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Invited review: Resource inputs and land, water and carbon footprints from the production of edible protein of animal origin

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Abstract. The objective of this review is to analyze crucial factors in the output from the production of proteins in food of animal origin, such as milk, meat and eggs. We then consider inputs such as land, water, fuel, minerals and feed, as well as characterize emissions. Finally, we estimate footprints for land (land footprint, LF), water (water footprint, WF) and greenhouse gas emissions (i.e., carbon footprint, CF) during the production process. The wide range of different land and water inputs per unit feed between various studies largely influences the results. Further influencing factors are species and categories of animals that produce edible protein, their yields and the feeding of animals. Coproducts with no or low humanly edible fractions and grassland as feed contribute to a lower need for arable land and lower LF, WF and CF. The most efficient land use or the lowest LF per kilogram of edible protein was estimated for higher milk and egg yields; the highest LF values were calculated for beef, followed by pork. The lowest WF and CF were calculated for edible protein of chicken meat and eggs. Edible protein from ruminants is mostly characterized by a higher CF because of the high greenhouse gas potential of methane produced in the rumen. A key prerequisite for further progress in this field is the harmonization of data collection and calculation methods. Alternatives to partial or complete replacement of protein of terrestrial animals, such as marine animals, insects, cell cultures, single-cell proteins or "simulated animal products" from plants, as well as changing eating patterns and reducing food losses are mentioned as further potential ways for more efficient feed production. For all those dealing with plant or animal breeding and cultivation and all those who are working along the whole food production chain, it is a major challenge to enhance the production of more food for more people with, at the same time, less, limited resources and lower emissions.

1 Introduction

With the increase in population and higher need for feed and food, a growing demand arises for limited natural resources, and emissions with greenhouse gas (GHG) potential such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other substances (e.g., N, P, trace elements) become elevated. These challenges characterize edible protein production all over the world (Guillou and Matheron, 2014; NRC, 2015). "More for more with less" could be a headline to characterize the present situation and the challenges for agricultural sciences (Windisch et al., 2013). Malnutrition in all its forms – undernutrition, micronutrient deficiencies (e.g., iron, iodine, vitamin A) and overnutrition – the so-called "triple burden" of malnutrition, is still recognized as a serious and intractable problem of humanity (Tompson and Amoroso, 2014). The latest estimates indicate that about 800 million people are still chronically undernourished (11.3 % of the global population) (FAO et al., 2014). Some more people suffer from micronutrient deficiency. Food of animal nutrition, also called animal source food (Neumann et al., 2002), may contribute to overcoming micronutrient deficiencies.

Table 1. Limited resources and emissions in the production of food of animal origin.

Limited resources	Emissions
Land (especially arable land)	Carbon dioxide (CO_2)
Water	Nitrogen compounds (e.g., NH_3, N_2O)
Fuel/energy	Methane (CH_4)
Some minerals (e.g., P)	Some minerals (e.g., P, Cu, Zn)

During the last few years many research groups have dealt with challenges and future developments for global food security (NRC, 2010; National Academies of Sciences, 2016; OECD/FAO, 2017), mainly under consideration of food of animal origin.

More recently, the NRC (2015) characterized the future by three general tendencies or developments:

- The global animal protein consumption will continue to increase based on population growth (from presently about 7.2 to about 9–10 billion people in 2050) and augmented per capita consumption of animal protein in many countries.

- Natural resources, such as land, water and energy, will be restricted and an increase in emissions and environmental changes, including climate change (see Table 1), is expected.

- Current and foreseeable rapid advances in basic biological sciences, as well as in social sciences and economics, will provide an opportunity to maximize the yield of investments in animal science research and development.

Protein of animal origin shall be the main topic of this review. The FAO (2009) estimates that there will be a 73 % increase in meat and egg consumption and a 58 % increase in dairy consumption compared to 2010 levels worldwide by the year 2050.

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; Cassidy et al., 2013). In some countries (e.g., USA) between 67 % (energy) and 80 % (protein) of the crops are used as animal feed (Cassidy et al., 2013). These developments and complex connections lead to the question of whether there is any need for food of animal origin. As vegans demonstrate, there is no essential need for food of animal origin if the human diet is supplemented with all essential nutrients. However, the consumption of meat, fish, milk, eggs and insects may contribute significantly to meeting the human requirements for amino acids (D'Mello, 2012; Smith et al., 2013) and some important trace nutrients (such as Ca, P, Zn, Fe, I, Se and vitamins A, D, E, B_{12}) especially for children juveniles, and for pregnant and lactating women. Human nutritionists recommend that about one-third of the daily protein requirements (0.66–1 $g\,kg^{-1}$ body weight; e.g., Bauer et al. (2013) of adults should originate from protein of animal origin. Consequently, about 20 g of the recommended daily intake of about 60 g protein should be of animal origin, which is lower than the present average consumption (about 24 g) throughout the world. It is a challenge for the future to overcome this imbalance (Smith et al., 2013). 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 %, respectively; FAO, 2009).

Eating food of animal origin, especially meat, is not only a reflection of nutritional needs, but it is also determined by taste, odor 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 (Kastner et al., 2012; Tilman et al., 2011) and the imitation of nutrition in a so-called "Western" style of life.

Alternatives to change the nutrition pattern and replace traditional foods of animal origin are discussed in Sect. 5.

Sustainable animal agriculture faces numerous challenges of meeting global food security in the context of environment, population and economy. The balance between the planet (global resources and emissions), people (social aspects of population all over the world) and profit (economic aspects, moneymaking) in the so-called 3P concept (Boonen et al., 2012; see Fig. 1 in this paper) is an important prerequisite for sustainable life and development on earth. Some authors are afraid that the balance between the three "P's" would become more and more disturbed and an ethical dimension should be introduced as the fourth dimension (Aiking, 2014; Makkar and Ankers, 2014). They believe that profit should certainly not be considered as the single objective of production.

Two options are available to overcome malnutrition:

(1) The production area and/or the number of animals can be increased.

(2) The productivity of land and animals can be improved (Edgerton, 2009).

In addition to previous contributions by our group to this topic (Niemann et al., 2011; Flachowsky and Kamphues, 2012; Flachowsky and Meyer, 2015a–c; Flachowsky and Meyer, 2017), the objective of this review is to analyze influencing factors on inputs and outputs of protein yield of various land animal protein sources such as milk, meat and eggs. Furthermore, we assess the inputs such as land, water, fuel and feed needed to produce food of animal origin. Additionally, we will characterize emissions and also calculate so-called footprints for land (LF), water (WF) and GHG emissions (carbon footprint, CF) arising during production of

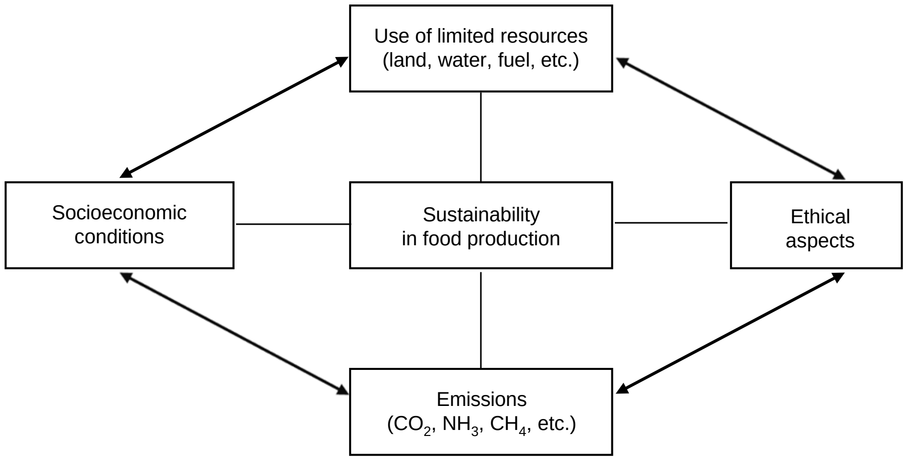

Figure 1. Sustainability as a balance between the use of limited natural resources, emissions, and socioeconomic and ethical conditions to produce food of animal origin (Flachowsky and Hachenberg, 2009).

food of animal origin. Finally, alternatives to traditional food proteins, such as aquaculture, insects, stem cells, simulated food of plant origin or changing the consumption pattern and reducing or avoiding of food losses are also discussed in Sect. 5.

