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**DECEMBER 2010**

**THE GREEN, BLUE AND GREY  
WATER FOOTPRINT OF FARM  
ANIMALS AND ANIMAL PRODUCTS**

**VOLUME 1: MAIN REPORT**

**VALUE OF WATER**

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## Summary

The projected increase in the production and consumption of animal products is likely to put further pressure on the globe's freshwater resources. The size and characteristics of the water footprint vary across animal types and production systems. The current study provides a comprehensive account of the global green, blue and grey water footprints of different sorts of farm animals and animal products, distinguishing between different production systems and considering the conditions in all countries of the world separately. The following animal categories were considered: beef cattle, dairy cattle, pig, sheep, goat, broiler chicken, layer chicken and horses.

The study shows that the water footprint of meat from beef cattle (15400 m<sup>3</sup>/ton as a global average) is much larger than the footprints of meat from sheep (10400 m<sup>3</sup>/ton), pig (6000 m<sup>3</sup>/ton), goat (5500 m<sup>3</sup>/ton) or chicken (4300 m<sup>3</sup>/ton). The global average water footprint of chicken egg is 3300 m<sup>3</sup>/ton, while the water footprint of cow milk amounts to 1000 m<sup>3</sup>/ton. Per ton of product, animal products generally have a larger water footprint than crop products. The same is true when we look at the water footprint per calorie. The average water footprint per calorie for beef is twenty times larger than for cereals and starchy roots. When we look at the water requirements for protein, we find that the water footprint per gram of protein for milk, eggs and chicken meat is about 1.5 times larger than for pulses. For beef, the water footprint per gram of protein is 6 times larger than for pulses. In the case of fat, we find that butter has a relatively small water footprint per gram of fat, even lower than for oil crops. All other animal products, however, have larger water footprints per gram of fat when compared to oil crops. The study shows that from a freshwater resource perspective, it is more efficient to obtain calories, protein and fat through crop products than animal products.

Global animal production requires about 2422 Gm<sup>3</sup> of water per year (87.2% green, 6.2% blue, 6.6% grey water). One third of this volume is for the beef cattle sector; another 19% for the dairy cattle sector. Most of the total volume of water (98%) refers to the water footprint of the feed for the animals. Drinking water for the animals, service water and feed mixing water account only for 1.1%, 0.8% and 0.03%, respectively.

The water footprints of animal products can be understood from three main factors: feed conversion efficiency of the animal, feed composition, and origin of the feed. The type of production system (grazing, mixed, industrial) is important because it influences all three factors. A first explanatory factor in the water footprints of animal products is the feed conversion efficiency. The more feed is required per unit of animal product, the more water is necessary (to produce the feed). The unfavourable feed conversion efficiency for beef cattle is largely responsible for the relatively large water footprint of beef. Sheep and goats have an unfavourable feed conversion efficiency as well, although better than cattle. A second factor is the feed composition, in particular the ratio of concentrates versus roughages and the percentage of valuable crop components versus crop residues in the concentrate. Chicken and pig have relatively large fractions of cereals and oil meal in their feed, which results in relatively large water footprints of their feed and abolishes the effect of the favourable feed conversion efficiencies. A third factor that influences the water footprint of an animal product is the origin of the feed. The water footprint of a specific animal product varies across countries due to differences in climate and agricultural practice in the regions from where the various feed components are obtained. Since sometimes a relatively large

fraction of the feed is imported while at other times feed is mostly obtained locally, not only the size but also the spatial dimension of the water footprint depends on the sourcing of the feed.

It is relevant to consider from which type of production system an animal product is obtained: from a grazing, mixed or industrial system. Animal products from industrial production systems generally have a smaller total water footprint per unit of product than products from grazing systems, with an exception for dairy products (where there is little difference). However, products from industrial systems always have a larger *blue* and *grey* water footprint per ton of product when compared to grazing systems, this time with an exception for chicken products. It is the lower *green* water footprint in industrial systems that explains the smaller total footprint. Given the fact that freshwater problems generally relate to blue water scarcity and water pollution and to a lesser extent to competition over green water, this means that grazing systems are preferable over industrial production systems from a water resources point of view. In the case of cattle, pigs, sheep and goats, the *total* water footprints per ton of product are larger for grazing systems because of the worse feed conversion efficiencies, but the fact that these systems depend more strongly on roughages (which are less irrigated and less fertilised than the feed crops contained in concentrate feed) makes that the blue and grey water footprints of products from grazing systems are smaller. This compensation through the feed composition does not occur for the case of chicken. The reason is that chicken strongly rely on concentrate feed in all production systems. Mixed production systems generally take a position in between industrial and grazing systems. Not accounted for in this study is that industrialized animal production often produces large amounts of animal waste that cannot be fully recycled in the nearby land. Such large amounts of waste produced in a concentrated place are known to pollute freshwater resources if not handled properly.

By focusing on freshwater appropriation, the study obviously excludes many other relevant issues in farm animal production, such as micro- and macro-cost of production, livelihood of smallholder farmers, animal welfare, public health and environmental issues other than freshwater.



## 1. Introduction

In the last few decades the world has seen a significant shift in food consumption patterns towards more animal products such as meat, milk and egg, mainly due to growing economies and rising individual incomes. In developing countries, in particular, consumption of meat, milk and dairy products has been growing the last few decades at 5-6 percent and 3.4-3.8 percent annually respectively (Bruinsma, 2003). The shift in consumption patterns coupled with high population growth and rapid urbanization in most developing countries is driving the total demand for animal products upward.

The global meat production has nearly doubled between 1980 and 2004, with the largest share of growth in developing countries (FAO, 2005). Related to the increased production there is a shift away from grazing systems. Although the traditional pastoral system plays a role, most of the increase in meat and milk production in the last three decades was achieved through production increase in the mixed and industrial production systems (Bouwman et al., 2005). The shift to more intensive production systems influences the composition of animal feed. Traditionally, animals have relied on locally available feed, such as grass, crop residues and wastes from human food. The more intensive production systems depend on concentrate feeds that are traded locally and internationally. In many countries, there is a tendency towards decreasing reliance on grazing and increasing dependence on concentrate feeds. Intensive animal production systems, in which animals are raised in confinement, currently account for 74 percent of the world's total poultry production, 40 percent of pig meat and more than two-thirds of egg production (Seré and Steinfeld, 1996). If this trend continues in the future, its implication will be far-reaching for both land and water resources requirements.

Animal production requires large volumes of water for feed production, drinking water and servicing animals. By far the largest water demand in animal production is the water needed to produce animal feed. Because of the increasing demand for animal products and the growing sector of industrial farming, the demand for feedstuffs grows as well, including cereals, starchy roots, fodder crops, oilseeds and oil meals. Such high demand for feed in turn causes a rising demand for water. Besides, intensification of animal production systems will lead to surface and ground water pollution, both from the use of fertilizers in feed crops production and improper storage and application of manures.

The global meat trade is projected to rise by more than 50 percent over the next 25 years (Bruinsma, 2003). Also international trade in feed is growing. As a result of the increasing global trade in feed crops and animal products and the growth of meat preservation over longer periods, many consumers have no longer any idea about the natural resource use and environmental impacts associated with the products they consume. Consumers of animal products are spatially disconnected from the processes necessary to produce the products (Naylor et al., 2005; Hoekstra, 2010). The concept of 'water footprint' provides an appropriate framework of analysis to find the link between the consumption of animal products and the use of the global water resources. The water footprint is defined as the total volume of freshwater that is used to produce the goods and services consumed by an individual or community (Hoekstra and Chapagain, 2008).

There are a few earlier publications on water use in animal production. The first and most comprehensive assessment of the water footprint of farm animals and animal products was carried out by Chapagain and Hoekstra (2003) and later updated by the same authors in their water footprint of nation's publication (Chapagain and Hoekstra, 2004). A study by FAO has quantified the global blue water use for feed production, animal drinking and servicing (Steinfeld et al., 2006). De Fraiture et al. (2007) have estimated the global water use for animal feed production, both green and blue but not distinguishing between the two. They considered water use for two lumped categories: feed crops and grazing. Zimmer and Renault (2003) made a rough estimation of the global water consumption for producing meat and other animal products, not showing details per country, animal category or product. Galloway et al. (2007) produced a study on the water consumption for chicken and pig for four countries: the USA, Japan, Brazil and the Netherlands. Peden et al. (2007) made an estimate of the global water consumption for producing the feed for farm animals. In addition to the studies mentioned there have been a few more specific studies for the Nile River Basin (Van Breugel et al., 2010) and for the USA (Renault and Wallender, 2000; Pimentel et al., 2004).

With the exception of Chapagain and Hoekstra (2003, 2004), none of the studies have estimated the water footprint of animal products by product and country at a global level. Although Chapagain and Hoekstra (2003, 2004) were able to estimate the water footprint of farm animals and animal products per country, they have taken a very crude assumption on the composition and amount of feed consumed by the different animals. Besides, the water footprints of feed crops were estimated based on national average climatic data. We have tried to improve the estimation of feed composition and feed amount per animal category and have used better estimates for the water footprints of feed crops.

The objective of the study is to assess the water footprint of farm animals and the various derived animal products for the period 1996-2005. We consider eight animal categories: beef and dairy cattle, pig, sheep, goat, broiler and layer chicken and horses. The main differences with Chapagain and Hoekstra (2003, 2004) are:

- We have estimated the amount of feed consumed per animal category, per production system and per country based on estimates of feed conversion efficiencies and statistics on the annual production of animal products. Chapagain and Hoekstra (2003, 2004) have taken rough assumptions on the quantities of feed consumed per animal category based on incidental data.
- We reckon with the relative occurrence of the three production systems (grazing, mixed and industrial) in each country, using the studies of Seré and Steinfeld (1996) and Wint and Robinson (2007). In Chapagain and Hoekstra (2003, 2004), for each country the dominant animal production system was selected, after which further calculations for this country were based on data for that specific production system.
- We have estimated the green, blue and grey water footprints of the feed crops using a spatially explicit crop water use model able to estimate actual crop water use (Mekonnen and Hoekstra, 2010a, 2010b). In the previous studies the potential rather than the actual crop water use was used. In addition, the estimate was based on country average climatic data which could lead to errors in large countries. Furthermore the earlier studies did not explicitly distinguish between the green and blue water footprint components and did not include the grey water footprint component at all.

## 2. Method and data

### 2.1 Method

We follow the water footprint definitions and methodology as set out in Hoekstra et al. (2009). The blue water footprint refers to consumption of blue water resources (surface and groundwater) along the supply chain of a product. ‘Consumption’ refers to loss of water from the available ground-surface water body in a catchment area. Losses occur when water evaporates, returns to another catchment area or the sea or is incorporated into a product. The green water footprint refers to consumption of green water resources (rainwater in so far as it does not become run-off). The grey water footprint refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards.

We consider eight farm animal categories: beef and dairy cattle, pig, sheep, goat, broiler and layer chicken and horses. When estimating total feed amounts and total water footprints per category, we include ‘buffaloes’ in the category of ‘beef cattle’ and ‘asses and mules’ in the category of ‘horses’.

The water footprint of a live animal consists of different components: the indirect water footprint of the feed and the direct water footprint related to the drinking water and service water consumed (Chapagain and Hoekstra, 2003, 2004). The water footprint of an animal is expressed as:

$$WF[a, c, s] = WF_{feed}[a, c, s] + WF_{drink}[a, c, s] + WF_{serv}[a, c, s] \quad (1)$$

where  $WF_{feed}[a, c, s]$ ,  $WF_{drink}[a, c, s]$  and  $WF_{serv}[a, c, s]$  represent the water footprint of an animal for animal category  $a$  in country  $c$  in production systems  $s$  related to feed, drinking water and service water consumption, respectively. Service water refers to the water used to clean the farmyard, wash the animal and carry out other services necessary to maintain the environment. The water footprint of an animal and its three components can be expressed in terms of  $m^3/yr/animal$ , or, when summed over the lifetime of the animal, in terms of  $m^3/animal$ . For beef cattle, pig, sheep, goat and broiler chicken – animals that provide their products after they have been slaughtered – it is most useful to look at the water footprint of the animal at the end of its lifetime, because it is this total that will be allocated to the various products (e.g. meat, leather). For dairy cattle and layer chicken, it is most straightforward to look at the water footprint of the animal per year (averaged over its lifetime), because one can easily relate this annual animal water footprint to its average annual production (milk, eggs).

The water footprint of an animal related to the feed consumed consists of two parts: the water footprint of the various feed ingredients and the water that is used to mix the feed:

$$WF_{feed}[a, c, s] = \frac{\sum_{p=1}^n (Feed[a, c, s, p] \times WF_{prod}^*[p]) + WF_{mixing}[a, c, s]}{Pop^*[a, c, s]} \quad (2)$$

$Feed[a,c,s,p]$  represents the annual amount of feed ingredient  $p$  consumed by animal category  $a$  in country  $c$  and production system  $s$  (ton/yr),  $WF_{prod}^*[p]$  the water footprint of feed ingredient  $p$  ( $m^3/ton$ ),  $WF_{mixing}[a,c,s]$  the volume of water consumed for mixing the feed for animal category  $a$  in country  $c$  and production system  $s$  ( $m^3/yr/animal$ ) and  $Pop^*[a,c,s]$  the number of slaughtered animals per year or the number of milk or egg producing animals in a year for animal category  $a$  in country  $c$  and production system  $s$ .

#### The water footprint of feed ingredients

The water footprints of the different crops, roughages and crop by-products ( $WF_{prod}^*[p]$ ,  $m^3/ton$ ) that are eaten by the various farm animals have been calculated following the methodology developed by Hoekstra and Chapagain (2008) and Hoekstra et al. (2009). The water footprints of feed crops were estimated using a crop water use model that estimates crop water footprints at a 5 by 5 arc minute spatial resolution globally (Mekonnen and Hoekstra, 2010a, 2010b). Grey water footprints were estimated by looking at leaching and runoff of nitrogen fertilisers only, following Mekonnen and Hoekstra (2010a,b). Since animal feed in a country originates from domestic production and imported products, for the calculation of the water footprint of animal feed in a country, we have taken a weighted average water footprint according to the relative volumes of domestic production and import:

$$WF_{prod}^*[p] = \frac{P[p] \times WF_{prod}[p] + \sum_{n_e} (T_i[n_e,p] \times WF_{prod}[n_e,p])}{P[p] + \sum_{n_e} T_i[n_e,p]} \quad (3)$$

in which  $P[p]$  is the production quantity of feed product  $p$  in a country (ton/yr),  $T_i[n_e,p]$  the imported quantity of feed product  $p$  from exporting nation  $n_e$  (ton/yr),  $WF_{prod}[p]$  the water footprint of feed product  $p$  when produced in the nation considered ( $m^3/ton$ ) and  $WF_{prod}[n_e,p]$  the water footprint of feed product  $p$  as in the exporting nation  $n_e$  ( $m^3/ton$ ). The water footprint of crop residues such as bran, straw, chaff and leaves and tops from sugar beet have already been accounted for in the main product, therefore their water footprint was set equal to zero.

#### Volume and composition of feed

The volume and composition of the feed consumed vary depending on the type of animal, the production system and the country. The amount of feed consumed is estimated following the approach of Hendy et al. (1995), in which the total annual feed consumption (including both concentrates and roughages) is calculated based on annual production of animal products and feed conversion efficiencies. Only for horses we have used the approach as in Chapagain and Hoekstra (2003), which means that we multiplied the estimated feed consumption per animal by the number of animals, thus arriving at an estimate of the total feed consumed by horses.

