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December 2011

A comparative study on the water footprint of poultry, pork and beef in different countries and production systems

Value of Water

Research Report Series No. 55

A COMPARATIVE STUDY ON THE WATER FOOTPRINT OF POULTRY, PORK AND BEEF IN DIFFERENT COUNTRIES AND PRODUCTION SYSTEMS

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DECEMBER 2011

VALUE OF WATER RESEARCH REPORT SERIES NO. 55

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Published by:
UNESCO-IHE Institute for Water Education
P.O. Box 3015
2601 DA Delft
The Netherlands

The Value of Water Research Report Series is published by UNESCO-IHE Institute for Water Education, in collaboration with University of Twente, Enschede, and Delft University of Technology, Delft.

Please cite this publication as follows:
Gerbens-Leenes, P.W., Mekonnen, M.M. and Hoekstra, A.Y. (2011) A comparative study on the water footprint of poultry, pork and beef in different countries and production systems, Value of Water Research Report Series No. 55, UNESCO-IHE, Delft, the Netherlands.

Acknowledgements

This research has been commissioned by Compassion in World Farming (CIWF), Godalming, Surrey, UK, with funding from CIWF, The Tubney Charitable Trust and the World Society for the Protection of Animals (WSPA). We like to thank Emily Lewis-Brown and Tracey Jones from CIWF, and Sofia Parente and Basia Romanowicz from the World Society for the Protection of Animals for their critical comments on a draft of this report.

Contents

Summary

Producing animal products requires large amounts of water. Agriculture accounts for 92 per cent of the global freshwater footprint. In agriculture, 29 per cent of the water is needed for growing animal feed, which means that about a quarter of the global water footprint relates to the consumption of animal products. This includes green water (rainwater), blue water (fresh surface or groundwater) and grey water (water needed to cope with pollution). It is likely that this fraction would increase further if production rises, especially in rapidly developing countries like Brazil and China. This report gives an overview of water footprints (green, blue and grey) for three types of meat (poultry, pork and beef) for Brazil, China, the Netherlands and the United States. The report addresses grazing, mixed and industrial production systems.

Major factors in meat water footprints

There are two major factors that determine the water footprint (WF) of animal products. The first factor is the feed conversion efficiency which measures the amount of feed to produce a given amount of meat, eggs or milk. As animals are generally able to move more and take longer to reach slaughter weight in grazing systems, they consume a greater proportion of food to convert to meat. Due to this, the feed conversion efficiency improves from grazing systems through mixed systems to industrial systems and leads to a smaller WF in industrial systems.

The second factor which affects the WF of meats is the composition of the feed eaten by the animals in each system; as the amount of feed concentrates increases, it increases the WF and an increase in roughage (grass, crop residues and fodder crops) consumption tends to reduce the WF. The increasing fraction of animal feed concentrates and decreasing fraction of roughages from grazing through mixed to industrial systems results in a smaller WF in grazing and mixed systems and a larger WF in industrial systems, especially the blue and grey WF. This is because feed concentrates have a relatively large water footprint, while roughages have a relatively small water footprint. In general, the water footprint of concentrates is five times larger than the water footprint of roughages. While the total mixture of roughages has a water footprint of around 200 m^3/tonne (global average), this is about 1,000 m^3/tonne for the package of ingredients contained in concentrates. As roughages are mainly rain fed and crops for concentrates are often irrigated and fertilized, the blue and grey water footprint of concentrates are even 43 and 61 times that of roughages, respectively.

Global average water footprints

While the favourable feed conversion efficiency suppresses the size of the WF in industrial systems, the comparatively high ratio of concentrates to roughages increases the WF in such systems; the net effect depends on the relative importance of the two factors, which differs per animal type and country. When the global average water footprints are considered, both the blue and grey water footprints of beef are found to be significantly greater in industrial systems and smaller in grazing systems. The reverse is true for poultry. Pork production in industrial systems has a slightly higher blue and grey WF than in grazing systems. Global average green water footprints decrease from grazing and mixed systems to industrial systems, for poultry, pork as well as for beef.

National water footprints

The countries studied here vary significantly from the global mean. For beef, for example, the water footprint of industrially produced beef in the Netherlands, the US and Brazil is smaller than the global average, while it is larger for industrially produced beef in China.

Comparing different meat types

In general the report finds that beef has a larger total water footprint than pork, which in turn has a larger water footprint than poultry, but the average global *blue* and *grey* WFs are similar across the three meat products. When we consider grazing systems, the blue and grey water footprints of poultry and pork are greater than those for beef, which can be explained by the fact that beef cattle in a grazing system largely depend on green water, while chicken and pigs in a grazing system still consume substantial amounts of feed concentrates from crops that are partly irrigated (blue water) and fertilized (grey water). 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 may be preferable from a water resources point of view.

Looking forward

A shift in food consumption patterns towards greater consumption of animal products may result in an intensification of production and a shift is likely to continue from grazing and mixed to industrial systems. The combination of production increase and a shift towards more industrial systems would increase the use of feed concentrates in livestock production. This would increase the water footprint of total production, but also the contribution of the blue and grey water footprint relative to the green water footprint. The water footprint of meat consumption can decrease to some extent by finding the right balance between efficiency of production and a low water footprint feed composition. Humanity can further reduce the WF of food through substitution of meat by plant based foods and by reducing food waste. The water footprint of meat production is one of several factors that play a role in the future of the livestock sector, to be weighted into decisions alongside considerations of animal welfare, public health issues, food security and other environmental concerns.

1. Introduction

Food contributes an important share of the total use of natural resources, such as water (Bruinsma, 2003; Hoekstra and Chapagain, 2008; Mekonnen and Hoekstra, 2010a). Animal products have a particularly large water requirement per unit of nutritional energy compared to food of plant origin. For example, the total water footprint of pork (expressed as litres per kcal) is two times larger than the water footprint of pulses and four times larger than the water footprint of grains (Mekonnen and Hoekstra, 2010b). Today, the global water footprint of animal production constitutes almost one third of the water footprint of total agricultural production.

Worldwide, a nutrition transition is taking place in which many people are shifting towards more affluent food consumption patterns containing more animal products (Bruinsma, 2003; Grigg, 1995; Popkin, 2002). Most areas of the world show economic development that results in increased purchasing power, causing not only demand for more food, but also a change in types of food (Latham, 2000). In recent decades, demand for animal products, such as meat, milk and eggs, has increased due to changes in food consumption patterns (Bruinsma, 2003; FAO, 2011). In affluent countries, the protein intake is generally larger than required due particularly to the excessive consumption of animal products. In general, the per capita consumption of meat and other animal products increases with average per capita income until it reaches some level of satisfaction (Gerbens-Leenes et al., 2010). High income countries, like the Netherlands or the United States, have a large consumption of animal products. In the United States, an average citizen consumes 123 kg of meat and 254 litres of milk per year, in the Netherlands average annual consumption is 71 kg of meat and 320 litres of milk (FAO, 2011). In Brazil, an emerging economy, annual meat consumption is 80 kg per capita, while milk consumption is much smaller, only half of the US consumption. In China, also an emerging economy, consumption of meat and milk is still small compared to other countries (FAO, 2011). If in developing countries, populations continue to increase, especially in combination with economic growth as is expected in Brazil and China (IMF, 2010; Bruinsma, 2003), demand for animal products is predicted to increase. This would require more water.

The production of meat, milk and eggs requires and pollutes large amounts of water, particularly for the production of animal feed (Chapagain and Hoekstra, 2003; Pimentel et al., 2004; Steinfeld et al., 2006; De Fraiture et al., 2007; Hoekstra, 2010; Mekonnen and Hoekstra, 2010b). Globally, agriculture accounts for 92 per cent of the global freshwater footprint; 29 per cent of the water in agriculture is used for animal production (Mekonnen and Hoekstra, 2011). On top of the agricultural water needs for feed, water is needed to mix the animal feed, for servicing, and for drinking. In the period 1996-2005, the annual global water footprint for animal production was 2,422 Gm^3 (of which 2112 Gm^3 green, 151 Gm^3 blue and 159 Gm^3 grey). Of this amount, 0.6 Gm^3 of blue water (0.03 per cent) was needed to mix the feed, 27.1 Gm^3 of blue water (1.12 per cent) was drinking water and 18.2 Gm^3 of blue water (0.75 per cent) was needed for servicing (Mekonnen and Hoekstra, 2010b). Water for animal products, therefore, mainly refers to water consumed or polluted to produce animal feed.

The water footprint (WF) is a tool to calculate water use behind consumer products. It measures freshwater consumption and pollution along product supply chains (Hoekstra et al., 2011). The WF is a multi-dimensional indicator, giving water consumption volumes by source and polluted volumes by type of pollution. The tool distinguishes between green, blue and grey water and in this way gives a comprehensive and complete overview of freshwater use and pollution. The *green* WF refers to the rainwater consumed (evaporated or incorporated into the product). The *blue* WF refers to surface and groundwater volumes consumed. The *grey* WF of a product refers to the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards. The significance of a large WF for any product will depend to some extent on where the water use arises, and may have a greater impact in dry areas and seasons than in water rich areas and seasons.

Recently, a comprehensive global study of the water footprint of farm animals and animal products has been carried out (Mekonnen and Hoekstra, 2010b). That study considers eight animal categories and three livestock production systems for the period 1996-2005. The animal categories are: beef and dairy cattle, pig, sheep, goat, broiler and layer chicken, and horses. The production systems are the grazing, mixed and industrial production systems. The aim of this report is to analyse in more detail differences of water footprints among developed and developing countries, as well as between different production systems for three types of meat: poultry, pork and beef. This study focuses on specific case studies which include two developing and two developed countries: Brazil and China, and the Netherlands and the United States. The data is derived from the studies of Mekonnen and Hoekstra (2010a, 2010b). The estimates in this study include the water footprint in feed production, the water footprint related to drinking and the water footprint related to cleaning the farm and the slaughter house. In feed production the grey water footprint of synthetic nitrogen fertilizers is considered, but not of other synthetic fertilizers or pesticides. The study does not include an estimate of the grey water footprint of manure.