2 Edible protein in food of animal origin

Providing humanly edible protein or, in other words, a group of essential amino acids (e.g., lysine, methionine, threonine, tryptophan) can be considered as the most important objective of animal husbandry. Table S1 in the Supplement shows the protein content of some food of land animal origin calculated by various authors and showing a considerable range of protein contents within and across studies. Except for milk, for their calculations, Mekonnen and Hoekstra (2010) used the lowest values for foods of animal origin when compared with estimates of other authors. For further calculations of the protein content of food of animal origin and various footprints (LF, WF and CF) for edible protein, data from our previous study (Flachowsky, 2002) will be used here.

The protein content of fish (filet) is given at 170–210 g kg^{-1} filet (e.g., Souci et al., 2006). Information about the protein content of insects as potential food is given in Table 17.

3 Inputs

3.1 Land

Land, especially arable land, is one of the most important limited factors. Only a small portion of the global surface (about 13.4 billion ha) is available as arable land (about 1.5 billion ha or about 12 % of the world's land area (FAO, 2013). This area could be extended to a certain degree (by about 120 million ha; FAO, 2013) but some areas simply cannot be used because of limited water resources, forests, urban settlements, environmental protection, deserts, mountains and other influencing factors. As a result of the finite area of arable land and the increase in population, the area of arable land available per person decreased from about 0.45 ha (1960) to about 0.25 ha (2010) and will further decrease to below 0.20 ha per person after 2020. More details about land availability were described and discussed recently (Flachowsky et al., 2017).

Land use and land use changes are interconnected with GHG emission and may also influence CF (Hörtenhuber et al., 2014; FAO, 2017). Plant breeding can be considered as the starting point for the whole human food chain (Flachowsky et al., 2013b; National Academies of Sciences, 2016). Therefore, the production of high, stable and yields of highly digestible phytogenic biomass with low external inputs of nonrenewable resources, such as water, fuel, arable land or fertilizers, is a real future challenge for plant breeders. Further challenges are the decrease in emissions of gases with GHG potential during cultivation, as well as the creation of high resistance against biotic and abiotic stressors, including adaptation to potential climate change and tolerance against drought and other harsh environmental conditions. Another objective is a low concentration of undesirable substances in the plants (Flachowsky and Meyer, 2015b). Originally, animal nutrition was based on feed made of nonhumanly edible fractions, such as roughage and coproducts of foods and food processing. Later, cereal grains and other humanly edible fractions became feed for animals and the competition between man and animals started (Windisch et al., 2013). For our model calculations about the arable land need per unit of edible protein of animal origin, the plant yields from Table S2 are used.

Apart from roughages and grains, coproducts from agriculture, such as cereal straw and sugar beet leaves, or from food production (e.g., cereal grain coproducts, oilseed coproducts) and the biofuel industry (e.g., distillers dried grains with solubles, rapeseed cake; Ertl et al., 2015; Knaus, 2012; Makkar, 2012; Wilkinson, 2011) are used in animal nutrition. This results in a more complicated calculation of arable land need for food of animal origin (Flachowsky et al., 2017). Some authors estimated humanly edible protein fractions of feeds and used these values (see Table S3) for ration planning. Expanded and improved utilization of food coproducts in animal feeding may decrease the pressure on the global grain demand.

From our view, it is incorrect, or at least a too simple view, to estimate the humanly edible fraction of forages and silages always as 0 (see Table S3; Wilkinson, 2011) because if produced on arable land, this could have been alternatively be used for cultivation of cereal grains or other edible cultures, as considered by Ertl et al. (2015) (Table S3).

3.2 Water

3.2.1 Water in feed production

Drinking water should be considered as one of the most important feeds or nutrients for animals. Mostly, animal nutritionists do not pay adequate attention to this feed. Therefore, some fundamentals of water as feed will be considered here (Legesse et al., 2017). Globally, water is one of the most limited natural resources (Pimentel et al., 2004). An adequate water supply for plants and animals is an indispensable prerequisite for healthy plants and animals and, likewise, high and stable yields (Jordaan and Bergman, 2017). There exist various calculations and estimations for water needs for adequate plant growth. Mekonnen and Hoekstra (2010) distinguish between green (naturally infiltrated into the soil), blue (water in rivers and aquifers) and grey (water required to assimilate the load of pollutants) water and calculated WF for various animal feeds (Table 2).

For more general calculations, Mekonnen and Hoekstra (2010) also give summarized values for concentrates and roughages (Table 3). Such values are used for further calculation in animal feeding and calculation of WF, but the calculation basis of these values it is not really clear. According to Hoekstra (2016), the WF was developed and applied within the water resources research. It is, however, questionable, if green (rain) and/or grey water should be considered for calculation of WF. Rain falls down, irrespective of whether is on grassland, arable land, forest, wasteland or settlement area. The grass can be used by (wild or domestic) animals, preserved as hay or silage, burned as heating material or it can rot on the grassland without human influence. Presently, grass use is more or less determined by chance, but it is considered in calculations of WF for forage or roughage as feed for animals. It should be possible to distinguish between water useable for human purposes and water that cannot be used by humans (e.g., rainwater on grassland). Animals, which consume such feeding stuffs from grassland, may contribute to stabilizing and improving human nutrition. There is no direct competition with human use purposes. Conversely, if rain falls on arable land, which could be used to cultivate food and feed plants for the human food chain, such water may well be considered in the WF. As an alternative, water could be differentiated into potentially humanly usable water, on the one side, as done in animal nutrition for humanly edible feeds or humanly edible protein and energy (e.g., Ertl et al., 2015; Wilkinson, 2011), and non-humanly usable water (not considered in the WF), on the other side.

Table 2. Water footprint (WF; sum of green, blue and grey water) of some selected plant products (Mekonnen and Hoekstra, 2010).

Plant product	WF ($m^3\,kg^{-1}$)	WF ($m^3\,MJ^{-1}$)
Sugar crops	0.20	2.9
Vegetables (for food)	0.32	5.6
Potatoes (starchy roots)	0.39	2.0
Cereal grains	1.64	2.1
Wheat	1.83	
Barley	1.35	
Maize	1.22	
Oil crops	2.36	3.4
Soybeans	2.14	
Pulses	4.06	5.0

Table 3. Average water footprint (WF; green, blue, grey and total; $m^3\,t^{-1}$) for concentrates and roughages (Mekonnen and Hoekstra, 2010).

