ARTICLE IN PRESS

Global Food Security (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

# Livestock: On our plates or eating at our table? A new analysis of the feed/food debate

Anne Mottet[a,*], Cees de Haan[b], Alessandra Falcucci[a], Giuseppe Tempio[a], Carolyn Opio[a], Pierre Gerber[a,c]

[a] Food and Agriculture Organization of the United Nations, Animal Production and Health Division, Viale delle Terme di Caracalla, 00153 Rome, Italy
[b] Independent consultant, The Netherlands
[c] Animal Production Systems Group, Wageningen University, P.O. Box 338, Wageningen, The Netherlands

ARTICLE INFO

*Keywords:*
Global livestock feed rations
Feed/food competition
Feed conversion ratios
Ruminants
Monogastrics

ABSTRACT

Livestock contribute to food security by supplying essential macro- and micro-nutrients, providing manure and draught power, and generating income. But they also consume food edible by humans and graze on pastures that could be used for crop production. Livestock, especially ruminants, are often seen as poor converters of feed into food products. This paper analyses global livestock feed rations and feed conversion ratios, with specific insight on the diversity in production systems and feed materials. Results estimate that livestock consume 6 billion tonnes of feed (dry matter) annually – including one third of global cereal production – of which 86% is made of materials that are currently not eaten by humans. In addition, soybean cakes, which production can be considered as main driver or land-use, represent 4% of the global livestock feed intake. Producing 1 kg of boneless meat requires an average of 2.8 kg human-edible feed in ruminant systems and 3.2 kg in monogastric systems. While livestock is estimated to use 2.5 billion ha of land, modest improvements in feed use efficiency can reduce further expansion.

## 1. Introduction

In 2015, almost 800 million people were still undernourished (FAO, 2015a). This includes insufficient access to balanced supply of macronutrients (carbohydrates, proteins and fats) but also “hidden hunger”, i.e. lack of, or inadequate intake of micronutrients, resulting in various forms of malnutrition, such as anaemia or vitamin A deficiency (FAO, 2015a).

Food from animal sources contributes 18% of global calories (kcal) consumption and 25% of global protein consumption (FAOSTAT, 2016). But it also makes an important contribution to food security through the provision of high-quality protein and a variety of micronutrients – e.g. vitamin A, vitamin B-12, riboflavin, calcium, iron and zinc – that can be locally difficult to obtain in adequate quantities from plant-source foods alone (Randolph et al., 2007; Murphy and Allen, 2003). Livestock's contribution goes beyond the production of meat, milk and eggs, however, and a number of factors determine their overall impact on food security (Gerber et al., 2015). Positive contributions include: (1) the direct supply of essential macro- and micronutrients; (2) the contribution of domesticated animals to agricultural productivity through manure and draught power; and (3) the income generated by livestock production at household and national level. Potentially negative contributions to food security include: (1) animal feed rations containing products that can also serve as human food; (2) the fact that animal feed may be produced on land suitable for human food production; and (3) the relatively low efficiency of animals in converting feed into human-edible products.

This paper aims to inform one important dimension of the debate on the contribution of animal production to food security. Beef production, in particular, is often criticized for its very high consumption of grain, with cited figures varying between 6 kg and 20 kg of grain per kg of beef produced (Eshel et al., 2014, Elliott, 2012; Godfray et al., 2010; Garnett, 2009). The upper bound of this range is, however, based on feedlot beef production, which accounts for 7% of global beef output according to Gerber et al. (2015) and FAO (2009), and 13% according to this analysis. It does not apply to the other forms of beef production that produce the remaining 87–93% of beef. Indeed, debate on the subject often lacks recognition of the wide diversity in production systems and in the goods and services delivered by livestock (Smith, 2015). And while some of the global discussion on food security may address the question of the feed/food competition, it often fails to mention the diversity of animal diets around the world and the various levels of efficiency in production systems (Godfray et al., 2010; Flachowsky, 2010). Some well-documented studies (e.g. Eshel et al.,

* Corresponding author.

http://dx.doi.org/10.1016/j.gfs.2017.01.001
Received 5 January 2016; Received in revised form 3 January 2017; Accepted 3 January 2017


Please cite this article as: Mottet, A., Global Food Security (2017), http://dx.doi.org/10.1016/j.gfs.2017.01.001

2014) covering the US livestock sector, are often quoted without clear reference to the geographic context they apply to (e.g. Carrington, 2014), and are therefore wrongly used to inform decision makers, and the public at large. For example, the literature often highlights the supposed efficiency of pigs and poultry in converting feed into meat. But these studies do not take account of the higher share of feed consumed in the form of grains edible by humans and of land suitable for food production used by monogastrics.

The livestock sector is expected to continue to grow. Demand for animal products is increasing in many parts of the world as a result of rising incomes, growing population and urbanization. Global demand for meat and milk is expected to increase by 57% and 48% respectively between 2005 and 2050 (Alexandratos and Bruinsma, 2012). Most of the past decades sector's growth took place in large-scale, specialized monogastric farms (FAO, 2009), and this trend can be expected to continue. This was achieved through an increased reliance by the sector on cultivated forages, grains and oilseed meals, but also on agricultural by-products such as brans, dried distillers' grains, pulps and molasses.

As this increase in demand for animal source food will have a major impact on global food systems and land use, there is a need to better inform policy makers and consumers about feed use and feed use efficiency in the livestock sector (Capper et al., 2013). To this end, this analysis addresses the food/feed competition looking at two main drivers: the feeding of human-edible materials to animals and the use of arable land to produce animal feed (instead of producing food directly). It relies on a new and unique database and provides broad quantitative estimates of livestock feed rations, feed demand, and related land use. It analyses the composition of feed rations and the efficiency with which human-edible and non-human-edible feed materials are converted into animal-source food and discusses land use implications. This paper is meant to inform policy makers and the wider global community with a quantitative assessment of the role of livestock in current and future food security.

## 2. Method and data

### 2.1. Terminology and feed classification

In this paper, feed rations correspond to both the intake and composition of the feed consumed by livestock. The classification of feed materials is summarized in Fig. 1. It is based first on whether the product from which they are derived is edible by humans (i.e. cereal grains, soybeans, pulses, banana and cassava) or not (roughages such as grass, crop residues and fodder beets, cotton and rape seeds). In the latter case, the feed material is always classified as not human-edible. If the product is human-edible, two cases are considered. First, the entire product is used as feed (e.g. cereal grains, pulses, cassava, soybeans) and the feed material is therefore human-edible. Second, only part of the product is used as feed. In that case, the Economic Fraction Allocation (EFA, Table S16 in Supplementary Information) is used to identify which co-product is the main driver of the land use. If the EFA of the part used as feed material is >66%, then the feed material is considered as the main driver of land-use and therefore in competition with food production. Practically, this is the case only for soybean cakes (EFA=72%). If it is <66%, the feed material is not considered as the main driver of land-use.