The steps followed to calculate the volumes and composition of feed are schematically shown in Figure 1. The total feed per production system for both ruminants and non-ruminants animals is calculated as follows:

$$Feed[a,c,s] = FCE[a,c,s] \times P[a,c,s] \quad (4)$$

where  $Feed[a,c,s]$  is the total amount of feed consumed by animal category  $a$  (ton/yr) in country  $c$  and production system  $s$ ,  $FCE[a,c,s]$  the feed conversion efficiency (kg dry mass of feed / kg of product) for animal category  $a$  in country  $c$  and production system  $s$ , and  $P[a,c,s]$  the total amount of product (meat, milk, or egg) produced by animal category  $a$  (ton/yr) in country  $c$  and production system  $s$ .

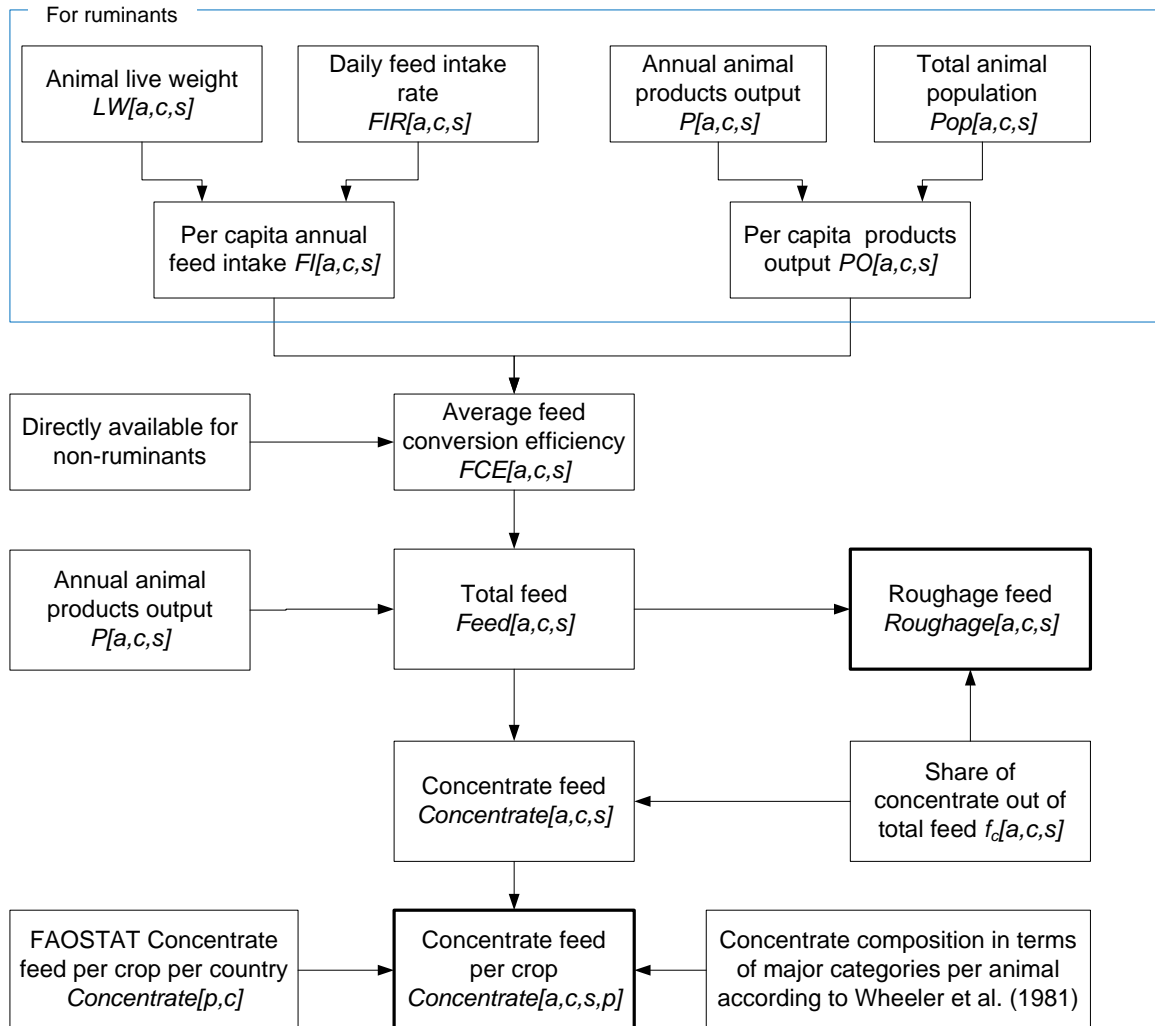


Figure 1. Steps in the calculation of feed amount per animal. For ruminants (beef cattle, dairy cattle, sheep and goat), feed conversion efficiencies are derived as indicated in the upper part of the scheme. For non-ruminants (pig, broiler and layer chicken), the feed conversion efficiencies are directly taken from the literature.

#### Estimating feed conversion efficiencies

Feed conversion efficiency is defined as the amount of feed consumed per unit of produced animal product (e.g. meat, milk, egg). Feed conversion efficiencies were estimated separately for each animal category (beef cattle, dairy cattle, sheep, goat, pig, broiler chicken and egg layer chicken), for each animal production system and per country. Although the term used may suggest precisely the opposite, animals that have a low ‘feed conversion efficiency’ are efficient users of feed. We use the term here as generally used in livestock studies. The feed conversion efficiencies ( $FCE$ , kg dry mass/kg product) for non-ruminants (pig and chicken) were adopted from Hendy et al. (1995). For ruminants (cattle, goat, sheep), feed conversion efficiencies were estimated through dividing feed intake per capita by annual production (of beef, milk, sheep and goat meat) per capita:

$$FCE[a, c, s] = \frac{FI[a, c, s]}{PO[a, c, s]} \quad (5)$$

where  $FI[a, c, s]$  is the feed intake per head by ruminant animal category  $a$  in country  $c$  and production system  $s$  (kg dry mass/yr/animal), and  $PO[a, c, s]$  the product output per head for ruminant animal category  $a$  in country  $c$  and production system  $s$  (kg product/yr/animal). The product output (beef, milk, sheep and goat meat) per animal for ruminants is calculated as:

$$PO[a, c, s] = \frac{P[a, c, s]}{Pop[a, c, s]} \quad (6)$$

in which  $P[a, c, s]$  is the total annual production of beef, milk, sheep meat or goat meat in country  $c$  in production system  $s$  (kg/yr) and  $Pop[a, c, s]$  the total population of beef cattle, dairy cattle, sheep or goat in that country and production system.

#### *Estimating the total annual production of animal products*

The annual production of animal products has been estimated as shown in Figure 2. The meat production ( $P_{meat}$ , ton/yr) per animal category  $a$  (beef cattle, pig, sheep and goat) in country  $c$  and production system  $s$  is estimated by multiplying the carcass yield per slaughtered animal by the annual number of animals slaughtered:

$$P_{meat}[a, c, s] = CY[a, c, s] \times SA[a, c, s] \quad (7)$$

The carcass yield ( $CY$ , kg/animal) for each animal category per production system was estimated by combining country average carcass yield data from FAO (2009) with data on animal live weight per production system per economic region (Hendy et al. 1995) and data on carcass weight as percentage of live weight (FAO, 2003). The obtained carcass yields were scaled such that the total meat production per animal category equals the value provided by FAO (2009). The number of slaughtered animals per production system ( $SA$ , number of animal/yr) was calculated by multiplying the total animal number by the animal off-take rate per production system:

$$SA[a, c, s] = Pop[a, c, s] \times OR[a, c, s] \quad (8)$$

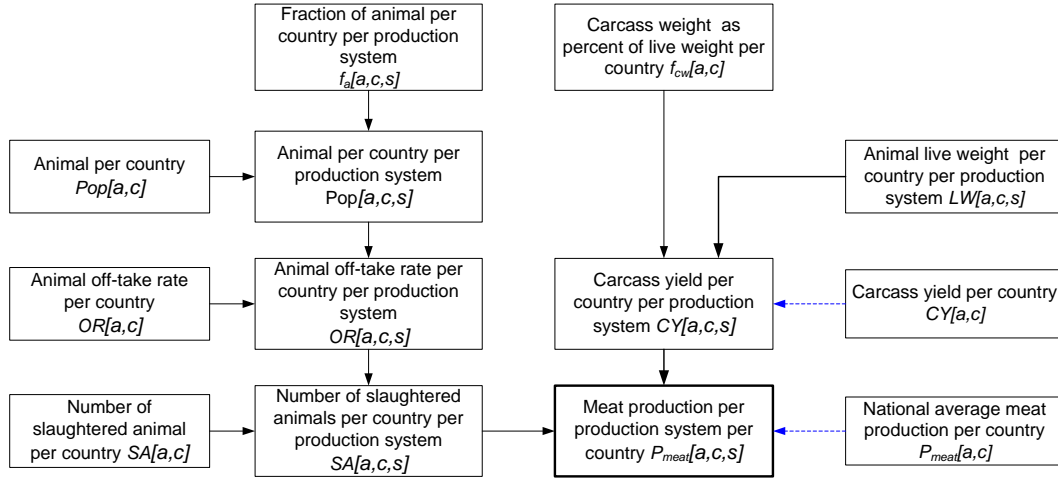
where  $Pop[a, c, s]$  is the population of animal category  $a$  in country  $c$  for production system  $s$  and  $OR[a, c, s]$  the off-take rate, which is the fraction of the animal population that is taken out in a given year for slaughter (dimensionless).

Milk and egg production per production system and country were calculated as:

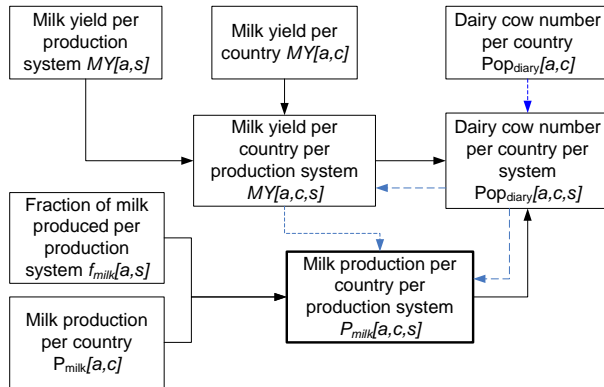
$$P_{milk}[a, c, s] = MY[a, c, s] \times DC[a, c, s] \quad (9)$$

$$P_{egg}[a, c, s] = f_{egg}[a, c, s] \times P_{egg}[a, c] \quad (10)$$

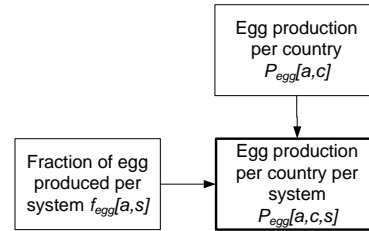
where  $P_{milk}[a,c,s]$  and  $P_{egg}[a,c,s]$  represent production of milk and egg in country  $c$  and production system  $s$  respectively (ton/yr),  $MY[a,c,s]$  milk yield per dairy cow in country  $c$  and production system  $s$  (ton/dairy cow),  $DC[a,c,s]$  the number of dairy cows in country  $c$  and production system  $s$ ,  $f_{egg}[a,c,s]$  the fraction of egg produced in country  $c$  and production system  $s$  and  $P_{egg}[a,c]$  the total amount of egg produced in country  $c$  (ton/yr).



(a) Meat production per production system and per country



(b) Milk production and yield per country per production system



(c) Egg production per country and per production system

Figure 2. Steps in the calculation of: (a) annual meat production (beef cattle, pig, sheep, goat, broiler chicken); (b) annual milk production (dairy cattle); and (c) annual egg production (layer chicken). Broken arrows indicate iteration and adjustment to fit to values of FAO (2009).

### Estimating the feed composition

Animal feeds are generally divided into ‘concentrates’ and ‘roughages’ (Box 2.1). The volume of concentrate feed has been estimated per animal category and per production system as:

$$Concentrate[a,c,s] = Feed[a,c,s] \times f_c[a,c,s] \quad (11)$$

where  $Concentrate[a,c,s]$  is the volume of concentrate feed consumed by animal category  $a$  in country  $c$  and production system  $s$  (ton/yr) and  $f_c[a,c,s]$  the fraction of concentrate in the total feed for animal category  $a$  in country  $c$  and production system  $s$ . For the latter variable, data have been obtained from Hendy et al. (1995) and Bouwman et al. (2005).

The composition of concentrate feeds varies across animal species and regions of the world. To our knowledge, there are no datasets with global coverage on the composition of feed for the different animals per country. Therefore, we have made a number of assumptions concerning the concentrate feed composition of the different animal species. According to Hendy et al. (1995), the diets of pig and poultry include, on average, 50-60% cereals, 10-20% oil meals and 15-25% 'other concentrates' (grain substitutes, milling by-products, non-conventional concentrates). Wheeler et al. (1981) provide the feed composition in terms of major crop categories for the different animal categories (Figure 3 and Figure 4). We have used these and other sources in combination with FAOSTAT country average concentrate feed values for the period 1996-2003 (FAO, 2009) to estimate the diet composition of the different animal species. In order to estimate the feed in terms of specific crops per animal, we first estimated the feed in terms of major crop categories following Wheeler et al. (1981). The feed in terms of major crop categories is further distributed to each crop proportional to the crop's share in its crops category as obtained from FAOSTAT (FAO, 2009). The roughage feed is divided into fodder, grass and crop residues using the data obtained from Bouwman et al. (2005).

*Box 2.1 Definition of feed components. Source: Hendy et al. (1995) and FAO(1983).*

Feeds are generally divided into 'concentrates' and 'roughages'.

- **Concentrates** are feeds which contain a high level of nutrients for a given weight of feed usually low in crude fibre content (less than 18% of dry matter content) and high in total digestible nutrients. Thus concentrates may be high in energy, as in the case of cereals and milling by-products or they may be high in protein, as are protein meals of either vegetable or animal origin. The concentrates considered in this study include all the feed material found in FAO (2009) and which are derived from crops. The concentrate feeds considered include cereals, roots and tubers, oil crops, oil meals, bran, molasses, pulses, sugar crops, fruits and vegetables.
- **Roughages** are feeds with low density of nutrients, with a crude fibre content over 18% of dry matter, include most fresh and dried forages and fodders. The main roughages are:
  - pastures: includes temporary and permanent pastures.
  - harvested roughages: include those which are sown and harvested annually for forage, fodder or silage. The principal types of harvest roughages include forage (green) cereals such as maize, oats and sweet sorghum; sugarcane, lucerne (alfalfa) and berseem (Egyptian clover); special high yielding grasses cultivated chiefly for silage (such as Thimoth grass); roots and tubers such as potatoes, beets, swedes, turnips; oilseeds such as winter rape; pulses such as field peas, beans, sweet lupins and vetches; vegetables such as pumpkins and cabbages. These feeds are sometimes processed for lower fibre content and bulk and are then usually classified as concentrate feeds (e.g. cassava chips and pellets, processed alfalfa, pea and bean meals).
  - other roughages: include a large variety of crop by-products such as straw and chaff from cereals and pulses; leaves and tops from sugar beet; fodder beets and vegetables; and other miscellaneous roughages such as acacia and ipil ipil (leucaena) leaves.

## 2.2 Data

A large amount of data has been collected from different sources. A major data source for animal stocks, numbers of animals slaughtered each year, annual production of animal products, and concentrate feed per country is FAOSTAT (FAO, 2009). Other important sources that have been used are: Seré and Steinfeld (1996), Hendy et al. (1995), Bouwman et al. (2005), Wint and Robinson (2007), Wheeler et al. (1981) and FAO (2003). Box 2.2 summarizes how specific data have been obtained from these different sources.