2. Methodology

2.1 Classification of livestock farming systems

Following the standards of the Food and Agriculture Organization, we distinguish three types of livestock farming systems: grazing, mixed and industrial systems (FAO, 1995; Seré and Steinfeld, 1996). *Grazing systems* have low stocking rates per hectare. They can be found worldwide, but form the dominant farming system only in developing countries with relatively low gross national incomes per capita (Chapagain and Hoekstra, 2003). These systems supply about nine per cent of the world meat production (FAO, 1995). In general, grazing systems have lower yields in terms of live weights of animals at slaughter, and milk and egg production (WUR, 2002; FAO, 2002; USDA, 2002). In contrast to what the term grazing suggests, animals do not only graze. They are also fed, among other things, grains, peas and oil seed cake (Chapagain and Hoekstra, 2003). In particular, chickens, broilers and laying hens consume large amounts of grains, in this so called grazing system (Mekonnen and Hoekstra, 2010b). Traditionally, grazing systems often occupy marginal lands which are not suitable for producing arable crops for human consumption. *Mixed systems* combine livestock farming with crop farming, producing the majority of the animal feed on the farm itself. These systems are very common and found throughout the world. Mixed cattle systems are the dominant systems for example in Brazil, China, Ethiopia, India, New Zealand and the United States. Mixed farming systems supply about 54 per cent of the world meat production and 90 per cent of world milk (FAO, 1995). *Industrial systems* have high stocking rates per hectare and less than ten percent of the animal feed is produced at the farm itself (FAO, 2000). For cattle, industrial systems are the dominant farming system in for example Japan and western European countries. For pigs and chicken for meat, industrial systems have become the main system for most parts of the world.

2.2. The water footprint concept

To assess the volumes of water required for meat, we use the definitions and methodology of the water footprint as set out in Hoekstra et al. (2011). The water footprint is an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer. Water use is measured in terms of water volumes consumed (evaporated or incorporated into a product) and water polluted per unit of time. A water footprint can be calculated for a specific product, e.g. for meat or milk, and for any well-defined group of consumers or producers. The water footprint is a geographically explicit indicator, showing not only volumes of water use and pollution, but also the locations.

We distinguish green, blue and grey water footprints. The *green* water footprint is the volume of rainwater consumed during the production process, for example the rainwater to grow pasture or feed crops for cattle. It refers to the total rainwater evapotranspiration from fields plus the water incorporated into the harvested products. The green water footprint is an indicator of the human use of so-called green water, water that refers to the precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this water evaporates or transpires through plants. Green water can be made productive for crop growth. Not all the green water, however, is available for crops. It is partly lost, because there is always evaporation from the soil and not all the annual periods are suitable for crop growth. The *blue* water footprint is an indicator of consumptive use of so-called blue water. It is defined as the volume of surface and groundwater consumed as a result of the production of a good or service. It can refer, for example, to the irrigation water consumed to grow maize. Consumption refers to the volume of freshwater used and then evaporated or incorporated into a product. The *grey* water footprint of a product, e.g. beef, is an indicator of freshwater pollution that can be associated with the production of the product over its full supply chain. The grey water footprint is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards. It is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards (Hoekstra et al., 2011).

It is important to consider the different components separately, because the green WF refers to rainwater consumption, while the blue and grey water footprint refer to the appropriation of rivers and groundwater. The blue water footprint refers to the consumptive use of rivers and groundwater, while the grey water footprint refers to the pollution of rivers and groundwater (expressed in terms of polluted water volume). The distinction between the green and blue water footprint is important because the hydrological, environmental and social impacts, as well as the economic opportunity costs of surface and groundwater use for production, differ from the impacts and costs of rainwater use.

The water footprint provides a useful overall number for the volume of fresh water appropriated and thus enables a comparison of water demands from different products or a comparison of the water demands for a particular product originating from different countries or production systems. For estimating local environmental impacts of water use, the water use needs to be evaluated in the context of local water scarcity (Hoekstra et al., 2011), however this has not been part of the scope of the current study.

2.3. Major factors in the water footprint of an animal product

The water footprint (WF) of a specific piece of meat or specific amount of another animal product is determined by the water consumption and pollution in each specific process step within the supply chain of the final product. From the perspective of water consumption and pollution, the most important processes are growing the feed, drinking by the animals and water use on the livestock farm and at the slaughter house for cleaning. In the supply chain of an animal product there are many more processes than growing feed, drinking by the animal and cleaning the farm with water. Each of these processes will involve materials and energy that by themselves have again a supply chain and water footprint involved, but all these components are very small – a few per cent at most – of the total water footprint of the final animal product (Hoekstra et al., 2011). Among the three processes studied here – feed production, drinking and cleaning farms and slaughter houses – the first one is again the major factor (Mekonnen and Hoekstra, 2010b).

The water footprint of an animal product depends on two main factors: (i) How much the animals eat, measured as the feed conversion efficiency, which is defined as the amount of feed dry mass input to produce a unit of meat output, and (ii) What the animals eat and the water footprint of the livestock feed. The water footprint of the total feed package depends on the feed composition and the origin of the various feed ingredients. Almost all human water use, 92 per cent of the total, takes place in agriculture (Mekonnen and Hoekstra, 2011). The water use for meat in the rest of the chain, from farm to fork, is a minor part of the total water footprint of animal products. We included the water needed for drinking and servicing, for mixing the feed, and for processing the meat. We excluded the water use in households. Figure 1 schematically shows the factors determining the water footprint of an animal product. An important underlying factor is the type of production system, since the type of system influences the feed conversion efficiency, the feed composition and the origin of the feed. A factor that is included in the scheme, but which is quantitatively very small, is the water consumed for drinking and other on-farm activities.

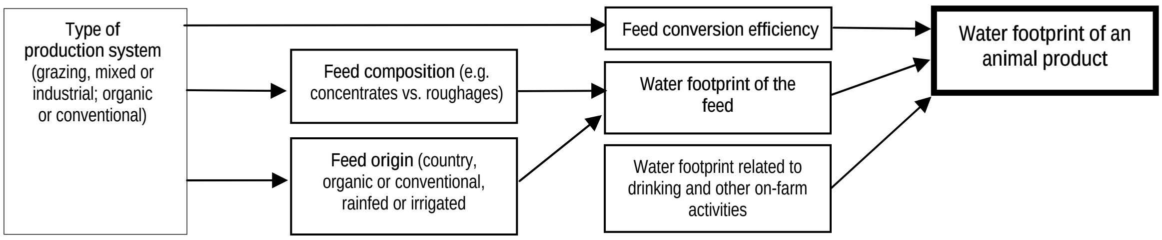

Figure 1. Factors determining the water footprint of an animal product. Three important factors are feed conversion efficiency, feed composition and feed origin, which are all partly influenced by the type of production system.

Figure 2 shows that the feed conversion efficiency depends on the type of production system. To make feed conversion efficiencies comparable, we look at three types of meat: poultry, pork and beef. In general, feed conversion efficiency improves from grazing to mixed systems and from mixed to industrial systems. Furthermore, feed conversion is more favourable for poultry and pork than for beef. Large differences in feed conversion efficiency occur between regions. For example, beef cattle need 40 kg of feed (dry mass) per kg of output in North America and 163 kg of feed (dry mass) per kg of output in South Asia (Mekonnen and Hoekstra, 2010b). It is affected by the higher level of physical activity of the animals, age at slaughter and breed.

The second main factor influencing the water footprint of an animal product is the water footprint of the animal feed. This depends on the composition of the feed and the origin of the feed (see details on animal feed in Appendix I). In general, industrial production systems have a relatively large fraction of concentrates in the animal feed and grazing systems a relatively small fraction. Figure 3 shows the average fraction of concentrate feed in the total feed for three meat types (poultry, pork and beef) in three production systems (grazing, mixed and industrial). For each type of meat, a declining trend in the concentrates fraction is shown when moving from industrial to grazing systems. It is also seen that – apart from differences caused by the type of production systems – chickens and pigs rely more heavily on concentrates than do beef cattle. In industrial pork systems concentrates make up 100 per cent of the feed.

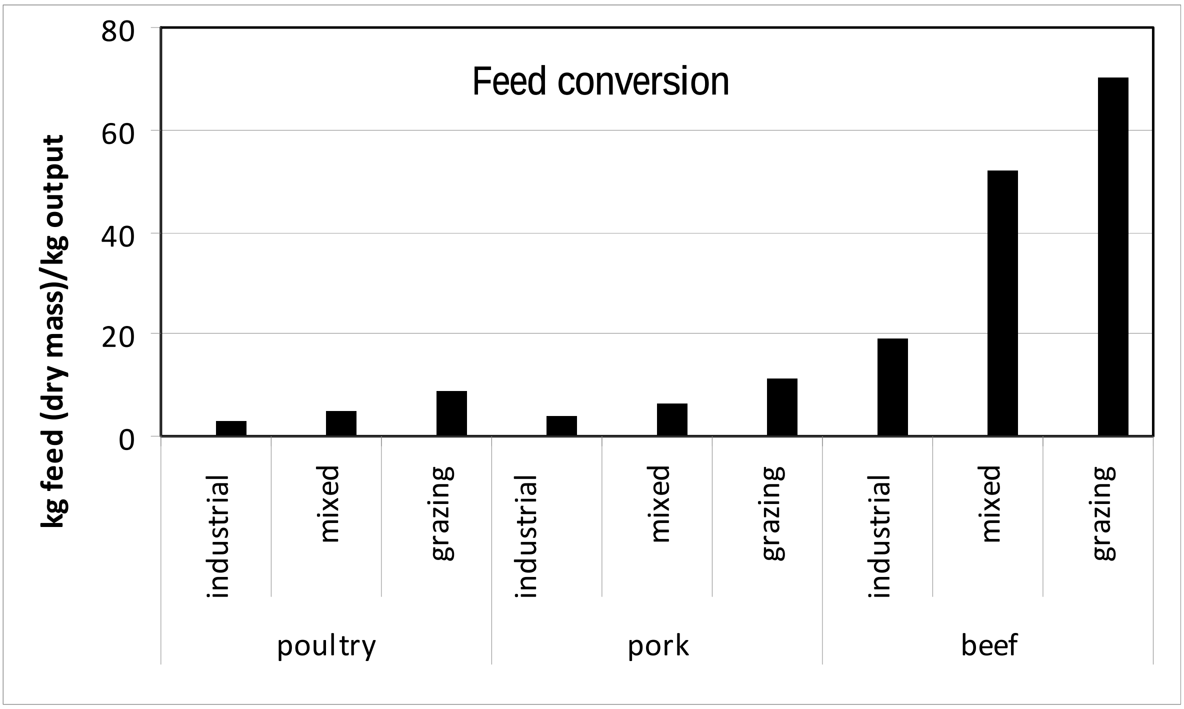

Figure 2. Average feed conversion for three types of meat for three types of production systems.