Also considered non-human-edible are minor feed materials such as synthetic amino acids, limestone, wastes from fruit harvests and second-grade crops deemed unfit for human consumption.

Feed intakes are usually expressed in kg dry matter (DM) per animal. The quality of food products and feed materials can be expressed in a number of ways (van Kernebeek et al., 2014), and the nature of their contribution to the diet/ration is relative to the specific needs of the consumer/animal as well as to the availability of alternative and/or complementary food products and feed materials. However, the paucity of data and limitations in modelling capacity made it difficult to include such diversity and interactions in the present analysis so that protein content was taken as the single metric of quality, both of feed and food.

The ability and performance of different livestock species and production systems to transform feed into animal products is usually measured by the feed conversion ratio (FCR), the quantity of feed per unit of output (milk, meat or eggs). In this paper, FCR1 is defined as the kg DM intake/kg protein product (Fig. 1 and Table 1). With a focus on feed/food competition, this study also considers FCR2, accounting only for human-edible feed material. In the current state of the industry, Soyatech (2003) estimate that 'About 85% of the world's soybeans are processed annually into soybean cake and oil, of which approximately 97% of the meal is further processed into animal feed'. Soybean cakes can therefore be considered inedible for humans but they are derived from an edible product and can be considered as the main driver of soybean production, as per our methodology (EFA > 66%). Therefore, FCR3 was also included in the analysis as kg of human-edible feed and soybean cakes/kg protein output. In addition protein FCR consider the protein content of the feed intake and FCR meat consider the meat output only.

### 2.2. Livestock production systems and feed rations

Our estimates of feed rations are based on the Global Livestock Environmental Assessment Model (GLEAM, Gerber et al., 2013). GLEAM is a spatially explicit model that represents bio-physical processes and activities along livestock supply chains under a life cycle assessment (LCA) approach. It has a high level of quantitative detail on herd production functions and resource flows, and relies on a farming system typology that includes the feed-base and the agro-ecological conditions, adapted from the classification principles of Seré and Steinfeld (1996). GLEAM includes six species of livestock – cattle,

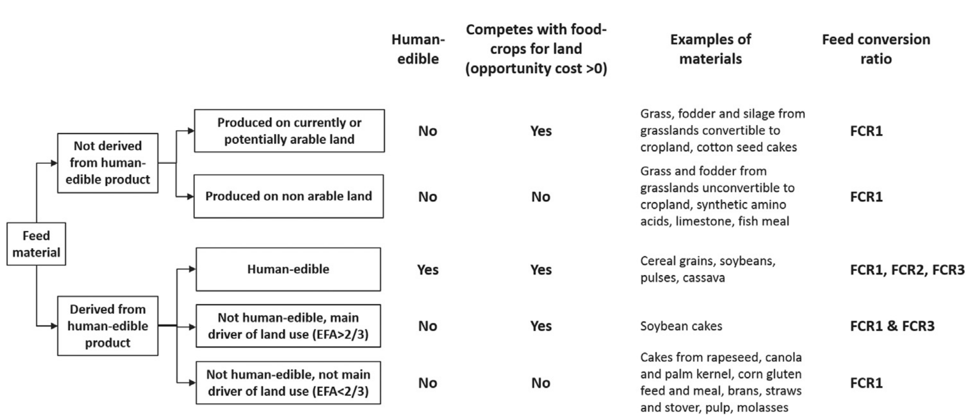



**Fig. 1.** Feed classification methodology.

**Table 1**
Protein production and feed conversion ratios by regions, species and production system.

| | | | Total protein production[a] (Mt/year) | FCR1 Kg DM feed/kg protein product[1] | FCR2 Kg DM human edible[b] feed/ kg protein product[a] | FCR2 meat Kg DM human-edible[b] feed/kg meat[c] | FCR3 Kg DM human-edible +soybean cakes[d]/kg protein product[1] | Protein FCR1 Kg protein feed/ kg protein product[a] | Protein FCR2 kg protein from human-edible feed[b]/kg protein product[a] | Protein FCR3 Kg protein from human-edible +soybean cakes[d]/ kg protein product[a] |
|---|---|---|---|---|---|---|---|---|---|---|
| Non OECD | Cattle & buffaloes | Grazing | 5881 | 195 | 1.6 | 0.9 | 1.9 | 20 | 0.2 | 0.3 |
| | | Mixed | 13,615 | 171 | 4.8 | 3.1 | 5.6 | 16 | 0.5 | 1.0 |
| | | Feedlots | 374 | 99 | 37.1 | 7.9 | 39.6 | 16 | 3.5 | 4.8 |
| | Small Ruminants | Grazing | 975 | 221 | 0.4 | 0.1 | 0.5 | 20 | 0.0 | 0.1 |
| | | Mixed | 1250 | 190 | 0.5 | 0.2 | 0.6 | 17 | 0.1 | 0.1 |
| | Poultry | Backyard | 942 | 78 | 2.1 | 1.5 | 8.8 | 16 | 3.5 | 3.5 |
| | | Layers | 6960 | 20 | 15.5 | – | 16.6 | 4 | 2.9 | 2.9 |
| | | Broilers | 8496 | 26 | 18.6 | 3.5 | 24.7 | 6 | 5.2 | 5.1 |
| | Pigs | Backyard | 3800 | 574 | 0.6 | 0.1 | 7.8 | 11 | 3.3 | 3.7 |
| | | Intermediate | 2441 | 35 | 18.8 | 3.8 | 24.4 | 7 | 4.9 | 4.9 |
| | | Industrial | 2937 | 27 | 19.1 | 3.9 | 23.9 | 6 | 4.6 | 4.6 |
| OECD | Cattle & buffaloes | Grazing | 5053 | 67 | 4.7 | 3.9 | 5.5 | 8 | 0.5 | 0.9 |
| | | Mixed | 7404 | 53 | 6.4 | 6.0 | 7.6 | 7 | 0.7 | 1.2 |
| | | Feedlots | 1152 | 62 | 44.3 | 9.4 | 45.4 | 6 | 4.1 | 4.7 |
| | Small Ruminants | Grazing | 242 | 132 | 3.2 | 0.8 | 3.5 | 16 | 0.4 | 0.5 |
| | | Mixed | 409 | 111 | 2.8 | 0.9 | 3.2 | 13 | 0.3 | 0.5 |
| | Poultry | Backyard | 18 | 59 | 0 | 0 | 1.0 | 10 | 0.5 | 0.5 |
| | | Layers | 2259 | 18 | 13.8 | 0 | 15.7 | 3 | 2.9 | 2.9 |
| | | Broilers | 4686 | 26 | 18.8 | 3.6 | 24.0 | 6 | 5.1 | 5.0 |
| | Pigs | Backyard | 99 | 57 | 0 | 0.0 | 1.4 | 7 | 0.6 | 0.7 |
| | | Intermediate | 180 | 35 | 21.1 | 4.3 | 25.1 | 6 | 4.5 | 4.5 |
| | | Industrial | 5428 | 29 | 20.0 | 4.0 | 24.1 | 6 | 4.4 | 4.4 |
| World | Ruminants | All | 36,355 | 133 | 5.9 | 2.8 | 6.7 | 2 | 0.6 | 1.0 |
| | Monogastrics | All | 38,246 | 30 | 15.8 | 3.2 | 20.3 | 14 | 2.0 | 4.2 |
| | All | All | 74,601 | 80 | 11.0 | 3.1 | 13.7 | 10 | 1.3 | 2.6 |

