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Water productivity in meat and milk production in the US from 1960 to 2016

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ABSTRACT

Global demand for livestock products is rising, resulting in a growing demand for feed and potentially burdening freshwater resources to produce this feed. To offset this increased pressure on water resources, the environmental performance of livestock sector should continue to improve. Over the last few decades, product output per animal and feedstuff yields in the US have improved, but before now it was unclear to what extent these improvements influenced the water productivity (WP) of the livestock products. In this research, we estimate changes in WP of animal products from 1960 to 2016. We consider feed conversion ratios (dry matter intake per head divided by product output per head), feed composition per animal category, and estimated the water footprint of livestock production following the Water Footprint Network's Water Footprint Assessment methodology. The current WP of all livestock products appears to be much better than in 1960. The observed improvements in WPs are due to a number of factors, including increases in livestock productivity, feed conversion ratios and feed crop yields, the latter one reducing the water footprint of feed inputs. Monogastric animals (poultry and swine) have a high feed-use efficiency compared to ruminants (cattle), but ruminants consume relatively large portion of feed that is non-edible for humans. Per unit of energy content, milk has the largest WP followed by chicken and pork. Per gram of protein, poultry products (chicken meat, egg and turkey meat) have the largest WP, followed by cattle milk and pork. Beef has the smallest WP. These data provide important information that may aid the development of strategies to improve WP of the livestock sector.

1. Introduction

The world population is expected to reach 9.8 billion by 2050 (UN-DESAPD, 2017) with much of the growth taking place in urban areas. Driven by growing population, increasing income, and urbanization, the demand for livestock products in 2050 will increase by 35% from its 2016 level (Alexandratos and Bruinsma, 2012; FAO, 2017). Much of the increase in livestock product consumption is expected to occur in developing countries.

Globally, the livestock sector contributes about 36% to the gross value of agricultural production (Alexandratos and Bruinsma, 2012), supports the livelihood of farmers and provides traction power for ploughing in smallholder crop production systems (Steinfeld and Gerber, 2010; Thornton, 2010). Livestock products supply about 12.9% of calories and 27.9% of protein consumed globally (Gerber et al., 2013). Unless proper policies targeting production systems and consumption trends are put in place, the growth in the livestock sector could put further pressure on already strained natural resources such as freshwater and land, and aggravate land degradation, water pollution, and greenhouse gas emissions. Various studies have highlighted the environmental impacts of the livestock sector including water consumption and pollution (Beckett and Oltjen, 1993; Capper, 2011; Deutsch et al., 2010; Mekonnen and Hoekstra, 2012; Steinfeld et al., 2006), nutrient emission (Bouwman et al., 2013; Capper, 2011; Galloway et al., 2010; Mekonnen and Hoekstra, 2015, 2018; Pelletier and Tyedmers, 2010), climate change (Gerber et al., 2013; Pelletier and

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Tyedmers, 2010; Steinfeld et al., 2006), and appropriation of biomass (Pelletier and Tyedmers, 2010; Wirsenius, 2003).

There is recognition of the need to improve the productivity and environmental performance of the livestock sector in order to minimize its environmental impacts and increase the sustainability of global food production. Improvements in livestock productivity, feed-use efficiency and feed crop yields, and wise sourcing of feeds are believed to reduce the sector's demand for resources such as land and water, and its environmental impacts (Mekonnen and Hoekstra, 2012; Steinfeld and Gerber, 2010; Steinfeld et al., 2006). Reducing food waste could also drastically reduce the environmental impacts of the sector (Foley et al., 2011; Kummu et al., 2012; Mekonnen and Fulton, 2018; West et al., 2014).

The US is the largest producer of livestock products, accounting for 17% of global cattle and chicken meat, 10% of pig meat, and 15% of milk production in 2016 (FAO, 2017). It was a major consumer of livestock products as well. In 2013, the US per capita consumption of bovine meat was four fold and the consumption of poultry meat and milk about three fold larger than the global average (FAO, 2017).

The objective of this study is to assess the water productivity (WP) of the major livestock products in the US and how WP has changed over the last few decades. We first characterize each livestock category, estimate the feed conversion ratio and the average volume and composition of the feed consumed by livestock category and then calculate the WP of the livestock products. The analysis was done for six livestock categories: beef cattle, dairy cattle, swine, broiler chicken, layer chicken, and turkeys.

A limited number of studies have quantified the volume and composition of feed consumed for each livestock category for the US (Eshel et al., 2014a; Peters et al., 2014) and at global level (Bouwman et al., 2005; Chapagain and Hoekstra, 2003; Mekonnen and Hoekstra, 2012; Wirsenius, 2003). A few other studies have assessed the blue water footprint (volume of surface water and groundwater consumed) specifically for beef cattle (Beckett and Oltjen, 1993; Capper, 2011) or dairy cattle (Capper et al., 2009). The only studies that show the effect of improvement in animal production on the water footprint (WF) in the US over time (Capper, 2011; Capper et al., 2009) focus on blue water consumption, leaving out green (rainwater) consumption, which constitutes the major part of the WF of livestock production (Mekonnen and Hoekstra, 2012). The current study goes beyond earlier studies by detailing the volume and composition of the animal feed for all animal categories, assessing both the green and blue WF of livestock production, and assessing the effect of increases in livestock productivity, feed conversion ratios and feed crop yields on the WP of all livestock categories.

2. Materials and methods

2.1. Water productivity

The water productivity of an animal product (WP, kg/m^3) is defined as the ratio of the product output per animal to the WF (green plus blue water consumption) over the lifetime and supply chain of the animal:

$$WP = \frac{PO}{WF} \tag{1}$$

where *PO* is the total amount of product (meat, milk, or egg) produced per animal (kg/animal), and *WF* the direct and indirect WF of the animal over its entire lifetime (m^3/animal). We consider six products (beef, milk, pork, chicken meat, eggs, and turkey meat) from six farm animal categories (beef cattle, dairy cattle, swine, broiler chicken, layer chicken, and turkeys). The WF includes both a green and blue component (Hoekstra et al., 2011). The blue WF refers to the volume of surface water and groundwater consumed (evaporated); the green WF refers to the rainwater consumed. We have not included water pollution (the grey WF) in this study.

The WF of a live animal is estimated as the sum of the WF of the feed, the WF related to drinking water consumed, and the WF related to service water consumed (Mekonnen and Hoekstra, 2012). The latter refers to the water used to clean the farmyard, wash the animal and carry out other services necessary to maintain the environment.

Detailed data on fertilizer, agro-chemicals, and energy inputs in the production of different feed crops is not available; therefore, we have left out the WF related to these inputs in crop production. Since the WF related to these inputs is very small compared to the total WF of feed production (Mekonnen et al., 2018), the potential error in the WF because of this assumption will be minor.

2.2. The water footprint of feed

The WF of an animal (m^3/animal) related to the feed consumed is estimated as:

$$WF_{feed} = \sum_{p=1}^{n} (Feed\,[p] \times wf_{feed}\,[p]) \tag{2}$$

where $Feed[p]$ is the total volume of feed ingredient p consumed by a certain animal category (t/animal), $wf_{feed}[p]$ the WF of feed ingredient p (m^3/t). The WFs of the different crops, roughages and crop by-products (in m^3/t) that are eaten by the various farm animals were calculated following the method developed by Hoekstra et al. (2011). The WFs of feed crops per state for the period 1960–2016 were estimated using the crop water use and the yield data per state from USDA (2017):

$$WF_{feed}\,[p] = \frac{CWU\,[p]}{Y\,[p]} \tag{3}$$

where $CWU[p]$ is the crop water use (total field evapotranspiration) related to feed crop p over the growing period (m^3/ha) and $Y[p]$ the yield of feed crop p (t/ha). Seasonal CWU for most of the feed crops was estimated using a grid-based dynamic water balance model that computes a daily soil water balance and calculates crop water requirements, and the actual green and blue CWU (Mekonnen and Hoekstra, 2011). The model was applied at 30 arc-min spatial resolution. The CWU was weighted based on harvested area of the crop and averaged at state level. Monthly values for reference evapotranspiration, precipitation, number of wet days and minimum and maximum temperature for the period 1960–2016 with a spatial resolution of 30 arc-min were extracted from CRU-TS-4.01 (Harris et al., 2014). Daily precipitation values were generated from the monthly average values using the CRU-dGen daily weather generator model (Schuol and Abbaspour, 2007). The green and blue WF of major feed crops between 1960 and 2016 is provided in Table S10.

