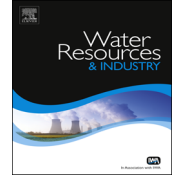




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The water footprint of poultry, pork and beef: A comparative study in different countries and production systems



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ABSTRACT

Agriculture accounts for 92% of the freshwater footprint of humanity; almost one third relates to animal products. In a recent global study, Mekonnen and Hoekstra (2012) [31] show that animal products have a large water footprint (WF) relative to crop products. We use the outcomes of that study to show general trends in the WFs of poultry, pork and beef. We observe three main factors driving the WF of meat: feed conversion efficiencies (feed amount per unit of meat obtained), feed composition and feed origin. Efficiency improves from grazing to mixed to industrial systems, because animals in industrial systems get more concentrated feed, move less, are bred to grow faster and slaughtered younger. This factor contributes to a general decrease in WFs from grazing to mixed to industrial systems. The second factor is feed composition, particularly the ratio of concentrates to roughages, which increases from grazing to mixed to industrial systems. Concentrates have larger WFs than roughages, so that this factor contributes to a WF increase, especially blue and grey WFs, from grazing and mixed to industrial systems. The third factor, the feed origin, is important because water use related to feed crop growing varies across and within regions. The overall resultant WF of meat depends on the relative importance of the three main determining factors. In general, beef has a larger total WF than pork, which in turn has a larger WF than poultry, but the average global *blue* and *grey* WFs are similar across the three meat products. When we consider

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grazing systems, the blue and grey water footprints of poultry and pork are greater than those for beef.

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1. Introduction

Food takes an important share in the total use of natural resources, such as water [2,23]. 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 (WF) of pork (expressed as litres per kcal) is two times larger than the WF of pulses and four times larger than the WF of grains [31]. Today, the global WF of animal production constitutes almost one third of the WF of total agricultural production [25] and this fraction is likely to increase [29].

Worldwide, a nutrition transition is taking place in which many people are shifting towards more affluent food consumption patterns containing more animal products [19,33,28]. 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 [27]. In recent decades, demand for animal products, such as meat, milk and eggs, has increased due to changes in food consumption patterns [2,15]. In affluent countries, the protein intake is generally larger than required, particularly due 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 [17]. If in developing countries, populations continue to increase, especially in combination with economic growth, as is expected in countries like Brazil and China [26,2], demand for animal products is predicted to increase. This would require more water.

Water consumption and pollution can be assessed using the water footprint concept (Hoekstra et al., 2011), which distinguishes a green WF (consumption of rainwater), a blue WF (consumption of surface and groundwater) and a grey WF (pollution of surface or groundwater). The production of meat requires and pollutes large amounts of water, particularly for the production of animal feed [4,32,37,6,21,22,31,34,35]. Globally, agriculture accounts for 92% of the global freshwater footprint; 29% of the water in agriculture is directly or indirectly used for animal production [25]. On top of the water needs for growing feed, water is needed to mix the animal feed, for maintaining the farm, and for drinking of the animals. In the period 1996–2005, the annual global WF for animal production was 2422 Gm³ (of which 2112 Gm³ green, 151 Gm³ blue and 159 Gm³ grey). Of this amount, 0.6 Gm³ of blue water (0.03%) was needed to mix the feed, 27.1 Gm³ (1.1%) was drinking water and 18.2 Gm³ (0.75%) was needed for the maintenance of livestock farms [31]. Water for animal products, therefore, mainly refers to water consumed or polluted to produce animal feed.

Recently, a comprehensive global study of the WF of farm animals and animal products has been carried out by Mekonnen and Hoekstra [31]. That study considered eight animal categories and three livestock production systems for the period 1996–2005. The production systems are the grazing, mixed and industrial production systems. This study analyses the results of Mekonnen and Hoekstra [31] to find the main explanatory factors behind the WF of meat and to consider differences between poultry, pork and beef, between developed and developing countries, and between different production systems. We use the definitions and methodology of the water footprint as set out in Hoekstra et al. [24]. Specific questions are: which factors determine the differences between WFs of production systems for the same meat type, and which factors determine the differences between WFs of different meat types? The WF 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. The study shows the general trends in WFs of meat production systems and provides information to improve present WFs and to decrease the environmental burden of a marginal increase of meat production.