DM=dry matter
[a] All outputs are included: meat and milk for ruminants, eggs and meat for layers, meat for all other monogastrics
[b] Only cereal grains, pulses, soybeans and roots
[c] Only the boneless meat output is considered. For ruminants that are milked, energy requirements for lactation and pregnancy and associated feed intake were subtracted. Layers are excluded.
[d] Cereal grains, pulses, soybeans, roots and soybean cakes

buffalo, sheep, goats, pigs and chickens. Ruminant production is differentiated into feedlot (for beef only), mixed and grazing systems; pig production into backyard, intermediate and industrial systems and chicken production into backyard, layers and broilers (Table SI 1 in Supplementary Information).

Feed rations were modelled differently for ruminants and monogastrics. For ruminants in industrialized countries, the composition and relative portions of the feed ration materials were taken from national inventory reports, literature and targeted surveys. For developing countries, due to scanty information, a feed allocation scheme was modelled, using the availability of feed resources (yields of crops and forage) and animal requirements (energy) and literature and expert knowledge. For monogastrics, feed materials were divided into three main categories: swill and scavenging; locally produced feed materials; and non-local materials. The proportions of the three main feed groups were defined based on availability (yields) where possible, literature and expert knowledge.

GLEAM feed rations were compared to results gathered from an extensive literature review, covering 121 peer-reviewed international and national publications presenting feed rations for combinations of species, systems and regions. No significant discrepancies were found and main feed materials, as well as their share in the total dry matter intake, were validated.

More details about the model, the data and the validation literature review as well as feed rations and intakes are provided in the Supplementary Information to this paper.

### 2.3. Land use for forage and feed production

Spatially explicit distribution of pasturelands and rangelands (Henderson et al., 2015) and the yield gap between actual and potential production (IIASA/FAO, 2012) were used to map grassland potentially convertible to arable lands and ones unsuitable for crop production. IIASA/FAO (2012) estimated the potential yield in Global Agro-Ecological Zones GAEZ 3.0 using soil suitability, terrain slopes, water supply systems and water deficit factor. Actual yields are downscaled from national statistics using land-cover spatial information and cultivation factors. A 25% ratio of actual/potential yield was considered to determine unconvertible grasslands, which corresponds to grasslands having a suitability for crop production ranked by IIASA/FAO (2012) as "marginal". This binary raster dataset was overlapped with the pasture-rangeland distribution. Spatial distribution of ruminant species (Robinson et al., 2014) was used to discriminate areas with and without animals. The spatial resolution of these datasets is 5′.

Total hectares of land necessary to feed animals present in each cell were calculated using intake calculated by GLEAM and area harvested and yield from IIASA/FAO (2012). When non-local feed resources are used to supply the animal requirements, trade at regional level is considered. In the case of soy and palm oil cakes, a global trade matrix was used. When different co-products are produced from one crop (e.g. grain and straw, oil and oil seed cakes), an allocation method was used to determine the share of land attributable to each material. The method is presented in Supplementary Information and is based on the approach developed by Gerber et al. (2013) for the calculation of greenhouse gas emissions. It relies on the relative mass fraction and value of the different co-products and by-products.

### 2.4. Projections of sector's trends

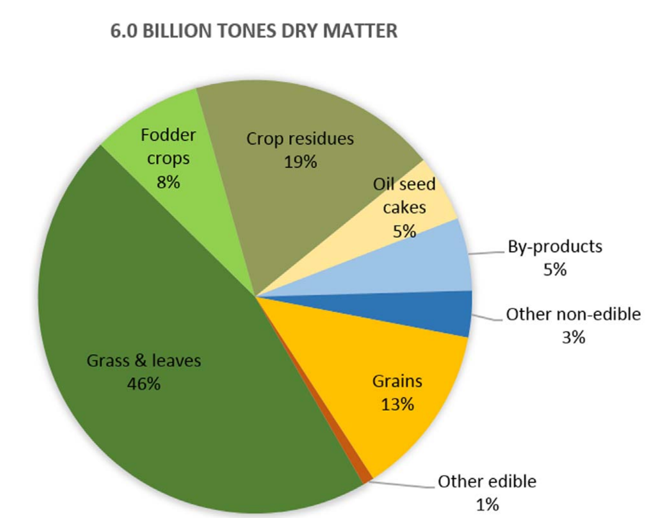
A study by Wirsenius et al. (2010) was used as a reference to estimate potential improvements in feed conversion ratios. The OECD-FAO Agricultural Outlook for 2016–2025 (OECD/FAO, 2016) was used to analyse future trends in the livestock sector and their implications for feed demand and land-use, as compared to the reference year 2010. The OECD/FAO projections represent the latest relatively accurate data available for medium-term analyses. In addition, they provide a breakdown between OECD and non-OECD countries as well as meat consumption breakdowns by species and yield trends for main crops, which are not available for longer-term projections. Furthermore, the fact that variables such as climate change and change in dietary preferences are generally not included in projections is assumed to be less of an issue for medium-term projections (up to 2025) than for long-term estimates (up to 2050).