2.3. Volume and composition of feed

Animals need a daily supply of nutrients required for maintenance, pregnancy, and production (milk, meat, egg). Feed intake by an animal is determined as a function of the energy requirement and the energy density of the feed mix (National Research Council, 2001). In estimating the volume and composition of feed consumed by each animal category, we followed the following steps: a) we characterized each animal category by describing the number of animals, death and culling rate, animal productivity, and the length of days an animal spent at each stage of the animal life cycle, b) we derived an aggregate feed conversion ratio (FCR) by dividing the total feed intake by the total animal output per animal category, c) we estimated total feed intake by each animal category as a function of FCR and total animal output in the US, and d) we derived feed composition per animal category. The FCRs, total feed intake and feed composition were determined for the period 1990–2016. The detail of each step is provided in the subsections below.

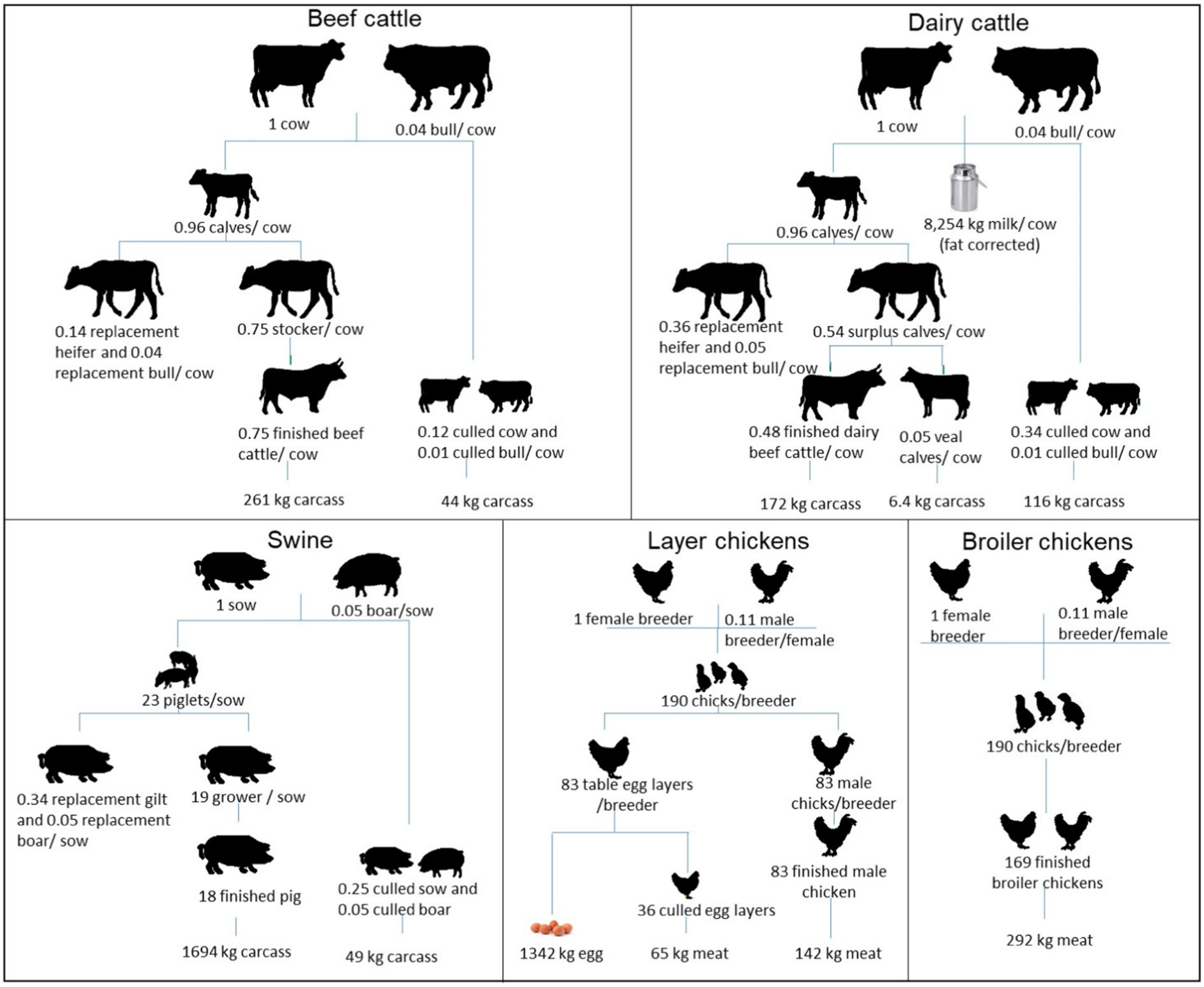

Fig. 1. Flow diagram of different livestock categories showing the flows of animals and final output for beef cattle, dairy cattle, swine, layer chickens, and broiler chickens.

2.4. Characterizing each animal category

Each animal category is composed of breeding female and male animals that produce young animals, some of which are kept as replacement for the breeding animals and the others are raised to finished animals as meat animals (beef cattle, swine, broiler chickens, turkeys), dairy cows to produce milk, and layer chickens to produce eggs. For each animal category, we described the number of animals, premature mortality rate, and flows from one to another life phase of the animal system. For each animal category, a single female breeding animal is taken as the basis of the analysis. Therefore, the number of male breeding animals, the number of young animals produced, and final output are expressed in terms of the female breeding animal. A flow diagram of different livestock categories is shown in Fig. 1. Descriptions of the six animal categories and assumptions made are provided in Tables S1 and S2.

2.5. Estimating feed conversion ratios

The feed conversion ratio is defined as the amount of feed consumed per unit of produced animal product (e.g. meat, milk, egg). Feed conversion ratios were estimated separately for each animal category (beef cattle, dairy cattle, sheep, swine, broiler chicken, egg layer chicken, and turkeys). The feed conversion ratios (*FCR*, kg dry matter/kg product) were estimated by dividing the total dry matter intake by the total animal output (of beef, milk, pork, chicken and turkey meat, and egg) per breeding female animal:

$$FCR = \frac{DMI}{PO} \tag{4}$$

where DMI is the dry matter intake (kg) and PO the total animal products output (kg) per breeding female animal. Total feed intake per animal category is the sum of the feed consumed by each animal in the production system. Total feed intake of each animal at each life phase was calculated as a product of the daily dry matter intake, the number of days an animal spent in that phase, and the number of animals in that phase. Thus, the total dry matter intake (DMI) per animal category per breeding female animal is calculated as:

$$DMI = \sum_{s=1}^{n} dDMI_s \times d_s \times N_s \tag{5}$$

where $dDMI_s$ is daily dry matter intake at life stage s, d_s the number of days an animal spends in stage s, N_s the total number of animals in that stage. The dDMI per animal at each life stage was obtained primarily from different US National Research Council (NRC) reports: for poultry (broiler chicken, layer chickens, and turkeys) from National Research Council (1994); for swine from National Research Council (2012); for beef cattle from National Academies of Sciences (2016); and for dairy cow from National Research Council (2001). The weaning weight, finishing weight, and length of each phase were collected from different literature (Table S2). The milk and egg production per animal were obtained from USDA (2017).