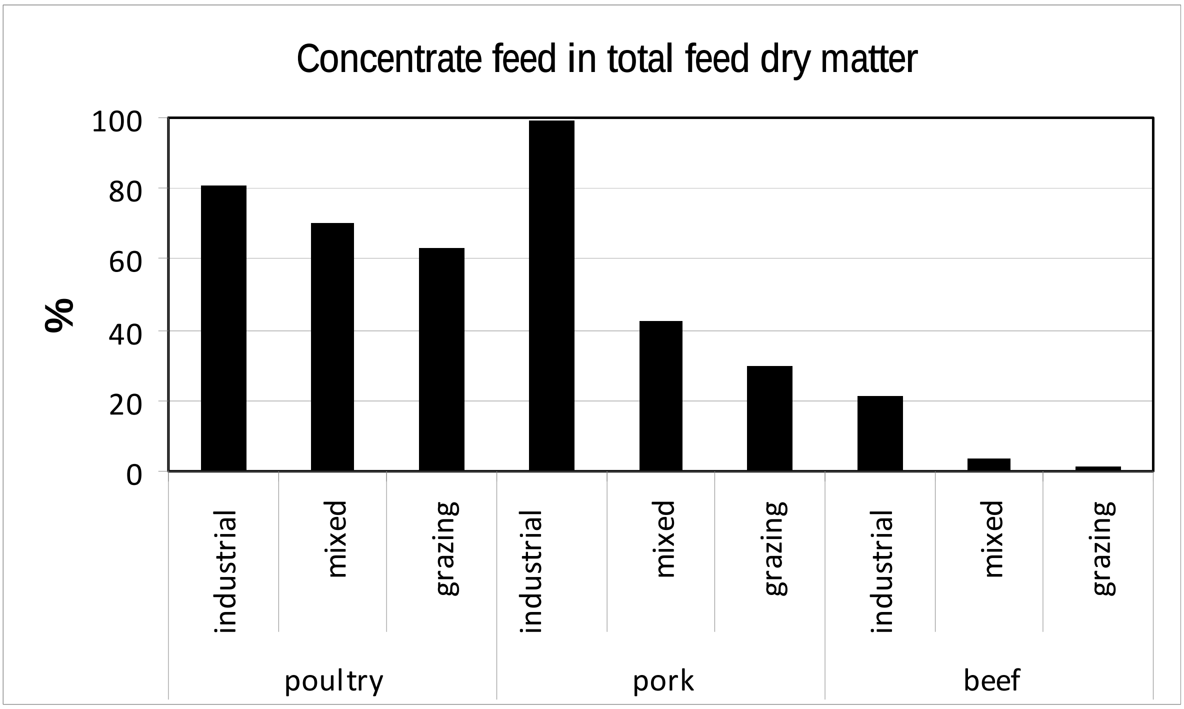

Figure 3. The average fraction of concentrate feed in the total feed for three types of meat for three types of production systems. The fraction of concentrates is important because concentrates have a larger water footprint than roughages.

Since the water footprint of meat is dominated by the water footprint of the animal feed, the composition of the feed is an important factor. Table 1 shows that there are large differences between water footprints (m^3 of water per tonne of feed) for the two main components of animal feed, the concentrates and the roughages. Feed concentrates have a relatively large water footprint, while roughages have a relatively small water footprint. In general, the water footprint of concentrates is five times larger than the water footprint of roughages. While the total mixture of roughages (grass, crop residues and fodder crops) has a water footprint of around 200 m^3/tonne (global average), this is about 1,000 m^3/tonne for the package of ingredients contained in concentrates. As roughages are mainly rain fed and crops for concentrates are often irrigated and fertilized, the blue and grey water footprint of concentrates are 43 and 61 times that of roughages, respectively.

Table 1. Average water footprint (m^3/tonne) of concentrates versus roughages.

	Green WF	Blue WF	Grey WF	Total WF
Concentrates	849	78	122	1048
Roughages	199	1.8	2	203
WF concentrates compared to WF roughages	4.3×	43×	61×	5.2×

Figures 2 and 3 together provide an interesting background to help understand the water footprint of animal products, because the feed dominates the water footprint for meat. Industrial systems use relatively large amounts of concentrates, causing a larger WF of the resultant products (in m^3/tonne) than grazing systems that use less concentrates. On the other hand, the more favourable feed conversion efficiency of industrial systems compared to mixed and grazing systems, suppresses the WF of the resultant products. The final WF is the net result of these two factors that influence the WF in two opposite directions. In some specific cases, the favourable effect of the feed conversion efficiency in an industrial system will override the unfavourable effect of the feed composition, so that the industrial system turns out to have a smaller water footprint. In other cases it will be the reverse. The net result may be different for the green, blue and grey water footprint. Since concentrates have a much larger water footprint than roughages, significantly if one considers the blue and the grey water footprint, it is the blue and the grey water footprint in particular that can be expected to be greatest in the water footprint of industrial systems.

The green, blue and grey WFs of feed ingredients differ between countries and depend on factors like climate, agricultural productivity (yields per unit of land), irrigation and fertilizer use. WFs of crops and feed ingredients are available for all countries in the world from Mekonnen and Hoekstra (2010a). However, figures are provided at a high level of spatial detail, the water footprint of one specific feed crop can differ between two adjacent farms, simply because of different practices between the farms regarding, for example, soil management and fertilizer and pesticide use.

2.4. Method for estimating the water footprint of meat

In this study, green, blue and grey WFs were assessed for three types of meat (beef, pork and poultry) for three types of production systems (grazing, mixed and industrial systems). This was done for four countries: Brazil, China, the Netherlands and the United States. The grazing system for beef in the Netherlands was not studied, as this system does not exist in the country. The water footprint of cattle, pigs and poultry was calculated as the sum of the water footprints related to feed, drinking and other on-farm and slaughter house activities. The water footprint of feed was calculated per type of animal, per type of production system and per country by multiplying the amounts of the various feed ingredients with their respective water footprint (accounting for the origin of the feed) and adding the water footprint related to mixing of the feed ingredients and processing the meat. Data was derived on feed ingredients, specific water footprints for feed ingredients and for mixing and processing (m^3 per tonne) from Mekonnen and Hoekstra (2010b). Following the method of Hoekstra et al. (2011), the water footprint of meat was calculated based on the water footprint of the animal at the end of its lifetime, the water consumed for processing the slaughtered animal into meat, the amount of meat derived from one animal, and the relative value of meat compared to the value of other products derived from the animal.

3. Results

In general, the water footprint of meat is dominated by the green portion of the water footprint. The blue and grey WFs are proportionately much smaller (Table 2).

Table 2. Green, blue and grey water footprint (litre/kg) of poultry, pork and beef for four countries and the world on average, specified by production system.

	Brazil			China			Netherlands*			United States			Global average		
	Graz.	Mix.	Ind.	Graz.	Mix.	Ind.	Graz.	Mix.	Ind.	Graz.	Mix.	Ind.	Graz.	Mix.	Ind.
Poultry															
Green WF	6363	4073	3723	4695	3005	1940	2535	1509	1548	2836	1688	1731	7919	4065	2337
Blue WF	35	32	32	448	296	201	113	76	78	294	182	187	734	348	210
Grey WF	364	233	213	1414	905	584	271	161	165	497	296	303	718	574	325
Pork															
Green WF	5482	5109	8184	11134	5401	3477	4048	3653	3776	5118	4953	3404	7660	5210	4050
Blue WF	1686	824	211	201	352	534	475	302	233	866	740	559	431	435	487
Grey WF	318	316	525	738	542	427	587	451	427	890	916	634	632	582	687
Beef															
Green WF	23729	20604	8422	16140	13227	10922	-	10319	3934	19102	12726	2949	21121	14803	8849
Blue WF	147	185	144	211	336	931	-	758	346	522	544	354	465	508	683
Grey WF	16	61	244	0	103	1234	-	664	225	590	768	551	243	401	712

Graz. = grazing; Mix. = mixed; Ind. = industrial

* Note: There is no grazing system for beef in the Netherlands.

Poultry

The average green WF of poultry per production system is shown for the four countries studied here – Brazil, China, the Netherlands and the United States – in Figure 4a. The average blue and grey WF are shown in Figures 4b and 4c. The total WFs are given in Appendix II. For poultry, industrial systems use 3.2 times less feed (dry mass) per unit of output than grazing systems (Mekonnen and Hoekstra, 2010b). The differences in feed composition of the different production systems are small: grazing production systems use a feed package that contains 63 per cent of concentrates, industrial systems have a feed package with 80 per cent of concentrates, while the mixed systems use feed packages with concentrate fractions in between. Since the feed compositions among the different systems are quite comparable, the water footprint of poultry is mainly determined by one factor – the feed conversion efficiency that varies across countries. This results in a smaller green, blue and grey water footprint for the industrial system if compared to the grazing system. This is in line with the global findings in Mekonnen and Hoekstra (2010b). For the US and the Netherlands the mixed and industrial poultry systems have similar water footprints. The blue WFs for poultry from the Chinese and the US industrial systems are similar to the global average of 200 litre per kg of poultry, while the blue water footprints of the grazing and mixed systems in these countries are smaller than the global average. For Brazil and the Netherlands, blue water footprints of all production systems are much smaller than global average numbers.