Type of feed	Green WF	Blue WF	Grey WF	Total WF
Concentrates	849	78	122	1048
Roughages	199	1.8	2	203

3.2.2 Water need for animal husbandry and drinking

Compared with the water need for feed production (compare Tables 2 and 3) only small amounts are required for animal management and drinking. The calculation of the WF for animal products includes the water required for feed production (about 98 % of total water; Gerbens-Leenes et al., 2013; Mekonnen and Hoekstra, 2010), drinking water for animals (about 1 %; Meyer et al., 2004, 2006) and management water (< 1 %; Krauss et al., 2016; Schlink et al., 2010).

Water need for animal farm management and hygiene, as well as for drinking

Despite the low water intake by animals in comparison with the water need for plant growth (see Sect. 3.2.1), particular consideration is to be given to water intake by animals because of the high importance for animal health and yields. Drinking water should be characterized by an adequate quality (Kamphues et al., 2007; see Table 4 in this paper). The specification of quality of drinking water for animals in the EU generally follows WHO (2006) and is characterized by the following statement:

> Water for drinking and aquaculture should be suitable for this specific animal species/category. In the case of specific doubts concerning a contamination of animals and/or food of animal origin by water for drinking, measurements to assess and to minimize the risks are required.

Conversely, an insufficient supply of drinking water of an adequate quality will result in adverse effects on animal health, performance and welfare as well as on the quality of food of animal origin (e.g., NRC, 1998; GfE, 2001; Kamphues et al., 2007). Adequate quality of drinking water is necessary for animal health and productivity and may also influence animal yields and finally WF. Various national recommendations have been published about tolerable concentrations of a number of ingredients in drinking water (see Table 4 for German recommendations). In some cases (e.g., F, Cu, Zn), the German parameters for drinking water suitability are stricter for animals than in the human regulations (see Table 4).

Water intake

In recent years, several authors have studied the water intake of animals depending on various factors like animal species and categories, animal performances, environmental conditions, diet composition, and water content of feeds. Tedeschi and Fox (2016) describe, in detail, influencing factors on water intake, such as feed composition, milk yield, environmental temperature, mud, breed, body fat content and stage of pregnancy. Table 5 shows some proportions between dry matter (DM) and water intake for important food-producing animals and horses as well as factors possibly influencing water intake.

Equations to calculate the water intake under consideration of certain variables are shown in Table 6 for ruminants. Similar equations are given for pigs (Table 7) and horses (Table 8). Animals lose water primarily through urine, faeces, pulmonary and cutaneous evaporation, and in the case of lactating or laying animals also via milk and eggs.

Cattle cover the largest part of their water demand through drinking. A smaller part of the need is usually satisfied by the intake of water included in feedstuffs. This portion depends on diet composition. It is higher in grazing animals and in animals fed with silage in comparison to dry feeds. The third and less important source is water originating from the metabolic oxidation of nutrients, mainly carbohydrates (Kolb, 1989). From the oxidation of 1 kg of fat, carbohydrates or protein, 1.07, 0.60 or 0.42 L of water, respectively, is produced (Schiavon and Emmans, 2000).

Numerous factors have effects on the voluntary water intake of ruminants. These factors can be divided into two subcategories: (1) animal factors such as animal species and categories, body size, activity level, animal feeding (including salt intake), and yield and (2) environmental factors such as ambient temperature, relative humidity and wind velocity (e.g., GfE, 2001; Kamphues et al., 2007; Meyer et al., 2004, 2006). Further research is needed to unveil the mechanisms used by animals that are resilient to water shortage and to determine how to increase water use efficiency in livestock.

Compared with ruminants, fewer studies about water intake are available for pigs (Table 7). Some detailed information about water intake of pigs of various age groups (2–5 $L\,kg^{-1}$ feed; see Table 7) are given by GfE (2008). The higher values per kilogram of feed probably result from water losses during drinking (GfE, 2008).

Nagai et al. (1994) measured the water intake of suckling pigs aged from 1 to 28 days. They began to drink water 3 to 5 h after birth. Water intake increased from 36 $mL\,day^{-1}$ at the age of 1 day to 403 $mL\,day^{-1}$ at the age of 28 days. Water consumption per kilogram of body weight remained constant between 51 and 62 mL.

For horses under normal keeping and feeding conditions, GfE (2014) sets a water intake between 3 and 3.5 $L\,kg^{-1}$ DM intake. In case of stronger work and higher temperatures, up to 7 $L\,kg^{-1}$ DM intake can be measured. These values agree with data by Martin-Rosset et al. (2015) presented in Table 8.

3.3 Further inputs

3.3.1 Fuels

Fuel is used in various forms (e.g., diesel, coal, gas, electricity) in many fields of agriculture (Frorip et al., 2012). Mikkola and Ahokas (2009) calculated a fuel consumption of between 55 and 60 $L\,ha^{-1}$ from measurements in central Europe, but Jokiniemi et al. (2012) measured 65–74 $L\,ha^{-1}$ grassland in Finland when baling and loader wagon operations for hay were included. Because of many influencing factors, these details will not be considered in the following calculations (e.g., Ahlgrimm et al., 2000).

3.3.2 Agrochemicals

Jokiniemi et al. (2012) conclude that the highest energy consumptions in plant production originate from agrochemicals, such as fertilizers, lime and pesticides. Mikkola and Ahokas (2009) calculated an indirect energy input in the form of agrochemicals of between 54 and 73 % of the total energy input. Rathke et al. (2002) found a correlation between fertilization and energy balance. Other authors (e.g., Rathke and Diepenbrock, 2006; Thorup-Kristensen et al., 2003) describe large ranges in energy input depending on plant culture and

Table 4. Recommendations to assess chemical and physicochemical quality of drinking water according to feed and food safety (Kamphues et al., 2007).

	Unit	Range or boundary values for suitability as drinking water for animals	Comments and remarks (possible disturbances)	Limits for drinking water according to human regulations (Germany)
Physicochemical characteristics				
pH[e]		> 5 < 9	Corrosion of water pipes	6.5–9.5
Electrical conductivity	$\mu S\,cm^{-1}$	< 3000	Higher values may be associated with diarrhea, reduced taste	2500
Soluble salts; total	$g\,L^{-1}$	< 2.5		
Oxidable[f]	$mg\,L^{-1}$	< 15	Measurement for oxidation potential in water	5
Chemical substances				
Ammonia (NH_4^+)	$mg\,L^{-1}$	< 3	Indication of impurities	0.5
Arsenic (As)	$mg\,L^{-1}$	< 0.05	Health disturbances, reduced yields	0.01
Lead (Pb)	$mg\,L^{-1}$	< 0.1	Avoidance of residues	0.01
Cadmium (Cd)	$mg\,L^{-1}$	< 0.02	Avoidance of residues	0.005
Calcium (Ca)[g]	$mg\,L^{-1}$	500	Lime scale in pipelines, technical malfunctions	Presently no limit
Chlorine (CI^-)	$mg\,L^{-1}$	< 250[a] < 500[b]	Indication of contamination (e.g., faeces), wet excreta[a]	250
Iron (Fe)[g]	$mg\,L^{-1}$	< 3	Palatability influenced, technical malfunctions, biofilms, antagonist to other trace elements	0.2
Fluorine (F)	$mg\,L^{-1}$	< 1.5	Disturbances of teeth and bones	1.5
Potassium (K)	$mg\,L^{-1}$	< 250[a] < 500[b]	see chlorine[a]	Presently no limit
Copper (Cu)[h]	$mg\,L^{-1}$	< 2	Consider total intake of sheep and calves	2
Manganese (Mn)	$mg\,L^{-1}$	< 4	Precipitation in water distribution system, biofilms possible	0.05
Sodium (Na)	$mg\,L^{-1}$	< 250[a] < 500[b]	see chlorine[a]	200
Nitrate (NO_3^-)	$mg\,L^{-1}$	< 300[c] < 200[d]	Methemoglobinemia possible, consider total NO_2 and NO_3 intake	50
Nitrite (NO_2^-)	$mg\,L^{-1}$	< 30		0.5
Mercury (Hg)	$mg\,L^{-1}$	< 0.003	General disturbances, intoxications	0.001
Sulfate (SO_4^{2-})	$mg\,L^{-1}$	< 500	Diarrhea	240
Zinc (Zn)[i]	$mg\,L^{-1}$	< 5	Mucous membrane alterations	Presently no limit