Beef cattle, swine, broiler chickens, and turkeys produce only meat, thus all the DMI was allocated to the meat produced. On the other hand, beside the main product milk, dairy cattle produce meat from culled breeding animals (bulls and cows), and the extra calves that are slaughtered for veal or enter the beef system as feeder cattle. Therefore, for the dairy cattle system the DMI was allocated to the main product milk and the co-product meat based on their respective economic value fractions. Similarly, laying hens produce meat from finished male chicks and culled laying hens in addition to the egg produced. The DMI of the layer chicken category was allocated to the egg and meat based on their respective value fractions. Value fraction is the ratio of the economic value of the product (e.g., value of milk) to the total market value of all products (total market value of milk and meat produced from the dairy herd).

The total animal output (*PO*) for meat production systems was calculated by multiplying the number of animals slaughtered by the respective carcass yield of the slaughtered animal. For milk and egg, the total output was estimated by multiplying the annual output by the number of producing animals in the category. The product output (beef, milk, pork, chicken meat, egg, and turkey meat) was obtained from USDA (2017). Table 1 presents livestock weight, productivity as output per head, and DMI for 2000.

Feed conversion ratios of the different animal categories have improved through both genetic and non-genetic research as shown in Table 2. The largest improvement in the FCR was observed for dairy cattle, with an annual improvement of 1.2%, followed by swine and layers, with annual improvement of 0.9% and 0.8%, respectively. Over the last few decades, animal productivity (output per animal) has increased (Table S4). Improvement in animal productivity will help to improve FCRs but it may also lead to increases in feed intake with no or minimal change in the FCR of the animal (Kenny et al., 2014). Therefore, in order to assess the effect of the change in FCR on the WP of livestock products, we estimated the change in the FCR as a function of change in animal productivity (output per animal) between 1960 and 2016:

$$FCR_y = FCR_{2000} \times \frac{PO_y}{PO_{2000}} \tag{6}$$

Table 1
Livestock productivity indicators, feed intake and feed consumption per live weight, carcass, and edible weight for US for year 2000.

Animal category	Live weight (kg/head)[a]	Production (kg of meat, milk, or egg per head)[a]	Feed consumption[b]		
			kg DM/kg live weight	kg DM/kg product	kg DM/kg edible product
Chicken (meat)	2.27	1.67	2.0	2.66	4.42
Broiler	2.27	1.67	2.1	2.87	4.76
Other chickens	2.41	1.45	1.3	2.12	3.51
Layers	2.41	15.5	15.7	2.43	2.74
Turkeys	11.6	9.1	3.0	3.84	4.86
Swine	119	88	3.3	4.43	6.07
Beef cattle	541	330	12.4	20.4	30.5
Beef cow	552	337	15.8	25.9	38.8
Other beef	526	321	2.5	4.13	6.16
Dairy cow	545	7883	13.6	0.94	0.94

[a] Data on live weight and productivity was derived from USDA (2017). The production per unit of animal are expressed as carcass weight for cattle and swine, ready-to-cook weight for poultry, weight of egg for layers, and weight of fat adjusted milk (Beever and Doyle, 2007) for dairy cow. Values are average for 2000.

[b] Dry matter intake per product was derived as described in Eqs. (4) and (5). The conversion factors from live-weight to carcass and carcass to edible weight for cattle and swine, live-weight to ready-to-cook and from ready-to-cook to edible weight for poultry, and from egg with shell to shelled egg are reported in Table S3 in the Supporting Information.

where FCR_y is the FCR for year y, PO_y is the product output per animal for year y, FCR_{2000} is the value as calculated for year 2000 by Eq. (4) and reported in Table 1, PO_{2000} the product output per animal for year 2000 and used in Eq. (4). This approach, however, may result in unrealistically large improvement in the FCR. Therefore, we set an upper limit for the average annual change in the calculated FCR values based on literature values (Table 2).

2.6. Total volume of feed consumed

For each animal category, the total annual feed consumption (including both concentrates and roughages) is calculated by multiplying the annual animal product output by the feed conversion ratios (Bouwman et al., 2005; Hendy et al., 1995; Mekonnen and Hoekstra, 2012):

$$Feed = FCR \times TP \tag{7}$$

where *Feed* is the total feed consumption of the animal category (t/y) and *TP* the total production of the animal product (t/y).

2.7. Composition of the feed per animal category

The total feed estimated in Eq. (7) is composed of different feed ingredients, which differ per animal category. The feed composition of animals is key in determining the WP of livestock products, because concentrates typically have a larger WF than roughages (Gerbens-Leenes et al., 2013; Mekonnen and Hoekstra, 2012). The composition of feed depends on the animal type, but also on the availability and cost of the different feed ingredients in different places. There are no databases specifying the ratios of feed ingredients per animal category. Therefore, we first derived the feed composition per animal category by combining the total feed estimated in Eq. (7), total national supply of concentrate and processed roughages, and USDA's indexes of feed consuming animal units (USDA-ERS, 2017). The index is based on the dry-weight quantity of feed consumed by the average milk cow in the years 1969–71. The index provides the number of animal units (indexed to an average milk cow) that consume grains, high protein (soybean and oil meals), and roughage (by products, silage, forage, pasture) feeds. The steps followed in deriving the feed composition at the national level were as follows: 1) the total national supply of concentrate and processed roughages were distributed to the indexes of feed consuming animal units that include all animal categories including sheep, goats, and horses; 2) for poultry (meat and egg) and pork production, the concentrate feed requirement was directly derived from step 1; 3) for beef we adopted the share of concentrate, forage, and non-forage-non-grain feed in the beef cattle feed from National Academies of Sciences (2016), and for dairy cows, the share of concentrate, forage, and non-forage non-grain feed in the dairy cow's diet was adopted from Thoma et al. (2013); we then distributed the aggregated concentrate, forage, and other feeds to the individual feed products within the group using the share of each feed item derived from step 1.

2.8. Replacing corn and soybean by distillers grains

In 2016, about 37.5 million metric tons of distillers grains were produced (46% dried DGs with solubles, 30% wet DGs, 10% dried DGs, 10% modified DGs, 4% condensed distillers solubles) (RFA, 2017). About 44% of the total DGs was fed to beef cattle, 30% to dairy cattle, 16% to swine, 9% to poultry, and 1% to other animals (RFA, 2017). In order to assess the effect on WP of replacing corn and soybean by DGs, we adopted the substitution rate per livestock category from Hoffman and Baker (2011). According to Alternative #2 of Hoffman and Baker (2011), 1 Mg of DGs will replace 1.2 Mg of corn for beef cattle, 0.73 Mg of corn and 0.63 Mg of soybean for dairy cattle, 0.70 Mg of corn and 0.30 Mg of soybean for swine, and 0.61 Mg of corn and 0.44 Mg of soybean for poultry.

Table 2
Improvement in the FCR per animal category.

Animal category	Year	Total change between the years stated (%)	Average annual change (%)	Data source
Dairy	1944–2007	77%	1.20%	Capper et al. (2009)
Swine	1972–2007	32%	0.90%	Buchanan-Smith (2016)
Layers	1960–2010	42%	0.85%	Pelletier et al. (2014)
Broiler	1960–2016	26%	0.45%	US National Chicken Council (2017)
Beef	1977–2007	18.6%	0.62%	Capper (2011)

Table 3
Feed conversion ratio, annual production, and total feed consumption (mean ± standard deviation) per animal category, for the US. Period 2014–2016.