Box 2.2. Overview of data sources.

- **Animal production systems:** Seré and Steinfeld (1996) have developed a classification of animal production systems based on agro-ecology, the distinction between pastoral, mixed and landless systems and on the presence of irrigation or not. They distinguish eleven animal production systems grouped under three headings: grazing (extensive), mixed and industrial (intensive). In this study we use the schematization into these three production systems.
- **Feed conversion efficiencies:** For ruminants, the feed conversion efficiencies were estimated as explained in Section 2.1. For non-ruminants (pig, broiler and egg laying chicken), feed conversion efficiencies per animal category, per production system and per economic region were obtained from Hendy et al. (1995). For both ruminants and non-ruminants, the feed conversion efficiency data were scaled such that at the level of world regions they match the efficiencies as reported in Bouwman et al. (2005).
- **Annual production of animal products:** Data on the annual production of animal products (beef, pig meat, sheep meat, goat meat, chicken meat, milk and egg) per production system for different economic regions were obtained from Seré and Steinfeld (1996). Production data per product and country for the period 1996-2005 were obtained from FAOSTAT (FAO, 2009). The two data sources have been combined to derive production data per animal category, production system and per country for the period 1996-2005. We scaled the production data per production system such that at national level, the production aggregated over the different production systems equals the production as reported in FAO (2009) for the period 1996-2005.
- **Number of animals:** Seré and Steinfeld (1996) provide the total animal population for the different production systems for the year 1995 for a number of geographic regions in the world. Wint and Robinson (2007) provide the total animal population for the year 2005 for the different production systems for developing countries. We have combined the two sources to obtain number of animals per animal category, per production system and per country. We scaled the numbers such that at national level, the number of animals aggregated over the different production systems equal the numbers as reported in FAO (2009) for the period 1996-2005.
- **Number of slaughtered animals and animal off-take rates:** The annual number of slaughtered animals for beef cattle, pig, sheep, goat and broiler chicken per country have been taken from FAO (2009). The animal off-take rates at national level have been derived from the same source by dividing the annual number of slaughtered animals by the total population. The off-take rate for the grazing system was assumed to be 90% of the national average off-take rate for the animal category considered (Bouwman, et al., 2005). Per country, the off-take rate for the mixed and industrial production systems were scaled until the total number of slaughtered animals per animal category equalled the value provided by FAO (2009).
- **Animal live weight:** Hendy et al. (1995) provide live weight of ruminant animals (beef cattle, dairy cattle, sheep and goat) by production system and economic region. FAO (2003) give animal live weight for cattle, pig, sheep, goat and chicken. We combined these two sources, taking advantage of the fact that Hendy et al. (1995) specify data per production system (but not per country) and FAO (2003) provides data per country (but not per system).
- **Carcass weight as percentage of live weight:** FAO (2003) provides carcass weight as percentage of live weight for the different animal categories per country.
- **Ruminant animals daily feed intake rate:** Daily feed intake rate for ruminant animals (beef cattle, dairy cattle, sheep and goat) was obtained from Hendy et al. (1995).
- **Share of concentrate feed in total animal feed:** The contribution of concentrate feeds such as cereals, oil-meals, roots and other crop products in the total feed composition was obtained from Hendy et al. (1995) and Bouwman et al. (2005).
- **Composition of the concentrate feed:** The composition of concentrate feed per animal category was estimated following mainly Wheeler et al. (1981) (Figure 3-4). In addition, we used Steinfeld et al. (2006) for data on the relative composition of poultry and pig feed for major countries (Figure 5-6). The data available in Wheeler et al. (1981) and Steinfeld et al. (2006) are not sufficient to specify the feed composition at the level of specific crops or crop products. In order to come to that level of detail we use the Supply and Utilization Accounts of FAOSTAT (FAO, 2009), which provide the total concentrate feed utilization per country per crop and crop product.
- **Composition of the roughage feed:** We used Bouwman et al. (2005) to estimate the composition of the roughage feed (grass, fodder crops, crop residues).
- **Water use for drinking and animal servicing:** Data were obtained from Chapagain and Hoekstra (2003). See Appendix IV.
- **Water use for mixing feed:** Following Chapagain and Hoekstra (2003), the water use for feed mixing is assumed to be 50% of total concentrate feed intake (or 0.5 litre per kg of concentrate feed intake).

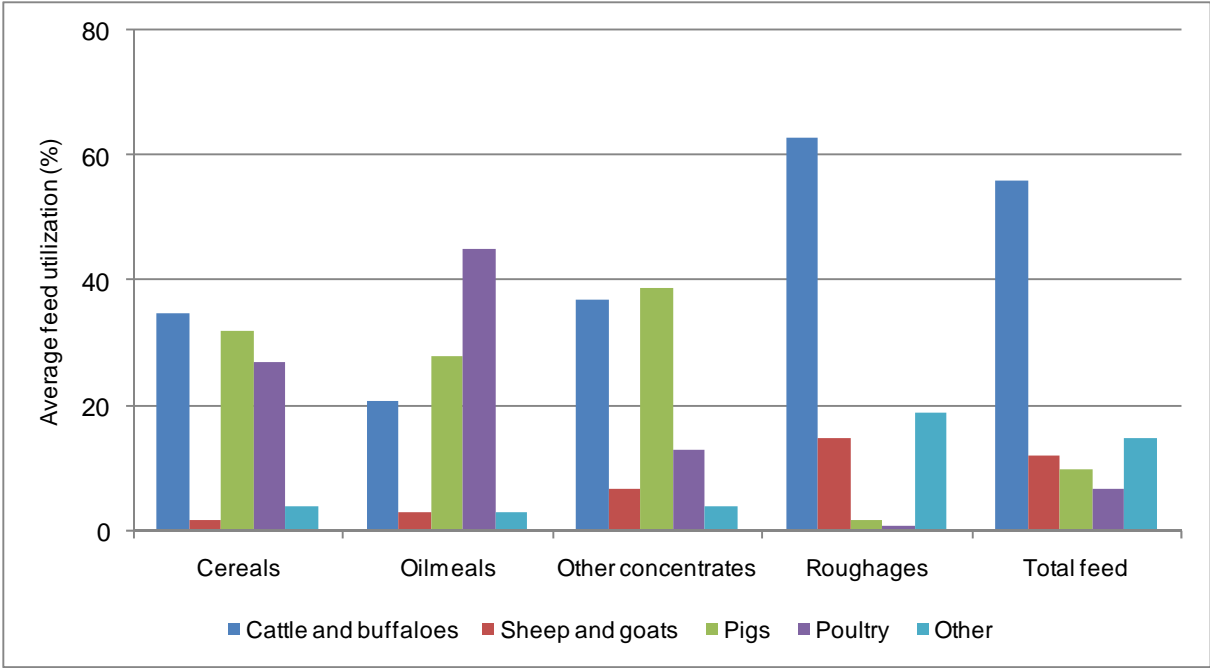


Figure 3. World average utilization of feeds by different animal species in metabolisable energy equivalents Source: Wheeler et al. (1981).

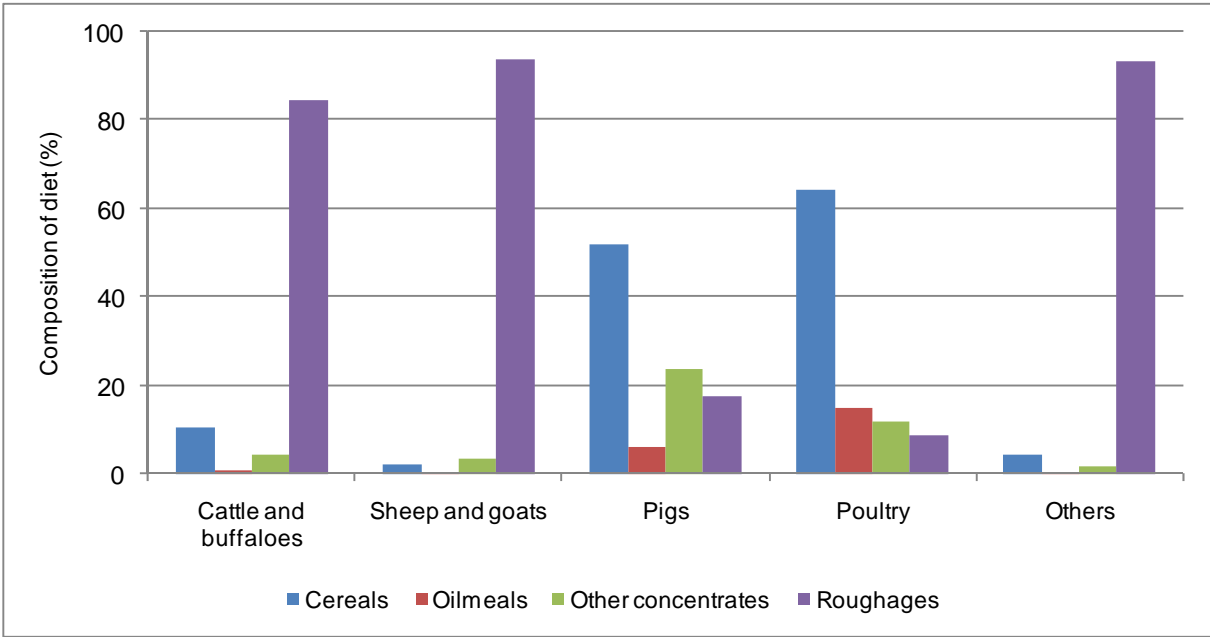


Figure 4. Aggregate world composition of diets for different species of animal in metabolisable energy equivalents Source: Wheeler et al. (1981).

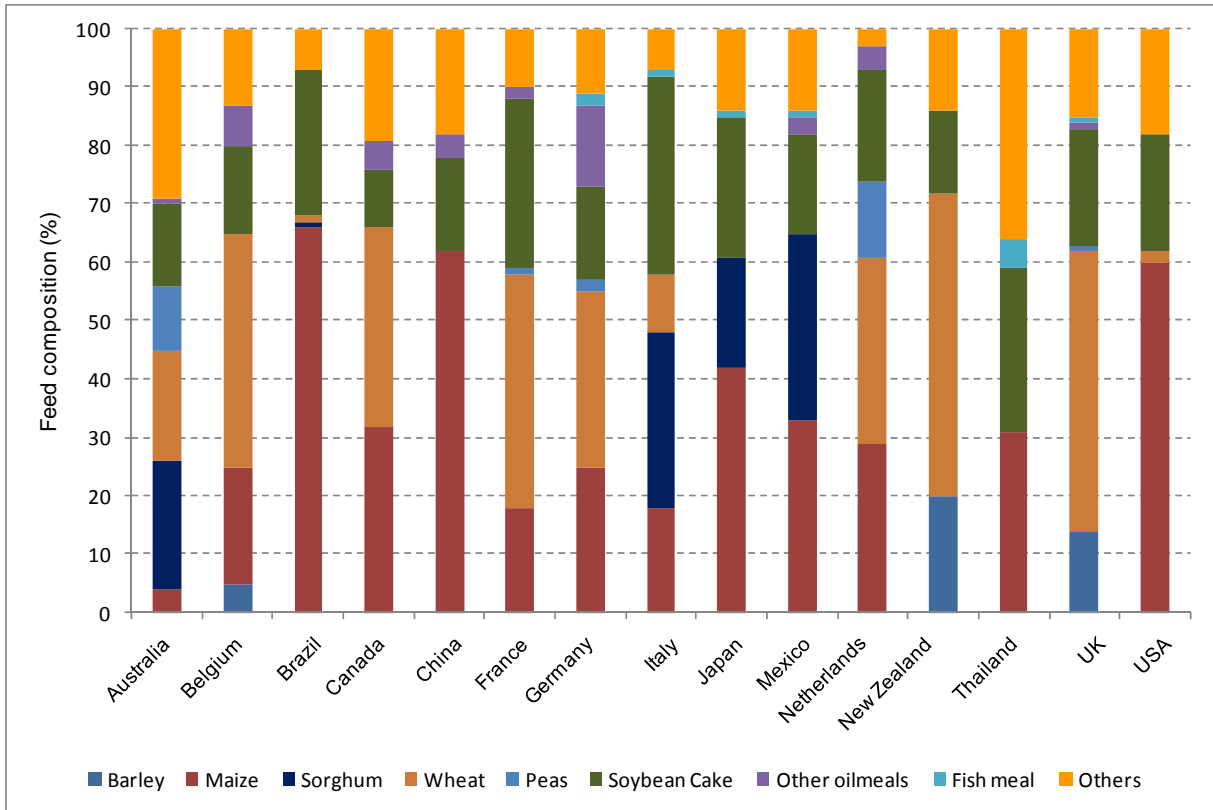


Figure 5. Relative composition of poultry feed basket in selected countries (by weight). Source: Steinfeld et al. (2006).

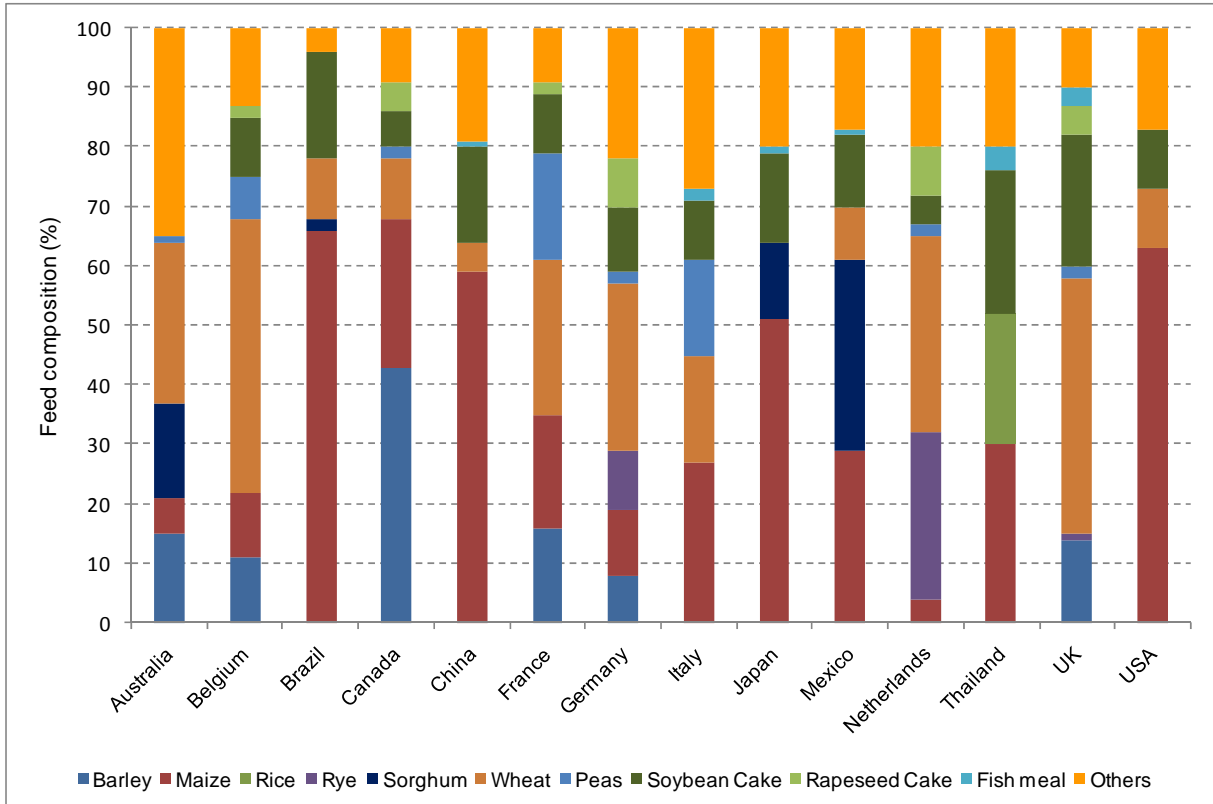


Figure 6. Relative composition of pig feed basket in selected countries (by weight). Source: Steinfeld et al. (2006).