## 3. Current livestock production systems: feed intake, food output and land use

### 3.1. The global livestock feed ration

The global livestock sector ingested an estimated 6.0 billion tonnes of feed (DM) in 2010. The three major feed materials were grass and leaves (46% or 2.7 million tonnes, Fig. 2 and Table SI 2 in Supplementary Information), followed by crop residues such as straws, stover or sugar-cane tops (19% or 1.1 billion tonnes DM). At global level, human-edible feed materials represented about 14% of the global livestock feed ration. Grains made up only 13% of the ration, but represented 32% of global grain production in 2010 (FAOSTAT, 2016). Oil seed cakes account for 5% (with about 300 million tonnes DM).

In grazing and mixed systems, the intake of ruminants is mainly composed (about 90%) of roughage: leaves, grass, silage and crop residues (Table SI 3 in Supplementary Information). Roughage is less important in feedlot systems, where grains in the fattening phase account for 38% of total DM intake in non-OCED countries and 72% in OECD countries. Cattle consume between 1.8 t per animal in feedlots systems in non-OECD countries, and 3.2 t in grazing systems in OECD countries. Monogastric animals can only digest simple carbohydrates, and therefore consume low amounts of roughage. They, however, use larger quantities of grains and agricultural co- and by-products. In industrial broilers and layers, and in pig production, grains contribute more than 50% of total DM intake, while oil seed cakes range from 9% to 25% of DM intake.




Fodder crops: grain and legume silage, fodder beets
Crop residues: straws and stover, sugar cane tops, banana stems
By-products: brans, corn gluten meal and feed, molasses, beetroot pulp and spent breweries, distilleries, biofuel grains
Other non-edible: second grade cereals, swill, fish meal, synthetic amino acids, lime
Other edible: cassava pellets, beans and soy beans, rapeseed and soy oil

**Fig. 2.** Global livestock feed ration composition (source: GLEAM 2.0).

### 3.2. Conversion of feed into animal-source food

Species and production systems do not contribute equally to the global supply of animal protein. Cattle and buffaloes make the largest contribution with 45%, including meat and milk, followed by chickens (31%, including meat and eggs) and pigs (20%). Small ruminants only produce about 4% of global animal-source protein (Table 1).

All animal species combined use about 80 kg DM per year to produce one kg of animal protein. FCR1 in ruminants can reach as much as 133 kg DM/kg protein while it is only 30 in monogastrics (Table 1). Monogastrics are thus more efficient feed convertors but they require higher-quality feed. There are also important differences between production systems and regions. Ruminants in non-OECD countries kept in mixed and grazing systems have the highest FCR1 (slightly under 200 kg DM/kg protein output for cattle and buffaloes and over 220 for small ruminants) because of sub-optimal animal husbandry practices (low-quality roughage and ill-balanced rations), poor animal health, limited breeding for productivity and multi-functionality of production systems. Feedlot cattle in non-OECD countries have a lower FCR1 (99 kg DM/kg protein output). The lowest FCR1 are found in industrial and intermediate monogastric production systems, and especially in industrial layers and pigs (respectively 20 and 27 kg of DM/kg protein in non-OECD countries and 18 and 29 kg in OECD countries), where feed is of higher quality and management parameters highly controlled. These data are in line with other assessments (Bouwman et al., 2005; Wirsenius et al., 2010; Herrero et al., 2013).

When considering only feed materials that are edible by humans (FCR2), at global level, ruminants use 5.9 kg of human-edible feed/kg of protein whereas monogastrics need 15.8 kg. The highest ratio, however, is found in cattle feedlots: 44.3 kg in OECD countries and 37.1 kg in non-OECD countries. It is also relatively high in industrial pigs, layers and broilers, ranging from 13.8 to 20.0 kg. At the other end of the scale, the lowest FCR2 are found in backyard monogastric systems and in grazing and mixed (crop/livestock) ruminant production. When adding soybean cakes, FCR3 are higher again for feedlots and industrial monogastrics. All livestock use about 13.7 kg of human-edible feed and soybean cakes/kg protein, with 6.7 kg for ruminants and 20.3 kg for monogastrics.

When looking at meat production only (FCR2 meat) ruminants use 2.8 kg human-edible feed per kg boneless meat produced while monogastrics use 3.2 kg (layers excluded). Industrial monogastric systems need between 3.5 and 4.0 kg. Cattle feedlots systems have high FCR2 meat, with about 9 kg in OECD countries and 8 kg in non-OECD countries.

Overall protein feed intake per protein produced is lower in monogastric systems than in ruminant systems, because they are better protein converters than ruminants and the protein in their feed ration is generally of higher quality. Grazing systems in non-OECD countries and backyard monogastric systems appear to have poor protein-use efficiency (20 kg and 16 kg and 11 kg protein feed /kg protein product respectively), because of the overall low productivity in those systems. They do, however, require relatively little human-edible protein. All ruminant systems, including feedlots, need about 0.6 kg human-edible-feed protein per kg of protein product. Backyard monogastrics need up to 0.1 kg of human-edible-feed protein per kg protein output. In contrast, industrial monogastric systems range from 2.9 to 5.2 kg human-edible-feed protein per kg of protein product. Ruminant systems, together with backyard pig and poultry systems, produce close to 41 Mt of animal protein per year while consuming about 37 Mt of human-edible-feed protein (Table 1). That means they make a positive net contribution to human-edible protein availability of about 4 Mt per year, in the current use of land and excluding indirect contributions to agricultural productivity. When adding soybean cakes,

**Table 2**
Global land-use for forage and feed production by regions and species (million ha).

| | | Grasslands suitable for crops | Grasslands unsuitable for crops | Cereal and legume silage, fodder beet | Cereals grains | Oil seed and oil seed cakes | Other crops[a] | By-products[b] | Crop residues[c] | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Non OECD | Cattle & buffaloes | 436.2 | 442.6 | 46.8 | 42.7 | 22.7 | 0 | 22.1 | 100.7 | 1113.8 |
| | Small Ruminants | 139.9 | 769.6 | 9.1 | 0.7 | 0.9 | 0 | 2.1 | 17.8 | 940.1 |
| | Poultry | 0 | 0 | 0 | 73.8 | 43.4 | 0.7 | 1.4 | 0 | 119.23 |
| | Pigs | 0 | 0 | 0 | 24.7 | 27.0 | 1.4 | 2.8 | 4.2 | 60.1 |
| OECD | Cattle & buffaloes | 88.5 | 40.0 | 9.6 | 28.0 | 8.2 | 0 | 3.7 | 2.2 | 180.2 |
| | Small Ruminants | 20.3 | 12.2 | 0.4 | 0.9 | 0.2 | 0 | 0.5 | 0.9 | 35.4 |
| | Poultry | 0 | 0 | 0 | 19.3 | 16.9 | 0.0 | 0.0 | 0 | 36.2 |
| | Pigs | 0 | 0 | 0 | 20.4 | 12.0 | 0.8 | 0.5 | 0.3 | 34.0 |
| World | Cattle & buffaloes | 524.7 | 478.5 | 56.5 | 70.7 | 30.9 | 0 | 25.8 | 103.0 | 1290.1 |
| | Small Ruminants | 160.3 | 781.8 | 9.5 | 1.6 | 1.1 | 0 | 2.6 | 18.6 | 975.5 |
| | Poultry | 0 | 0 | 0 | 93.1 | 60.3 | 0.7 | 1.4 | 0 | 155.5 |
| | Pigs | 0 | 0 | 0 | 45.1 | 39.0 | 2.5 | 3.3 | 4.4 | 94.0 |
| | All | 684.9 | 1260.4 | 65.9 | 210.5 | 131.3 | 2.9 | 33.1 | 126.0 | 2,505.6 |