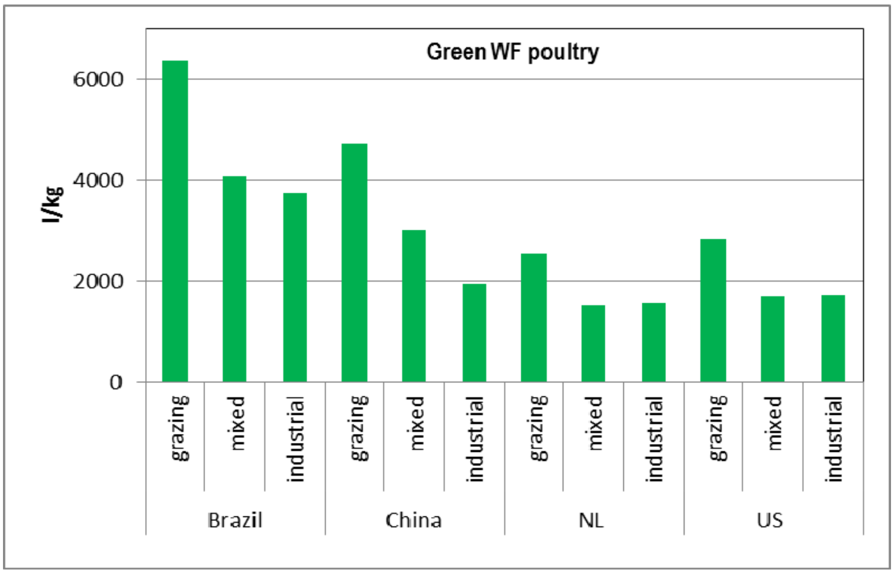

Figure 4a. Green water footprint of poultry for four countries and three production systems.

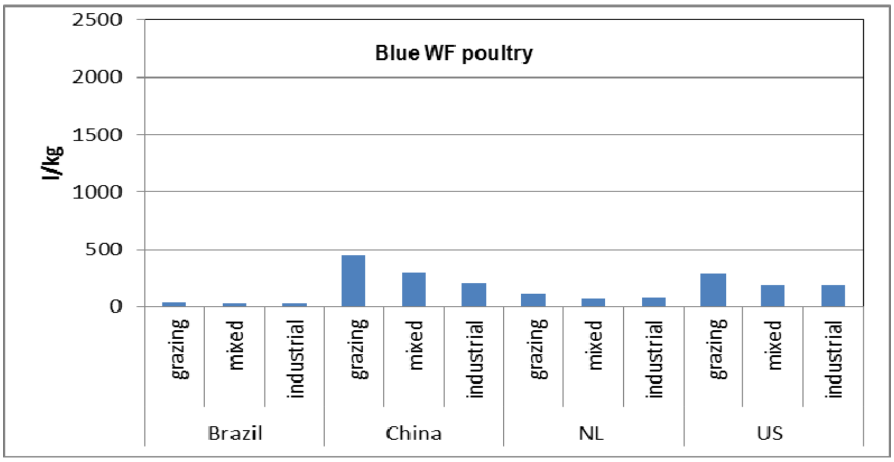

Figure 4b. Blue water footprint of poultry for four countries and three production systems.

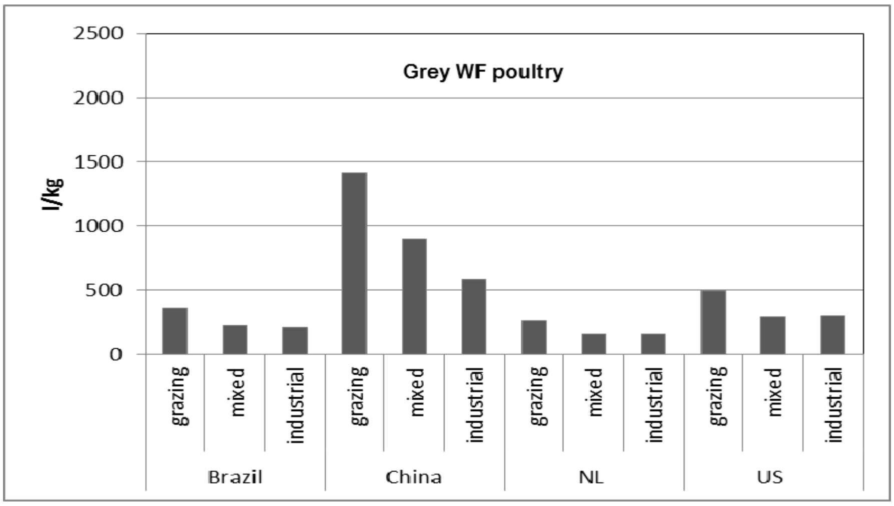

Figure 4c. Grey water footprint of poultry for four countries and three production systems.

Pork

Figure 5a shows the green WF of pork per country and production system; Figures 5b and 5c show the blue and grey WF. Feed conversion efficiencies improve from grazing to mixed to industrial systems. Industrial systems use on average 2.9 times less feed than grazing systems to produce the same amount of pork (Figure 2). The industrial pork systems use only concentrate feeds, with a relatively large WF. Concentrate percentages are much lower for mixed and grazing systems (Figure 3). The effect of the large concentrate share in the total feed and the fact that concentrate feed has a larger WF than roughages becomes visible in the green WF of industrial pork in Brazil. The fodder crops used in grazing pig systems in Brazil are largely replaced by maize in industrial pig systems. The green WF of maize is much larger than the green WF of the fodder crops, so that – although the amount of maize in industrial systems is less than the amount of fodder crops in grazing systems – in Brazil the total green WF per unit of pork turns out larger for industrial systems compared to grazing systems. In China and the United States, the differences in feed conversion efficiency between industrial and grazing systems are so large, that the favourable feed composition of the grazing system doesn't compensate. In the Netherlands, the resultant green WFs are similar for the three production systems. Figure 5b shows that for Brazil, the Netherlands and the US, blue WFs of pork decrease from grazing to mixed to industrial systems. The global average trend and the data for China, however, show a smaller blue WF in grazing than mixed and the largest WF in industrial pork production (Mekonnen and Hoekstra, 2010b). For grey WFs we find no general trend among the four countries. The grey WF of pork is relatively large in the United States for grazing and mixed systems, and in China for grazing systems. Grey WFs are relatively small in Brazil for grazing and mixed systems. The global average indicates a slightly smaller grey WF in mixed, then grazing than industrial systems.

Beef

Feed conversion efficiency in beef production improves from grazing and mixed to industrial systems. Industrial systems use 3.7 times less feed than the grazing systems to produce the same amount of beef (Figure 2). The fraction of concentrates in the total feed mix, however, is larger for the industrial systems than for the mixed and grazing systems. Figure 3 shows that concentrate percentages range from 2 per cent for grazing systems, to 4 per cent for mixed systems to 21 percent for industrial systems. Figure 6a shows that for the green water footprint the combined effect of the two factors is that green WFs decrease from grazing and mixed to industrial systems. For blue and grey WFs in beef production, we show a general trend of higher WFs in industrial systems in Brazil and China (Figures 6b and 6c). Global average blue and grey WFs for beef increase from grazing to mixed to industrial systems (Mekonnen and Hoekstra, 2010b). Figure 6b shows that China and Brazil are in accordance with the global average picture. In the Netherlands and the United States, however, we do not observe the global trend. In these countries, the mixed systems show the largest blue WFs. The small blue and grey WF of beef in grazing and mixed systems in Brazil and China show that these are systems where cattle graze in pastures that are not fertilized and are fed crop residues. This is not the case in the Netherlands and the US where cattle are supplemented with concentrates (especially in winter). The figures do not show data for grazing beef in the Netherlands, because this system is rare in the country.

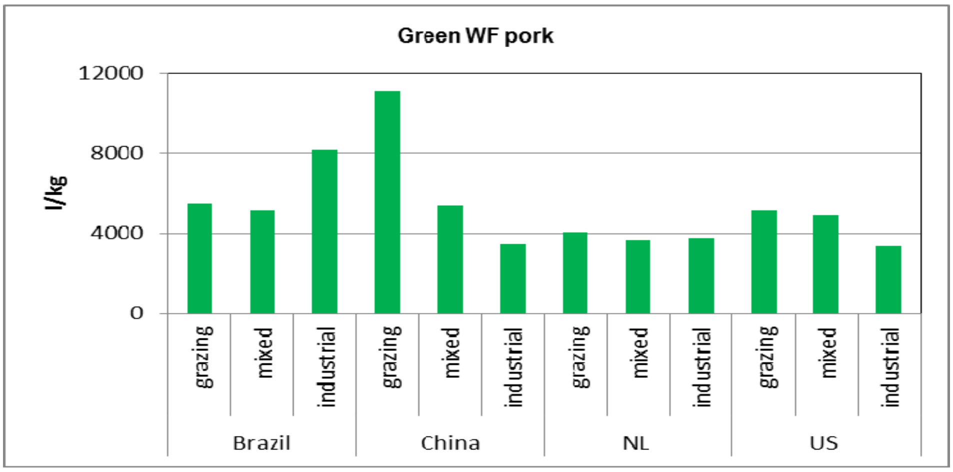

Figure 5a. Green water footprint of pork for four countries and three production systems.

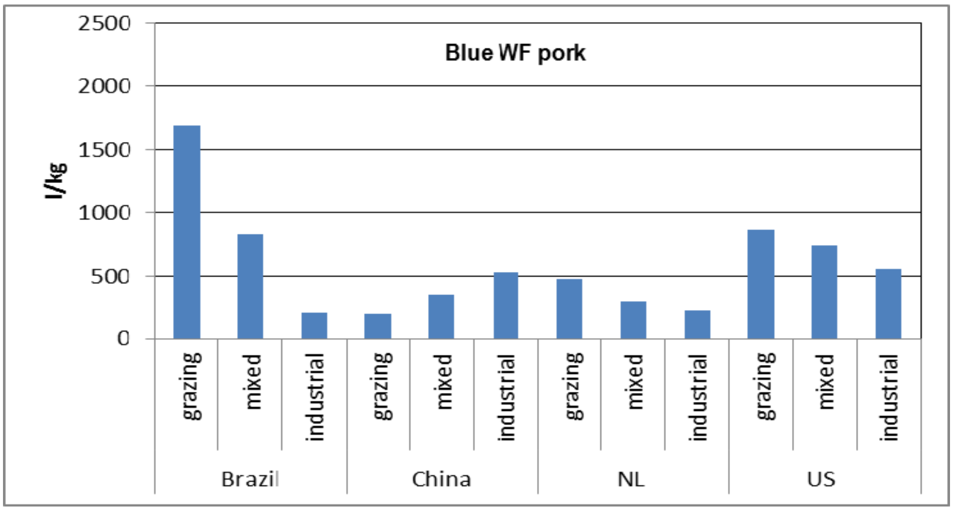

Figure 5b. Blue water footprint of pork for four countries and three production systems.