Animal category	Feed conversion ratio (kg DM/kg product)[a]	Annual production of product (Tg/y)[b]	Annual feed consumption (Tg DM/y)
Chicken (meat)	2.67	18 ± 0.7	49 ± 2
Broiler chickens	2.68	18 ± 0.7	48 ± 2
Egg chickens[c]	1.98	0.24 ± 0.01	0.48 ± 0.02
Layers	2.26	6 ± 0.39	14 ± 1.8
Turkeys	3.58	2.6 ± 0.25	9.4 ± 0.6
Swine	4.04	11 ± 0.08	44 ± 0.3
Beef cattle	18.9	11 ± 0.46	211 ± 11.3
Beef herd	23.5	8.6 ± 0.46	201 ± 11.3
Dairy herd[c]	3.76	2.6 ± 0.09	10 ± 0.4
Dairy cow	0.85	91 ± 3.7	77 ± 3.5

[a] Feed conversion ratios are expressed in dry matter intake per unit carcass weight for cattle and swine, ready-to-cook weight for poultry, weight of egg in shell for layers, and weight of fat adjusted milk (Beever and Doyle, 2007) for dairy cow.

[b] Data on total animal products output averaged over the period 2014–2016 was obtained from USDA (USDA, 2017). The outputs are expressed in carcass weight for cattle and swine, ready-to-cook weight for poultry, weight of egg in shell for layers, and weight of fat adjusted milk (Beever and Doyle, 2007) for dairy cow.

[c] The dairy cattle herd produces mainly milk but also beef from the culled milk cow and bulls, and the calves that are used to produce veal, or finished to produce beef. Therefore, part of the feed of the dairy cow herd is allocated to the beef sector based on the relative economic value of beef versus milk production. Similarly, culled layer chickens produce chicken meat, thus part of the feed in layers is allocated to chicken meat using the economic value fraction.

2.9. Derivation of variability ranges

Variability ranges for the estimated WP of livestock products were based on the interannual variability of input data such as feed intake and animal productivity. We also considered the inter-state variation in the WF of the feeds.

3. Results

3.1. Trends in livestock production

Livestock production has increased considerably between 1960 and 2016 (Fig. 2). The largest increase was observed for chicken and turkey meat: 10 and 6.3 times from 1960 to 2016, respectively. Cattle meat production fluctuated, with an initial increase between 1960 and 1976, then a decline before a rise again, with an overall increase of 53% between 1960 and 2016. Chicken and turkey meat production per animal increased 1.9 and 1.8 times between 1960 and 2016, respectively. Milk production per dairy cow more than tripled from 1960 to 2016. Cattle meat, pork, and egg production per animal increased by 65%, 54%, and 34%, respectively, during the same period.

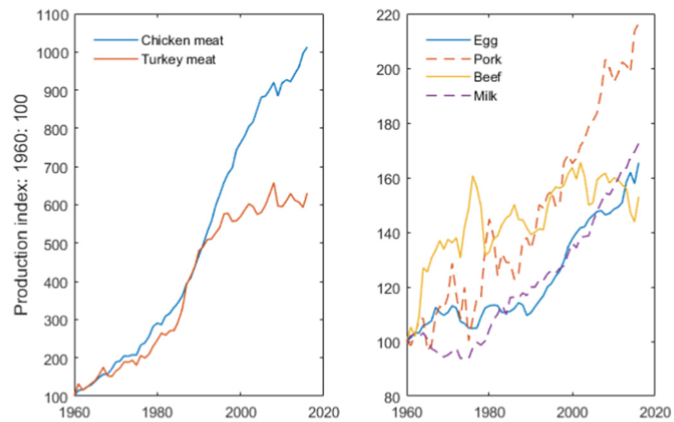

Fig. 2. Livestock production (chicken, turkeys, and cattle meat, pork, egg, and milk) in the US from 1960 to 2016.
Data from USDA (2017).

3.2. Trends in livestock productivity

In 2016 fewer animals were needed to produce a larger amount of animal products: there were 47% fewer dairy cows producing 73% more milk in 2016 compared to 1960; the number of slaughtered cattle in 2016 was 21% more but produced 53% more meat compared to 1960 (USDA, 2017). Improved efficiency in all animal categories has enabled higher production with few animals (Fig. 2).

The improvement in feed-use efficiency has helped to decrease the dry matter (DM) feed consumption per unit of output produced. The feed conversion ratio (FCR), which is the amount of DM intake per unit of animal products output (meat, milk, egg) has declined for all livestock (red broken line in Fig. 3). The largest decrease in the FCR was observed for dairy cow, with a 65% decline between 1960 and 2016. The FCR of poultry (broiler chicken, egg chicken and turkey) declined by 25% during the same period. For swine and beef cattle, the FCR has decreased by 35% and 32% from 1960 to 2016, respectively.

Not all ingested feed is converted to animal products because a significant amount of the feed intake by the animal is utilized for maintenance and reproduction. Thus, increase in animal output per head will not directly translate into improvement in the FCR. For example, milk production per dairy cow has more than tripled but the FCR has improved by only 65% between 1960 and 2016. The FCRs per animal category from 1960 to 2016 are provided in Table S5.

3.3. Quantity and composition of feed

Table 4 presents the feed conversion ratios, total production and feed consumption per animal. The feed conversion ratios measure the efficiency of the different livestock in converting the dry matter intake into final output. Thus, higher values indicate low feed-use efficiencies or large feed intake per unit of output produced.

Feed conversion ratios differ considerably across livestock categories. FCRs are influenced by climate, quality of feed, microorganisms in the gut, and genetics of the individual animals (Reyer et al., 2015). Beef cattle feed intake per unit of output is 4.7 times larger than that of

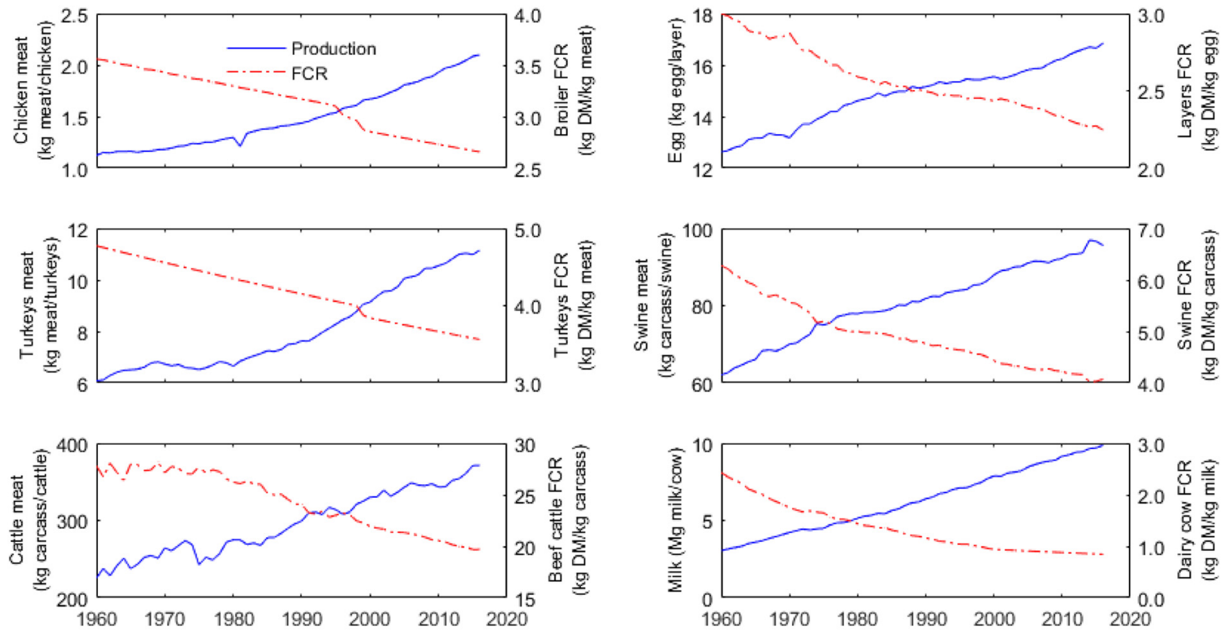

Fig. 3. Product output per animal and feed conversion ratio (FCR) for broilers, turkeys, swine, beef cattle, layers, and dairy cow in the US from 1960 to 2016. Product output per animal data are from USDA (2017). The FCR shows how efficient the different animals are in converting the feed to final product. The lower the FCR the higher the efficiency of the livestock in converting feed to product.