2. Methodology

The analysis of the driving factors behind the WFs of poultry, pork and beef is based on the earlier study of Mekonnen and Hoekstra [31]. We use the approach and data from that study to have a more in depth analysis of the meat producing systems in China, Brazil, the US and the Netherlands.

2.1. Classification of livestock farming systems

Following the Food and Agriculture Organization (FAO), we distinguish three types of livestock farming systems: grazing, mixed and industrial systems [36]. *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 [4]. These systems supply about 9% of the world meat production [36]. In general, grazing systems have lower yields in terms of live weights of animals at slaughter, and milk and egg production [42,38]. 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 [4]. Particularly chickens consume large amounts of grains in this so-called grazing system [31]. Traditionally, many of the grazing occurred on marginal lands which are not suitable for producing arable crops for human consumption, but today this is often not the case. *Mixed systems* combine livestock and 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 US. Mixed farming systems supply about 54% of the world meat production and 90% of world milk [36]. *Industrial systems* have high stocking rates per hectare and less than 10% of the animal feed is produced at the farm itself. For cattle, industrial systems are the dominant farming system in for example Japan and western European countries. For pigs and chickens for meat, industrial systems have become the main system for most parts of the world.

2.2. The water footprint concept

Water footprint accounting is a tool to calculate water use behind consumer products. It can be applied at the level of a single product, a producer of a number of products, a consumer, a group of consumers or within a geographically delineated region. Here, we focus on the WF of a product, i.e. meat. The WF measures freshwater consumption and pollution along product supply chains [24]. The WF is a multi-dimensional indicator, giving water consumption volumes by source and polluted volumes by type of pollution. A distinction is made between green, blue and grey water, to give a comprehensive and complete overview of freshwater consumption 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 distinction between the green and blue WF is important because the hydrological, environmental and social implications, as well as the economic opportunity costs of surface and groundwater use for production, differ from the implications and costs of rainwater use. 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. The WF 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 footprint needs to be evaluated in the context of local water scarcity and waste assimilation capacity [24]. However this has not been part of the scope of the current study.

2.3. Method for estimating the water footprint of meat

We analyzed green, blue and grey WFs for three types of meat (beef, pork and poultry) for three types of production systems (grazing, mixed and industrial) for four countries: Brazil, China, the Netherlands and the US. We selected Brazil and China in the category of developing countries because of their large size and the growing importance of the livestock industry. We selected the Netherlands and the US in the category of developed countries because of their large livestock industry. Moreover, the Netherlands represents a country with a livestock sector that heavily depends on import of animal

feed, while the US rely more on domestic production. The grazing system for beef in the Netherlands was not studied, as this system does not exist in the country. We calculated the WF of beef cattle, pigs and poultry as the sum of the WFs related to feed, drinking and other on-farm and slaughterhouse activities. We calculated the WF of feed per type of animal, per type of production system and per country by multiplying the amounts of the various feed ingredients with their respective WF (accounting for the origin of the feed) and adding the WF related to mixing of the feed ingredients and processing the meat. We derived data on feed ingredients, specific WFs for feed ingredients and for mixing and processing (m^3 per tonne) from Mekonnen and Hoekstra [30]. Following the method of Hoekstra et al. [24], we calculated the WF of meat based on the WF 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

The WF of a specific piece of meat is determined by the water consumption and pollution in each 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 WF involved, but all these components are very small – a few percent at most – of the total WF of the final animal product [24]. Among the three processes studied here – feed production, drinking and cleaning farms and slaughterhouses – the first one is the major factor.