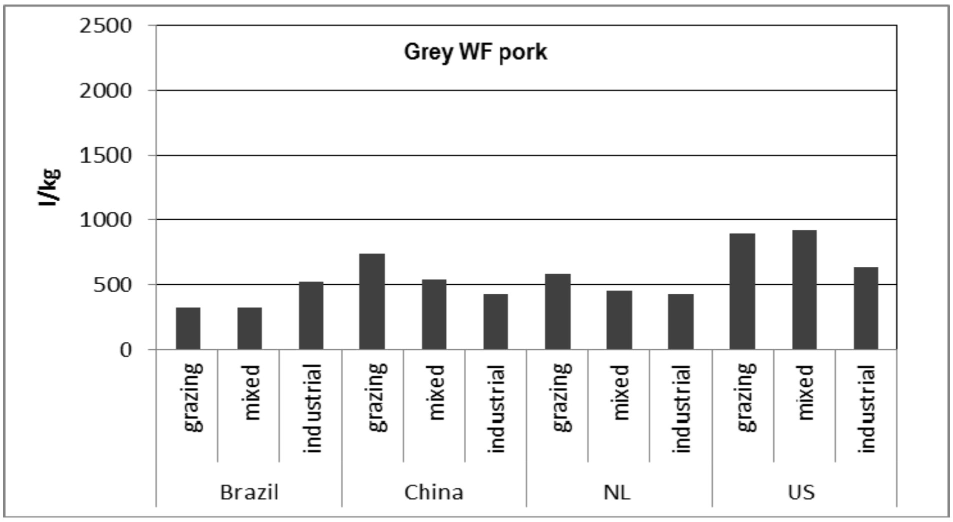

Figure 5c. Grey water footprint of pork for four countries and three production systems.

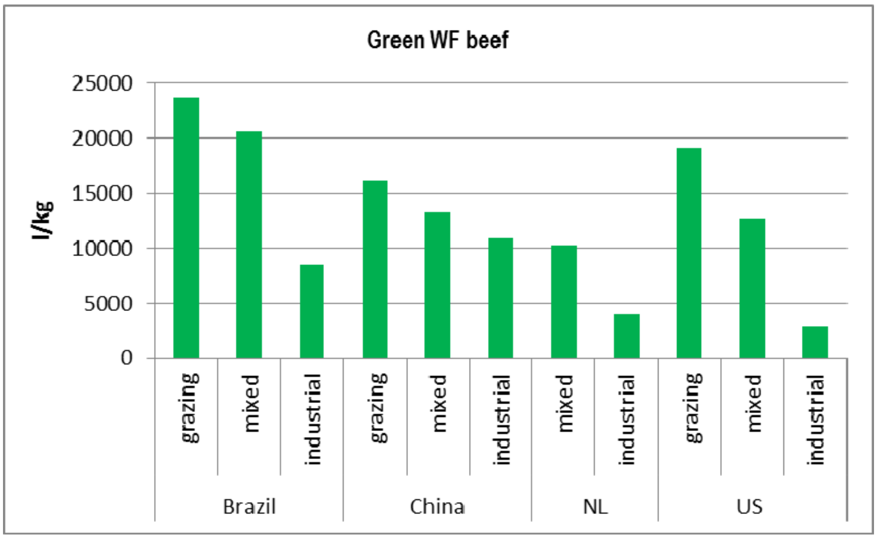

Figure 6a. Green water footprint of beef for four countries and three production systems. Note that there is no grazing system for beef in the Netherlands.

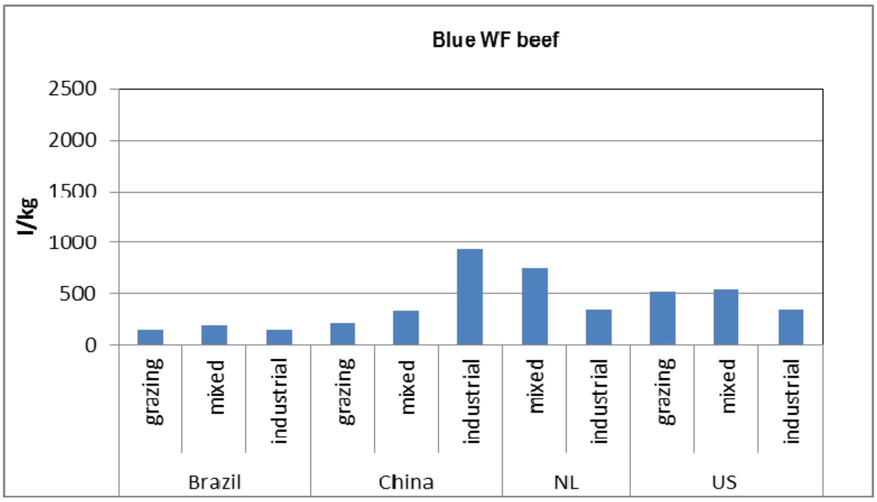

Figure 6b. Blue water footprint of beef for four countries and three production systems.

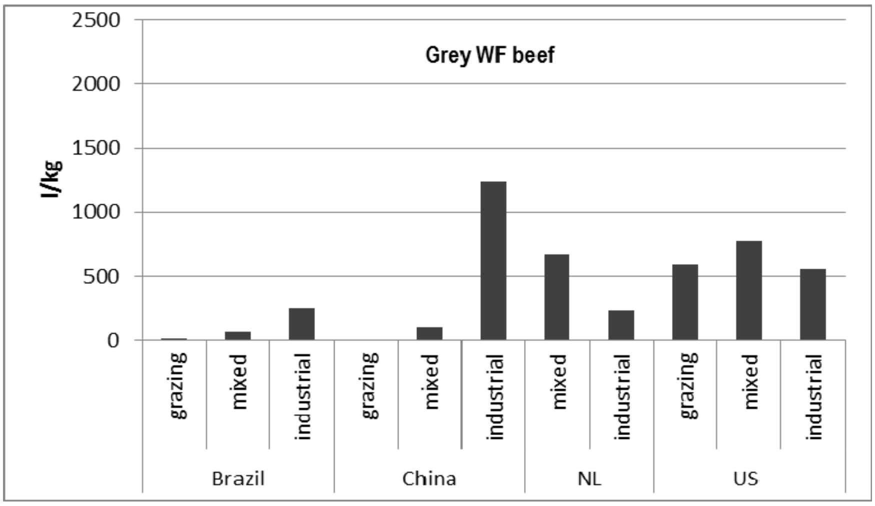

Figure 6c. Grey water footprint of beef for four countries and three production systems.

The differences can be explained by looking more closely at the feed composition of the different systems in the four countries. Figures 7a, b and c show the green, blue and grey water footprint of the feed components of beef for the four countries and the three production systems.

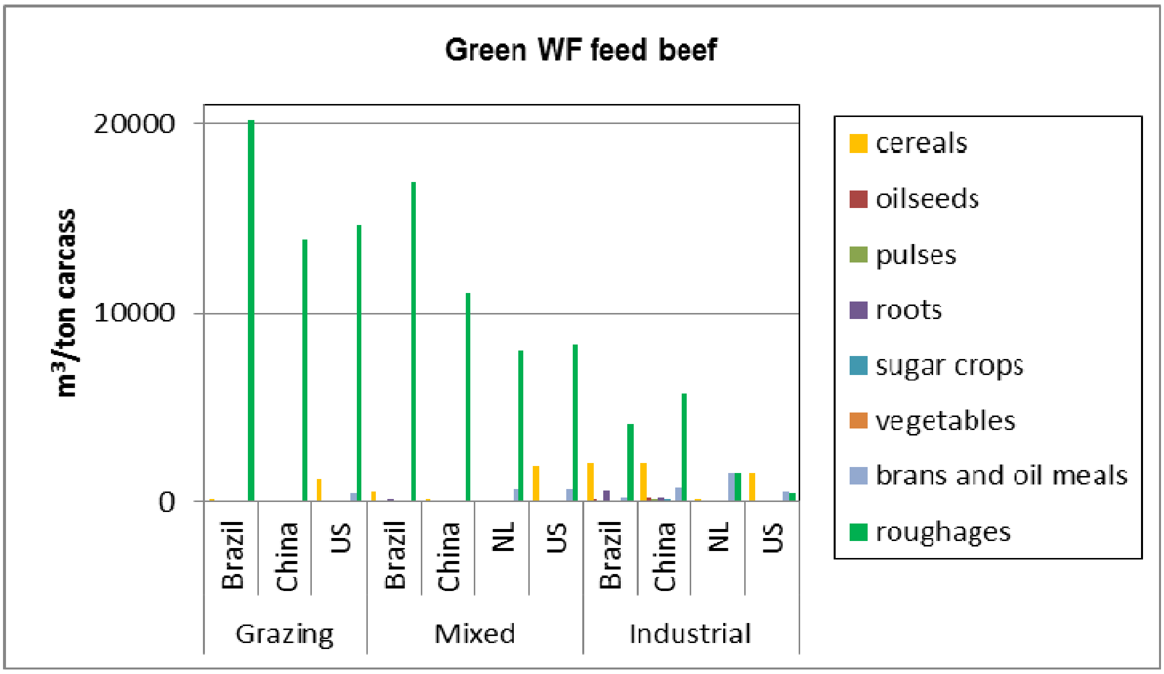

Figure 7a. Green water footprint of beef per feed component for four countries and three production systems.