[a] Pulses, cassava and banana
[b] Corn gluten feed and meal, brans, middling, molasses, sugar beet pulp, and by-products from breweries, distilleries and biofuels
[c] Straws, sugar cane tops, banana stems

they represent a deficit of 11 Mt protein per year.

### 3.3. Land-use implications

Total area of agricultural land currently used for livestock feed production at global level is 2.5 billion ha (Table 2), which is about half of the global agricultural area as reported by FAOSTAT (2016) The largest share of this area is made up of grasslands, with almost 2 billion ha.

The usually reported area of permanent grasslands is 3.5 billion ha (FAOSTAT, 2016), of which about 1.5 billion ha has no livestock because it corresponds to very marginal rangelands and shrubby ecosystems (Map 1). This study finds that out of the total grassland area currently used by livestock, 684.9 million ha could be converted to cropland. That is equivalent to 14% of global agricultural land and half of global arable land, while the remaining 1.3 billion ha of pastures and rangelands can be considered non-convertible.

Producing cereal grain for livestock uses up a total of 210.5 million ha, or some 31% of the global area devoted to cereal production (FAOSTAT, 2016). The production of cereals for monogastrics occupies 138 million ha, or 20% of the global cereal-growing area. In addition, the global livestock sector uses about 66 million ha to produce cereal and legume silage and fodder beets. Using the allocation method based on mass and value of co-products, about 131 million ha can be attributed to the sector for oil seed cakes and 126 million ha for crop residues. Total arable land used to feed livestock reaches about 560 million ha, or about 40% of the global arable land.

## 4. Trends, feed demand and land use in the livestock sector

According to the OECD-FAO Agricultural Outlook for 2025, and using meat projections as a proxy since milk projections are not broken down by species, the livestock sector is expected to increase by 21% between 2010 and 2025 (Table 3). The fastest-growing subsectors are small ruminants and poultry in non-OECD countries (+32% and +33% respectively, Table SI 17 in Supplementary Information). The pig sector in non-OECD countries is expected to grow by 19%, cattle and buffaloes by 21%. In OECD countries, poultry production is expected to grow by 24%, followed by small ruminants (+15%), pig production (+10%) and cattle (+4%).

With conservative FCR1 improvements (0–5% lower depending on the species), demand for non-human-edible feed materials (mainly grass, fodder crops, crop residues and agricultural by-products) would grow by 17% in non-OECD countries and 7% in OECD countries (Table 3). With more optimistic improvements 5–15% lower FCR), demand for non-human-edible feed materials would increase by 7% in non-OECD countries and 2% in OECD countries. In contrast, demand for human-edible feed materials (grains but also cassava or soybeans) would grow by between 14% (optimistic FCR1 improvements) and 20% (conservative FCR1 improvements) in non-OECD countries and 7% and 12% in OECD countries, respectively.

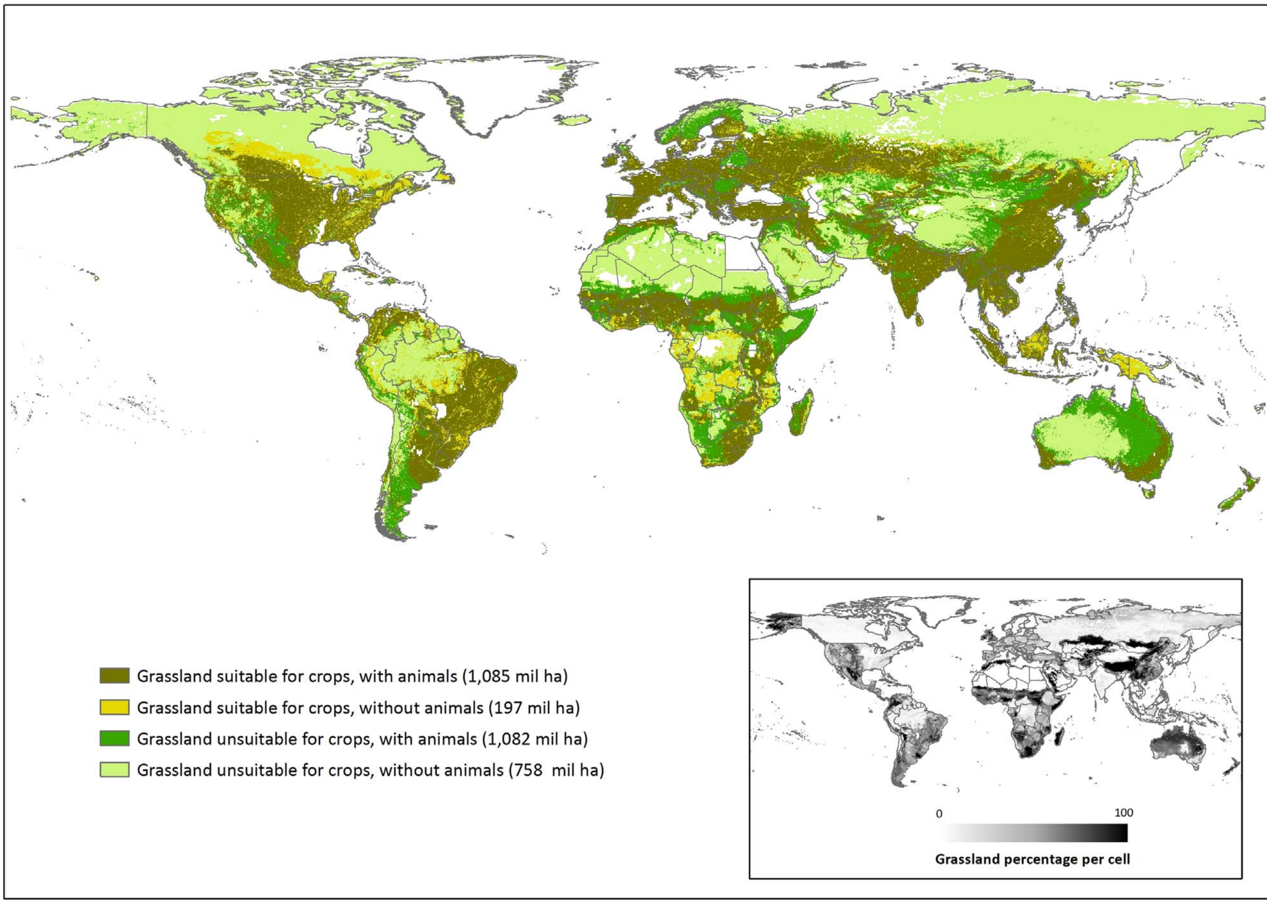
Given the OECD-FAO Agricultural Outlook projections in crop yields for 2025, the area necessary to produce the required human-edible feed materials in non-OECD countries is expected to decrease by 4–10% between 2010 and 2025, depending on the FCR improvement scenario. In OECD countries, it is expected to decrease by 4% or increase by 1% depending on FCR improvement scenario. Assuming constant yields on grasslands in the next 10 years, the global area required to produce the grass and leaves portion of the ration is expected to increase by 14% between 2010 and 2025 (15% in non-OECD and 3% in OECD) with limited improvements in FCR1, but only by 4% if improvements are higher. This represents an additional 309 million hectares of grasslands in non-OECD countries if improvements in feed conversion ratios in the next 10 years remain modest, or 95 million hectares with more optimistic improvements. This would mean further expansion of the sector into currently non-agricultural areas.