### 3. Results

#### 3.1 Quantity and composition of animal feed

Table 1 provides global average feed conversion efficiencies for different animal categories and production systems. Region-specific feed conversion efficiencies are presented in Appendix I. Ruminants (cattle, sheep, goat) are less efficient in converting feed into meat than non-ruminants (pig, chicken), amongst other due to the lower quality of feed they consume. Particularly meat production from cattle costs a lot of feed per unit of product obtained. Although ruminants need more feed, their feed largely consists of forage and other materials that humans cannot eat, while non-ruminants consume large amounts of concentrate feed that could be used for human consumption. Non-ruminants thus most obviously compete with humans for food, but in an indirect way ruminants also compete for food with humans. In some cases the roughages eaten by ruminants are produced with land and water resources that cannot alternatively be allocated to crop production for human consumption (e.g. in the case of grazing in dry or wetlands), but often the land and water resources used for roughages supply can alternatively be used for crop growth for human consumption, so that ruminants compete with humans for food also through consumption of roughages.

*Table 1. Global average feed conversion efficiency per animal category and production system.*

| Animal category | Feed conversion efficiency (kg dry mass feed/kg output) |       |            |         |
|-----------------|---|-------|------------|---------|
|                 | Grazing   | Mixed | Industrial | Overall |
| Beef cattle     | 70.1  | 51.8  | 19.2       | 46.9    |
| Dairy cattle    | 3.5   | 1.6   | 1.1        | 1.9     |
| Broiler chicken | 9.0   | 4.9   | 2.8        | 4.2     |
| Layer chicken   | 9.3   | 4.4   | 2.3        | 3.1     |
| Pig             | 11.3  | 6.5   | 3.9        | 5.8     |
| Sheep and goat  | 49.6  | 25.8  | 13.3       | 30.2    |

Non-ruminants are responsible for 60% of the global consumption of concentrate feeds; ruminants account for 40%. Figure 7 shows the consumption of different concentrates by different animal categories. Chickens take the largest share in total concentrate feed consumption (30%). Three fifth of the concentrate feed consumption by chicken in the world is for broiler chicken and two fifth for layer chicken. Pig meat production takes nearly the same share (29%) in global concentrate feed consumption, while dairy cattle are responsible for 25% and beef cattle 14%. Our estimated shares of different animal categories in the total concentrate feed consumption is very close to the estimates made by Hendy et al. (1995).

Annual concentrate feed consumption averaged over the period 1996-2005 expressed in commodity fresh weight amounted to 1195 million tons per year. This value is very close to the feed data provided by FAO (2009) for the period 1996-2003 (1229 million ton/yr). The feed data analysed and presented here focus on commodities derived from crop production. Figure 8 presents a summary of the global total feed utilization of cereals, oil meals and cakes, roots and tubers, bran and others. Cereals make up the largest percentage of the total concentrate feed use (57%), followed by oil meals (15%), roots (11%) and brans (10%).

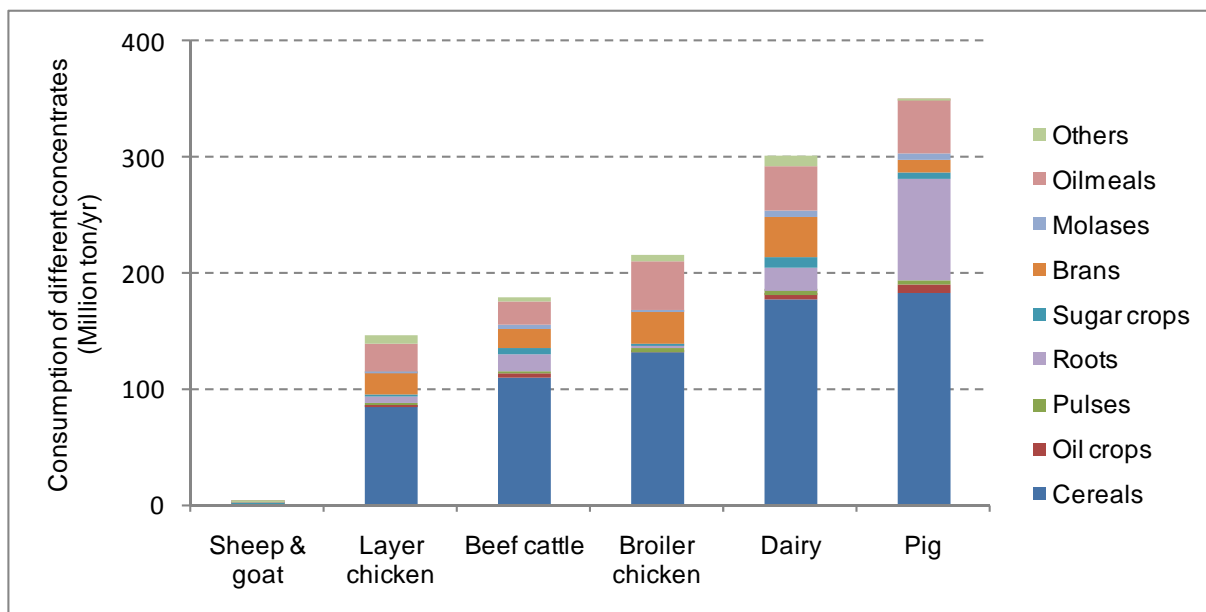


Figure 7. Consumption of different concentrates per animal category.

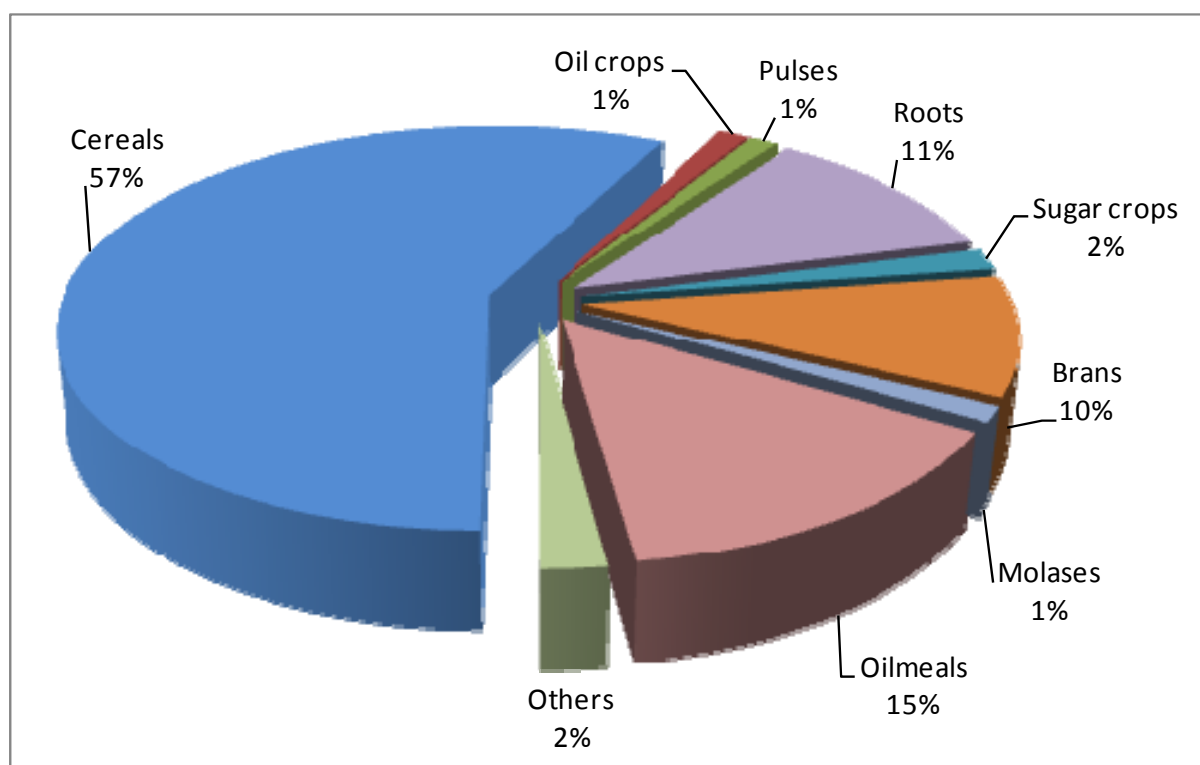


Figure 8. Contribution of different crops (on fresh weight basis) toward global total concentrate feed utilization. Period 1996-2005.

The estimated global amount of feed consumption per animal category and world region is presented in Appendix II. Feed consumption per production system is shown in Appendix III. The total feed consumption over the period 1996-2005 was 4996 million ton feed in dry matter per year, on average. Roughages account for the largest share out of this total, accounting for 80%, and feeds derived from crop production account for the remaining 20%. Considering only plant-based feed materials, our global estimate of total feed in dry matter

(4996 Mton dry mass/yr) is about 6% lower than the estimate of Wirsenius (2000) (5300 Mton dry mass/yr) and 8% more than the estimate of Bouwman et al. (2005) for 1995 (4637 Mton dry mass/yr). Our estimate of global utilization of roughages (4010 Mton dry mass/yr), which includes pasture, forages, straws, sugar crops tops and leaves, oil crops stalks and husks is 15% lower than the estimate of Wirsenius (2000) (4740 Mton dry mass/yr) and 5% larger than the estimate of Bouwman et al. (2005) for 1995 (3832 Mton dry mass/yr).

### *3.2 The water footprint of animal feed*

The water footprint per ton of feed differs among crops and across countries. Since the most significant part of the animal water footprint comes from the feed they consume, the water footprint per unit of feed is an important factor in the determination of the water footprint of animals and their associated derived products. Table 2 shows the average water footprint of selected feed ingredients for selected countries. Crop residues and by-products such as bran, straw, chaff and leaves and tops from sugar beet have a water footprint of about zero, because the water footprint of crop growing is mainly attributed to the main crop products, not the low-value residues or by-products. As a result they provide an opportunity to reduce the water footprint of animal production. Huge reduction in the water footprint of animals can also be obtained by using crops with a relatively low water footprint per ton such as sugar beet. Therefore, careful selection of feeds that meet the nutrient requirement of the animals and at the same time have a smaller water footprint per ton could significantly reduce the indirect use of freshwater resources associated with animal production.

### *3.3 The water footprint of live animals at the end of their lifetime and animal products per ton*

Table 3 shows, for each animal category, the average water footprint of an animal at the end of its life time and the annual water footprint of an animal. Dairy cows have the largest annual water footprint (2056 m<sup>3</sup>/yr/animal), which is more than the average human being. Broiler chicken have the smallest footprint (26 m<sup>3</sup>/yr/animal).

Table 4 presents the green, blue and grey water footprints of some selected animal products per production system for selected countries. Appendix V presents the full result of our analysis: green, blue and grey water footprints of all farm animals and animal products considered, per production system and per country. The water footprints of animals and animal products vary greatly across countries and production systems. When we look at global averages, however, we see that the water footprint of meat increases from chicken meat (4300 m<sup>3</sup>/ton), goat meat (5500 m<sup>3</sup>/ton), pig meat (6000 m<sup>3</sup>/ton), sheep meat (10400 m<sup>3</sup>/ton) to beef (15400 m<sup>3</sup>/ton). The differences can be partly explained from the different feed conversion efficiencies of the animals. Beef production, for example, requires eight times more feed (in dry matter) per kilogram of meat compared to producing pig meat, and eleven times if compared to the case of chicken meat. This is not the only factor, however, that can explain the differences. Another important factor is the feed composition. Particularly the fraction of concentrate feed in the total feed is important, because concentrate feed generally has a larger water footprint than roughages. Chicken, which are efficient from a total feed point of view, are no longer that efficient when we look at the fraction of concentrates in their feed. This fraction is 73% for broiler chicken (global average), while it is only 5% for beef cattle.

Table 2. Average water footprint of selected feed components for selected countries (m<sup>3</sup>/ton) (1996-2005).

| Feed             | Water footprint component | Australia | Brazil | China | Egypt | Germany | India | Mexico | USA  | World Average |
|------------------|---------------------------|-----------|--------|-------|-------|---------|-------|--------|------|---------------|
| Wheat            | Green                     | 1994      | 1850   | 839   | 784   | 608     | 643   | 1021   | 1842 | 1277          |
|                  | Blue                      | 17        | 9      | 455   | 590   |         | 1162  | 318    | 88   | 342           |
|                  | Grey                      | 102       | 129    | 308   | 316   | 178     | 294   | 203    | 227  | 207           |
| Barley           | Green                     | 1638      | 1411   | 847   | 666   | 499     | 1247  | 941    | 908  | 1213          |
|                  | Blue                      |           | 7      | 20    | 1591  |         | 780   | 376    | 204  | 79            |
|                  | Grey                      | 155       | 139    | 145   | 861   | 194     | 96    | 120    | 145  | 131           |
| Maize            | Green                     | 718       | 1619   | 791   | 311   | 440     | 2225  | 1490   | 523  | 947           |
|                  | Blue                      | 521       | 1      | 74    | 713   | 20      | 103   | 62     | 63   | 81            |
|                  | Grey                      | 135       | 124    | 295   | 364   | 118     | 195   | 308    | 176  | 194           |
| Millet           | Green                     | 2954      | 3344   | 1600  | 11982 | 2509    | 3719  | 2953   | 2990 | 4306          |
|                  | Blue                      |           | 164    | 40    | 26    | 84      | 76    | 59     | 61   | 57            |
|                  | Grey                      | 228       | 141    | 222   | 79    | 128     | 233   | 302    | 309  | 115           |
| Cassava          | Green                     | 444       | 433    | 357   | 422   | 394     | 258   | 529    | 471  | 550           |
|                  | Blue                      |           | 1      |       |       |         |       |        |      |               |
|                  | Grey                      | 32        | 17     | 56    | 31    | 29      | 24    | 22     | 22   | 13            |
| Sugar beet       | Green                     | 116       | 39     | 147   | 14    | 60      | 63    | 49     | 67   | 82            |
|                  | Blue                      | 3         | 59     |       | 164   | 3       |       | 26     | 37   | 26            |
|                  | Grey                      | 63        | 12     | 82    | 50    | 21      | 29    | 14     | 20   | 25            |
| Soybeans         | Green                     | 1714      | 2186   | 2231  | 1869  | 1533    | 3322  | 1629   | 1562 | 2037          |
|                  | Blue                      | 65        | 1      | 129   | 122   | 23      | 18    | 98     | 92   | 70            |
|                  | Grey                      | 10        | 15     | 106   | 43    | 11      | 92    | 10     | 10   | 37            |
| Rapeseed         | Green                     | 2095      | 2771   | 1483  | 1556  | 1155    | 1646  | 2567   | 2743 | 1703          |
|                  | Blue                      |           | 2      | 7     | 1213  | 1       | 1467  | 4      | 3    | 231           |
|                  | Grey                      | 420       | 98     | 466   | 197   | 259     | 235   | 341    | 360  | 336           |
| Sesame seed Cake | Green                     | 1422      | 1813   | 1851  | 1550  | 1272    | 2756  | 1352   | 1296 | 1690          |
|                  | Blue                      | 54        | 1      | 107   | 101   | 19      | 15    | 81     | 76   | 58            |
|                  | Grey                      | 8         | 12     | 88    | 35    | 9       | 76    | 8      | 8    | 31            |
| Cottonseed Cake  | Green                     | 254       | 648    | 328   | 154   | 245     | 1170  | 425    | 388  | 471           |
|                  | Blue                      | 276       | 52     | 111   | 670   | 178     | 341   | 195    | 169  | 270           |
|                  | Grey                      | 53        | 81     | 114   | 103   | 53      | 172   | 48     | 68   | 91            |
| Fodder crops     | Green                     | 254       | 158    | 2461  | 232   | 131     | 412   | 117    | 244  | 207           |
|                  | Blue                      | 204       | 148    |       |       |         |       | 33     | 44   | 27            |
|                  | Grey                      | 15        | 7      | 105   | 285   | 30      | 31    | 11     | 35   | 20            |
| Pasture          | Green                     | 762       | 307    | 225   | 225   | 131     | 407   | 174    | 372  | 315           |
|                  | Blue                      |           |        |       |       |         |       |        |      |               |
|                  | Grey                      |           |        |       |       |         |       |        |      |               |

Source: data for feed crops based on Mekonnen and Hoekstra (2010b); data for pasture from this study. The water footprints shown in this table refer the weighted average of domestically produced and imported feeds.