The WF of meat depends on three 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, (ii) what the animals eat, i.e. the feed composition and (iii) the feed origin that determines the WF of the livestock feed. The WF at a specific location is determined by local climatic conditions, such as rainfall and temperature, in combination with soil conditions and agricultural practice. In general, high yield levels go along with relatively small WFs and the other way around. The WF of the total feed package depends on the feed composition and the origin of the various feed ingredients. The water use for meat in the rest of the chain, from farm to fork, is a minor part of the total WF of animal products. Fig. 1 schematically shows the factors determining the WF of meat. 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.

Fig. 2 shows the feed conversion efficiencies averaged for China, Brazil, the Netherlands and the US for the three meat types. Feed conversion efficiencies depend on the type of production system. In general, the feed conversion efficiency improves from grazing to mixed systems to industrial systems. Furthermore, feed conversion is more favourable for poultry and pork than for beef. It is affected by the higher level of physical activity of the animals, age at slaughter and breed.

The second main factor influencing the WF of meat is the WF of the animal feed. This depends on the composition and the origin of the feed. In general, industrial production systems have a relatively large fraction of concentrates in the animal feed and grazing systems a relatively small fraction.

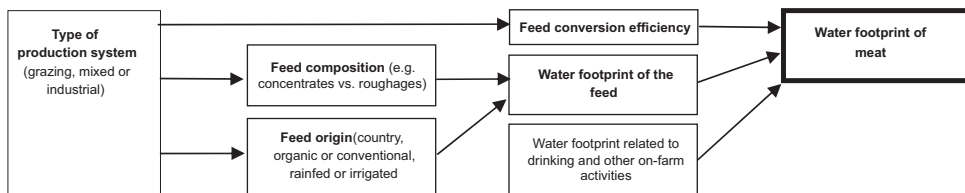


Fig. 1. Factors determining the water footprint of meat.

Fig. 3 shows the share of concentrate feed in the total feed averaged for China, Brazil, the Netherlands and the US. Irrespective the type of production system, chickens and pigs rely more heavily on concentrates than beef cattle. In industrial pork systems, concentrates make up hundred per cent of the feed.

Since the WF of meat is dominated by the WF of the animal feed, the composition of the feed is an important factor. Table 1 gives the main components contained in feed concentrates and roughages. Table 2 shows that there are large differences between the WFs (m^3 of water per tonne of feed) of concentrates and roughages. Feed concentrates have a relatively large WF, while roughages have a

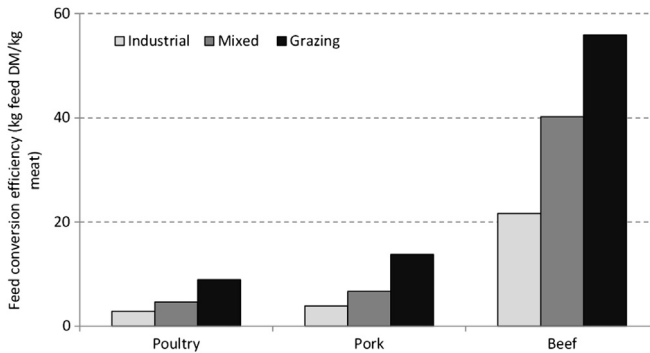


Fig. 2. Feed conversion efficiencies for poultry, pork and beef averaged for China, Brazil, the Netherlands and the US. Data from Mekonnen and Hoekstra [30]. DM=dry mass.