Table 4
Total consumptive water footprint of animal production in the US (million m^3/y). Period 2014–2016.

Animal category	Grains	Oilseeds meal	Other by-products	Forage	Pasture	Direct water	Total
Broilers	19,514	16,742	984	–	–	362	37,603
Layers	5445	4669	275	–	–	49	10,438
Turkeys	3758	3222	189	–	–	11	7180
Swine	20,504	9001	1039	–	–	1873	32,417
Beef cattle	11,306	8526	14,756	64,496	31,135	928	131,146
Dairy cow	3931	14,577	11,706	16,810	8772	300	56,095
Total	64,458	56,737	28,950	81,306	39,907	3522	274,879

swine and 7.1 times that of broiler chicken. While beef production requires a relatively large amount of feed per unit of output, there is a large difference in the FCR of beef coming from beef herd and dairy herd. In the dairy production system, the total feed consumed is allocated to the milk and beef produced based on the relative values of milk and beef production. The largest fraction is attributed to the milk, which explains the relative good FCR of beef in the dairy production system (de Vries et al., 2015). FCRs do not only depend on the productivity of the different livestock, but also on the type and quality of feed consumed (Herrero et al., 2013). Poultry and swine depend fully on energy and nutrient rich concentrate feeds that are potentially human edible, which contributes to high feed-use efficiency. On the other hand, beef cattle largely feed on pasture and forages (human inedible) with low energy and nutrient density, which results in low feed use efficiency (high FCR).

A more reasonable comparison of the FCR of the different animals can be done when the ratios are expressed per unit of protein and energy. Feed conversion ratios expressed in terms of total and human edible feed consumption per unit of dry matter, protein, and energy in animal products are shown in Fig. 4. When FCRs are expressed as kg protein in total feed per kg protein in edible animal product or as kcal total feed per kcal edible animal product, the FCRs of dairy cow, poultry (meat and egg chickens, turkeys) and swine are very comparable. Dairy cattle, poultry and swine are relatively efficient in converting feed protein to protein in the form of edible animal product and in converting energy in feed to energy in the form of edible animal product compared to beef cattle. Another important reason for the high FCR of beef cattle is the high cost of maintenance, which can range from 60% to 90% of the total energy use (Caton et al., 2000). About 52% of the metabolizable energy required for maintenance is consumed by the parent population of the beef herd compared to 4% in poultry and 20% in swine population (Webster, 1989).

The comparison among the six animal categories changes when we focus only on the human edible portion of the animal feed. Since a large portion of beef cattle feed comes from forage and pasture, the FCR of beef cattle in terms of human edible feed consumed per unit of output is smaller than for the other meat producing animals (poultry and swine) (Wilkinson, 2011). The FCR of beef cattle is also relatively small in terms of the kg protein in human edible feed per kg protein in edible animal product, and in terms of kcal of human edible feed per kcal of edible animal product.

The environmental burden of the different feeds differs widely, thus lower FCRs may not necessarily mean low environmental impacts. For example, poultry and swine have low feed requirement per unit of output, but high demand on human consumable feed products that require high input of artificial fertilizer and irrigation water. As a result, poultry and swine may put more pressure on scarce freshwater resources than beef cattle that rely on grazing, crop residues, and forages.

Total animal products output in terms of weight has increased by 48%, whereas total animal feed consumption increased by only 8% between 1960 and 2016. The increase in animal productivity (Fig. 3), the shift to more monogastric animals and improved nutritional value of feedstuffs has slowed down the increase in overall animal feed requirement. The largest increases in feed consumption were for meat chickens and turkey, with growth factors of 7.6 and 4.7, respectively, between 1960 and 2016. Feed consumed by swine, layer chickens, and beef cattle increased by 41%, 24%, and 8%. For dairy cow, due to the large decrease in the FCR, the total feed has decreased by 40% between 1960 and 2016. Feed composition has shifted from pasture and crop byproducts to grains and oil meals. The largest increase in animal feed was observed for grain and oil meals, which increased by 52% and 23%, respectively. This relates to the shift from pasture-based extensive

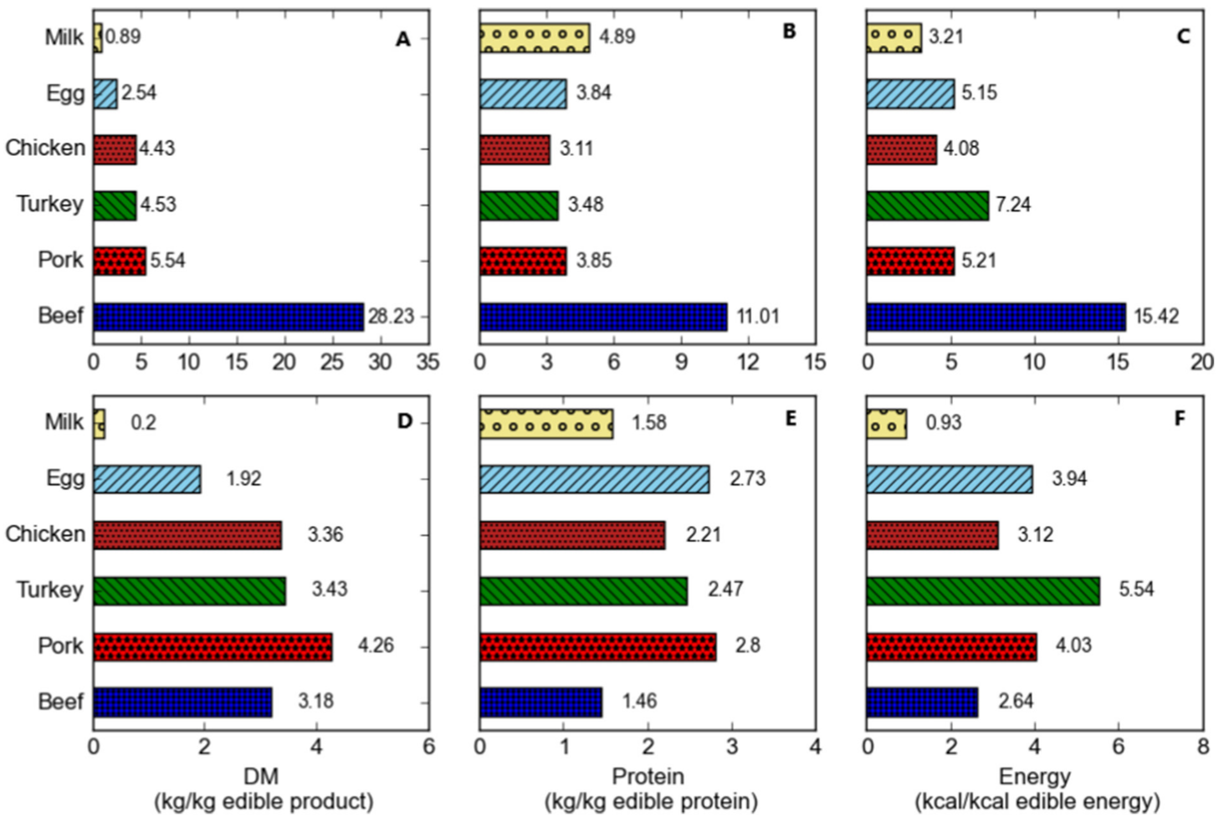

Fig. 4. Feed conversion ratio of different animals expressed in terms of total feed consumed (A-C) and human edible feed consumed (D-F) per unit of edible output. The FCR is expressed in kg DM intake per kg edible animal product (A), kg protein in feed per kg protein in edible animal product (B), kcal feed per kcal edible animal product (C), kg of human edible DM intake per kg edible animal product (D), kg protein in human edible feed per kg protein in edible animal product (E), and kcal of human edible feed per kcal of edible animal product (F).

systems to more intensive animal production systems and to the increasing fraction in total livestock of monogastric animals that rely on human edible feeds. The shift to monogastric animals (poultry and swine) in meat production is also evident from the decline in the contribution of beef in total meat production from 67% in 1960 to 30% in 2016.