Table 3. Average annual water footprint of one animal, per animal category (1996-2005).

| Animal category | Water footprint of live animal at end of life time (m <sup>3</sup> /ton) | Average animal weight at end of life time (kg) | Average water footprint at end of life time (m <sup>3</sup> /animal) | Average life time (yr) | Average annual water footprint of one animal (m <sup>3</sup> /yr/animal) |
|-----------------|--|--|--|------------------------|--|
| Dairy cattle    |  |  | 20558  | 10                     | 2056   |
| Horse           | 40612  | 473  | 19189  | 12                     | 1599   |
| Beef cattle     | 7477   | 253  | 1889   | 3.0                    | 630  |
| Pig             | 3831   | 102  | 390  | 0.75                   | 520  |
| Sheep           | 4519   | 31.3   | 141  | 2.1                    | 68   |
| Layer chicken   |  |  | 47   | 1.4                    | 33   |
| Goat            | 3079   | 24.6   | 76   | 2.3                    | 32   |
| Broiler chicken | 3364   | 1.90   | 6  | 0.25                   | 26   |

#### *Total water footprint per ton of product*

For all farm animal products, except dairy products, the total water footprint per unit of product declines from the grazing to the mixed production system and then again from the mixed to the industrial production system. The reason is that, when moving from grazing to industrial production systems, feed conversion efficiencies become better. Per unit of product, about three to four times more feed is required for grazing systems when compared to industrial systems (see Table 1). More feed implies that more water is needed to produce the feed. However, the fact that feed conversion efficiencies in grazing and industrial production systems differ by a factor 3 to 4 does not mean that the water footprints of animal products are 3 to 4 times larger when derived from a grazing instead of an industrial system. This is because the feed composition of animals raised in grazing systems is generally more favourable from a water resources point of view. For all animal categories, the fraction of concentrate feed in the total feed is larger for industrial systems if compared to mixed production systems and larger for mixed systems if compared to grazing systems. The water footprint per kg of concentrate feed is generally larger than for roughages, so that this works to the disadvantage of the total water footprint of animals raised in industrial systems and to the advantage of the total water footprint of animals raised in grazing systems. This effect, however, does not fully compensate for the unfavourable feed conversion efficiencies in grazing systems. An exception is in dairy farming, where the total water footprint per unit of product is comparable in all three production systems. For dairy products, the water footprint happens to be smallest when they are derived from a mixed system and a bit larger but comparable when obtained from a grazing or industrial system.

#### *Blue and grey water footprints per ton of product*

All the above is about comparing the *total* water footprints of animal products. The picture changes when we focus on the *blue* and *grey* water footprint components. With the exception of chicken products, blue and grey water footprints always increase from grazing to industrial production systems. Figure 9 illustrates this by showing the blue water footprint of a number of animal products across the three production systems. For the grey water footprint similar pictures can be obtained. The larger blue and grey water footprints for products obtained from industrial production systems are caused by the fact that concentrate feed takes a larger share in the total feed in industrial systems when compared to grazing systems. For beef cattle in grazing systems, the

global average share of concentrate feed in total feed is 2%, while in industrial systems it is 21%. Mixed systems are generally somewhere in between. Although the feed crops that are contained in the concentrate feed are often to a great extent based on green water, there is a blue water footprint component as well, and the larger the consumption of feed crops compared to roughages, the larger the total amount of blue water consumed. This explains the larger blue water footprint per ton of product in industrial production systems for beef, milk, cheese, and pig, sheep and goat meat. The application and leaching of fertilizers and other agro-chemicals in feed crop production results in the fact that the grey water footprint of animal products from industrial systems, where the dependence on feed crops is greatest, is larger than for grazing systems. Given the fact that freshwater problems generally relate to blue water scarcity and water pollution and to a lesser extent to competition over green water, this means that – from a water resources point of view – grazing systems are preferable over industrial production systems for cattle, pig, sheep and goat.

In the case of chicken products (chicken meat and egg), the industrial production system has, on average, a smaller blue and grey water footprint per ton of product compared to the other two production systems. The reason is that chicken strongly rely on concentrate feed in all production systems, intensive or extensive. Broiler chicken in extensive systems have a share of concentrate feed in total feed of 63%, while this is 81% in intensive industrial systems. There is still a difference, but the differences in feed composition for both broiler and layer chicken is less outspoken if compared to the other animal categories. As a result, the relatively unfavourable feed conversion efficiency in extensive systems is not compensated by a more favourable composition of the feed as is the case in the other animal categories.

#### *Country differences*

In general terms, one can say that the type of production system is highly relevant for the size, composition and geographic spread of the water footprint of an animal product, because the type of production system determines feed conversion efficiency, feed composition and origin of feed. Similarly we observe that the country of production influences the water footprint of animal products in general terms as well. The Netherlands, for example, shows lower total water footprints for most animal products if compared to the USA. The USA, in turn, generally shows lower total water footprints for animal products than India. These crude general differences between countries are related to existing country differences in feed conversion efficiencies, but also to the fact that water footprints of feed crops vary across countries as a function of differences in climate and agricultural practice.

#### *Water footprint components - example for beef*

For all animal products, the water footprint related to the animal feed takes by far the largest share in the total water footprint. Further one can say that the green water footprint is always much larger than the blue and grey water footprints. As an example, Table 5 shows in detail the components of the water footprint of producing a kilogram of beef. The water footprint is dominantly green water (94%) and the largest share comes from the feed the cattle consume (99%). Drinking and service water contribute only 1% toward the total water footprint, but 30% to the blue water footprint. The major fraction (83%) of the water footprint of a beef cow is attributed to the derived beef, but smaller fractions go to the other products: offal, leather and semen.

Table 4. The green, blue and grey water footprint of selected animal products for selected countries (m<sup>3</sup>/ton).

| Animal products  | Farming system   | Australia |      |      | Brazil |      |      | China |      |      | India |      |      | Netherlands |      |      | Russia |      |      | USA   |      |      | Global average |      |      |
|------------------|------------------|-----------|------|------|--------|------|------|-------|------|------|-------|------|------|-------------|------|------|--------|------|------|-------|------|------|----------------|------|------|
|                  |                  | Green     | Blue | Grey | Green  | Blue | Grey | Green | Blue | Grey | Green | Blue | Grey | Green       | Blue | Grey | Green  | Blue | Grey | Green | Blue | Grey | Green          | Blue | Grey |
| Beef             | Grazing          | 18056     | 745  | 55   | 23729  | 150  | 16   | 16140 | 0    | 0    | 25913 | 0    | 0    |             |      |      | 15182  | 411  | 200  | 19102 | 525  | 590  | 21121          | 465  | 243  |
|                  | Mixed            | 14455     | 623  | 61   | 20604  | 187  | 61   | 13227 | 339  | 103  | 16192 | 533  | 144  | 10319       | 761  | 664  | 11615  | 451  | 204  | 12726 | 546  | 768  | 14803          | 508  | 401  |
|                  | Industrial       | 4730      | 304  | 96   | 8421   | 147  | 244  | 10922 | 933  | 1234 | 12412 | 1471 | 866  | 3934        | 349  | 225  | 23591  | 1002 | 871  | 2949  | 356  | 551  | 8849           | 683  | 712  |
|                  | Weighted average | 14507     | 613  | 62   | 19228  | 178  | 82   | 12795 | 495  | 398  | 15537 | 722  | 288  | 5684        | 484  | 345  | 16264  | 585  | 372  | 12933 | 525  | 733  | 14414          | 550  | 451  |
| Sheep meat       | Grazing          | 13236     | 438  | 9    | 19440  | 372  | 1    | 9606  | 0    | 0    | 11441 | 0    | 0    |             |      |      | 14236  | 351  | 3    | 11910 | 312  | 18   | 15870          | 421  | 20   |
|                  | Mixed            | 6554      | 427  | 22   | 10649  | 421  | 9    | 5337  | 454  | 14   | 7528  | 582  | 316  | 8248        | 422  | 35   | 7176   | 379  | 7    | 9842  | 318  | 74   | 7784           | 484  | 67   |
|                  | Industrial       |           |      |      | 4747   | 445  | 12   | 2366  | 451  | 22   | 4523  | 593  | 484  |             |      |      | 3044   | 469  | 9    | 0     | 0    | 0    | 4607           | 800  | 216  |
|                  | Weighted average | 10151     | 434  | 15   | 11772  | 421  | 7    | 5347  | 452  | 14   | 7416  | 582  | 314  | 8248        | 422  | 35   | 9284   | 395  | 5    | 10948 | 315  | 44   | 9813           | 522  | 76   |
| Goat meat        | Grazing          | 4809      | 245  | 0    | 15860  | 328  | 0    | 5073  | 0    | 0    | 8081  | 0    | 0    |             |      |      | 7086   | 219  | 0    |       |      |      | 9277           | 285  | 0    |
|                  | Mixed            | 2435      | 233  | 0    | 8745   | 349  | 0    | 2765  | 283  | 0    | 4544  | 381  | 9    | 2443        | 453  | 4    | 3615   | 247  | 0    |       |      |      | 4691           | 313  | 4    |
|                  | Industrial       |           |      |      | 3754   | 406  | 0    | 1187  | 437  | 0    | 2046  | 436  | 30   |             |      |      | 1546   | 322  | 1    |       |      |      | 2431           | 413  | 18   |
|                  | Weighted average | 3733      | 240  | 0    | 8144   | 372  | 0    | 2958  | 312  | 0    | 4194  | 393  | 13   | 2443        | 454  | 4    | 4432   | 266  | 0    |       |      |      | 5185           | 330  | 6    |
| Pig meat         | Grazing          | 4299      | 3721 | 247  | 5482   | 1689 | 318  | 11134 | 205  | 738  | 3732  | 391  | 325  | 4048        | 479  | 587  | 7176   | 357  | 282  | 5118  | 870  | 890  | 7660           | 431  | 632  |
|                  | Mixed            | 2056      | 1909 | 118  | 5109   | 828  | 316  | 5401  | 356  | 542  | 4068  | 893  | 390  | 3653        | 306  | 451  | 7212   | 472  | 289  | 4953  | 743  | 916  | 5210           | 435  | 582  |
|                  | Industrial       | 7908      | 651  | 656  | 8184   | 215  | 525  | 3477  | 538  | 925  | 9236  | 2014 | 1021 | 3776        | 236  | 427  | 5165   | 397  | 207  | 3404  | 563  | 634  | 4050           | 487  | 687  |
|                  | Weighted average | 5284      | 1226 | 414  | 6080   | 749  | 379  | 5050  | 405  | 648  | 5415  | 1191 | 554  | 3723        | 268  | 438  | 6937   | 429  | 276  | 4102  | 645  | 761  | 4907           | 459  | 622  |
| Chicken meat     | Grazing          | 4862      | 276  | 336  | 6363   | 35   | 364  | 4695  | 448  | 1414 | 11993 | 1536 | 1369 | 2535        | 113  | 271  | 8854   | 334  | 321  | 2836  | 294  | 497  | 7919           | 734  | 718  |
|                  | Mixed            | 2893      | 173  | 200  | 4073   | 32   | 233  | 3005  | 297  | 905  | 7676  | 995  | 876  | 1509        | 76   | 161  | 5259   | 210  | 190  | 1688  | 183  | 296  | 4065           | 348  | 574  |
|                  | Industrial       | 2968      | 176  | 205  | 3723   | 24   | 213  | 1940  | 195  | 584  | 3787  | 496  | 432  | 1548        | 77   | 165  | 2976   | 124  | 108  | 1731  | 187  | 303  | 2337           | 210  | 325  |
|                  | Weighted average | 2962      | 176  | 205  | 4204   | 30   | 240  | 2836  | 281  | 854  | 6726  | 873  | 768  | 1545        | 77   | 165  | 6036   | 235  | 219  | 1728  | 187  | 303  | 3545           | 313  | 467  |
| Egg              | Grazing          | 2243      | 146  | 173  | 432    | 24   | 25   | 3952  | 375  | 1189 | 10604 | 1360 | 1176 | 1695        | 76   | 161  |        |      |      | 1740  | 183  | 331  | 6781           | 418  | 446  |
|                  | Mixed            | 1435      | 99   | 111  | 257    | 24   | 15   | 2351  | 230  | 708  | 6309  | 815  | 699  | 1085        | 51   | 103  | 4617   | 170  | 168  | 1113  | 121  | 212  | 3006           | 312  | 545  |
|                  | Industrial       | 1570      | 107  | 121  | 3625   | 28   | 213  | 2086  | 206  | 628  | 3611  | 472  | 400  | 1187        | 55   | 113  | 4455   | 164  | 162  | 1218  | 132  | 232  | 2298           | 205  | 369  |
|                  | Weighted average | 1555      | 106  | 120  | 2737   | 27   | 161  | 2211  | 217  | 666  | 4888  | 635  | 542  | 1175        | 55   | 111  | 4511   | 166  | 164  | 1206  | 130  | 230  | 2592           | 244  | 429  |
| Milk             | Grazing          | 780       | 74   | 20   | 1046   | 22   | 7    | 1580  | 106  | 128  | 1185  | 105  | 34   | 572         | 50   | 32   | 0      | 0    | 0    | 1106  | 69   | 89   | 1087           | 56   | 49   |
|                  | Mixed            | 700       | 64   | 35   | 1254   | 42   | 36   | 897   | 147  | 213  | 863   | 132  | 65   | 431         | 40   | 23   | 1143   | 60   | 39   | 582   | 59   | 88   | 790            | 90   | 76   |
|                  | Industrial       | 517       | 48   | 43   |        |      |      |       |      |      |       |      |      | 500         | 43   | 25   | 1488   | 76   | 56   | 444   | 61   | 100  | 1027           | 98   | 82   |
|                  | Weighted average | 704       | 63   | 33   | 1149   | 33   | 22   | 927   | 145  | 210  | 885   | 130  | 63   | 462         | 41   | 25   | 1273   | 65   | 45   | 647   | 60   | 89   | 863            | 86   | 72   |
| Butter           | Grazing          | 4246      | 400  | 107  | 5691   | 122  | 39   | 8600  | 577  | 696  | 6448  | 572  | 188  | 3111        | 272  | 176  |        |      |      | 6022  | 373  | 482  | 5913           | 305  | 265  |
|                  | Mixed            | 3808      | 347  | 192  | 6822   | 230  | 196  | 4880  | 799  | 1161 | 4697  | 716  | 352  | 2345        | 218  | 123  | 6221   | 324  | 213  | 3169  | 321  | 478  | 4297           | 492  | 415  |
|                  | Industrial       | 2814      | 261  | 231  | 0      | 0    | 0    | 0     | 0    | 0    | 0     | 0    | 0    | 2720        | 233  | 136  | 8098   | 415  | 302  | 2417  | 330  | 543  | 5591           | 532  | 448  |
|                  | Weighted average | 3829      | 344  | 178  | 6254   | 179  | 117  | 5044  | 789  | 1141 | 4819  | 706  | 341  | 2513        | 224  | 134  | 6927   | 355  | 247  | 3519  | 324  | 483  | 4695           | 465  | 393  |
| Milk powder      | Grazing          | 3628      | 342  | 91   | 4862   | 104  | 34   | 7348  | 493  | 595  | 5510  | 489  | 160  | 2658        | 232  | 151  | 0      | 0    | 0    | 5145  | 319  | 412  | 5052           | 261  | 227  |
|                  | Mixed            | 3253      | 296  | 164  | 5829   | 197  | 167  | 4169  | 683  | 992  | 4013  | 612  | 301  | 2003        | 186  | 105  | 5315   | 277  | 182  | 2708  | 274  | 409  | 3671           | 421  | 354  |
|                  | Industrial       | 2405      | 223  | 198  | 0      | 0    | 0    | 0     | 0    | 0    | 0     | 0    | 0    | 2324        | 199  | 116  | 6920   | 355  | 258  | 2065  | 282  | 464  | 4777           | 455  | 382  |
|                  | Weighted average | 3271      | 294  | 152  | 5344   | 153  | 100  | 4309  | 674  | 975  | 4117  | 603  | 291  | 2147        | 191  | 114  | 5919   | 303  | 211  | 3007  | 277  | 413  | 4011           | 398  | 336  |
| Cheese           | Grazing          | 3857      | 380  | 97   | 5169   | 126  | 36   | 7812  | 540  | 633  | 5857  | 535  | 171  | 2826        | 263  | 160  |        |      |      | 5470  | 355  | 438  | 5371           | 293  | 241  |
|                  | Mixed            | 3459      | 331  | 174  | 6197   | 225  | 178  | 4432  | 742  | 1055 | 4267  | 666  | 320  | 2130        | 214  | 111  | 5651   | 310  | 194  | 2878  | 307  | 435  | 3903           | 463  | 377  |
|                  | Industrial       | 2556      | 253  | 210  |        |      |      |       |      |      |       |      |      | 2471        | 227  | 124  | 7356   | 393  | 275  | 2196  | 315  | 493  | 5078           | 500  | 406  |
|                  | Weighted average | 3478      | 328  | 162  | 5681   | 178  | 107  | 4581  | 732  | 1036 | 4377  | 657  | 310  | 2283        | 219  | 121  | 6292   | 338  | 224  | 3196  | 310  | 439  | 4264           | 439  | 357  |
| Leather (bovine) | Grazing          | 17601     | 801  | 54   | 22821  | 219  | 15   | 14300 | 0    | 0    | 25195 | 0    | 0    |             |      |      | 16922  | 529  | 223  | 21290 | 657  | 658  | 20905          | 535  | 240  |
|                  | Mixed            | 14090     | 682  | 59   | 19815  | 255  | 59   | 11719 | 377  | 91   | 15743 | 593  | 140  | 11883       | 947  | 765  | 12946  | 574  | 228  | 14185 | 681  | 856  | 16701          | 644  | 453  |
|                  | Industrial       | 4610      | 407  | 93   | 8099   | 217  | 235  | 9677  | 904  | 1093 | 12068 | 1505 | 842  | 4530        | 513  | 259  | 26295  | 1189 | 971  | 3287  | 497  | 614  | 9487           | 805  | 763  |
|                  | Weighted average | 14150     | 673  | 60   | 18445  | 246  | 79   | 11323 | 515  | 352  | 15103 | 777  | 280  | 6067        | 589  | 369  | 18093  | 723  | 414  | 14450 | 658  | 819  | 15916          | 679  | 498  |