[a] Poultry. [b] Further animal species. [c] Ruminants. [d] Calves and other animals. [e] pH < 5: acid and possible corrosive; addition of organic acids may decrease pH. [f] Parameter for organic substances in water (< 5 $mg\,L^{-1}$ for added water). [g] Deposits in pipelines and drinking bowls. [h] Recommendations difficult for sheep and milk replacers for calves (use milk replacers low in copper). [i] Recommendations for milk replacer for calves.

agricultural management. Kool et al. (2012) analyzed the energy input for production of fertilizers such as N, P, and K fertilizer and calculated footprints per kilogram of fertilizer (Table 9). The values are characterized by large ranges, too.

Another point is the limited availability of some plant nutrients. This limitation mainly relates to phosphorous (Hall and Hall, 1984; Scholz and Wellmer, 2013). Two recent papers propose a hierarchy of limited natural resources with phosphorus at the top and suggest replacing fossil fuel energy (Wellmer and Scholz, 2017, 2016). Therefore, animal excreta should be efficiently used in order to save inorganic resources (Talgre et al., 2009; Thyberg and Tonjes, 2017). Nitrogen is available in almost unlimited amounts in the air, but its potential to be obtained as an aerial plant nutrient is presently only used by legumes.

Table 5. Dry matter (DM) and water intake (in relation to DM intake) of various animal species and categories (Kamphues et al., 2014).

Animal species/ category	DM intake (% of body weight)*	Water-to-DM intake ratio ($L\,kg^{-1}$)	Possibly influencing factors
Cattle			
Dairy cow	2–4	3–5	Milk yield, temperature
Beef cattle, heifer	2	3	
Sheep			
Ewe	2–3	3–4	Milk yield, temperature
Fattening lamb	4	2–2.5	
Goat (milk)	2.5–6	3.5–4	Milk yield, temperature
Horses	2–3.	2–4	
Work	5	> 5	Work, sweat, temperature
Pigs			
Sow	2–3	3–4	Milk yield, temperature
Fattening pigs	3–5	3 (2–4)	
Laying hen	5–8	2–5	Temperature
Chicken for fattening	7–13.5	2–5	Temperature
Turkey for fattening	3–10	2–5	Temperature
Duck (Peking)	7–12.5	3.5–5	Temperature

* High values for high yields and young animals.

Table 6. Some equations to predict the water intake of ruminants depending on various influencing factors by several authors.

Species	Equations, y: water intake ($L\,day^{-1}$)	Authors
Dairy cows (Lactation)	$y = 15.3 + 2.52 \times$ milk yield ($kg\,day^{-1}$) $+ 0.45 \times$ DM[a] content of ration (%)	Castle and Thomas (1975)
	$y = 15.99 + 1.58 \times$ DM intake ($kg\,day^{-1}$) $+ 0.9 \times$ milk yield ($kg\,day^{-1}$) $+ 0.05 \times$ Na intake ($g\,day^{-1}$) $+ 1.2 \times$ minimal night temperature (°C)	Murphy et al. (1983); NRC (2001)
	$y = 14.3 + 1.28 \times$ milk yield ($kg\,day^{-1}$) $+ 0.32 \times$ DM content of ration (%)	Dahlborn et al. (1998)
	$y = -26.12 + 1.516 \times$ average of environment temperature (°C) $+ 1.299 \times$ milk yield ($kg\,day^{-1}$) $+ 0.058 \times$ body weight (kg) $+ 0.406 \times$ Na[b] intake ($g\,day^{-1}$)	Meyer et al. (2004)
Dairy cows (dry)	$y = -10.34 + 0.2296 \times$ DM content of ration (%) $+ 2.212 \times$ DM intake ($kg\,day^{-1}$) $+ 0.03944 \times$ CP[c] content of ration (% of DM)	Holter and Urban (1992)
	$y = 1.16 \times$ DM intake $+ 0.23 \times$ DM content $+ 0.44 \times$ current temperature $+ 0.061 \times$ (current temperature $- 16.4)^2$	Tedeschi and Fox (2016)
	$y = 0.01 \times$ body weight $+ 0.32 \times$ DM content $+ 0.52 \times$ current temperature $+ 0.053 \times$ (current temperature $- 16.4)^2$	Tedeschi and Fox (2016)
Beef cattle	$y = -3.85 + 0.507 \times$ average of environmental temperature (°C) $+ 1.494 \times$ DM intake ($kg\,day^{-1}$) $- 0.141 \times$ roughage of ration (% of DM) $+ 0.248 \times$ DM content of roughage (%) $+ 0.014 \times$ body weight (kg)	Meyer et al. (2006)
Heifers	$y = -5.206 + 0.038 \times$ body weight (kg) $+ 0.610 \times$ average of environmental temperature (°C) $+ 0.098 \times$ roughage of ration (% of DM) $- 0.086 \times$ relative air moisture (%) $+ 0.530 \times$ DM intake ($kg\,day^{-1}$)	Grabow et al. (2009)
Sheep	$y = 3.86 \times$ DM intake $- 0.99$	NRC (2007); Forbes (1986)

[a] Dry matter. [b] Sodium. [c] Crude protein.

Table 7. Equations to predict the water intake of pigs depending on various influencing factors by some authors.

Category	Calculation equations (y: water intake; L day^{-1})	Authors
Lactating sows (third week of lactation)	y (in relation to feed intake; $\text{FI}^a = 2.52 \times \text{FI}(\text{kg d}^{-1}) + 4.22$ y (in relation to body mass; $\text{BW}^b) = 0.01 \times \text{BW(kg)} + 16.1$	Gill (1989)
Fattening pigs	y (in relation to FI) $= 2.13 \times \text{FI}(\text{kg day}^{-1}) + 1.57$ y (in relation to BW) $= 0.076 \times \text{BW(kg)} + 1.96$	Schiavon and Emmans (2000)
Piglets	$y = 0.149 + 3.053 \times \text{DM}^c$ intake (kg day^{-1}) $y = 0.788 + 2.23 \times$ DM intake $(\text{kg day}^{-1}) + 0.367 \times \text{kg BW}^{0,6}$	Brooks et al. (1984) Thulin and Brumm (1991)
Weeks 1–9	$y = (0.48 + 1.13\,\text{DM intake; kg day}^{-1})^2$	Gill (1989)
Weaned piglets	$y = (0.61 + 1.06\,\text{DM intake; kg day}^{-1})^2$	Gill (1989)

[a] Feed intake. [b] Body weight. [c] Dry matter.

Table 8. Total water intake of horses related to dry matter and body weight at an ambient temperature of 15 °C (Martin-Rosset et al., 2015).