The total annual feed requirement in the US averaged over 2014–2016 was 412 ± 12 Tg DM/y (Table 3). The largest share of the total feed (53%) was used for beef cattle, 19% for dairy cow, 12% for broilers (meat chicken), and 11% for swine.

The feed compositions vary among the livestock categories (Fig. 5). Monogastric animals (broilers, turkey, egg chicken, and swine) rely mostly on concentrate feed: 66% grains and 28% oil meals for poultry, and 79% grains and 17% oil meals for swine. In contrast, pasture and forage contribute the largest share to the feed of ruminants. Beef cattle's feed is composed of 42% pasture, 39% forage, and 7% crop byproducts. The feed of dairy cattle is 32% from pasture, 28% from forage, 16% from oil meals, and 16% from crop byproducts. A detailed breakdown of feed per livestock category is presented in Table S6.

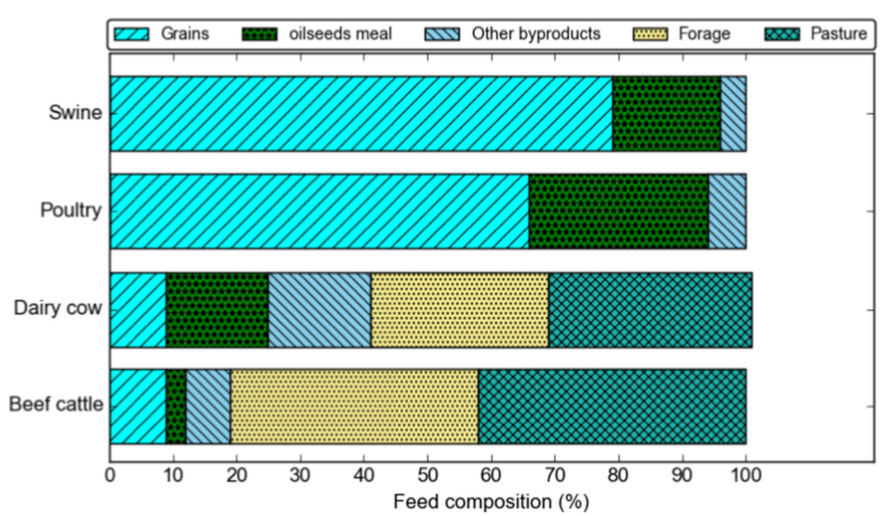

Fig. 5. Feed composition per livestock category.

3.4. The water footprint of animal production

The total consumptive WF per animal category and feed type is shown in Table 4. The total WF of livestock production in the US averaged over the period 2014–2016 was 275 km^3/y (91% green and 9% blue WF). About 99% of the WF of livestock production is related to the feed they consume. Direct water use in the animal farms (drinking and service water) accounts for only 1.3% of the WF. A large share of the WF of the feed is related to forage including corn & sorghum silage, alfalfa, and other forages (30%), followed by corn (18%), soybean meal (16%), and pasture (15%).

Beef cattle contributes most (48%) to the total WF of livestock production in the US, followed by dairy cattle (20%), broilers (14%), and swine (12%). Although, beef cattle contribute most to the total WF of livestock production, about 84% of the WF is related to forages, pasture, and crop byproducts that account for 49%, 24%, and 11% of the WF of beef production, respectively. In contrast, a large share of the WF related to the production of poultry and swine products is related to grains (corn, soybean, wheat, sorghum, and oats), accounting for 52 to 63% of the WF of poultry and swine products. The total WF has decreased by 36% between 1960 and 2016. This is due to the combined effect of increase in animal productivity (output per head) and the increase in yields of feed crops that resulted in a decrease of average WF of animal feed. A detailed breakdown of the WF per feed type per livestock category is presented in Table S7. The green, blue, and total consumptive WF per animal category between 1960 and 2016 is presented in Table S8.

3.5. Changes in the water productivity of livestock products

The WP of all livestock products has increased considerably from 1960 to 2016 (Fig. 6). The biggest increase was for dairy milk, which increased 4.9 times, followed by pork, which increased 3.8 times between 1960 and 2016. The WP of poultry products (chicken and turkey meat and egg) increased 3.2 times during the same period. For beef, WP has doubled during the same period. The increase in WP is attributable to a combination of factors, including the improvement in livestock productivity (output per head) as shown in Fig. 3, the decrease in feed requirement per unit of output (FCR), and the increase in yields of feed crops that resulted in a decline in the average WF of feed. The fluctuations in WP around the increasing trend lines are mainly due to interannual variations in rainfall. WP declines occur during dry years when yield of feed crops drop due to rainfall shortage. The largest decline in WP occurred in 2012, which was drought year (Scientific American, 2013). Rainfed feedstuffs were particularly affected by the drought causing a relatively large decrease in the WP. Feeds that are irrigated were also affected but the use of irrigation water helps to reduce the effect of droughts. Annual WP per livestock category is provided in Table S9.

3.6. Water productivity per livestock product

The WP in kg/m^3 for the six livestock products in the US is shown in Fig. 7(A). The WP of livestock products varies depending on the feed conversion ratio and the feed composition. The average WP of the different livestock products ranges from 0.06 kg/m^3 for beef to 1.54 kg/m^3 for milk. The variability ranges in the WPs are also shown in Fig. 7. While the WP of cattle meat varies widely around the mean (with a standard deviation of ± 68% around the mean WP), the WP of pork has the lowest variability with a standard deviation of ± 29%. The large variability in the WP beef is due mainly to the wide variability of the WF of forages (alfalfa, other hay & haylage, silage, and pasture) across the US.

Since the animal products considered have different nutritional values, we have normalized the WP values on the basis of the protein and energy content of the final livestock products. As shown in Fig. 7(B and C), comparing WP across animal products in terms of the nutritional content (protein or energy) per cubic meter of water consumed gives another picture than when we compare WP across animal products in terms of the product weight obtained per cubic meter of water consumed. When we look in terms of the energy content of the final product (Fig. 7C), milk and chicken meat have the largest WP, followed by pork and egg. In terms of protein content of the final product (Fig. 7B), the poultry products (chicken meat, turkey meat, and egg) have the largest WP, followed by pork and cattle milk.