## 5. Discussion

### 5.1. Feed/food competition and the role of livestock in the bio-economy

The annual feed intake of livestock (6 billion tonnes DM) represents 60% of the total food and feed combined biomass, including residues and by-products, or about 20% of the global human appropriation of biomass (Pelletier and Tyedmers, 2010; Imhoff et al., 2004; Krausmann et al., 2013).

Today, crop production, processing and the agrifood chains produce large amounts of residues as well as co- and by–products, which constitute nearly 30% of global livestock feed intake. These products will be produced in larger amounts as the human population grows and consumes always more processed food. Livestock play, and will




**Map 1.** Global grasslands suitable and unsuitable for crop production and share in land-use. Threshold of 25% ratio of actual/potential yield used for suitability, as defined by IIASA/FAO (2012). Livestock distribution based on Gridded Livestock of the World (Robinson et al., 2014).

continue to play a critical role in adding value to these residual products, a large share of which could otherwise be an environmental burden.

But livestock also make an indirect contribution to the bio-economy and overall food output by increasing crop productivity through manure and draught power. For example, Gebresenbet and Kaumbutho (1997) estimate that cattle, together with camels, horses and donkeys, provide transport and draught power for ploughing fields on about 15% of farms in Southern Africa and 81% of farms in Northern Africa. In Europe, the share of manure in total nitrogen inputs was estimated at 38% and as much as 61% in the Netherlands (European Commission, 2012). These results are generally in line with the discussion put forward by van Zanten et al. (2015), arguing that livestock can make substantial contribution to protein supply, without triggering feed/food competition.

### 5.2. Growing demand and need for efficiency gains

Given the rising demand for livestock products, the area of land needed for livestock is expected to increase if feed conversion ratios do not improve significantly. Efficiency should not only be considered at animal level but also at production system level. The main factors driving FCR within a given species are feed quality, followed by animal genetics and health conditions (Gerber et al., 2015). The scenarios used in this study provide some insight on a range of feasible FCR improvements which can be considered rather conservative compared to past improvements. Through improved feed formulation, genetic selection and better veterinary services, feed conversion ratios in poultry and pigs have been halved over the last three decades in Brazil and Thailand (de Haan et al., 2001), and Europe (Albers, 2013) and globally for broilers (FAO, 2009). Genetic improvements have led

**Table 3**
Projected changes in meat production between 2010 and 2025 (OECD/FAO, 2016) and related animal feed demand and area needed.

| 2025/2010 | Meat production | Feed intake | | | | Area | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Low FCR increase | | High FCR increase | | Low FCR increase | | High FCR increase | |
| | | Human-edible[a] | Non human-edible | Human-edible[a] | Non human-edible | Human-edible[a] | Non human-edible | Human-edible[a] | Non human-edible |
| Total non OECD | 24% | 20% | 17% | 14% | 7% | −4% | 15% | −10% | 5% |
| Total OECD | 14% | 12% | 7% | 7% | 2% | 1% | 3% | −4% | −2% |
| Total World | 21% | 17% | 15% | 11% | 6% | −2% | 14% | −8% | 4% |

FCR=Feed Conversion Ratio
[a] Only cereal grains, pulses, soybeans and roots

to increases in average milk production per lactation and the number of days required to achieve slaughter weights in poultry in the UK (Wilkinson, 2011). Marginal additional gains are expected in these systems and can be achieved through precision livestock farming and the development of feed additives. In other regions, especially in sub-Saharan Africa and South Asia, progress can also be made in feed quality through improved grasslands and better use of crop residues, including treatments to increase their feeding value. Herd management, and in particular the proportion of breeding stock that needs to be fed but does not contribute directly to human-edible output (e.g. replacement heifers), is also a major driver of FCR and can be improved through interventions in reproduction and animal health. Finally, the proportion of dual-purposes animals in herds/flocks, such as dairy cows or laying hens, for which maintenance energy is distributed over two products, also influences FCR significantly (Wilkinson, 2011).

### 5.3. Comparison with previous global assessments

Despite its crucial importance in animal systems and food security, there is no census-based global database on feed. All global analyses thus rely, at least partially, on modelling. Our estimates draw on an improved version of GLEAM's feed module (Gerber et al., 2013). Results were compared against literature and existing global statistics and appear in line with both the results of an extensive examination of 121 peer-reviewed papers, which are presented in the Supplementary Information section, as well as with FAOSTAT (2016) food balance sheets. They were also compared and found in line with other model-based assessments in terms of feed rations composition and feed use efficiencies for different species (Bouwman et al., 2005; Steinfeld et al., 2006; Wirsenius et al., 2010; Herrero et al., 2013; Dijkstra et al., 2013) and impact of improvements in feed conversion ratios on land-use (Wirsenius et al., 2010). Although simplifications and generalizations were necessary given the paucity of data, our assessment includes more categories and rations than past work, including the distinction of cattle feedlots and a particular focus on human-edible feed materials and soybean cakes, and protein feed intake per kg of protein produced. This provides a more realistic estimate of FCR, as argued by Wilkinson (2011). The analysis of land-use implications also revealed that factoring in the quality of land (grassland convertibility to cropland) led to findings that defied simple conclusions of resource use by livestock, as also demonstrated by Peters et al. (2014).