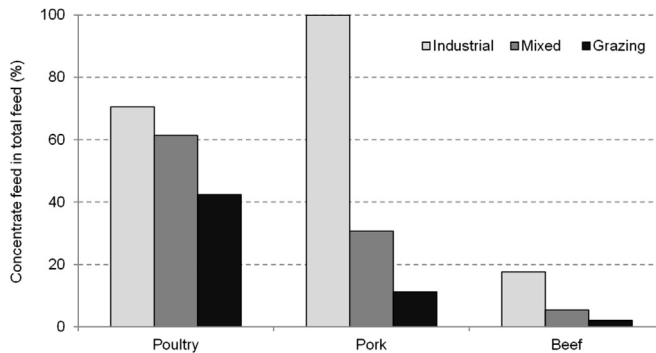


Fig. 3. Share of concentrate feed in total feed for poultry, pork and beef averaged for Brazil, China, the Netherlands and the US. Data from Mekonnen and Hoekstra [30].

Table 1

Overview of the main sorts of components contained in concentrates and roughages [30].

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	

Table 2
Average water footprint (m^3/tonne) of concentrates versus roughages [30].

	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 ×

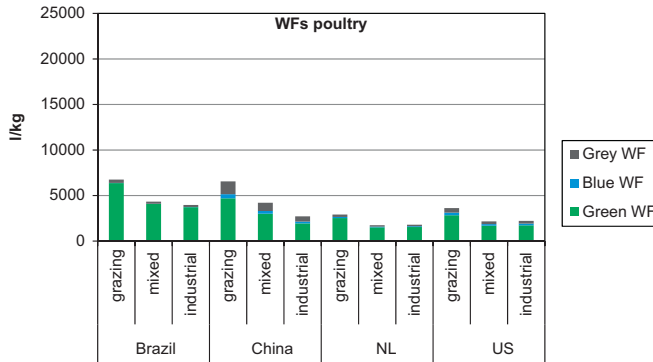


Fig. 4. Green, blue and grey WFs of poultry for Brazil, China, the Netherlands and the US for the grazing, mixed and industrial production systems. Data from Mekonnen and Hoekstra [30] (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relatively small WF. As an average, the WF of concentrates is five times larger than the WF of roughages. While the total mixture of roughages (grass, crop residues and fodder crops) has a WF of around $200 \text{ m}^3/\text{tonne}$ (global average), this is about $1000 \text{ m}^3/\text{tonne}$ 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 WFs of concentrates are 43 and 61 times that of roughages, respectively.

3.1. Poultry

Fig. 4 gives the green, blue and grey WFs of poultry for Brazil, China, the Netherlands and the US for the grazing, mixed and industrial production systems. For poultry, industrial systems use 3.2 times less feed (dry mass) per unit of output than grazing systems. Grazing production systems use a feed package that contains 40% of concentrates (the average for the four countries considered), while industrial systems have a feed package with 70% of concentrates. Mixed systems use feed packages with concentrate fractions in between. For the four countries considered, the WF of poultry is mainly determined by one factor—the feed conversion efficiency. This results in a smaller green, blue and grey WF for the industrial system if compared to the grazing system. This is in line with the global findings in Mekonnen and Hoekstra [30]. For the US and the Netherlands the mixed and industrial poultry systems have similar WFs.

3.2. Pork

Fig. 5 shows the green, blue and grey WFs of pork for Brazil, China, the Netherlands and the US for the grazing, mixed and industrial production systems. 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. The industrial pork systems use only concentrate feeds, with a relatively large WF. Concentrate percentages are much lower for mixed and

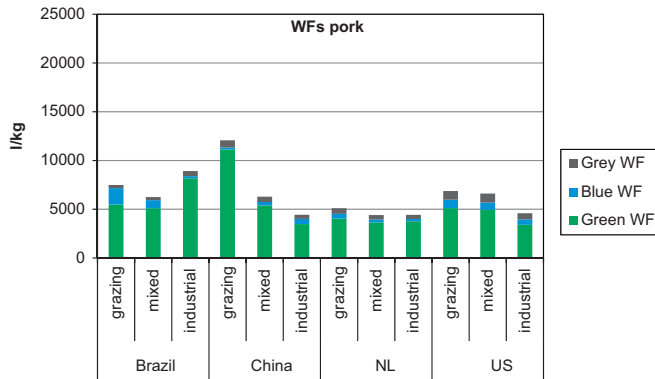


Fig. 5. Green, blue and grey WFs of pork for Brazil, China, the Netherlands and the US for the grazing, mixed and industrial production systems. Data from Mekonnen and Hoekstra [30] (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