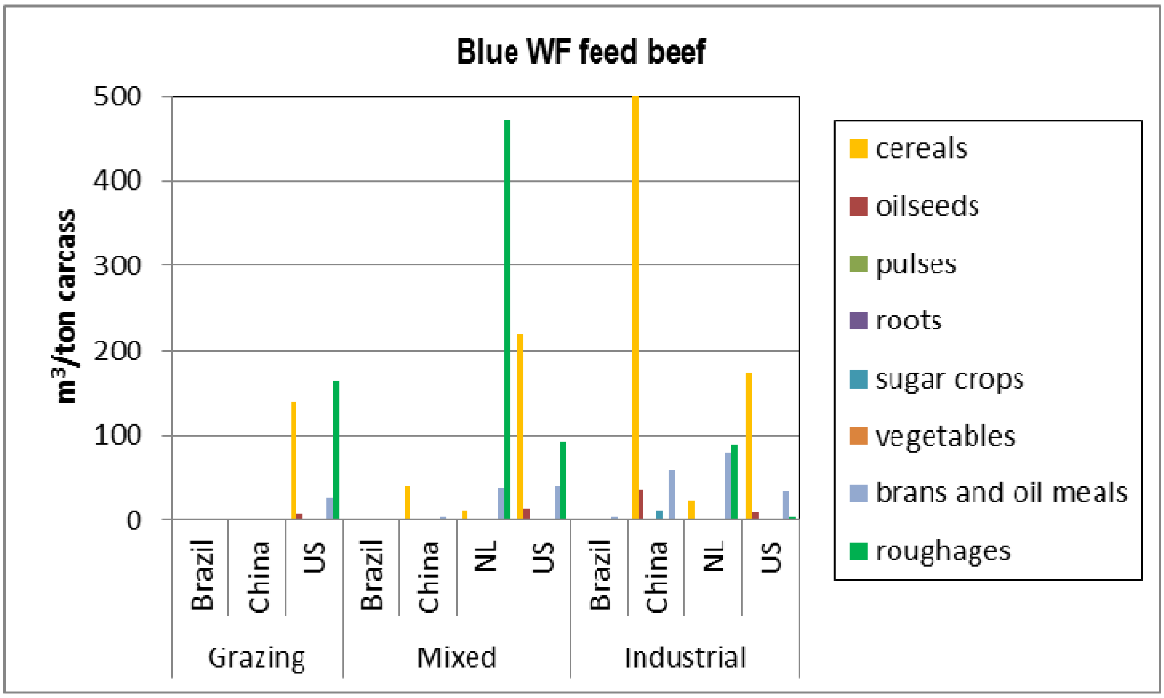

Figure 7b. Blue water footprint of beef per feed component for four countries and three production systems.

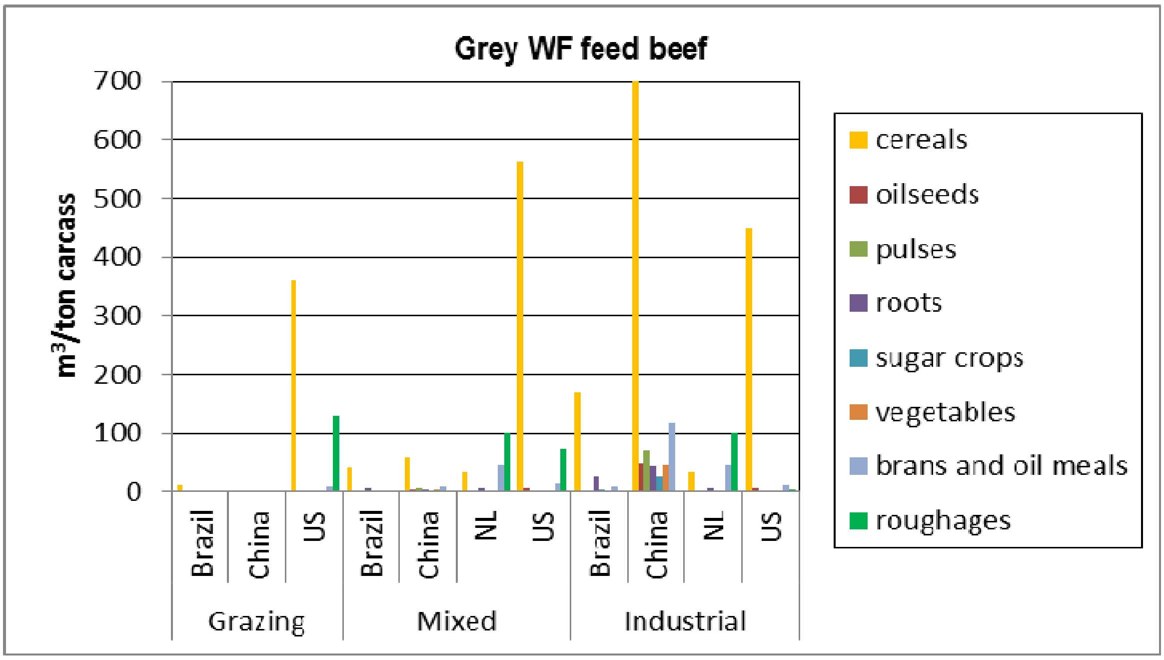

Figure 7c. Grey water footprint of beef per feed component for four countries and three production systems.

Production systems in the United States differ from the other countries in the feed they provide for cattle. Cattle in US grazing systems are also fed large amounts of grains, predominantly maize, which is irrigated and fertilized. Differences were also observed among similar production systems in the four countries. In Brazil and China in grazing and mixed systems, cattle are mainly fed on pasture and crop residues that have no blue and grey WFs. Another difference is that the concentrates in Chinese industrial systems have relatively large blue and grey WFs, resulting in a large total blue and grey WF for Chinese beef. This is because Chinese concentrates are dominated by maize and paddy rice which are irrigated and fertilized. In the United States in grazing and mixed systems, cattle are fed a combination of roughages (pasture) and concentrates (grains), and in the Netherlands in mixed systems, cattle are fed with roughages, a combination of pasture and fodder crops. We assumed that there is no blue and grey WF related to the production of pasture, but grains and fodder crops do have blue and grey WFs. In other words, systems that belong to the same category, grazing, mixed or industrial, differ in the feed they provide to animals. Often, the feed ingredients have different WFs, resulting in differences in the total green, blue and grey WF of the meat.

4. Discussion

4.1. Limitations

The study is based on the report of the green, blue and grey water footprint of farm animals and animal products by Mekonnen and Hoekstra (2010b). That study used a top down approach from a country perspective. It has encountered many uncertainties. For example, there was no data available for animal distribution over the three different production systems for the OECD countries, so the study had to make assumptions. Alongside this, the precise feed composition per animal category per country was not available. Therefore, the study estimated the average amount of feed consumed per animal category for the three production systems. Results for a specific country or case, therefore, might differ from the OECD or country average. Where differences occur between systems, e.g. animal production systems with high or low levels of animal welfare, it would be interesting to assess related differences in water footprints. That would require information on specific farm conditions.

Another issue is that assessments for grey water footprints were made that only took into account leakage of artificial nitrogen fertilizer in feed crop production. The use of other fertilizer ingredients and pesticides were excluded. Due to limited data availability, the grey WF of manure when brought back on the land in excessive amounts is also not assessed, nor is the potential grey WF related to the use of antibiotics in wastewater from industrial farms. In this way, grey water footprints are underestimated, particularly in industrial systems. Industrial systems rely more heavily on concentrate feed, the production of which often includes the intensive use of fertilizers and pesticides, which partly leach into the groundwater or run off to surface water bodies. Furthermore, in grazing and mixed systems manure is part of the system of recycling nutrients, while in industrial systems manure is instead a waste, often disposed onto limited available lands thereby contributing to leaching of nutrients and thus the eutrophication of water bodies.

For pastures, it was assumed that they are not irrigated or fertilized. However, in some countries, for example in the Netherlands, pastures receive fertilizers and are sometimes irrigated in dry periods. The assumption that pasture does not have a blue and grey WF leads to an underestimation of blue and grey WFs for those systems with a large use of fertilized and irrigated pasture, for example the mixed and industrial Dutch beef systems.

This study relies on a definition of feed conversion efficiency that considers feed input per unit of meat output. Although this is a common approach in livestock studies (Hendy et al, 1995; Bouwman et al., 2005), this approach ignores the fact that feed may have various origins and rely on natural resources of different qualities. One can argue that efficiency is more than turning an amount of feed into another amount of meat; efficiency is also about efficient use of resources that offer different opportunities. Cows using marginal land which is unsuitable for producing crops for human consumption can be considered to be efficient, whereas cows or other animals eating from land that could also produce crops for direct human consumption is less efficient (Gill et al., 2010). The problem here is that the concept of efficiency can actually be interpreted in alternative ways. A further investigation would be needed to evaluate from different perspectives the efficiency of the use of rain fed marginal lands for grazing and foraging versus the efficiency of the use of arable land and irrigation water to produce feed for animals in industrial systems. With the water footprint figures in this study the distinction has been made between green water (rainwater) and blue water (irrigation water withdrawn from ground or surface water), but the scarcity of the water in the places where the water footprints are located or the extent to which the water could be applied for alternative purposes has not been considered. Particularly when cattle graze on marginal lands and fully depend on green water, there are few alternative uses for these natural resources (apart from leaving them to nature).

4.2. Implications

The water footprint of any type of meat is determined mostly by the feed of the animals (Mekonnen and Hoekstra, 2010b). Globally, the main component of the WF of animal feed relates to pasture (38 per cent of the total water footprint), followed by maize (17 per cent), fodder crops (8 per cent), soybean cake (7 per cent), wheat (6 per cent), barley (6 per cent) and oats (3 per cent). Specific production systems in individual countries, however, deviate from these global figures. In the Netherlands, for example, the feed industry uses large amounts of cassava for pig feed. In general, feed concentrates have relatively large blue and grey water footprints, while crop residues, waste and roughages have relatively small water footprints. Industrial systems use a lot of feed concentrates and these generally have a higher blue and grey water footprint than pasture or roughage. A shift in food consumption patterns towards greater consumption of animal products would put pressure on production systems to produce more. This may also stimulate a shift from grazing and mixed to industrial systems with larger output per unit of feed. The combination of production increase and the shift towards more industrial systems will increase the use of feed concentrates in livestock production and overall water footprints of the livestock sector. Besides a total increase of the water footprint for total production, this would particularly increase the blue and grey water footprints per unit of product.