### 5.4. Methodological limitations, constraints and ways forward

The feed/food debate boils down to a question of allocating land and other resources to the production of one or the other. To address the question we considered special FCR looking specifically at human-edible feed materials and soybean cakes, which production can be considered as the main driver of land-use. Soybean cakes were also considered inedible by Kebreab (2013), but FCR increases from 10.4 to 13.7 (+32%) when adding soybean cakes to edible materials. “Opportunity costs” of using land for animal feed or human food would have been an important additional criteria. This would require economic instruments for a complete analysis and is not yet feasible because of the lack of integration between biophysical and economic models and scarce data on production cost in non-OECD countries.

Uncertainties related to available data and our knowledge of animal numbers, feed rations and feed use efficiency are also recognized by other authors as a major challenge, especially in regions where livestock is developing fast, such as East and Southeast Asia and sub-Saharan Africa. They were to some extent reduced by country level validation as well as by consolidation with other modelling initiatives.

The methodology used to estimate the area of grasslands convertible to crop lands relies on the ratio between actual and potential yield. A threshold of 25% was considered, but this could be seen as rather optimistic. Selecting a threshold of 10% (which correspond to considering only very marginal grasslands as convertible) would have increased the area of grassland suitable for crop production from 685 million ha, to 819 million ha. It should also be noted that this approach hides regional and local specificities and trends (e.g. conversion of rangelands into crop lands in agro-pastoral systems).

Changing consumption patterns due to health or environmental concerns were not included in the projections used in this paper. Future trends in demand will, however, significantly influence the way feed/food competition plays out in the future. Some authors have indeed argued that sustainable intensification and efficiency gains will not be sufficient to achieve food security, and that the world will need to reduce its consumption of animal products (see for example Smil, 2014; Naylor et al., 2005). By opting for a mid-term horizon, this paper avoided the complexity and uncertainty related to long-term modelling of consumer preference, or other trends such as climate change. Nevertheless, policies aimed at managing demand for animal products or pricing the environmental impact of feed production could also be considered as a way of reducing feed/food competition.

The assessment of long term trends, alternative scenarios to current production systems and policy options was however not in the scope of this paper. Carrying out this type of analysis would require a different modelling framework, adding the economic and dynamic dimensions to the static-biophysical model underpinning this study. For example, the impact of feed demand on international cereal trade and prices is not considered. Doing so would require to combine the biophysical approach, encompassing the diversity of feed rations, with a partial equilibrium model, such as the ones used by Galloway et al. (2007), or Rosengrant et al. (2012), and the efforts currently made between GLEAM and the Global Agriculture Perspectives System (FAO, 2015b) for the 2080 projections of demand in animal products.

The results presented here regarding feed rations, animal productivity and land use are expected to improve economic modelling and projections, often based on crude statistics and livestock production data. For example, the fact that livestock consumes about one third of global cereal production and about 100 million tonnes of agricultural co- and by-products is a major element in modelling the aggregated demand for crop products, but so is the almost 50% of the feed intake coming from grasslands. Animal intake of cereals affects the price elasticity of demand, given that elasticity is typically greater for animal consumption (able to reduce the short cycle subsectors (feedlots, pigs) when prices are high, and expand when they are low, absorbing surpluses).

## 6. Conclusion

Livestock consume about 6 billion tonnes DM as feed per year, of which 86% is made of materials that are currently not eaten by humans. In addition, soybean cakes, which production can be considered as main driver or land-use, represent 4% of the global livestock feed intake. Livestock play a key role in the bio-economy by converting forages, crop residues and agricultural by-products into high-value products and services. The production of global feed requires 2.5 billion ha of land, which is about half of the global agricultural area. Most of this area, 2 billion ha, is grassland, of which about 1.3 billion ha cannot be converted to cropland (rangeland). This means that 57% of the land used for feed production is not suitable for food production.

Contrary to commonly cited figures, our estimates show that to produce 1 kg of boneless meat requires 2.8 kg human-edible feed in ruminant systems and 3.2 in monogastric systems (layers excluded). These global figures, however, conceal a vast range of feed conversion ratios and feed qualities, between and within species and production systems. Very low efficiencies in terms of overall feed input can be found in extensive grazing ruminant systems due not only to low productivity but also to low nutritional density of feed. But when expressed in terms of human-edible protein, those systems are efficient converters of vegetal protein into animal protein, better than industrial monogastric systems that consume less feed but larger amounts of human-edible feed and soybean cakes per unit of product. These results allow to nuance the severity of the feed/food competition that is often put forward.

This paper demonstrates that modest yield improvements can significantly reduce projected further land expansion for feed production. It also illustrates the complementarity between improving yields at animal level and crop level, and thus the need to evaluate options that improve the efficiency of the entire food system, i.e. the efficiency of the complex web of processes and flows that link natural resources to consumers that require more animal-derived foods. Animal production, in its many forms, plays an integral role in the food system, making use of marginal lands, turning co-products into edible goods, contributing to crop productivity and turning edible crops into highly nutritious, protein-rich food. Quantifying the land and biomass resources engaged in livestock production and the food output they generate, but also improving our modelling capacity by including trends in consumer preferences, climate change impacts, and industrial processes to improve the human edibility of certain feed materials is arguably basic information needed as part of further research into the challenge of sustainably feeding 9.6 billion people by 2050.

## Acknowledgements

The authors thank the editors and 2 anonymous reviewers as well as Henning Steinfeld, Philippe Lecomte, Gareth Salmon and Harinder Makkar for useful comments.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gfs.2017.01.001.

