2013.

[181] A. Romero Perez, K. A. Beauchemin, E. K. Okine, and S. M. Duval, "Effects of 3-nitrooxipropanol on methane production using the rumen simulation technique (Rusitec)," *Advances in Animal Biosciences*, vol. 4, p. 389, 2013.

[182] S. Duval and M. Kindermann, "Nitrooxy alkanoic acids and derivates thereof in feed for reducing methane emission in ruminants, and/or to improve ruminant performance. S Duval and M Kindermann, Assignees US Patent No 20, 120, 315, 339," 2012.

[183] G. Martinez-Fernandez, L. Abecia, A. Arco, G. Cantalapiedra-Hijar, A. I. Martin-Garcia, and E. Molina-Alcaide, "Effects of ethyl-3-nitrooxy propionate and 3-nitrooxypropanol on ruminal

fermentation, microbial abundance, and methane emissions in sheep," *J. Dairy Sci.*, vol. 97, pp. 3790-3799, 2014.

[184] C. K. Reynolds, D. J. Humphries, P. Kirton, M. Kindermann, S. Duval, and W. Steinberg, "Effects of 3-nitrooxypropanol on methane emission, digestion, and energy and nitrogen balance of lactating dairy cows," *J. Dairy Sci.*, vol. 97, pp. 3777-3789, 2014.

[185] J. Haisan, Y. Sun, L. L. Guan, K. A. Beauchemin, A. Iwaasa, and S. Duval, "The effects of feeding 3-nitrooxypropanol on methane emissions and productivity of Holstein cows in mid lactation," *J. Dairy Sci.*, vol. 97, pp. 3110-3119, 2014.

[186] S. Godbout, M. Verma, J. P. Larouche, L. Potvin, A. M. Chapman, and S. P. Lemay, "Methane production potential (B0) of swine and cattle manures--a Canadian perspective," *Environ. Technol.*, vol. 31, pp. 1371-1379, 2010.

[187] G. Flachowsky and P. Lebzien, "Possibilities for reduction of nitrogen (N) excretion from ruminants and the need for further research - a review," *Landbauforsch Völk*, vol. 56, pp. 19-30, 2006.

[188] R. L. M. Schils, A. Verhagen, H. F. M. Aarts, P. J. Kuikman, and L. B. J. Sebek, "Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in the Netherlands," *Global Change Biol.*, vol. 12, pp. 382-391, 2006.

[189] W. S. Kraatz, B. Berg, and K. J. Küstermann, *Hülsbergen. Energy and carbon balancing in livestock kepping. Proc world congress: Agricultural engineering for a better world Bonn 03-07092006, VDI-Berichte Nr 1958.* Germany: VDI-Verlag Düsseldorf, 2006.

[190] R. Brunsch, S. Kraatz, W. Berg, and C. Rus, "Measurements of energy efficiency in animal keeping on the base of energy balances (In German)," *KTBL-Schrift*, vol. 463, pp. 115-125, 2008.

[191] S. Kraatz, "Energy efficiency in animal keeping shown in dairy cattle keeping (In German)," PhD-Thesis, Humboldt-University Berlin, 2009.

[192] A. Wilfart, J. Prudhomme, J. P. Blancheton, and J. Aubin, "LCA and emergy accounting of aquaculture systems: Towards ecological intensification," *J. Environ. Manage*, vol. 121, pp. 96-109, 2013.

[193] W. Brade, U. Dämmgen, P. Lebzien, and G. Flachowsky, "Milk production and emissions of greenhouse gases: Consequences for the future milk cattle breeding in Germany?," *Tieraerztl Umschau*, vol. 63, pp. 189-199, 2008.

[194] W. Brade, U. Dämmgen, P. Lebzien, and G. Flachowsky, "Influence of a changed milk fat/milk protein ratio by breeding measures on the greenhouse gas emissions in the milk production," *Züchtungskunde*, vol. 80, pp. 360-369, 2008.

[195] F. Forabosco, M. Lohmus, L. Rydhmer, and L. F. Sundstrom, "Genetically modified farm animals and fish in agriculture: A review," *Livestock Science*, vol. 153, pp. 1-9, 2013.

[196] FAO, "Food wastage footprint - impacts on natural resources.," Summary Report, Rome2013.

[197] K. Plassmann and G. Edwards-Jones, "Where does the carbon footprint fall? Developing a carbon map of food production, Sustainable Markets Discussion Paper No. 4," p. iii + 34, 2009.

[198] A. Laurent, S. I. Olsen, and M. Z. Hauschild, "Limitations of carbon footprint as indicator of environmental sustainability," *Environ. Sci. Technol.*, vol. 46, pp. 4100-4108, 2012.

[199] M. Owsianiak, G. Lemming, M. Z. Hauschild, and P. L. Bjerg, "Assessing environmental sustainability of remediation technologies in a life cycle perspective is not so easy," *Environ. Sci. Technol.*, vol. 47, pp. 1182-1183, 2013.

BIBLIOGRAPHY

[1] G. Andersen, *Food table for the practice: The little souci-fachmann-kraut (In German)*. Stuttgart: Wissenschaftliche Verlagsgesellschaft mbH, 2011.

[2] C. Basset-Mens, S. Ledgard, and M. Boyes, "Eco-efficiency of intensification scenarios for milk production in New Zealand," *Ecol. Econ.*, vol. 68, pp. 1615-1625, 2009.

[3] C. Cederberg, U. Sonesson, M. Henriksson, V. Sund, and J. Davis, *Greenhouse gas emissions from Swedish production of meat, milk and eggs 1990 and 2005*. Goeteborg: SIK, The Swedish Institute for Food and Biotechnology, 2009.