Type of ration	Physiological state	Water intake ($\text{L kg DM}^*\ \text{intake}^{-1}$)	Water intake ($\text{L 100 kg body weight}^{-1}\ \text{day}^{-1}$)
Mixed ration (Roughage plus > 15 % concentrate)	Growing and adult horses (maintenance)	3.0–3.5	5.0–6.0
Primarily roughage	Mare (early pregnancy)	3.5–4.0	6.0–7.0
Mixed ration (Roughage plus > 15 % concentrate)	Mare (early lactation)	4.5	10.0–11.0
Primarily roughage	Mare (late lactation)	4.0	9.0–10.0
Mixed ration (Roughage plus > 15 % concentrate)	Light work Middle work Heavy work	3.0–4.0 4.0 4.5–5.0	6.0–7.0 8.0–9.0 9.5–10.5

* Dry matter.

Table 9. Examples for emissions during production of fertilizers ($\text{kg CO}_{2\,\text{eq.}}\ \text{kg}^{-1}$ product; Kool et al., 2012).

Fertilizer (kg)	$\text{kg CO}_{2\,\text{eq.}}$
N	5.66 (3.42–8.43)
P_2O_5	1.36 (0.14–2.15)
K_2O	1.23 (0.36–1.91)
Lime	0.074 (0.054–0.089)

3.4 Feeds and feeding

Sufficient amounts of high-quality feeds are the most important prerequisites for a sustainable production of protein of animal origin, as previously summarized (Flachowsky and Meyer, 2015a, c). Challenges for plant breeders to develop adequate plants were recently reviewed and summarized and will therefore not be discussed in detail here (see Flachowsky and Meyer, 2015b; National Academies of Sciences, 2016). Information about the level of feed intake, the roughage-to-concentrate ratio and the influence of coproducts on animal yields are shown in the following tables in more detail.

Tilman et al. (2011) estimate nearly a doubling of global needs for cereal grain between 2005 and 2050. This seems to be impossible to meet and elimination or reduction of cereals from animal rations is required. Coproducts from the food and biofuel industry may replace 50 to 100 % of cereal grains or protein sources in animal nutrition, particularly for ruminants (e.g., Knaus, 2012). Ruminants are very efficient in converting fibrous forages including coproducts from agriculture (e.g., cereal straw; Flachowsky, 1987), which are characterized by a high fiber content. Chemical treatments of such low-quality roughages (e.g., Jentsch et al., 1978a, b; Ochrimenko et al., 1986) may also improve the feed base.

Tables S4 and S5 show coproducts exemplarily used as a replacement for cereal grains and other human foods and the resulting influence on the so-called protein score. A protein score greater than 1 demonstrates a more efficient conversion from feed into humanly edible protein than values lower than 1.

Very high milk yields (40 kg per day; Table S4) require more cereals or more humanly edible protein in the diet and the protein score is lower than 1. That means that the consumed humanly edible protein fraction is larger than the protein output via milk. Of concentrate, 50 % is replaced by coproducts in rations of the most important food-producing animals (Table S5) under consideration of a middle level of yield. In all cases, the protein score increased with replacement of concentrate by coproducts.

The content of insects as potential food is given in Table 17.

4 Outputs

4.1 Edible protein yield

Table S6 shows the influence of animal species/categories and animal yield level on DM intake, expected roughage-to-concentrate ratio and the edible protein yield per day. These values can be considered as the starting point for all adequate calculations.

The protein output is mainly influenced by animal species and yields of animals. Optimal feeding of animals on the basis of scientific knowledge about energy and nutrient requirements is an important prerequisite for adequate yields.

4.2 Land and land footprints

Land use for edible protein of animal origin is mainly influenced by animal species and animal yield, as recently demonstrated (de Vries and de Boer, 2010; Flachowsky et al., 2017; Nijdam et al., 2012).

4.2.1 Influence of crop yield, land use and coproducts

Important influencing factors are the land used (grassland or arable land), the kind of cultivated crops and their yields (Table S7), and the replacement of cultivated crops with coproducts (Table S8). The higher the animal performances and the greater the plant yields, the lower the land areas required to produce 1 kg of edible protein of animal origin.

Analogue tendencies are observed in the calculations after replacement of cereals with coproducts.

4.2.2 Miscellaneous factors

Apart from plant and animal yields, the LF of grassland and coproduct feeding to animals is also substantially influenced by additional factors such as

- changes in nutritional quality of crops (e.g., low content of antinutritive substances; increased content of amino acids achieved by plant breeding; Flachowsky et al., 2013a; National Academies of Sciences, 2016);
- feeding according to energy and nutrient requirements depending on animal species, categories and performance;
- high quality of roughages (e.g., pasture, hay, silages; Tedeschi and Fox, 2016);
- optimal supplementation of rations with mixed feeds, feed additives (Pape, 2006) and bio-fortified plants (Parisi et al., 2016);
- adequate protein supply and amino acid supplementation, which is important not only for animal performance but also to minimize N excretion and GHG emissions;
- adequate farm and veterinarian service to assure high animal welfare and to avoid diseases and reduce animal mortality.

4.2.3 Data variability

Large ranges in land use per kilogram of edible protein have also been reported by others (Tables S9 and S10). Ridoutt et al. (2014) analyzed six diverse beef cattle systems in southern Australia and found 86–172 m^2 of land per kilogram of animal live weight. For beef cattle, similar values and large ranges are shown in Tables S9 and S10. The smallest area is needed per kilogram of protein of chicken meat, eggs and milk, followed by pork. Extensive pastoral systems require the largest area, but the plant yields are very low. Still, this land offers no alternative possibilities for agricultural use.

4.3 Water and water footprints

The sum of WF results from green, grey and blue water (Mekonnen and Hoekstra, 2010). The term WF had been developed and applied within water resource research and should also be used in the future in other areas of research and application (Hoekstra, 2016). Based on water need for feed (e.g., 1048 L kg^{-1} concentrate; 203 L kg^{-1} roughage; see Table 3), some authors calculated WF for food of animal origin. The first studies were carried out by Hoekstra (2010). Then later papers (e.g., Mekonnen and Hoekstra, 2012) were based on or cited data from Hoekstra (2010). The low water need for drinking and management is mostly neglected there. In our own calculation, we assumed 2 % for these purposes. Table 10 shows the influence of milk yield and coproduct portion on the WF per kilogram of milk and per kilogram of edible protein.

In many cases, though, it is not clear if the calculation data are expressed on feed base (original matter) or as fed to animals (not on DM base). This, however, leads to highly different interpretations.

Table 11 demonstrates the influence of various rations on daily weight gain of bulls and the WF per kilogram of body

Table 10. Model calculation of water footprint (WF) for milk depending on milk yield and coproducts in feeding.

Milk yield ($kg\,day^{-1}$)	DM[a]-intake[b] ($kg\,day^{-1}$)	Roughage part (%; DM base)	Coproducts in concentrate (%)	Concentrate intake ($kg\,DM\,day^{-1}$)	Coproduct intake ($kg\,day^{-1}$)	Water intake via feed ($L\,day^{-1}$)	WF ($L\,kg\,milk^{-1}$)	WF (m^3 kg edible $protein^{-1}$)
5	10	95	100[c]	0.5	0.5	1930	386	11.4
10	12	90	100[c]	1.2	1.2	2190	219	6.4
20	16	75	50[d]	4.0	2.0	4530	226	6.6
40	25	50	25[e]	12.5	3.12	12 390	310	9.1

[a] Dry matter. [b] WF of feed from Mekonnen and Hoekstra (2010): 1048 L kg $concentrate^{-1}$; 203 L kg $roughage^{-1}$; see Table 3. [c] Includes 25 % wheat bran; 25 % dried sugar beet pulp. [d] Includes 30 % cereal grains; 10 % soybean meal; 10 % rapeseed meal. [e] Includes 12.5 % wheat bran; 12.5 % dried sugar beet pulp; 50 % cereal grains; 15 % soybean meal; 10 % rapeseed meal.

weight gain, per kilogram of beef and per kilogram of edible protein.