3.7. Effect of substituting corn and soybean with distillers grains on the WP of livestock products

The US ethanol industry produces a large amount of animal feed in the form of distillers grains (DGs). The DGs are good low-cost animal feed with high energy and protein content. For ruminant animals, the energy content of distillers grains is larger than corn, providing approximately 30 to 50% more energy compared to an equivalent amount of corn (Erickson et al., 2005). Because of the high energy and protein content of DGs, they can substitute for corn and soybean meal in cattle diets (Hoffman and Baker, 2011) (see Sub-section 2.8). As a byproduct of corn ethanol production, the WF of DGs is smaller than the WF of

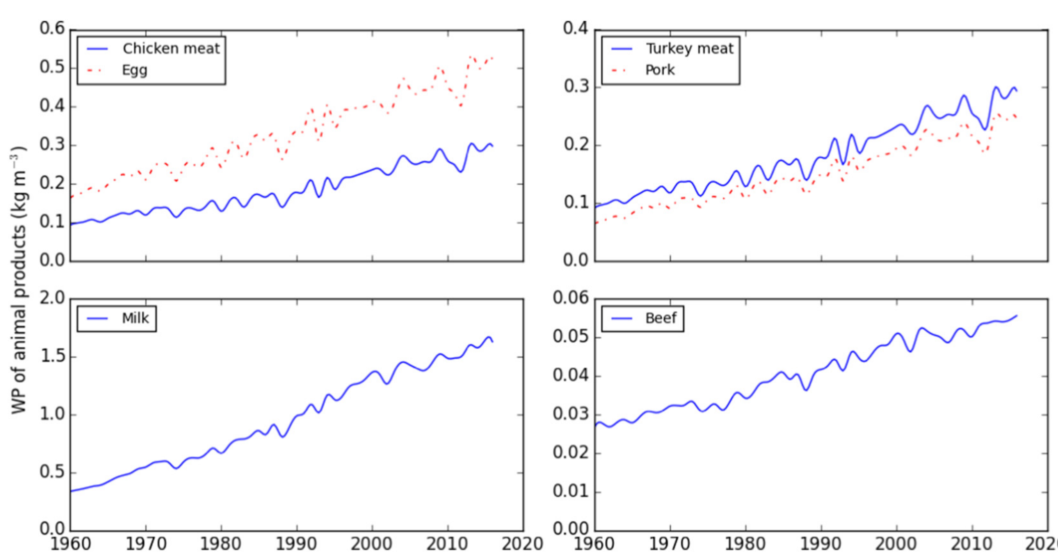

Fig. 6. Long-term changes in the WP of chicken meat, turkey meat, egg, pork, beef, and milk for the US.

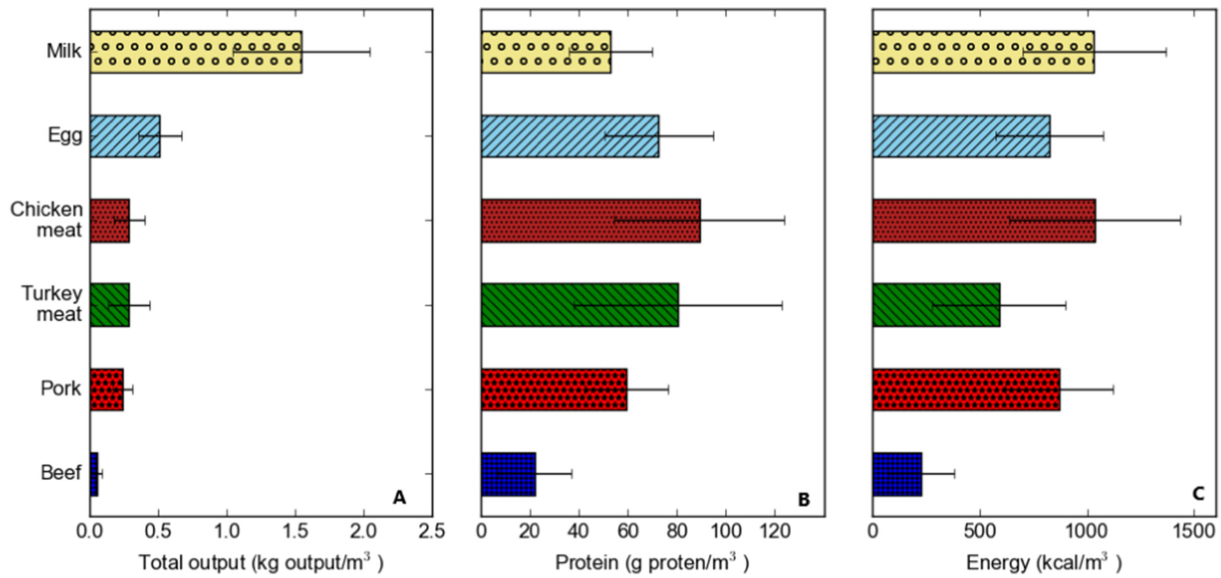

Fig. 7. Water productivity of the six livestock categories in terms of product weight (A), protein content in the animal product (B), and energy content of the animal product (C) per cubic meter of water consumed, in the US averaged over 2014–2016. Variability is visualized through the standard deviation (± 1SD) around the mean.

corn or soybean as primary products. Thus, using DGs for animal feed to substitute corn and soybean will reduce the WF of the feed for livestock.

The WP of the animal products increases in all cases but with different magnitudes depending on the volume of corn versus soybean substituted (Fig. 8). The increase in WP is largest for dairy milk because here the DGs replace a relatively large portion of soybean, which has a relatively large WF. This simple example illustrates that choosing feed ingredients and sourcing wisely, and particularly substituting crops with co-products or crop residues, will help to improve the WP of livestock products, thus reducing the pressure the sector puts on scarce water resources.

4. Discussion

The result from the current study can be compared with values found in the literature at three levels: feed conversion ratios, total feed requirement, and finally the WP of livestock products (Table 5). The feed conversion ratios and the total feed values estimated in the current

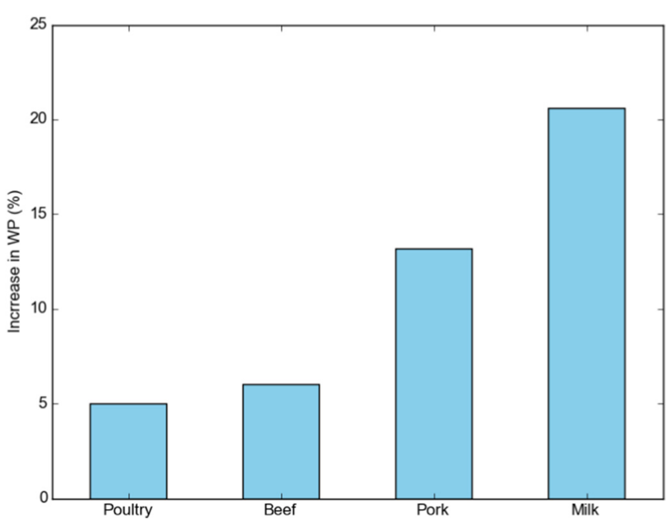

Fig. 8. The increase in water productivity of the different animal products by partial replacement of corn and soybean by DGs in the diet of the four livestock categories considered for the US.

study are very close to the values from literature. The feed conversion ratios from Bouwman et al. (2005) for swine is relatively large compared to the other studies. Otherwise, the estimated FCR is very close values from the literature. The similarities in the FCR between the current study and the value from Peters et al. (2014) are not that surprising because of the similarities in the approach used in the two study. In calculating the FCR, this study and Peters et al. (2014) have followed a stocks and flows approach for each livestock category at different stage of development. The total feed per livestock category estimated in the current study is also close to the literature values. The current study has underestimated the total feed by 11–15% compared to that found in the literature. The total feed estimate of Bouwman et al. (2005) for 1995 was 4.1% larger than the value from the current study.