[4] C. Cederberg and B. Mattsson, "Life cycle assessment of milk production — a comparison of conventional and organic farming," *J. Clean Prod.*, vol. 8, pp. 49-60, 2000.

[5] C. Cederberg and A. Flysjo, "Life cycle inventory of 23 dairy farms in South-Western Sweden," SIK Rapport, 2004.

[6] J. W. Casey and N. M. Holden, "Analysis of greenhouse gas emissions from the average Irish milk production system," *Agricultural Systems*, vol. 86, pp. 97-114, 2005.

[7] R. Fritsche and U. Eberle, *Greenhouse gas emissions during production and processing of fods (In German)*. Darmstadt: Öko-Institut eV, 2007.

[8] GEMIS, "Global emissions-model of integrated systems (In German), Version 45. Available: http://wwwoekode/service/gemis," 2009.

[9] GfE, *Recommendations for energy and nutrient requirements of beef cattle (In German). No. 6;. In: Energy and nutrient requirements of domestic animals*. Frankfurt: DLG-Verlags-GmbH, 1995.

[10] GfE, *Recommendations for energy and nutrient requirements of laying hens and broilers (In German). No. 7. In: Energy and nutrient requirements of domestic animals*. Frankfurt: DLG-Verlags-GmbH, 1999.

[11] GfE, *Recommendations for energy and nutrient requirements of pigs (In German). No. 10. in: Energy and nutrient requirements of domestic animals*. Frankfurt: DLG-Verlags GmbH, 2006.

[12] G. Haas, F. Wetterich, and U. Kopke, "Comparing intensive, extensified and organic grassland farming in Southern Germany by process life cycle assessment," *Agr. Ecosyst. Environ.*, vol. 83, pp. 43-53, 2001.

[13] J. Hirschfeld, J. Weiß, M. Precht, and T. Korbun, *Climate effects of agriculture in Germany (In German)*. Berlin: Schriftenreihe des IÖW 186/08, 2008.

[14] G. F. lachowsky, U. Meyer, and M. Grün, "Plant and animal breeding as starting points for sustainable," *Sustainable Agriculture Reviews: E. Lichtfouse*, pp. 201-224 2012.

[15] T. Lindenthal, T. Markut, S. Hörtenhuber, G. Rudolph, and K. Hanz, "Climate advantages once more demonstrated: Climate balance of organic products (In German)," *Ökologischer Landbau*, vol. 153, pp. 51-53, 2010.

[16] S. Ledgard, J. Finalyson, M. Patterson, R. Carran, and M. Wedderburn, "Effects of intensification of dairy farming system in New Zealand on whole-system resource use efficiency and environmental emissions," in *Proceedings of the 4th International Conference, Oct 6-8, Byxholm, Denmark*, 2004, pp. 48-52.

[17] A. Ogino, K. Kaku, T. Osada, and K. Shimada, "Environmental impacts of the Japanese beef-fattening system with different feeding lengths as evaluated by a life-cycle assessment method," *J. Anim. Sci.*, vol. 82, pp. 2115-2122, 2004.

[18] A. Ogino, H. Orito, K. Shimada, and H. Hirooka, "Evaluating environmental impacts of the Japanese beef cow-calf system by the life cycle assessment method," *Animal Science Journal*, vol. 78, pp. 424-432, 2007.

[19] H. W. Phetteplace, D. E. Johnson, and A. F. Seidl, "Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States," *Nutr. Cycl. Agroecosys*, vol. 60, pp. 99-102, 2001.

[20] PAS, "2050 Scenario building to test and inform the development of a BSI method for assessing greenhouse gas emissions from food. Available from: BSI http://www.bsi-global.com,2011," Report Submitted by ADAS, Project ref no: YAW3408nd.

[21] T. Reitmayr, "The development of a computerized coefficient system for the economic and ecological evaluation of agricultural forms of land use - illustrated by an example Entwicklung eines rechnergestutzten Kennzahlensystems zur okonomischen und okologischen Beurteilung von agrarischen Bewirtschaftungsformen - dargestellt an einem Beispiel," *Agrarwirtschaft, Sonderheft*, p. 302, 1995.

[22] S. Subak, "Global environmental costs of beef production," *Ecol. Econ.*, vol. 30, pp. 79-91, 1999.

[23] E. H. Schlich and U. Fleissner, "The ecology of scale: Assessment of regional energy turnover and comparison with global food," *Int. J. Life Cycle Ass.*, vol. 10, pp. 219-223, 2005.

[24] M. Sevenster and F. A. De Jong, "Sustainable dairy sector. Global, regional and live cycle facts and figures on greenhouse-gas emissions," Report CE Delft, Solutions for Environment, Economy and Technology, Publ. No: 0877892008.

[25] X. P. C. Verge, J. A. Dyer, R. L. Desjardins, and D. Worth, "Greenhouse gas emissions from the Canadian dairy industry in 2001," *Agricultural Systems*, vol. 94, pp. 683-693, 2007.

[26] I. A. J. Van Der Zijpp, "Animal production systems: On integration and diversity," Habilitation Thesis, Univ of Wageningen, Wageningen, The Netherlands, 2001.

[27] A. Woitowicz, "Auswirkungen einer einschränkung des verzehrs von lebensmitteln tierischer herkunft auf ausgewählte nachhaltigkeitsindikatoren – dargestellt am beispiel konventioneller und ökologischer wirtschaftsweise," PhD, Technical University Munich, 2007.