Calculations in Tables 10 and 11 show considerably lower WF than data by Hoekstra (2010) and Mekonnen and Hoekstra (2012), as presented in Table 12. No reasons for the differences are obvious. Zonderland-Thomassen et al. (2014) calculated WF of beef cattle and sheep production systems in New Zealand and came to the conclusion that the need for a harmonized methodology and specific local contextual information is an important factor when interpreting the results.

Table 13 summarizes the water need for feed production, management water and drinking water. Based on these data, WF per kilogram of product and per kilogram of edible protein were calculated. The differences between numbers in Tables 10 and 11 in comparison to Table 13 are based on a certain portion of coproducts in the ration considered in the feeding of cows (Table 10) and growing bulls (Table 11). The highest WF per kilogram of edible protein can be calculated for growing and fattening pigs and beef cattle with low animal yields, followed by laying hens (see Table 13).

4.4 Carbon footprints

Carbon footprints are defined as the total amount of GHG emissions along the human food supply chain. These are defined depending on their GHG potential: 1 for CO_2, 23 for CH_4 and 296 for N_2O (IPCC, 2006). The supply chain includes the plant production, including cultivation, harvest, treatment and storage, feed preparation, feeding of food-producing animals, preparation of food and, finally, distribution to market and households.

Beginning with once- and twice-yearly studies in 1998–2000, about 20 annual studies were published in the last years (Avadi and Freon, 2013). The studies dealt with calculations of CF for nearly all types of food of animal origin (see summary by Lesschen et al., 2011).

Results of CF calculations for food of animal origin depend on many influencing factors such as animal species and categories, animal yields and endpoints of animal production. From nutritional and scientific points of view, edible protein seems to be the most favorable reference value (see Flachowsky and Kamphues, 2012).

Table 14 demonstrates some important emission sources and steps to calculate emissions per cow and year or per kilogram of milk. The values per cow or per kilogram of milk depend mainly on the levels of emissions and on the milk yield. The calculation shows that in this case about two-thirds of emissions come from methane.

The CO_2 emission directly from the animals can be considered as emission neutral. CO_2 is fixed through photosynthesis of plants and excreted by the animals as a result of animal metabolism. Nevertheless, the CO_2 emission must be observed along the whole food chain and assessments must be based on the burning of fossil carbon during feed production and land use changes (Caffrey and Veal, 2013; Hergoualch and Verchot, 2011; Kim et al., 2009).

Methane is emitted under anaerobic conditions from the enteric fermentation in the digestive tract of animals, mainly in the rumen, but also during manure management. Details about the enteric methane production and reduction potential are described in many papers (e.g., Bannink et al., 2008; Beauchemin et al., 2009) and prediction equations are given (e.g., Ellis et al., 2010; Montes et al., 2013). The methane emissions from manure management are generally not directly associated with animals, but the emissions can be considerably high (Montes et al., 2013), especially if the excreta are stored under anaerobic conditions.

Animals do not excrete N_2O directly, but it can be formed in manure depending on the storage conditions and following land application (e.g., Flachowsky and Brade, 2007; Montes et al., 2013). Nitrous oxide is mainly produced in soils through microbial nitrification (the oxidation of ammonium [NH_4^+] to nitrate NO_3^-) and denitrification (reduction of NO_3^- to N_2; Stevens et al., 1997). These microbial processes depend on temperature, moisture content and oxidation status of the environment. More details about N_2O production and emission from the soil were described by many authors and will not be considered further in this paper (e.g., Bessou et al., 2010; Lampe et al., 2006; Schmeer et al., 2014; van Groenigen et al., 2005; Weisskopf et al., 2010).

Table 11. Model calculation of water footprint (WF) for beef cattle from 150 to 550 kg body weight depending on the daily weight gain and coproducts in feeding.

Beef cattle (weight gain g day^{-1})	DM[a] intake (kg day^{-1})	Roughage part (%; DM base)	Concentrate intake (kg DM d^{-1})	Coproducts in concentrate (%)	Coproduct intake (kg DM d^{-1})	Water intake via feed[b] (L d^{-1})	WF (L kg BW gain^{-1})	WF (L kg beef^{-1})	WF (m^3 kg edible protein^{-1})
500	6.5	95	0.3	100[c]	0.3	1 160	2320	4 640	48.8
1000	7.0	80	1.3	75[d]	1.0	1 420	1 420	1420	15.1
1500	7.5	65	2.45	50[e]	1.2	2 200	1 470	980	10.4

[a] Dry matter. [b] WF of feed by Mekonnen and Hoekstra (2010): 1048 L kg concentrate^{-1}; 203 L kg roughage^{-1}; see Table 4. [c] Includes 50 % wheat bran; 50 % dried sugar beet pulp. [d] Includes 25 % cereal grain; 30 % wheat bran; 30 % sugar beet pulp; 10 % rapeseed meal; 5 % soybean meal. [e] 50 % cereal grains; 12.5 % wheat bran; 12.5 % dried sugar beet pulp; 15 % rapeseed meal; 10 % soybean meal.

Table 12. Water footprint (L kg^{-1}) of animal products in various publications.

Animal products	Hoekstra (2010)	Mekonnen and Hoekstra (2012)
Milk	1000	1020
Beef	15 500	15 415
Pork	4800	5988
Chicken	3900	4325
Eggs	3300	3265

The public interest in CF is discussed in the context of global warming and possible climate changes (IPCC, 2006, 2014). Results of CF calculation for foods of animal origin depend on many influencing factors such as animal species and categories, animal feeding and yields, and endpoints of animal production (see Table 15). Feeding may influence the CF of food of animal origin. In the case of ruminants, higher animal yields require higher amounts of concentrate. The proportion of coproducts (e.g., Ahlgrimm et al., 2000; Ertl et al., 2015; Makkar, 2012) used in animal nutrition has not only nutritional implications, but it also affects the results of calculations on land use (Vandehaar, 1998). There are large differences in protein yield per animal per day or per kilogram of body weight and day depending on animal species and categories as well as on their performances and the fractions considered as edible.

Fossil energy inputs are not considered in these calculations. Frorip et al. (2012) analyzed the fossil energy consumption in animal production on the basis of farm studies and calculated an energy input per kilogram of milk of 5.4 MJ. In the literature review of the same authors, 14 references showed a range between 1.6 and 7 MJ kg^{-1} milk. These disparate values show the difficulties of considering these and further inputs during calculations of CF.

Table S6 shows the highest protein yields per kilogram of body weight for growing broilers as well as for laying and lactating animals and the lowest values for growing and fattening ruminants. Based on those values, emissions per kilogram of edible protein are given in Table 15. 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).

5 Improvement of protein supply for humans and animals

Apart from intensification of plant and animal production, there are also other possibilities to improve the protein supply for humans and animals. These are alternative protein sources for food and feed (see in Sects. 5.1 until 5.5), as well as changing eating patterns (see in Sect. 5.6) or reducing food losses (see in Sect. 5.7).