grazing systems. 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 US, the differences in feed conversion efficiency between industrial and grazing systems are so large, that the favourable feed composition of the grazing system does not compensate. In the Netherlands, the resultant green WFs are similar for the three production systems. For Brazil, the Netherlands and the US, blue WFs of pork decrease from grazing to mixed to industrial systems. The data for China, however, show a smaller blue WF in grazing than mixed and the largest WF in industrial pork production. For grey WFs, we find no general trend among the four countries. The grey WF of pork is relatively large in the US for grazing and mixed systems, and in China for grazing systems. Grey WFs are relatively small in Brazil for grazing and mixed systems.

3.3. Beef

Fig. 6 gives the WFs for 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. The fraction of concentrates in the total feed mix, however, is larger for the industrial systems than for the mixed and grazing systems. The concentrate percentages range from 2% for grazing systems, to 4% for mixed systems to 18% for industrial systems. For the green WF 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 larger WFs in industrial systems in Brazil and China.

In the Netherlands and the US, 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. The differences can be explained by looking more closely at the feed composition of the different systems in the four countries. Production systems in the US 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

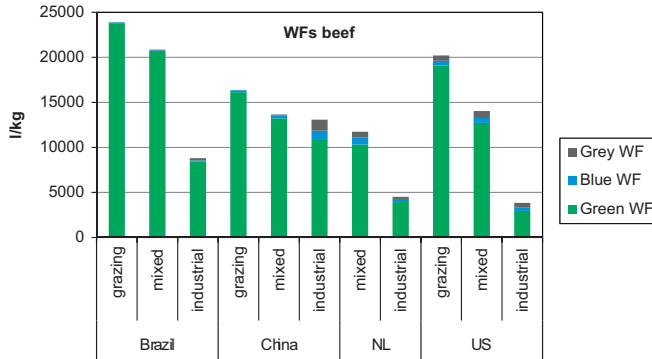


Fig. 6. Green, blue and grey water footprints of beef for Brazil, China, the Netherlands and the US for the grazing, mixed and industrial production systems. Note: there is no grazing system for beef in the Netherlands. Data from Mekonnen and Hoekstra [30] (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

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 US 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

This paper is based on the study of the green, blue and grey water footprint of farm animals and animal products of Mekonnen and Hoekstra [30]. That study used a top-down approach with a country perspective, which means that some assumptions had to be taken. For example, there were no data available for animal distribution over the three different production systems for the OECD countries. For developing countries, data were used from Seré and Steinfeld [36] on animals per production system per world region in combination with data from Wint and Robinson [41] per country. For OECD countries, regional data from Seré and Steinfeld [36] were taken for the countries within a world region equally. Another assumption concerns the precise feed composition per animal category per country. The study estimated the average amount of feed consumed per animal category for the three production systems by estimating the share of concentrate feed in total animal feed based on data from Hendy et al. [20] and Bouwman et al. [1]. Compositions of concentrates were derived from Wheeler et al. [40], Steinfeld et al. [37] and FAO [14].

Another issue is that we made assessments for grey water footprints that only took into account leakage of artificial nitrogen fertilizer in feed crop production. We excluded the use of other fertilizer ingredients and pesticides. Because of limited data availability, we also did not assess the grey WF of manure when brought back on the land in excessive amounts and also not the potential grey WF related to the use of antibiotics in wastewater from industrial farms. In this way, we underestimated grey water footprints, particularly in industrial systems. Industrial systems more heavily rely on concentrate feed, the production of which often comes along with the intensive use of fertilizers and pesticides, which partly leach to 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 rather a waste, often disposed onto limited available lands and therefore contributing to leaching of nutrients and thus the eutrophication of water bodies.