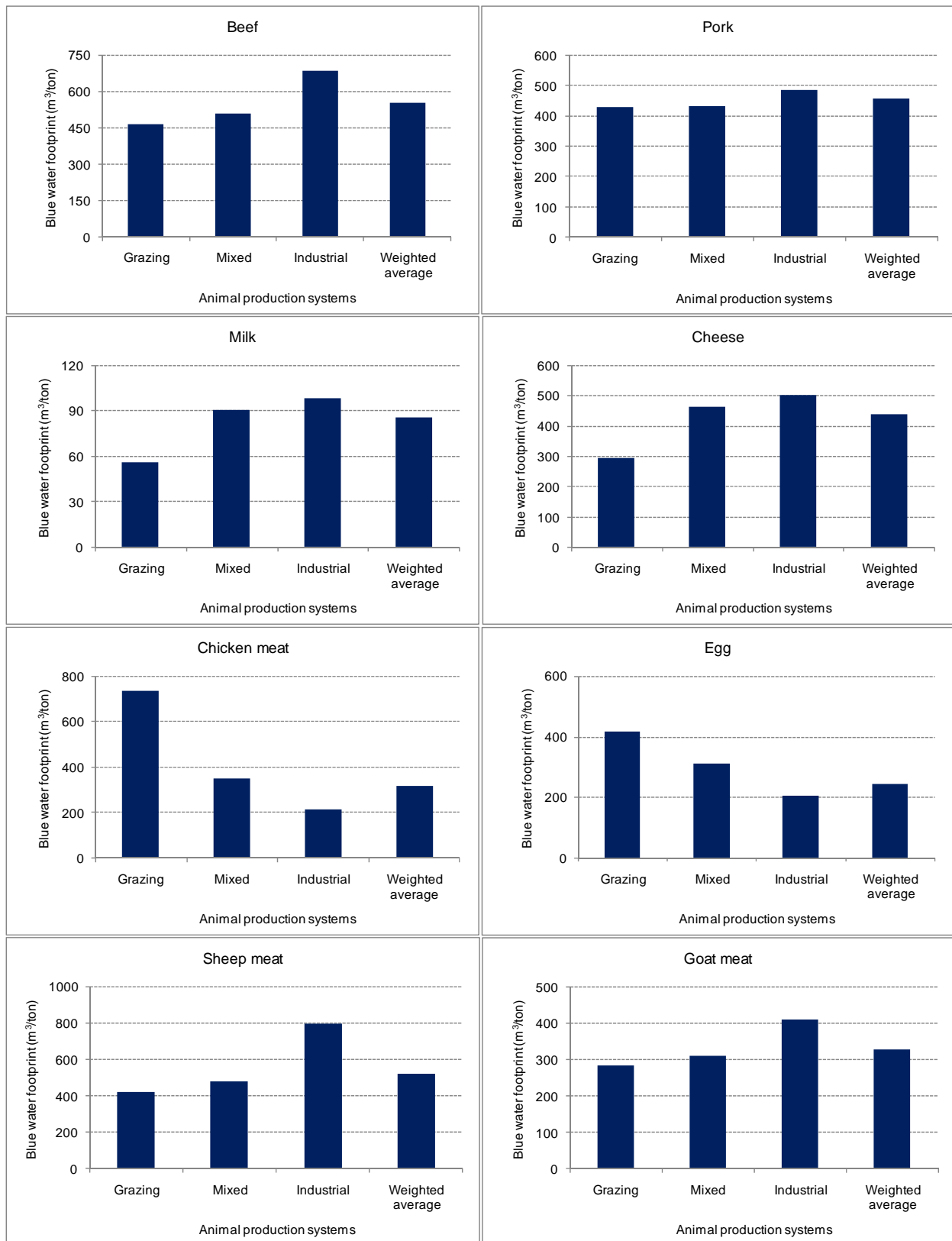


Figure 9. Global average blue water footprint per production system for selected animal products (1996-2005).

Table 5. The components of the water footprint of a beef cow and its derived products.

| Feed crop*                     | Feed amount (kg/kg carcass) | Weighted average water footprint of feed (litre/kg) |      |      | Water footprint (litre/kg carcass) |      |      |       |
|--------------------------------|-----------------------------|---|------|------|------------------------------------|------|------|-------|
|                                |                             | Green   | Blue | Grey | Green                              | Blue | Grey | Total |
| Maize                          | 1.0102                      | 695   | 111  | 181  | 702                                | 112  | 182  | 996   |
| Wheat                          | 0.2441                      | 1322  | 77   | 140  | 323                                | 18.8 | 34.0 | 375   |
| Barley                         | 0.2657                      | 1143  | 59   | 126  | 304                                | 15.6 | 33.4 | 353   |
| Soya bean cake                 | 0.1858                      | 1451  | 72   | 19   | 270                                | 13.4 | 3.6  | 286   |
| Sorghum                        | 0.1028                      | 1228  | 130  | 92   | 126                                | 13.4 | 9.5  | 149   |
| Oats                           | 0.0603                      | 1457  | 212  | 125  | 87.8                               | 12.8 | 7.6  | 108   |
| Rice, paddy                    | 0.0754                      | 997   | 259  | 165  | 75.1                               | 19.6 | 12.4 | 107   |
| Cassava                        | 0.1451                      | 498   | 0    | 12   | 72.3                               | 0.0  | 1.8  | 74.1  |
| Oilseed cakes, other           | 0.0275                      | 2158  | 37   | 50   | 59.4                               | 1.0  | 1.4  | 61.7  |
| Rape and mustard cake          | 0.0479                      | 977   | 132  | 151  | 46.8                               | 6.3  | 7.2  | 60.4  |
| Rye                            | 0.0233                      | 1573  | 38   | 109  | 36.7                               | 0.9  | 2.5  | 40.1  |
| Millet                         | 0.0107                      | 2718  | 130  | 172  | 29.0                               | 1.4  | 1.8  | 32.2  |
| Cereals, not specified         | 0.0308                      | 874   | 66   | 41   | 26.9                               | 2.0  | 1.3  | 30.2  |
| Sunflower seed cake            | 0.0249                      | 968   | 63   | 98   | 24.1                               | 1.6  | 2.4  | 28.1  |
| Pulses, not specified          | 0.0132                      | 1133  | 307  | 618  | 15.0                               | 4.1  | 8.2  | 27.2  |
| Molasses                       | 0.0597                      | 311   | 110  | 29   | 18.6                               | 6.6  | 1.7  | 26.9  |
| Groundnut cake                 | 0.0171                      | 1265  | 121  | 106  | 21.7                               | 2.1  | 1.8  | 25.6  |
| Soybeans                       | 0.0140                      | 1744  | 41   | 24   | 24.5                               | 0.6  | 0.3  | 25.4  |
| Potatoes                       | 0.0796                      | 254   | 10   | 48   | 20.2                               | 0.8  | 3.8  | 24.9  |
| Cottonseed cake                | 0.0280                      | 481   | 259  | 86   | 13.5                               | 7.3  | 2.4  | 23.1  |
| Cottonseed                     | 0.0181                      | 618   | 353  | 124  | 11.2                               | 6.4  | 2.2  | 19.8  |
| Peas, dry                      | 0.0126                      | 1149  | 21   | 336  | 14.4                               | 0.3  | 4.2  | 18.9  |
| Sunflower seed                 | 0.0054                      | 2744  | 144  | 234  | 14.8                               | 0.8  | 1.3  | 16.9  |
| Sugar cane                     | 0.0698                      | 171   | 35   | 16   | 11.9                               | 2.5  | 1.1  | 15.5  |
| Plantains                      | 0.0091                      | 1392  | 27   | 3    | 12.7                               | 0.2  | 0.0  | 13.0  |
| Beans, dry                     | 0.0029                      | 3270  | 48   | 575  | 9.4                                | 0.1  | 1.6  | 11.1  |
| Rapeseed                       | 0.0049                      | 1877  | 3    | 305  | 9.3                                | 0.0  | 1.5  | 10.8  |
| Vegetables fresh not specified | 0.0369                      | 152   | 49   | 69   | 5.6                                | 1.8  | 2.5  | 10.0  |
| Copra cake                     | 0.0046                      | 1567  | 2    | 10   | 7.2                                | 0.0  | 0.0  | 7.2   |
| Sweet potatoes                 | 0.0170                      | 285   | 7    | 57   | 4.8                                | 0.1  | 1.0  | 5.9   |
| Yams                           | 0.0166                      | 326   | 0    | 1    | 5.4                                | 0.0  | 0.0  | 5.5   |
| Palm kernel cake               | 0.0075                      | 659   | 0    | 27   | 4.9                                | 0.0  | 0.2  | 5.2   |
| Dates                          | 0.0009                      | 2397  | 2074 | 97   | 2.1                                | 1.8  | 0.1  | 4.0   |
| Sesame seed cake               | 0.0015                      | 2111  | 53   | 53   | 3.1                                | 0.1  | 0.1  | 3.3   |
| Sugar beet                     | 0.0165                      | 154   | 16   | 30   | 2.5                                | 0.3  | 0.5  | 3.3   |
| Oilseeds, not specified        | 0.0024                      | 802   | 94   | 35   | 2.0                                | 0.2  | 0.1  | 2.3   |
| Other minor feed crops         | 0.0122                      | 325   | 66   | 40   | 3.9                                | 0.8  | 0.5  | 5.2   |

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| Feed crop*  | Feed amount (kg/kg carcass) | Weighted average water footprint of feed (litre/kg) |      |      | Water footprint (litre/kg carcass) |       |       |         |
|---|-----------------------------|---|------|------|------------------------------------|-------|-------|---------|
|   |                             | Green   | Blue | Grey | Green                              | Blue  | Grey  | Total   |
| Crop residues   | 21.943                      | 0   | 0    | 0    | 0.0                                | 0.0   | 0.0   | 0.0     |
| Fodder crops  | 2.4632                      | 168   | 29   | 21   | 415                                | 71.8  | 50.7  | 537     |
| Pasture (grass)   | 31.525                      | 303   | 0    | 0    | 9556                               | 0.0   | 0.0   | 9556    |
| Water for feed mixing   |                             |   |      |      |                                    | 1.5   |       | 1.5     |
| Water footprint related to feed   |                             |   |      |      | 12391                              | 314   | 388   | 13107   |
| Drinking water  |                             |   |      |      |                                    | 110   |       | 110     |
| Service water   |                             |   |      |      |                                    | 29    |       | 29      |
| Total water footprint of beef cattle (litre/kg carcass)                   |                             |   |      |      | 12391                              | 453   | 388   | 13246   |
| Total water footprint of a 253 kg beef cow (in litre)                     |                             |   |      |      |                                    |       |       |         |
| (assuming a total carcass weight of 143 kg)                               |                             |   |      |      |                                    |       |       |         |
|   |                             |   |      |      | 1769000                            | 64600 | 55300 | 1889000 |
| ... of which 83% is attributed to the 101 kg of resultant beef, so that   |                             |   |      |      |                                    |       |       |         |
|   |                             |   |      |      | 14400                              | 550   | 450   | 15400   |
| ... of which 10% is attributed to the 18 kg of resultant offal, so that   |                             |   |      |      |                                    |       |       |         |
|   |                             |   |      |      | 10400                              | 400   | 330   | 11200   |
| ... of which 5% is attributed to the 6.1 kg of resultant leather, so that |                             |   |      |      |                                    |       |       |         |
|   |                             |   |      |      | 15900                              | 680   | 500   | 17100   |
| ... of which 2% is attributed to the 0.03 kg of resultant semen, so that  |                             |   |      |      |                                    |       |       |         |
|   |                             |   |      |      | 1069000                            | 40600 | 33400 | 1143000 |

\* The feed amounts included here represent the global average feed intake of beef cattle. Obviously, the feed composition of individual cows will deviate based on the production system and composition of the concentrate feed applied.