5.1 Aquaculture

Aquaculture, although already having a long tradition, is a rapidly growing sector of production of food protein of animal origin. Recently, some authors tried to determine CF for various forms of aquaculture. Mungkung et al. (2013) carried out a case study of combined aquaculture systems for carp and tilapia. The system studied included fingerling production in hatcheries, fish rearing in cages and transport of feed and harvested fish to markets. Avadi and Freon (2013) reviewed 16 life cycle assessment (LCA) studies applied to fisheries and considered the following aspects in their comparison: scope and system boundaries, functional unit allocation strategies for coproducts, conventional and fishery-specific impact categories, fuel use, impact assessment methods, level of detail of inventories, normalization of results, and sensitivity analysis. Fishery-specific impact categories and fuel use in fishing operation were identified as the main contributors to environmental impact. Nijdam et al. (2012) analyzed 18 studies for seafood from fisheries and 11 from aquaculture, and they compared results with data of land animals (Table 16). The authors summarized CF between 1 and 86 for seafood from fisheries and 3 and 15 kg $CO_{2\,eq.}$ per kilogram of product for seafood from aquaculture.

Table 13. Influence of animal species, categories and performances on yield of edible protein and water footprint (WF) per kilogram of edible protein.

Protein source (Body mass)	Performance (per day)	Dry matter intake ($kg\,day^{-1}$)	Roughage part (DM[c] basis, %)[3]	Edible protein yield ($g\,day^{-1}$)[d]	Water need for feed ($m^3\,day^{-1}$)[e]	WF ($m^3\,kg\,product^{-1}$)[f]	WF ($m^3\,kg$ edible $protein^{-1}$)
Dairy cow (650 kg)	2 kg milk	8	100	67	1.62	0.82	24.6
	5 kg milk	10	95	163	2.55	0.52	16.0
	10 kg milk	12	90	323	3.45	0.35	10.9
	20 kg milk	16	75	646	6.63	0.34	10.5
	40 kg milk	25	50	1292	15.64	0.40	12.3
Dairy goat (60 kg)	0.5 kg milk	1	100	17	0.20	0.40	11.8
	1 kg milk	1.5	90	34	0.43	0.43	12.6
	2 kg milk	2	80	68	0.75	0.38	11.0
	5 kg milk	2.5	50	170	1.57	0.31	9.3
Beef cattle (350 kg)	200 g ADG[a]	6.0	100	19	1.22	6.20	64.7
	500 g ADG	6.5	95	48	1.60	3.26	34.0
	1000 g ADG	7.0	85	95	2.30	2.35	24.7
	1500 g ADG	7.5	70	143	3.43	2.33	24.5
Growing/ fattening pig (80 kg)	200 g ADG	1.5	30	18	1.18	6.00	66.1
	500 g ADG	1.8	20	45	1.58	3.22	35.8
	700 g ADG	2	10/	63	1.93	2.81	31.3
	1000 g ADG	2.2	0	90	2.31	2.36	26.1
Chicken for fattening (1.5 kg)	20 g ADG	0.06	15	2.4	0.055	2.75	23.0
	40 g ADG	0.07	10	4.8	0.068	1.75	14.4
	60 g ADG	0.08	0	7.2	0.084	1.45	11.8
Laying hen (1.8 kg)	20 % LP[b]	0.09	30	1.4	0.071	7.20	51.4
	50 % LP	0.10	20	3.4	0.088	3.60	26.5
	70 % LP	0.11	10	4.8	0.106	3.15	22.5
	90 % LP	0.12	0	6.2	0.126	2.90	20.8

[a] Average daily gain. [b] Laying performance. [c] Dry matter. [d] See Table S2. [e] WF of feed by Mekonnen and Hoekstra (2010): 1048 L kg $concentrate^{-1}$; 203 L kg $roughage^{-1}$. [f] Water for management (drinking and cleaning) is assumed to be about 2 % of water for feed.

Table 14. Calculation of emissions per cow and year (650 kg body weight, 8000 kg milk $year^{-1}$, one calf per year; Dämmgen and Haenel, 2008).

Source of emissions		Emissions		
	($kg\,cow^{-1}\,year^{-1}$)	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[a]			1	1.8
Total		336	143	5
CO_2 equivalents of emission	($kg\,cow^{-1}$)	336	3290	1500
	(% of total emissions)	6	65	29
CO_2 equivalents	($kg\,cow^{-1}\,year^{-1}$)		5200	
	($g\,kg\,milk^{-1}$)[b]		650	

[a] No land use change. [b] Without calf and heifer.

Table 15. Influence of animal species, categories and performances on emissions and footprints (per kilogram of edible protein; own calculations based on data from Flachowsky and Kamphues, 2012).

Protein source (Body weight)	Performance per day		N excretion (% of intake)	Methane emission ($g\ day^{-1}$)[c]	Emissions ($g\ kg\ protein^{-1}$)			
					P	N	CH_4[c]	$CO_{2\,eq.}$
Dairy cow (650 kg)	10	kg milk	75	310	0.10	0.65	1.0	30
	20	kg milk	70	380	0.06	0.44	0.6	16
	40	kg milk	65	520	0.04	0.24	0.4	12
Dairy goat (60 kg)	2	kg milk	75	50	0.08	0.5	0.8	20
	5	kg milk	65	60	0.04	0.2	0.4	10
Beef cattle (350 kg)	500	g[a]	90	170	0.30	2.3	3.5	110
	1000	g[a]	84	175	0.18	1.3	1.7	55
	1500	g[a]	80	180	0.14	1.0	1.2	35
Growing/ fattening pig (80 kg)	500	g[a]	85	5	0.20	1.0	0.12	16
	700	g[a]	80	5	0.12	0.7	0.08	12
	900	g[a]	75	5	0.09	0.55	0.05	10
Broiler (1.5 kg)	40	g[a]	70	Traces	0.04	0.35	0.01	4
	60	g[a]	60		0.03	0.25	0.01	3
Laying hen (1.8 kg)	50	%[b]	80	Traces	0.12	0.6	0.03	7
	70	%[b]	65		0.07	0.4	0.02	5
	90	%[b]	55		0.05	0.3	0.02	3

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

Table 16. Carbon footprints of protein of food of animal origin according to several life cycle assessment studies summarized by Nijdam et al. (2012).

Protein sources	Number of studies	$kg\ CO_{2\,eq.}\ kg\ product^{-1}$	$kg\ CO_{2\,eq.}\ kg\ protein^{-1}$
Cow's 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 aquaculture	($n = 11$)	3–15	4–75

These authors and Avadi and Freon (2013) define the need for standardization of fishery LCAs to improve research and enhance further studies on sustainability of seafood and fishery-based agrifood.

5.2 Insects

Apart from milk, meat, eggs and fish, there are also other sources of protein of animal origin, such as wild animals and insects, consumed by humans. Nothing is known about CF of food from wild animals.

Insects and their larvae are used as food in many countries. The most commonly eaten insect groups are the Coleoptera (beetles), Lepidoptera (caterpillars of butterflies and moths), Hymenoptera (bees, wasps, ants), Orthoptera (grasshoppers, locusts, crickets, termites), Hemiptera (cicadas, leaf and plant hoppers, true bugs, scale insects), Odonata (dragonflies) and Diptera (flies) (EFSA, 2015). They are rich in protein (5 to about 80 %; Table 17) and contain considerable amounts of fat (10–50 % of DM; Makkar et al., 2014; Sanchez-Muros et al., 2014; van Huis, 2013). More than 2 billion people worldwide include processed insects in their diets (van Huis, 2013). Experts (e.g., van Huis, 2013) believe that in total about 1900 insect species are used as food and feed.