In this study, we were not able to establish a relationship between water footprints and animal welfare, either positive or negative. The reason is that it is not sufficiently clear how animal welfare relates to feed composition and feed conversion efficiency. Grazing and mixed systems have greater animal welfare potential than industrial systems. If we take those systems as a proxy for a high animal-welfare system, high animal welfare will have the advantages and disadvantages of mixed and grazing systems: lower water footprint because of the larger use of roughages compared to concentrates but a potentially larger water footprint because of reduced feed conversion efficiency.

An animal welfare issue that may relate to water footprint is the ban on the use of animal ingredients for livestock feed imposed by the European Union in an effort to prevent BSE. Although the initiative was taken to prevent humans from becoming ill, it also improves animal welfare. The feed ban, however, leads to the animal wastes in feed being replaced by other ingredients, for example soybeans, so that water footprints increase (assuming that the animal wastes are low-value products with a small water footprint). On the other hand, if eliminating the sub-therapeutic use of antibiotics is considered part of high welfare systems, this can reduce the grey water footprint of such systems compared to conventional industrial systems.

In organic agricultural systems, there is the advantage of a reduced grey water footprint related to the use of artificial fertilizer and pesticides use in feed crop production. In organic livestock farming, one of the principles is the strong attention paid to animal welfare. Some regulations dictate, for example, that organically reared animals have permanent access to open pasture, have roughage for feeding and that the feed meets their nutritional requirements at each stage of the animal's development (European Commission, 2011a).

Another issue is that in industrial systems animals are slaughtered at a very young age. Beef cattle in the US, for example, are slaughtered before they are two years old. This practice is efficient from an economic perspective, and also from a natural resources use perspective (including total water footprint), but not from an animal welfare perspective. The rapid animal growth in industrial systems is only possible due to the feed composition. Cattle in US feedlots are fed with large amounts of maize, an unnatural feed ingredient for cows that affects their stomachs (Pollan, 2006). This study has shown that the large blue and grey water footprint of maize nullifies the effect of the high efficiency, so that in the end, from a blue and grey water footprint perspective, the industrial and grazing systems in the US are comparable.

5. Conclusions

The water footprint of any sort of meat is determined mostly by the feed of the animals. We observe two main factors which drive the water footprints of poultry, pork and beef.

The first factor is the food conversion efficiency (how much feed dry mass is required to produce meat – irrespective of whether it is grazing forage or concentrates). There is an efficiency increase from grazing to mixed to industrial systems, because less feed is needed to produce a unit of meat as the animals in industrial systems are fed more concentrated feed stuffs, move less, are bred to grow faster and are slaughtered at a younger age. The factor contributes to a general decrease of the total water footprints, including green, blue and grey water footprints, from grazing to mixed to industrial systems.

The second factor is the feed composition (what the animals eat), more particularly the ratio of concentrates to roughages. There is an increase in the fraction of concentrates in animal feed from grazing to mixed to industrial systems. In general, concentrates have a larger water footprint than roughage. The second factor contributes to an increase of the water footprint, especially the blue and grey water footprint, from grazing and mixed to industrial systems.

The overall effect of the two factors depends on the magnitude of the two individual factors. Specific focus on the blue and grey water footprints is warranted because in the case of blue water (groundwater, surface water) agricultural water demand competes with various other human demands for water, like water demands for households and industries.

Water footprints for each meat type

For poultry, there are small differences among the feed compositions of the three production systems. Broiler feed is dominated by grains. In grazing systems, concentrates make up 60 per cent of the feed, in industrial systems 80 per cent. For poultry, the high feed conversion efficiency in the industrial systems results in smaller green, blue and grey WFs in those systems compared to grazing systems in the four countries studied. In the US and the Netherlands the mixed poultry systems have similar green, blue and grey water footprints if compared to the industrial systems.

For pork, the net result of the two opposite factors does not show a general direction. This is mainly caused by the large differences in the feed composition of pigs in the countries studied. Only for China was a decreasing trend observed of green water footprints from grazing, to mixed to industrial systems. In Brazil the industrial system has the largest green WF. In the Netherlands green WFs are almost the same for all systems. In the US, green WFs are the same for grazing and mixed systems and smaller for the industrial systems. Blue water footprints decrease from grazing, to mixed to industrial systems in Brazil, the Netherlands and in the US, but are greatest in industrial systems in China. Grey water footprints do not show a general trend. In China and the Netherlands they decrease from grazing, to mixed to industrial systems. In Brazil grey water footprints are smallest for grazing and mixed systems and largest for the industrial systems. In the US mixed systems have the largest water footprints and the industrial systems the smallest.

For beef, green WFs decline from grazing and mixed to industrial systems. For blue and grey WFs, Brazil and China follow the global trend that industrial systems have the largest blue and grey WFs (Table 2). In the US it is the other way around. In the Netherlands, where there is no grazing system for beef, the industrial system has a smaller blue and grey water footprint for beef than the mixed system. This has to do with specific characteristics of the composition of the feed. Globally, industrial systems have the largest blue and grey WFs for beef and grazing systems have the smallest blue and grey WFs.

Comparing beef versus pork and poultry

In general, feed conversion efficiencies are largest for poultry and pigs and smallest for cattle. This explains the general finding that beef has a much larger water footprint than poultry and pork. However, the large use of concentrates in the feed of broilers in all systems and of pigs in industrial systems causes a relatively large blue and grey WF for poultry and pork, in several cases larger than for beef.

Differences among countries

Large differences were observed between countries. The Netherlands shows efficient systems with relatively small total WFs for all meat types in all production systems. China has relatively large blue and grey WFs for beef from industrial systems. Brazil shows relatively large green WFs for poultry for all systems, for beef for grazing and mixed systems, and relatively large blue WFs for pork from grazing systems.

Reducing the water footprint of meat

Differences between countries indicate that there are possibilities to decrease water footprints of meat production by finding a proper balance between a low-WF feed composition and high feed conversion efficiency. The water footprint related to the consumption of animal products, globally 2,422 Gm^3 or one third of the total water footprint of agriculture, can also decrease by replacing animal products by food products of plant origin, or by reducing food waste**.** The water footprint of meat is in general far greater than the water footprint of plant based sources of equivalent foods (Mekonnen and Hoekstra, 2010b). As shown by Hoekstra (2010), the food-related water footprint of a consumer in an industrialized country can be reduced by 36 per cent by shifting from an average meat-based diet to a vegetarian diet. Chapagain and James (2011) found that in the UK the water footprint of avoidable food waste amounts to 6 per cent of the total water footprint of a UK citizen. The water footprint of food in general and of meat in particular can be significantly reduced by changes on the consumption side, but this would require a major transition in the present nutrition pattern and the generation of food wastes, especially in western countries.

Obviously, the water footprint of the livestock sector is only one of the concerns to be taken into account. Other factors include animal welfare, food security, public health concerns and environmental issues other than water, like contribution to emission of greenhouse gases.

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Appendix I: Animal feed

Livestock feed includes a large range of different feed ingredients grouped into two categories, roughages and concentrates. Roughages are feeds with a low nutrient density and high fibre content. Concentrates contain a high level of nutrients and are derived from crops (Hendy et al., 1995; FAO, 1983). Table I-1 gives an overview of the main sorts of components within concentrates and roughages.

Table I-1. Overview of the main sorts of components contained in concentrates and roughages.

Concentrates	Roughages
Cereals	Pastures
Roots and tubers	Forage (green) cereals
Oil crops and oil meals	High yielding grasses for silage
Brans	Fodder crops
Molasses	Other roughages (e.g. by-products such as straw)
Pulses	
Sugar crops	
Fruits and vegetables	

Feed packages of livestock show enormous variation and depend on the nutritional requirements of the animals and the availability and prices of the various optional ingredients. In the European Union, feed ingredients include roughages and concentrates and no processed animal based proteins. In 2006, the BSE-affair stimulated the EU to impose stringent regulations concerning the quality of livestock feed. The EU introduced a ban on feeding livestock for food purposes with processed animal based proteins (European Commission, 2011b; Elferink et al., 2007). Since there is good knowledge on the nutritional requirements of livestock and feed, the composition of concentrates can be designed using available feed ingredients and adding certain nutrients when necessary (Elferink and Nonhebel, 2007). Livestock feed requirements differ among animals and animal breeds and depend, among other things, on the age and activity of the animal (Field and Taylor, 2009). Modern breeds are bred to grow fast and produce high yields; these animals require a greater input of concentrated feeds to support their very high metabolic demands. The composition of concentrate feed shows large differences across countries and also changes in time. In general, chickens and pigs depend much more on concentrates than cattle and industrial systems use more concentrates than extensive systems. On average, the share of concentrates in the feed of chicken is 75% of the total dry mass intake. For pigs this is 55%, for dairy cows 27% and for beef cattle 5%. These are global averages (Mekonnen and Hoekstra, 2010b); percentages can be quite different across countries and production systems. For beef cattle in grazing systems, for example, the fraction of concentrates in the total feed is between zero (in China and Brazil) and six percent (in North America), whereas this is 10% to 75% for beef cattle in raised in industrial systems. Grazing systems, for example for beef, are dominated by the use of roughages produced at the farm itself, while industrial systems are disassociated from the land base and rely on concentrates from the feed industry. Pigs in industrial systems are generally fed on a diet based completely on concentrates.

Broiler feed

For broilers, feed and water must be available at all times (Field and Taylor, 2009). Broiler feed mainly consists of cereal grains, grain by-products, fats and protein sources. Grains include maize, wheat, sorghum, barley and oats. In general, a feed containing a variety of grain types has a better quality than a feed with only one grain type (Field and Taylor, 2009). Fats include animal and vegetal fats. Protein sources include plant and animal sources, such as soybean meal, cottonseed meal, peanut meal, corn gluten meal, fish meal, milk by-products, meat by-products, tankage (animal feed obtained from the residue from tanks in which animal carcasses have been rendered), blood meal and feather meal (Elferink et al., 2008). However, in the EU, processed animal based proteins, other than from fish, are not allowed. In addition to the feed, broilers are provided vitamin and mineral supplementation. Also, chemical feed additives, such as antibiotics may be used to promote growth.