\*\* The percentage of the total water footprint of a beef cow attributed to each product refers to the 'value fraction' for that product (Appendix V). The amount of a certain product (in kg) coming from the total animal is based on the 'product fraction' for that product (Appendix V). In the blue water footprint, we added the water footprint of processing the slaughtered cow into the derived products.

### 3.4 Water footprint of animal versus crop products per unit of nutritional value

As a general picture we find that animal products have a larger water footprint per ton of product than crop products. As we see from Table 6, the global average water footprint per ton of crop increases from sugar crops (roughly 200 m<sup>3</sup>/ton) and vegetables (~300 m<sup>3</sup>/ton) to pulses (~4000 m<sup>3</sup>/ton) and nuts (~9000 m<sup>3</sup>/ton). For animal products, the water footprint increases from milk (~1000 m<sup>3</sup>/ton) and egg (~3300 m<sup>3</sup>/ton) to beef (~15400 m<sup>3</sup>/ton). Also when viewed from a caloric standpoint, the water footprint of animal products is larger than for crop products. The average water footprint per calorie for beef is twenty times larger than for cereals and starchy roots. When we look at the water requirements for protein, we find that the water footprint per gram of protein for milk, eggs and chicken meat is about 1.5 times larger than for pulses. For beef, the water footprint per gram of protein is 6 times larger than for pulses. In the case of fat, we find that butter has a relatively small water footprint per gram of fat, even lower than for oil crops. All other animal products, however, have larger water footprints per gram of fat when compared to oil crops. The general conclusion is that from a freshwater resource perspective, it is more efficient to obtain calories, protein and fat through crop products than animal products. A note should be made here, however, that types of proteins and fats differ across the different products.

Table 6. The water footprint of some selected food products from vegetable and animal origin.

| Food item       | Water footprint per ton (m <sup>3</sup> /ton) |      |      |       | Nutritional content |                |            | Water footprint per unit of nutritional value |                           |                   |
|-----------------|---|------|------|-------|---------------------|----------------|------------|---|---------------------------|-------------------|
|                 | Green   | Blue | Grey | Total | Calorie (kcal/kg)   | Protein (g/kg) | Fat (g/kg) | Calorie (litre/kcal)                          | Protein (litre/g protein) | Fat (litre/g fat) |
| Sugar crops     | 130   | 52   | 15   | 197   | 285                 | 0.0            | 0.0        | 0.69  | 0.0                       | 0.0               |
| Vegetables      | 194   | 43   | 85   | 322   | 240                 | 12             | 2.1        | 1.34  | 26                        | 154               |
| Starchy roots   | 327   | 16   | 43   | 387   | 827                 | 13             | 1.7        | 0.47  | 31                        | 226               |
| Fruits          | 726   | 147  | 89   | 962   | 460                 | 5.3            | 2.8        | 2.09  | 180                       | 348               |
| Cereals         | 1232  | 228  | 184  | 1644  | 3208                | 80             | 15         | 0.51  | 21                        | 112               |
| Oil crops       | 2023  | 220  | 121  | 2364  | 2908                | 146            | 209        | 0.81  | 16                        | 11                |
| Pulses          | 3180  | 141  | 734  | 4055  | 3412                | 215            | 23         | 1.19  | 19                        | 180               |
| Nuts            | 7016  | 1367 | 680  | 9063  | 2500                | 65             | 193        | 3.63  | 139                       | 47                |
| Milk            | 863   | 86   | 72   | 1020  | 560                 | 33             | 31         | 1.82  | 31                        | 33                |
| Eggs            | 2592  | 244  | 429  | 3265  | 1425                | 111            | 100        | 2.29  | 29                        | 33                |
| Chicken meat    | 3545  | 313  | 467  | 4325  | 1440                | 127            | 100        | 3.00  | 34                        | 43                |
| Butter          | 4695  | 465  | 393  | 5553  | 7692                | 0.0            | 872        | 0.72  | 0.0                       | 6.4               |
| Pig meat        | 4907  | 459  | 622  | 5988  | 2786                | 105            | 259        | 2.15  | 57                        | 23                |
| Sheep/goat meat | 8253  | 457  | 53   | 8763  | 2059                | 139            | 163        | 4.25  | 63                        | 54                |
| Bovine meat     | 14414   | 550  | 451  | 15415 | 1513                | 138            | 101        | 10.19   | 112                       | 153               |

In order to reduce the pressure on the world's water resource associated with their consumption pattern, individuals have the option of shifting from a meat-rich to a vegetarian diet. The water footprint of an individual consumer depends to a large extent on the type of diet of the individual. Meat-based diets have a larger water footprint compared to a vegetarian diet. The average USA citizen consumes almost four times the amount of protein compared to the global average (FAO, 2009). About 63% of the daily protein intake comes from animal based products. This high level of consumption of animal-based products is directly reflected in the relative large water footprint of the average American citizen (Hoekstra and Chapagain, 2007). Replacing 50% of all animal products by an equivalent amount of high nutritious crop products such as pulses, groundnuts and potatoes will result a 30% reduction of the food-related water footprint. A vegetarian diet compared with the average current per capita food intake in the USA can reduce the water footprint of an individual by as much as 58%.

### 3.5 The total water footprint of animal production

During the period 1996-2005, the total water footprint for global animal production was 2422 Gm<sup>3</sup>/yr (87.2% green, 6.2% blue and 6.6% grey water). The different components of the global water footprint of animal production are shown in Table 7. The largest water footprint for the animal production comes from the feed they consume, which accounts for 98% of the total water footprint. Drinking water, service water and feed mixing water further account only for 1.1%, 0.8% and 0.03% of the total water footprint, respectively. The estimate of drinking and service water is in line with Peden et al. (2007). Grazing accounts for the largest share (38%), followed by maize (17%) and fodder crops (8%).

The global water footprint of feed production is 2376 Gm<sup>3</sup>/yr, of which 1463 Gm<sup>3</sup>/yr refers to crops and the remainder to grazing (Table 8). The total water footprint of feed crops amounts to 20% of the water footprint of total crop production in the world, which is 7404 Gm<sup>3</sup>/yr (Mekonnen and Hoekstra, 2010b). The globally aggregated *blue* water footprint of feed crop production is 105 Gm<sup>3</sup>/yr, which is 12% of the blue water footprint of total crop production in the world (Mekonnen and Hoekstra, 2010b). This means that an estimated 12% of the global consumption of groundwater and surface water for irrigation is for feed, not for food, fibres or other crop products. Globally, the total water footprint of animal production (2422 Gm<sup>3</sup>/yr) constitutes 29% of the water footprint of total agricultural production.

When we consider the total water footprint per animal category (Table 9), we find that beef cattle have the largest contribution (33%) to the global water footprint of farm animal production, followed by dairy cattle (19%), pig (19%) and broiler chicken (11%). The green, blue and grey water footprints per animal category and production system are shown in Table 10. Altogether, mixed production systems account for the largest share (57.4%) in the total water footprint of animal production. Grazing and industrial production systems account for 20.3% and 22.3%, respectively. In the grazing system, over 97% of the water footprint related to feed comes from grazing and fodder crops and the water footprint is dominantly (94%) green. In the mixed and industrial production systems, the green water footprint forms 87% and 82% of the total footprint, respectively. The blue water footprint in the grazing system accounts for 3.6% of the total water footprint and about 33% of this comes from the drinking and service water use. In the industrial system, the blue water footprint accounts for 8% of the total water footprint.

*Table 7. Global water footprint of animal production by component.*

| Feed crop                   | Total water footprint (Mm <sup>3</sup> /yr) |       |       |        |           |
|-----------------------------|---|-------|-------|--------|-----------|
|                             | Green                                       | Blue  | Grey  | Total  | Share (%) |
| Grazing                     | 912816                                      | 0.0   | 0.0   | 912816 | 37.7      |
| Maize                       | 302595                                      | 33581 | 74960 | 411136 | 17.0      |
| Fodder crops                | 167896                                      | 9900  | 10903 | 188699 | 7.79      |
| Soybean cake                | 168221                                      | 6559  | 3178  | 177958 | 7.35      |
| Wheat                       | 122934                                      | 8345  | 16214 | 147493 | 6.09      |
| Barley                      | 116844                                      | 6778  | 14410 | 138031 | 5.70      |
| Oats                        | 48508                                       | 10370 | 4753  | 63631  | 2.63      |
| Sorghum                     | 40781                                       | 3376  | 2798  | 46954  | 1.94      |
| Rice, paddy                 | 24699                                       | 7497  | 4863  | 37059  | 1.53      |
| Oilseed cakes, other        | 22159                                       | 409   | 525   | 23093  | 0.95      |
| Rape and mustard cake       | 16841                                       | 2457  | 3134  | 22432  | 0.93      |
| Cassava                     | 17630                                       | 8.6   | 849   | 18488  | 0.76      |
| Cereals, not else specified | 15683                                       | 881   | 979   | 17543  | 0.72      |
| Sweet potatoes              | 12927                                       | 210   | 2781  | 15918  | 0.66      |
| Rye                         | 13628                                       | 249   | 1057  | 14934  | 0.62      |
| Pulses, not else specified  | 7829  | 1242  | 4300  | 13371  | 0.55      |

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| Feed crop                            | Total water footprint (Mm <sup>3</sup> /yr) |               |               |                |               |
|--------------------------------------|---|---------------|---------------|----------------|---------------|
|                                      | Green                                       | Blue          | Grey          | Total          | Share (%)     |
| Sunflower seed cake                  | 11279                                       | 626           | 905           | 12809          | 0.53          |
| Potatoes                             | 9602  | 369           | 2500          | 12471          | 0.51          |
| Millet                               | 9617  | 607           | 458           | 10682          | 0.44          |
| Soybeans                             | 9786  | 374           | 212           | 10372          | 0.43          |
| Groundnut cake                       | 8874  | 658           | 575           | 10107          | 0.42          |
| Peas, dry                            | 6666  | 144           | 1736          | 8546           | 0.35          |
| Cottonseed cake                      | 4851  | 2889          | 775           | 8514           | 0.35          |
| Molasses                             | 4214  | 1808          | 410           | 6432           | 0.27          |
| Cottonseed                           | 3252  | 2480          | 618           | 6350           | 0.26          |
| Vegetables fresh not else specified  | 3665  | 703           | 1977          | 6345           | 0.26          |
| Beans, dry                           | 4003  | 54            | 922           | 4979           | 0.21          |
| Sunflower seed                       | 4045  | 200           | 314           | 4560           | 0.19          |
| Rapeseed                             | 3338  | 11            | 763           | 4111           | 0.17          |
| Copra cake                           | 3581  | 3.5           | 23            | 3608           | 0.15          |
| Sugar cane                           | 2148  | 590           | 217           | 2955           | 0.12          |
| Palm kernel Cake                     | 2519  | 0.7           | 93            | 2612           | 0.11          |
| Sesame seed cake                     | 2111  | 53            | 46            | 2210           | 0.09          |
| Plantains                            | 2078  | 52            | 4             | 2134           | 0.09          |
| Sugar beet                           | 1070  | 70            | 285           | 1425           | 0.06          |
| Oilseeds, not else specified         | 990   | 150           | 50            | 1191           | 0.05          |
| Bananas                              | 761   | 53            | 41            | 855            | 0.04          |
| Yams                                 | 767   | 0.5           | 3.3           | 771            | 0.03          |
| Dates                                | 244   | 279           | 15            | 538            | 0.02          |
| Apples                               | 326   | 118           | 38            | 483            | 0.02          |
| Tomatoes                             | 102   | 93            | 39            | 234            | 0.01          |
| Roots and tubers, not else specified | 177   | 4.1           | 27            | 208            | 0.01          |
| Fruits, other                        | 116   | 25            | 9             | 150            | 0.01          |
| Groundnuts                           | 70  | 8             | 5             | 83             | 0.00          |
| Coconuts                             | 38  | 0.0           | 0.1           | 38             | 0.00          |
| Cocoa beans                          | 16  | 0.0           | 0.2           | 16             | 0.00          |
| Onions                               | 0.7   | 1.6           | 0.2           | 2.5            | 0.00          |
| Sesame seed                          | 1.8   | 0.3           | 0.2           | 2.2            | 0.00          |
| Palm-kernels                         | 0.8   | 0.0           | 0.0           | 0.8            | 0.00          |
| Mixing water for feed preparation    | 0.0   | 610           | 0.0           | 610            | 0.03          |
| Drinking water                       |   | 27099         |               | 27099          | 1.12          |
| Service water                        |   | 18213         |               | 18213          | 0.75          |
| <b>Total water footprint</b>         | <b>2112301</b>                              | <b>150660</b> | <b>158762</b> | <b>2421722</b> | <b>100.00</b> |

Table 8. The global water footprint of animal production compared to the global water footprint of total agricultural production for the period 1996-2005 (Gm<sup>3</sup>/yr).

|  | Green | Blue | Grey | Total |
|--|-------|------|------|-------|
| <b>Water footprint of total agricultural production</b>  |       |      |      |       |
| Water footprint of crop production*  | 5771  | 899  | 733  | 7404  |
| Water footprint of grazing   | 913   | -    | -    | 913   |
| Direct water footprint of livestock**  | -     | 46   | -    | 46    |
| Total  | 6684  | 899  | 733  | 8317  |
| <b>Water footprint of animal production</b>  |       |      |      |       |
| Water footprint of feed crop production  | 1199  | 105  | 159  | 1463  |
| Water footprint of grazing   | 913   | -    | -    | 913   |
| Direct water footprint of livestock**  | -     | 46   | -    | 46    |
| Total  | 2112  | 151  | 159  | 2422  |
| Water footprint of animal production as a percentage of the total water footprint in agricultural production | 32%   | 17%  | 22%  | 29%   |

\* Source: Mekonnen and Hoekstra (2010b).

\*\* Water footprint of drinking, servicing and feed mixing.

A substantial part of the water footprint of an animal product produced in one country often resides outside that country. This is most in particular the case for products originating from industrial production systems, because those systems use the largest fraction of concentrate feed. Feed crops are often imported rather than produced domestically. Soybean cake, for example, which is an important feed ingredient in industrial livestock raising, is often imported. In the period 1996-2005, 49% of global soybean production was exported, either in the form of soybean or in the form of soybean cake (FAO, 2009).

Table 9. The total water footprint per animal category (1996-2005).

| Animal category | Global total number of animals* (millions) | Average annual water footprint per animal** (m <sup>3</sup> /yr per animal) | Annual water footprint of animal category (Gm <sup>3</sup> /yr) | %   |
|-----------------|--|---|---|-----|
| Beef cattle     | 1267                                       | 630   | 798   | 33  |
| Dairy cattle    | 228  | 2056  | 469   | 19  |
| Pig             | 880  | 520   | 458   | 19  |
| Broiler chicken | 9923                                       | 26  | 255   | 11  |
| Horse           | 112  | 1599  | 180   | 7   |
| Layer Chicken   | 5046                                       | 33  | 167   | 7   |
| Sheep           | 1052                                       | 68  | 71  | 3   |
| Goat            | 750  | 32  | 24  | 1   |
| Total           | 19258                                      |   | 2422  | 100 |

\* Source: FAO (2009).

\*\* See Table 3.