The feed conversion of insects is estimated to be better than that of other animals, and thus their CF is expected to be lower (e.g., Oonincx and de Boer, 2012; Oonincx et al., 2010). However, more research in these fields (e.g., Lundy and Parrella, 2015) and also concerning feeding and feed supplementation of insects is required (van Huis, 2013). Another topic would be the still missing public acceptance of insect-based food of animal origin in some regions of the world (EFSA, 2015).

5.3 Cultured "lab-grown" meat

The dream to produce "cultured meat", also called "cell cultured", "synthetic" or "clean meat", is very old. In 1931, Winston Churchill was very hopeful that we should, 50 years hence, escape the absurdity of growing a whole chicken in order to eat the breast wing by growing these parts separately under a suitable medium. About 75 years later, Bill Gates concluded that remaking meat was one sector of food industry that was ripe for innovation and growth. However, we are still waiting for a real progress in these processes of creating lab-grown or "in vitro" meat. Presently, about 30 laboratories around the world are conducting research on cultured meat. In cultures with an adequate growth medium, it could be achieved that bovine skeletal muscle stem cells managed to produce beef with the same nutritional value as livestock and could therefore replace protein of animal origin (Post, 2014a, b). Sheep, pig, turkey and fish muscle cells have also been identified for the same purposes (Benjaminson et al., 2002; Dodson et al., 1988, 1997). Protein synthesis by cultured skeletal muscle cells, in theory, should be very efficient.

Apart from further investigations for optimization of protein and fat content of cultured meat, more studies concerning psychological obstacles and public acceptance are necessary and complete LCAs for all these future ways to produce valuable food proteins are needed.

5.4 "Simulated" food

Foods of plant origin with a high protein concentration such as grain-based products, leguminous vegetables, nuts or extracted proteins from leaves of plants may replace animal protein in the human diet (see also Sect. 5.5). There exist some alternatives and initiatives to replace protein of animal origin with other ways to produce similar products (e.g., soy milk, tofu, rice milk). Mostly, such food is processed from valuable protein sources of plant origin (e.g., soybean, wheat, rice, maize, barley, pea, sorghum, lupine and chickpea). Some authors tried to develop new analogue meat and milk products by combining proteins from various plant sources (Aiking, 2011; Day, 2013). The ideas about such developments are not new, but the public acceptance is still limited.

5.5 Single-cell proteins, algae and further new food and feed sources

Apart from food of animal origin (see above), single cell proteins may also be a further alternative to meet the protein and amino acid requirements of humans and provide them with a high enjoyment value of the foods (Anupama and Ravindra, 2000; Zepka et al., 2010).

Algae are considered as a potential food and feed reserve (e.g., Tredici, 2010). They are rich in protein (40–70 % in DM) and fat (40–45 %) and have a long history of use in human and animal nutrition (Bux and Christi, 2016). However, due to the high production costs as well as difficulties incorporating algal material into palatable food preparations, the use of algal protein is still in its infancy (Becker, 2007). However, Tredici (2010) believes that the photobiology of microalgae mass culture can be significantly improved and a higher yield can be achieved. Guccione et al. (2014) studied the yield potential of various *Chlorella* strains and concluded that there are large differences between them. The highest yields, extrapolated to one hectare and year were 16 t of protein and 11 t of lipids.

Yeasts have been used by humans for thousands of years in traditional fermentation processes, but also as sources of proteins (> 45 % protein in DM; Bekatorou et al., 2006) and food and feed additives. They may utilize various carbohydrates, but the various processes are expensive in substrate input and costs.

Proteins extracted from leaves (termed leaf protein concentrates) may also contribute as protein sources for humans and animals (e.g., Dewan et al., 2007; Mendieta-Araica et al., 2011).

Windisch et al. (2013) analyzed the more effective use of known feed sources, such as seed meals by reduction or inhibition of antinutritive substances (e.g., glucosinolates in rapeseed; aflatoxins in peanut meal; gossypol in cottonseed meal) or the exploitation of new feeds (such as *Jatropha curcas* through elimination of various toxins). More effective utilization of coproducts resulting from agriculture (e.g., cereal straw, sugar beet leaves) and biofuel production (e.g., Makkar, 2012) can also be considered as feed resources.

5.6 Change of eating pattern

Apart from food of animal origin and other food sources (see above), there are also further alternatives to meet the protein and amino acid requirements of humans and to have a high enjoyment value of the foods. These include changing eating patterns, reducing food losses along the food production chain and developing simulated food from processed plant proteins or cultured muscle cells.

Changing eating patterns (Guyomard et al., 2012) and consuming less or no livestock products, especially meat, are often seen as possible solutions to reduce the environmental impact of animal agriculture (Baroni et al., 2007; Pimentel

Table 17. Examples for the variation in protein content of various insect species (% of dry matter; summarized by EFSA, 2015; Flachowsky and Klüß, 2015).

References	Numbers of investigated species	Crude protein
Bukkens (1997)	50	7.5–79.6
Finke (2002)	75	22.5–80.0
St-Hilaire et al. (2007)	Black soldier fly (prepupa)	43.6
	Housefly (pupa)	70.4
Grabowski et al. (2008)	17	40.0–86.6
Oonincx and de Boer (2012)	6	38.3–76.1
Rumpold and Schluter (2013)	234*	4.9–74.8
Sanchez-Muros et al. (2014)	72	9.5–70.1
Makkar et al. (2014)	Black soldier fly larva (1–5)*	41.1–43.6
	Housefly maggot meal (19–29)	42.3–60.4
	Mealworm (2–10)	47.2–60.3
	Grasshopper meal (7–9)	29.2–65.9
	House cricket (2–4)	55.0–67.2
	Silkworm pupa meal (6–11)	51.6–70.6

* Number of samples.

and Pimentel, 2003) and to reduce the per capita LF (Flachowsky et al., 2017; Peters et al., 2007).

5.7 Reduction in food losses and waste

The issue of global food losses and waste has recently received much attention. According to FAO (2011), about one-third of food produced for human consumption globally – about 1.3 billion t of edible food per year – is lost or wasted. This amount is equal to about 24 % of all calories currently produced for human consumption. In developing countries food waste and losses occur mainly at the early stages of the food value chain; in medium- or high-income countries food is wasted or lost mainly at later stages of the food chain (FAO, 2011). Reduction of food waste and loss is essential to improve food security, sustainability of food production and to reduce the environmental footprints, such as LF, WF and CF of food systems (Blanke, 2015; Parfitt et al., 2010). A reduction of losses can be easily achieved by adequate management measurements. LCAs of food waste also demonstrate the environmental burdens of the waste elimination (Thyberg and Tonjes, 2017).

6 Conclusions

In conclusion, food security and optimal human nutrition taking into account limited resources, increased emissions and expected climate change can be considered as the top challenge for all those dealing with feed and food production and nutrition. We conclude that more work is needed to understand the values underlying different approaches to food sustainability aspects, such as harmonization of data collection and calculation methods. In the future, footprints for land (LF), water (WF) and GHG emissions (CF) could be very helpful tools for strategic decisions. Apart from life cycle assessments for traditional ways of food production, adequate studies applying accepted methods are required for enhancing research on alternative methods of food production.

More food for more people with less and limited resources available and at the same time lower emissions is a big challenge for all those working along the whole food production chain and thereby dealing with plant or animal breeding and cultivation.

Data availability. No data sets were used in this article.

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