For pastures, we 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 [20,1], 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 living on marginal land that humans cannot eat from is as efficient as it gets, whereas cows or other animals eating from land that could also produce crops for direct human consumption is less efficient [18]. The problem is here 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 we have made the distinction between green water (rainwater) and blue water (irrigation water withdrawn from ground or surface water), but we did not show 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. Particularly when cattle graze on marginal lands and fully depend on green water, there are few alternative uses for the natural resources used (apart from leaving them to nature).

4.2. Implications

The water footprint of any type of meat is mostly determined by the feed of the animals. Globally, the main component of the WF of animal feed relates to pasture (38% of the total water footprint), followed by maize (17%), fodder crops (8%), soybean cake (7%), wheat (6%), barley (6%) and oats (3%) [31]. 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 larger blue and grey water footprint than pasture or roughage. A shift in food consumption patterns towards larger 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. 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.

4.3. Reducing the water footprint of meat and moving to sustainable consumption

In a recent report, Burlingame and Dernini [3] emphasize the need for a more sustainable food production and consumption system. One of the requirements of a sustainable diet is that it goes along with low natural resource use and environmental impact. From a resource-use point of view, 1 l of green water consumption is equivalent to one litre of blue water consumption, but the impact of a green WF on the environment is generally much smaller than the impact of a blue WF. Grey WFs are a concern because they refer to pollution of groundwater surface water. This means that from a

sustainable consumption perspective, particularly meat types with a large blue and grey WF need to be avoided. Differences among 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. Especially the two developing countries have potential to decrease WFs per unit of feed and increase the efficiency of feed conversion, improving the sustainability of the system. For example, China shows above average grey WFs, indicating inefficient fertilizer use. The water footprint related to the consumption of animal products, globally 2422 Gm³ per year (almost 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 equivalent plant-based foods [31]. As shown by Hoekstra [21], the food-related water footprint of a consumer in an industrialized country can be reduced by 36% by shifting from an average meat-based diet to a vegetarian diet. Chapagain and James [5] found that in the UK the water footprint of avoidable food waste amounts to 6% of the total water footprint of a UK citizen. The water footprint of food in general and meat in particular can be significantly reduced by changes at the consumption side, but this would require a major transition in the present nutrition pattern and a reduction of food wastes, especially in the western countries. At present, food choices are driven by increased welfare, losing connection with local cultural heritage and paying little attention to the environment [3].

5. Conclusions

The WF of any sort of meat is mostly determined by the feed of the animals. We observe three main explanatory factors behind the WFs 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. This factor causes a general decrease of the WF of meat 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 WF than roughage. The second factor contributes to an increase of the WF, especially the blue and grey WF, from grazing and mixed to industrial systems. The third factor is the origin of the feed. The overall effect of the three factors depends on the relative importance of the separate factors, which varies case by case. Specific focus on the blue and grey WFs is warranted because in the case of blue water (groundwater, surface water) agricultural water demands compete with various other human demands for water, like water demands for households and industries.

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 WFs if compared to the industrial systems. For pork, the net result of the three 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, we observe a decreasing trend of green WFs 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 WFs 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 WFs do not show a general trend. In China and the Netherlands, they decrease from grazing, to mixed to industrial systems. In Brazil, grey WFs are smallest for grazing and mixed systems and largest for the industrial systems. In the US, mixed systems have the largest WFs 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. 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 WF 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.

In general, feed conversion efficiencies are largest for broilers and pigs and smallest for cattle. This explains the general finding that beef has a much larger WF 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.

We observe large differences across 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.

In the western countries, the WF of meat can be reduced by changing consumption, requiring a transition in the present nutrition pattern and a reduction of food wastes. Obviously, the WF 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.

Conflict of Interest

None.

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