## References

Alexandratos, N., Bruinsma, J., 2012. ,. World agriculture towards 2030/2050: the 2012 revision. ESA Work. Pap, 3.
Albers, G., 2013. Efficiency in Animal Protein Production, Available at ⟨http://www.hypor.com/~/media/Files/Hypor/Global%20Convention/14.-Gerard-Albers.-Efficiency-in-Animal-Protein-Production.pdf⟩
Bouwman, A.F., Van der Hoek, K.W., Eickhout, B., Soenario, I., 2005. Exploring changes in world ruminant production systems. Agric. Syst. 84 (2), 121–153.
Capper, J., Berger, L., Brashears, M., 2013. Animal feed vs. human food: challenges and opportunities in sustaining animal agriculture toward 2050. Counc. Agric. Sci. Technol. 53, 1–16.
Carrington, D., 2014. Giving up beef will reduce carbon footprint more than cars, says expert. The Guardian, available at ⟨http://www.theguardian.com/environment/2014/jul/21/giving-up-beef-reduce-carbon-footprint-more-than-cars⟩
de Haan, C., Schilhorn van Veen, T., Brandenburg, B., Gauthier, J., le Gall, F., Mearns, R., Simeon, M., 2001. Livestock development, implications for rural poverty, the environment, and Global food security. Dir. Dev. World Bank.
Dijkstra, J., France, J., Ellis, J.L., Strathe, A.B., Kebreab, E., Bannink, A., 2013. Production efficiency of ruminants: feed, nitrogen and methane. In Sustainable Animal Agriculture (pp. 10-25). In: Kebreab, E. (Ed.), Wallingford. CAB International, UK.
Eshel G., Shepon, A., Makov, T., Milo, R.,: 2014. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States In ⟨http://www.pnas.org/content/111/33/11996.full.pdf⟩
European Commission, 2012. Agri-environmental indicator — Gross nitrogen balance. Available at ⟨http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_gross_nitrogen_balance⟩
FAO, 2009. State of Food and Agriculture: livestock in the balance. FAO, Rome.
FAO, 2015a. State of Food Insecurity. FAO, Rome.
FAO, 2015b. Global Agriculture Perspectives System (GAPS), Version 1.0. Global Perspectives Studies Team. ESA. FAO, Rome.
FAOSTAT, 2016.
Flachowsky, G., 2010. Food production Through better animal Husbandry. E-Lett. Sci. 327 (5967), 812–818.
Galloway, J.N., Burke, M., Bradford, G.E., Naylor, R., Falcon, W., Chapagain, A.K., Steinfeld, H., 2007. International trade in meat: the tip of the pork chop. AMBIO: A J. Hum. Environ. 36 (8), 622–629.
Garnett, T., 2009. Livestock-related greenhouse gas emissions: impacts and options for policy makers. Environ. Sci. Policy 12 (4), 491–503.
Gebresenbet, G., Kaumbutho, P.G., 1997. Comparative analysis of the field performances of a reversible animal-drawn prototype and conventional mouldboard ploughs pulled by a single donkey. Soil Tillage Res. 40 (3–4), 169–183.
Gerber, P.J., Mottet, A., Opio, C.I., Teillard, F., 2015. Environmental impacts of beef production: review of challenges and perspectives for durability. Meat Sci. 109, 2–12.
Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities. FAO, Rome.
Godfray, H.C.J., Bedd ington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327 (5967), 812–818.
Henderson, B.B., Gerber, P.J., Hilinski, T.E., Falcucci, A., Ojima, D.S., Salvatore, M., Conant, R.T., 2015. Greenhouse gas mitigation potential of the world's grazing lands: modeling soil carbon and nitrogen fluxes of mitigation practices. Agric. Ecosyst. Environ. 207, 91–100.
Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Obersteiner, M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc. Natl. Acad. Sci. 110 (52), 20888–20893.
IIASA/FAO, 2012. ,. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy.
Imhoff, M.L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., Lawrence, W.T., 2004. Global patterns in human consumption of net primary production. Nature 429 (6994), 870–873.
Kebreab, E. (Ed.), 2013. Sustainable animal agriculture.. CABI.
Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.D., 2013. Global human appropriation of net primary production doubled in the 20th century. PNAS 110, 25.
Murphy, S.P., Allen, L.H., 2003. Nutritional importance of animal source foods. J. Nutr. 133 (11), 3932S–3935S.
Naylor, R., Steinfeld, H., Falcon, W., Galloway, J., Smil, V., Bradford, E., Mooney, H., 2005. Losing the links between livestock and land. Science 310 (5754), 1621–1622.
OECD/FAO, 2016. OECD-FAO Agricultural Outlook. OECD Publishing, Paris, 2016–2025.
Pelletier, N., Tyedmers, P., 2010. Forecasting potential global environmental costs of livestock production 2000–2050. Proc. Natl. Acad. Sci. 107 (43), 18371–18374.
Peters, C.J., Picardy, J.A., Darrouzet-Nardi, A., Griffin, T.S., 2014. Feed conversions, ration compositions, and land use efficiencies of major livestock products in US agricultural systems. Agric. Syst. 130, 35–43.
Randolph, T.F., Schelling, E., Grace, D., Nicholson, C.F., Leroy, J.L., Cole, D.C., Ruel, M., 2007. Role of livestock in human nutrition and health for poverty reduction in developing countries. J. Anim. Sci. 85 (11), 2788–2800.
Robinson, T.P., Wint, G.R.W., Conchedda, G., Van Boeckel, T.P., Ercoli, V., Palamara, E., et al., 2014. Mapping the global distribution of livestock. PLoS ONE 9 (5), e96084. http://dx.doi.org/10.1371/journal.pone.0096084.
Seré, C., Steinfeld, H., 1996. World livestock production systems: current status, issues and trends (FAO Animal Production and Health Paper 127). FAO, Rome.
Smil, V., 2014. Eating meat: constants and changes. Glob. Food Secur. 3 (2), 67–71.
Smith, J., 2015. The meat we eat, the lives we lift. livestock (like people) are different the world over. Economist, (Available at)⟨http://www.economistinsights.com/opinion/meat-we-eat-lives-we-lift⟩.
Soyatech, 2003. Whole Soybeans as Food Ingredient. Available at ⟨http://www.soyatech.com/pdf/wholesoyorder.pdf⟩
Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., Haan, C.D., 2006. Livestock's long shadow: environmental issues and options. FAO, Rome.
Elliot, L., 2012. The era of cheap food may be over, The Guardian 2 September 2012.
van Kernebeek, H.R.J., Oosting, S.J., Feskens, E.J.M., Gerber, P.J., De Boer, I.J.M., 2014. The effect of nutritional quality on comparing environmental impacts of human diets. J. Clean. Prod. 73, 88–99.
van Zanten, et al., 2015. The role of livestock in a sustainable diet: a land-use perspective. Animal 10 (4), 547–549.
Wilkinson, J.M., 2011. Re-defining efficiency of feed use by livestock. Animal 5 (07), 1014–1022.
Wirsenius, S., Azar, C., Berndes, G., 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agric. Syst. 103 (9), 621–638.