Studies that have estimated the WP or the WF (inverse of the WP) of livestock products are very limited. The most comprehensive studies on the WF of livestock products are those by Chapagain and Hoekstra (2003) and Mekonnen and Hoekstra (2012). We calculated the WP of the livestock products as inverse of the green plus blue WF values from Mekonnen and Hoekstra (2012) in order to compare the values from current study against Mekonnen and Hoekstra (2012). The WP value from the two studies for milk, chicken meat, and pork are very close with a difference of 2–13%. The WP value from the current study is 25% and 27% smaller than the value from Mekonnen and Hoekstra (2012) for beef and egg, respectively. The difference could be the difference in the approach used and difference in the WF of the feeds used in the two studies.

Although the result from the current study is close to the literature values, there are a number of limitation and uncertainties surrounding the result. Owing to data limitations, we have made a number of assumptions to come to the final result. In particular, the feed quantity and the feed mix were derived based on literature and national level data that didn't take into account the variation within different production systems across the US and different years. Decision on the amount and type of feeds supplied to the livestock depends on the availability, price, and transportation cost of the feed. However, in the current study we have assumed the different livestock in a certain category are fed the same type and quantity of feed across the US. Besides, in deriving the FCR we have taken the feed requirement per unit of body weight or output from the literature. These feed requirements are an optimal feed requirement of the animal rather than actual

Table 5
Comparison of the results from the current study with literature values for the US.

	Study	Period	Chicken (meat)	Turkeys	Swine	Layers	Beef cattle	Dairy cow	Total
Feed conversion ratio (kg DM/kg product)	Peters et al. (2014)	2003–2012	2.6	3.4	3.6	2.3	20[a]	0.9	
	Eshel et al. (2014b)	2000–2012	1.8	2.6	3.2				
	Bouwman et al. (2005)	1995	3.1		6.2		24	1.0	
	Mekonnen and Hoekstra (2010)	1996–2005	3.4		4.0	2.3	24	1.1	
	Current study	2014–2016	2.7	3.6	4.0	2.3	20	0.9	
Total feed (Mt DM/y)	Eshel et al. (2014b)	2000–2012	40	9.0	43	9.7	283	73	457
	Bouwman et al. (2005)	1995							475
	Mekonnen and Hoekstra (2010)	1996–2005	48		35	12	286	83	463
	Current study	2014–2016	49	9.4	44	14	219	77	412
WP (kg/m^3)	Mekonnen and Hoekstra (2012)	1996–2005	0.31		0.21	0.75	0.07	1.55	
	Current study	2014–2016	0.29	0.29	0.25	0.58	0.06	1.54	

[a] Took weighted average of the FCR of beef from beef herd and dairy herd.

consumption. Therefore, we may have overestimated the FCR and the dry matter intake estimated in the current study.

The other issue involves the source of feed. Feed can be sourced from domestic production or/and imported. In the current study we have assumed the feed comes fully from domestic sources. As the US is the major producer of the different feeds, this assumption at the US level may have little effect. Nonetheless, we believe some of the potential uncertainties are captured in the uncertainty ranges provided for the WP values.

The current study has left out information on the WP of meat and milk from sheep and goats. The main reason for not including these products in the analysis was that they have minor contributions to the national meat and milk production. In addition, there was no consistent data on the production (output per year) and productivity (output per animal) over the study period. Future studies may include these products in the analysis as information on the WP of meat and milk from sheep and goats could provide additional information for developing strategies.

The study also focused on the water consumption related to feed production and neglected the water pollution associated with feed production and nutrient from the manure waste. Nutrients loads from artificial fertilizers and manure could have a very high impact on the water quality in some part of the US. Therefore, future studies need to be able to account for such negative effects. There is a need for better documentation of the volume and type of feed consumed by each livestock category in order to reduce the uncertainty.

5. Conclusion

This study shows that water productivities of all animal products in the US improved since 1960. Compared to 1960, less water was needed per unit of animal product in 2016: about one half for beef and one fourth for milk. The improvement in WP is attributed to a combination of factors: larger livestock output per head, lower feed requirement per head, and larger yields of feed crops. Increases in crop yields helped to decrease the water intensities or WF of the feedstuffs, thus reducing the water required per unit of feed consumed. However, the livestock sector still consumes large amounts of water, contributing to the competition over scarce freshwater resources. To address its potential impacts on the water resource, coordinated action is required to further improve the WP.

The WP of livestock products is a function of the feed conversion ratio and the WF of the feed products. The feed conversion ratio, defined as the feed consumed per unit of product output, covers two factors: from feed to animal and from animal to product output. The latter part is captured by the measure of livestock productivity, defined as product output per animal. Further improvement in WP requires a combination of measures. Livestock productivity and feed-use efficiency can be improved by better animal management. The WF of feeds can be lowered by increasing the use of crop residues and crop byproducts with small WF, and by sourcing feed from places where it has a smaller WF. The WP of livestock products can be raised by improving the feed conversion ratio and by reducing the WF of the feed. Feed conversion ratios can be influenced by choosing different breeds. The WF of the feed can be reduced by selecting feeds with smaller WF, substituting crops with by-products and crop residues, and sourcing feeds from places where the WF is lower. The use of by-products and crop residues will reduce the overall water demand to produce feed, thus reducing water abstractions from aquifers and rivers. The study shows that by partially replacing corn and soybean in the animal diet by DGs, the WP improves between 4.0% (for poultry) and 21% (for dairy milk).

The current study provides quantitative analysis of the amount and composition of feed for livestock and how productivity improvements have helped to reduce the amount of feed required per unit of livestock product in the US. A detailed estimate of the quantity and type of feeds per livestock category, as done in this study, can facilitate the assessment of environmental impacts of each livestock category.

In terms of total feed consumed, the calculated FCRs show that monogastric animals (poultry and swine) have a lower feed requirement per unit of output than beef cattle. In terms of human edible products, the FCR of beef cattle is smaller in terms of human edible feed consumed per unit of output than the other meat producing animals (poultry and swine) because beef production relies on non-human edible forage, pasture, and crop by-products. The relatively low FCRs (high feed-use efficiencies) of the monogastric animals in terms of total feed consumed is due to the high quality of the feed they consume. Therefore, we need to take care not to misinterpret the low FCR in terms of total feed consumed as indicator of low environmental impact. Monogastric animals largely or fully depend on concentrate feeds such as corn, soybean, and other crops that could be used for human consumption. In addition, these concentrate feeds are mostly produced in intensive agriculture that requires large amounts of nutrients and irrigation water, thus putting pressure on freshwater resources in terms of consumption and pollution. Although a large fraction of the feed for beef cattle comes from pasture with no irrigation and artificial fertilizer inputs, the high FCR of beef cattle lowers its output per cubic meter of water compared to swine or poultry. Unlike poultry and swine, the parent population of the beef herd consumes a large share of the metabolizable energy required for maintenance, making the overall beef production less efficient in terms of converting feed to final product. Therefore, manipulating the traits of the breeding cow as well as the slaughter animal would help to increase the overall efficiency of the beef production system (Webster, 1989).

The observed increasing trends in WP of all livestock products are encouraging, but the question is whether these trends will continue. Another question is: what benchmark level could be used as a reference to measure the progress in the livestock WP? There are a number of efforts to benchmark the WP or WF of crops (Chukalla et al., 2017; Edreira et al., 2018; Mekonnen and Hoekstra, 2014) but none in the case of livestock products. Setting benchmarks, estimating the WP gaps, and identifying the critical factors are potential future areas of research.

The increase of WP of livestock products is mostly in the hands of livestock farmers, who choose breeds and determine feed composition and sourcing, and feed crop farmers, who can increase the WP in feed production by soil mulching and applying better agricultural practices that result in higher yields at the same or less water consumption. Governments can play a role by providing incentives or regulations to stimulate certain choices and practices and discourage others. A particular role for government is to promote the use of crop residuals and by-products as feed rather than primary crops.

Declaration of competing interest

The authors declare no competing financial interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105084.

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