Pig feed

Pigs are historically scavengers and in early domestication they were kept to utilize human food wastes (Elferink et al., 2008). For pigs producing pork, the choice of pig feed is dominated by the costs of the feed, because about 65 per cent of the cost of pork production is related to the feed (Elferink and Nonhebel, 2007). Pig feed is dominated by cereal grains: maize, grain sorghum, barley and wheat, including the by-products. The selection of grain type or combination of grain types for pig feed depends on the availability and relative cost. In general, cereal grains contain too little proteins, minerals and vitamins for pig needs. Therefore, the feed is enriched with other ingredients to attain recommended levels of nutrients, for example with soybean meal, and – outside the EU – meat, blood or bone meal. Other ingredients are pulses (peas, beans, lupines) and by-products from starch and sugar production. In the Netherlands, imported cassava is applied in great quantities (Elferink and Nonhebel, 2007). In addition, often amino acids (e.g. lysine), vitamins, and minerals (e.g. calcium and copper) are added. Next to this, pig feed is adapted to the specific requirements of pigs that depend on the growth rate in their life stage and on sex, i.e. the phase feeding and the split-sex feeding. The possibility to enrich pig feed with nutrients to comply with nutritional standards for pigs makes it possible to use a wide range of ingredients for pig feed (Elferink and Nonhebel, 2007).

Beef cattle feed

Beef cattle are mainly fed grass, 32 kg per kg carcass as a global average, followed by crop residues (22 kg per kg carcass), fodder crops (2.5 kg/kg) and maize (1 kg/kg carcass) (Mekonnen and Hoekstra, 2010b). There are large differences among countries, however. In the US in the 1940s, a practice started to feed cattle larger amounts of grains, replacing forage. Initially this resulted in over-fat cattle. Breeding programmes were initiated to genetically improve cattle that could produce leaner meat based on grain (Field and Taylor, 2009). Today, US beef production uses a feed combination of grass and grains. Calves are weaned at 6 to 12 months and then spend some time grazing until they are about 12 to 16 months. After that, they spend their time in a feedlot receiving a grain-based diet for six months. At 18 to 22 months, the cattle is slaughtered (Explore Beef, 2011). In the Netherlands, beef cattle are mainly fed with maize gluten pellets, by-products of starch production, citrus pulp and palm and oil seed scrap (Elferink and Nonhebel, 2007).

Appendix II: Total water footprint of poultry, pork and beef in Brazil, China, the Netherlands and the US

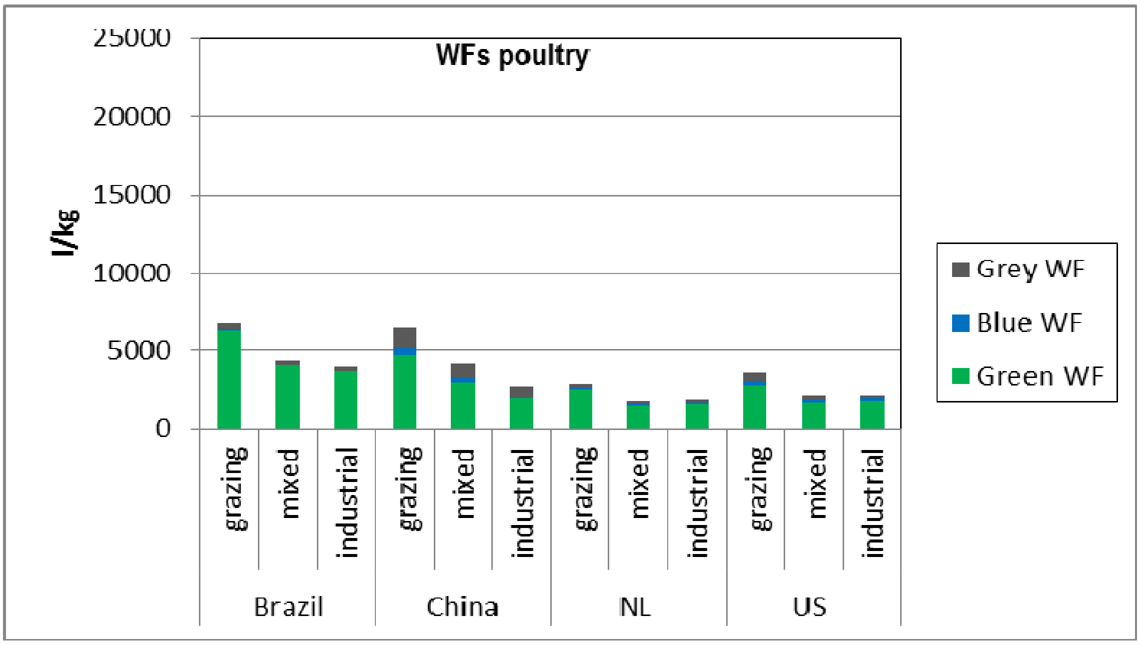

Figure II-1. Total water footprint of poultry for four countries and three production systems.

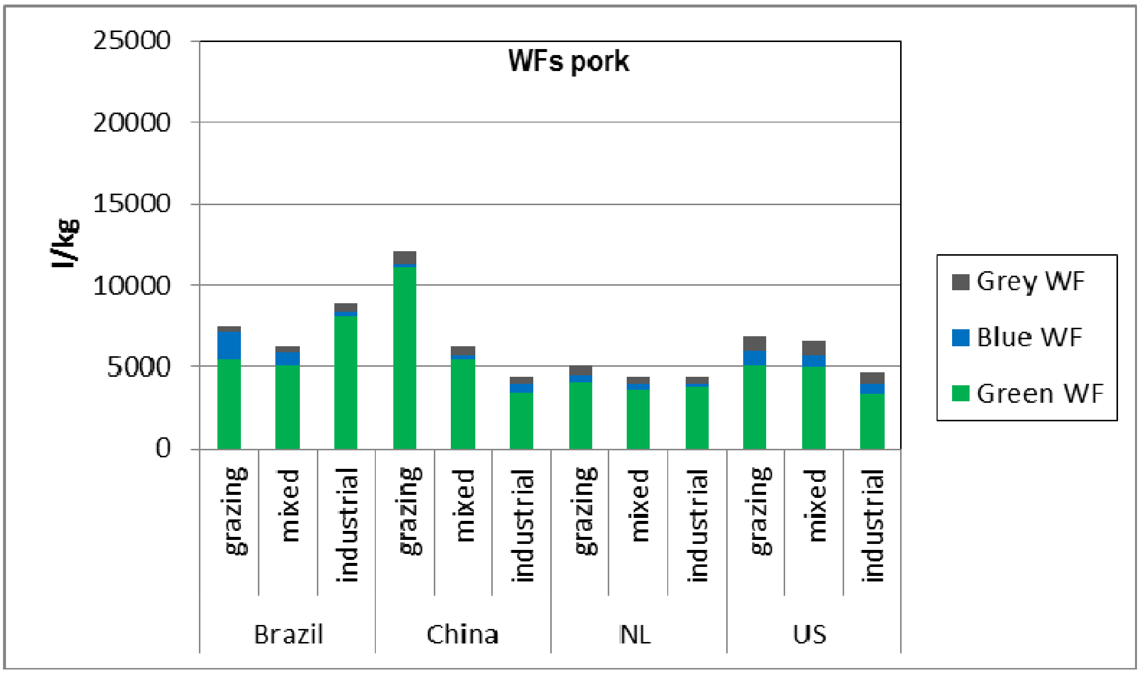

Figure II-2. Total water footprint of pork for four countries and three production systems.

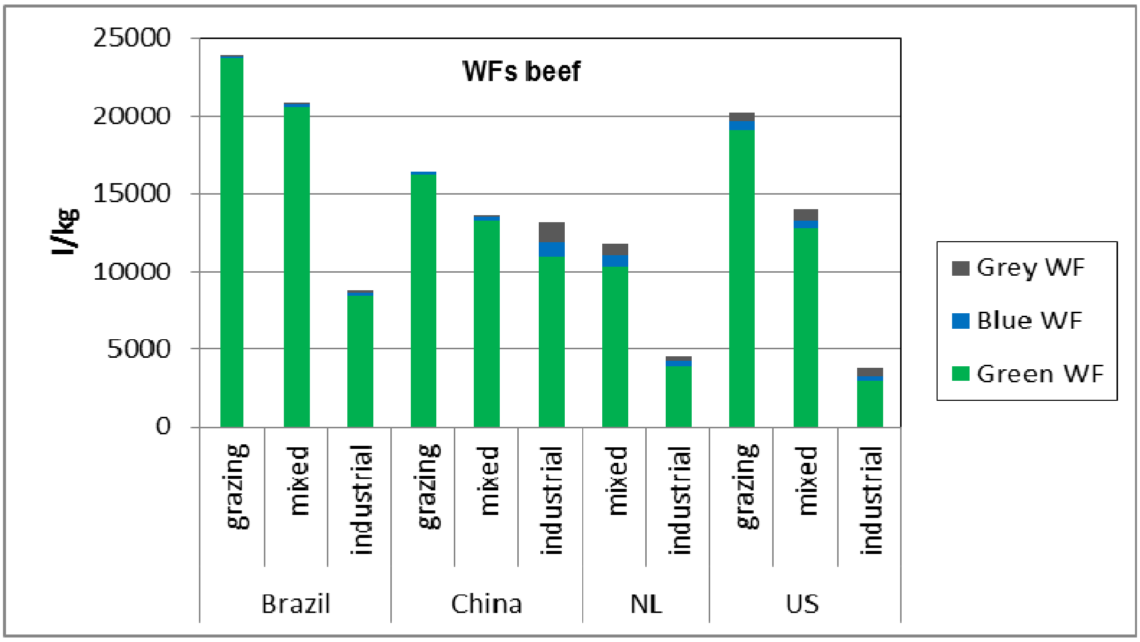

Figure II-3. Total water footprint of beef for four countries and three production systems. Note: there is no grazing system for beef in the Netherlands.

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