Table 10. The green, blue and grey water footprints per animal category and production system (Gm<sup>3</sup>/yr) for the period 1996-2005.

| Animal category | Grazing production system |      |      | Mixed production system |      |      | Industrial production system |      |      | World total |      |      |
|-----------------|---------------------------|------|------|-------------------------|------|------|------------------------------|------|------|-------------|------|------|
|                 | Green                     | Blue | Grey | Green                   | Blue | Grey | Green                        | Blue | Grey | Green       | Blue | Grey |
| Beef cattle     | 185                       | 4.5  | 2.1  | 443                     | 20   | 12   | 112                          | 10   | 9.0  | 740         | 35   | 23   |
| Dairy cattle    | 83                        | 3.6  | 3.7  | 269                     | 27   | 26   | 48                           | 4.1  | 3.8  | 400         | 35   | 34   |
| Pig             | 27                        | 1.5  | 2.2  | 237                     | 19   | 27   | 111                          | 14   | 19   | 376         | 34   | 48   |
| Broiler chicken | 37                        | 3.4  | 3.3  | 100                     | 8.3  | 14   | 73                           | 6.3  | 10   | 210         | 18   | 28   |
| Horse           | 82                        | 3.0  | 1.4  | 69                      | 7.1  | 2.4  | 13                           | 0.8  | 0.6  | 164         | 11   | 4    |
| Layer chicken   | 4.5                       | 0.3  | 0.3  | 52                      | 5.4  | 9.4  | 77                           | 6.5  | 12   | 133         | 12   | 22   |
| Sheep           | 34                        | 1.2  | 0.0  | 28                      | 2.0  | 0.2  | 5.0                          | 1.0  | 0.2  | 66.5        | 4.3  | 0.5  |
| Goat            | 8.2                       | 0.3  | 0.0  | 13                      | 0.9  | 0.0  | 2.0                          | 0.4  | 0.0  | 22.7        | 1.5  | 0.0  |
| Total           | 461                       | 17.8 | 13.2 | 1210                    | 90   | 90   | 442                          | 43   | 55   | 2112        | 151  | 159  |



## 4. Discussion

The result of the current study can be compared with results from earlier studies. However, only a few other studies on the water footprint per unit of animal product and the total water footprint of animal production are available. We will first compare our estimates of the water footprints per ton of animal product with two earlier studies and subsequently we will compare the total water footprint related to animal feed production with five earlier studies.

The rough estimates made by Pimentel et al. (2004) for the water footprints of beef and meat from sheep, pig and chicken are partly very close to our global estimates but partly also quite different. They report a water footprint of chicken meat of 3500 m<sup>3</sup>/ton, which is only a bit lower than our global average estimate of 4300 m<sup>3</sup>/ton, and even closer if we subtract the grey water footprint component from our estimate (which is not included in Pimentel's studies). They report a water footprint of pig meat of 6000 m<sup>3</sup>/ton, which happens to coincide with our global average estimate (but our estimate includes the grey water footprint component). For sheep meat, they report a water footprint of 51000 m<sup>3</sup>/ton and for beef 43000 m<sup>3</sup>/ton, values that are very high when compared to our estimates (10,400 m<sup>3</sup>/ton for sheep meat and 15400 m<sup>3</sup>/ton for beef). We consider the values reported by Pimentel as crude first estimates, for which the underlying assumptions have not been spelled out, so that it is difficult to explain differences with our estimates.

The study of Chapagain and Hoekstra (2004) is the only publication with global estimates of the water footprint of animal products with specifications by country. At a global level, the estimated water footprints per ton of animal and animal product compare very well with the estimates from Chapagain and Hoekstra (2004), with an  $r^2$  of 0.88 (Figure 10a). The good agreement at the global level between the two studies is probably that the global average water footprints for various feed ingredients are very close in the two studies. The trend line in Figure 10a is slightly above 1, which is caused by our higher estimates for the water footprints of sheep and goat meat. For most other animal products, the current study gives a bit lower estimates than the earlier study.

When we compare our estimates with Chapagain and Hoekstra (2004) at a country level, more differences are found (Figure 10b-f). The two studies show a relatively good agreement for pig meat, chicken meat and egg – although for egg the earlier study systematically gives higher numbers – but little agreement for beef and dairy products. In general we find that Chapagain and Hoekstra (2004) underestimated the water footprints for African countries and overestimated the water footprints for OECD countries. As already pointed out in the introductory chapter, there are three main reasons why the estimates from the current study can differ from the 2004-study and are considered more accurate. First, the current study is based on better data for the estimation of the quantity and composition of animal feed. Second, the current study reckons with the relative presence of the three production systems per country and accounts for the differences between those systems. Third, we have estimated the water footprints of the various feed ingredients more accurately by using a high-resolution grid-based crop water use model, including the effect of water deficits where they occur, making explicit distinction between the green and blue water footprint components and including the grey water footprint component.

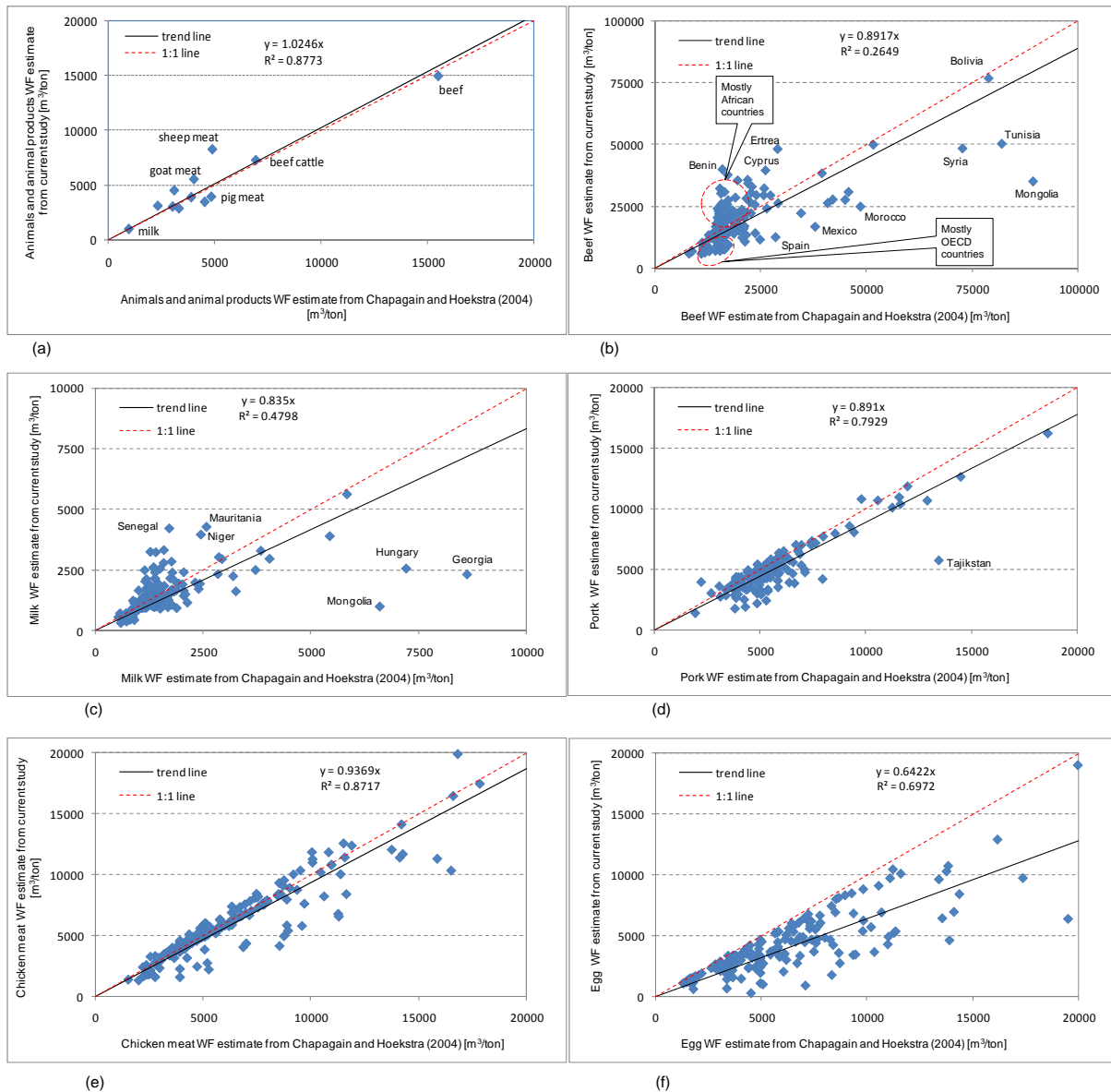


Figure 10. Comparison of average water footprint of (a) animals and animal products at global level, and (b) beef (c) milk, (d) pig meat, (e) chicken meat and (f) egg at the country level as estimated in the current study and Chapagain and Hoekstra (2004). From the current study we show here the sum of green and blue water footprints, excluding the grey water footprint, because that component was excluded in the 2004-study.

As one can see in the overview presented in Table 11, our estimate of the total evaporative water use (green plus blue water footprint) for producing animal feed ( $2217 \text{ Gm}^3/\text{yr}$ ) is 3% larger than the estimate by De Fraiture et al. (2007) and 5% smaller than the estimate by Zimmer and Renault (2003). Our estimate of the global consumptive water use for producing feed crops ( $1312 \text{ Gm}^3/\text{yr}$ ) does not significantly differ from the estimate by De Fraiture et al. (2007). Our estimate of global consumptive water use for grazing ( $913 \text{ Gm}^3/\text{yr}$ ) is 9% larger than the estimate by De Fraiture et al. (2007). The differences with three other studies that reported on the consumptive water use related to grazing are much larger, which is caused by another definition applied. Postel et al. (1996) estimated the water evaporated from grazing land to be  $5800 \text{ Gm}^3/\text{yr}$ . In more recent studies, Rost et al. (2008) and Hanasaki et al. (2010) estimate the total evapotranspiration from grazing land to be  $8258 \text{ Gm}^3/\text{yr}$  and  $12960 \text{ Gm}^3/\text{yr}$ , respectively. However, unlike the current study, the estimates in these three studies refer to the total evapotranspiration from grazing lands rather than to the evaporation related to the grass actually consumed.

According to De Fraiture et al. (2007), reported ‘grazing lands’ are only partly actually grazed. Besides, the harvest efficiency – the fraction of grass actually consumed by the animal compared to the standing biomass – is quite small. In a recent study in the USA, Smart et al. (2010) showed that, depending on the animal stocking density, harvest efficiencies reach between 14-38%.

Table 11. Comparison of the results of the current study with the results from previous studies.

| Study                     | Period    | Global water footprint* related to animal feed production (Gm <sup>3</sup> /yr) |       |       |
|---------------------------|-----------|---|-------|-------|
|                           |           | Grazing   | Crops | Total |
| Postel et al. (1996)      | 1995      | 5800  | -     | -     |
| Zimmer and Renault (2003) | 2000      | -   | -     | 2340  |
| De Fraiture et al. (2007) | 2000      | 840   | 1312  | 2152  |
| Rost et al. (2008)        | 1971-2002 | 8258  | -     | -     |
| Hanasaki et al. (2010)    | 1985-1999 | 12960   | -     | -     |
| Current study*            | 1996-2005 | 913   | 1304  | 2217  |

\* The numbers in the table, also the ones from the current study, refer to the green plus blue water footprint. None of the previous studies included the grey water footprint component.

There are several uncertainties in this study in the quantification of the water footprint of animals and animal products. Due to a lack of data, many assumptions have to be made. There are a number of uncertainties in the study, but particularly two types of uncertainty may have a major effect on the final output of the study. First, data on animal distribution per production system per country for OECD countries is not available. Wint and Robinson (2007) provide livestock distributions per production system per country for developing countries but not for OECD countries. For these countries we are forced to use the data from Seré and Steinfeld (1996), who provide livestock distribution per economic region. These data have the limitation that they are not country-specific and may lead to wrong distribution of animals into the different production system for some countries. The second major uncertainty is related to the precise composition of feed per animal category per country. Such data are not directly available so that we had to infer these data by combining different data sources and a number of assumptions.

Although the scope of this study is very comprehensive, there are many issues that have been left out. One issue is that we neglected the indirect water footprints of materials used in feed production and animal raising. We expect that this may add at most a few per cents to the water footprint estimates found in this study (based on Hoekstra et al., 2009). In the grey water footprint estimations we have looked at the water pollution by nitrogen-fertilisers only, excluding the potential pollution by other fertiliser components or by pesticides or other agro-chemicals. Besides, we have not quantified the grey water footprint coming from animal wastes, which is particularly relevant for industrial production systems. Intensive animal production often generates an amount of waste that cannot be fully recycled on the nearby land. The large amount of waste generated in a concentrated place can seriously affect freshwater systems (FAO, 2005; Steinfeld et al., 2006; Galloway et al., 2007). Finally, by focusing on freshwater appropriation, the study obviously excludes many other relevant issues in farm animal production, such as micro- and macro-cost of production, livelihood of smallholder farmers, animal welfare, public health and environmental issues other than freshwater.





## 5. Conclusion

The present study estimates the water footprint of farm animals and animal products per production system and per country. The results show that:

- Although beef cattle, sheep and goat require much more feed per unit of meat produced than pig and broiler chicken, the fraction of concentrate feed in the total feed is much larger for the latter (Section 3.1). Since concentrate feed has a larger water footprint per unit of weight than roughages (Section 3.2), the water footprints of the different sorts of meat are closer than one would expect on the basis of feed conversion efficiencies alone (Section 3.3).
- The total water footprint of an animal product is generally larger when obtained from a grazing system than when produced from an industrial system, because of a larger *green* water footprint component. The *blue* and *grey* water footprints of animal products are largest for industrial systems (with an exception for chicken products). From a freshwater perspective, animal products from grazing systems are therefore to be preferred above products from industrial systems (Section 3.3).
- The water footprint of any animal product is larger than the water footprint of a wisely chosen crop product with equivalent nutritional value (Section 3.4).
- 29% of the total water footprint of the agricultural sector in the world is related to the production of animal products. One third of the global water footprint of animal production is related to beef cattle (Section 3.5).

The global meat production has almost doubled in the period 1980-2004 (FAO, 2005) and this trend is likely to continue given the projected doubling of meat production in the period 2000-2050 (Steinfeld et al., 2006). To meet this rising demand for animal products, the on-going shift from traditional extensive and mixed farming to industrial farming systems is likely to continue. Because of the larger dependence on concentrate feed in industrial systems, this intensification of animal production systems will result in increasing blue and grey water footprints per unit of animal product. The pressure on the global freshwater resources will thus increase both because of the increasing meat consumption and the increasing blue and grey water footprint per unit of meat consumed.

Managing the demand for animal products by promoting a dietary shift away from a meat-rich diet will be an inevitable component in the environmental policy of governments. In countries where the consumption of animal products is still quickly rising, one should critically look how this growing demand can be moderated. On the production side, it would be wise to include freshwater implications in the development of animal farming policies, which means that particularly feed composition, feed water requirements and feed origin need to receive attention. Animal farming puts the lowest pressure on freshwater systems when dominantly based on crop residues, waste and roughages. Policies aimed to influence either the consumption or production side of farm animal products will generally entail various sorts of socio-economic and environmental trade-offs (Herrero et al., 2009; Pelletier and Tyedmers, 2010). Therefore, policies aimed at reducing the negative impacts of animal production and consumption should be able to address these potential tradeoffs. Policies should not affect the

required increase in food security in less developed countries neither the livelihood of the rural poor should be put in danger through intensification of animal farming.

This study provides a rich data source for further studies on the factors that determine how animal products put pressure on the global water resources. The reported incidents of groundwater depletion, rivers running dry and increasing levels of pollution form an indication of the growing water scarcity (UNESCO, 2009; Postel, 2000; Gleick, 1993). Since animal production and consumption play an important role in depleting and polluting the world's scarce freshwater resources, information on the water footprint of animal products will help us understand how we can sustain the scarce freshwater resources.

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